Reliability of nanocrystalline diamond MEMS capacitive switches

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***Abstract*—A solution to mitigate the dielectric charging and to improve reliability of RF MEMS switches is the replacement of the commonly used dielectrics with others that allow fast draining of the injected charges. One of the materials that have been successfully incorporated is diamond. The present paper presents both the charging and discharging process characteristics in MEMS having nanocrystalline diamond dielectric films. The study is performed by monitoring the charging and discharging current transient in MIM capacitors and the shift of the bias for minimum up state capacitance before and after progressively increasing stressing time tests. The results reveal that diamond is very promising material to improve the device reliability.**

Keywords—Diamond; RF MEMS; Dielectric Charging; Reliability

I. INTRODUCTION

Micro electro mechanical Switches (MEMS) offer many advantages over the conventional semiconductors counterparts for RF application, such as low insertion loss, low power consumption and higher linearity [1]. Beside that and the fact that a lot of research effort has been already spent their commercialization is still hindered by issues related to the charging of the solid dielectric film. Both silicon dioxide and silicon nitride deposited by low temperature processes that are commonly used as insulating films have been found to store charges for very long time, longer than 10^4 sec [2]. These stored charges are responsible for undesirable device behavior such as shift of pull – in and pull – out voltage, up to device failure due to bridge stiction [3].

A solution to mitigate the dielectric charging and thus to improve the device reliability requires the introduction leakage paths, a technique that has not been fully developed yet [4] or the replacement of the commonly used insulating films with others that allow the fast draining of the injected charges. One of the materials that have been successfully incorporated is non crystalline diamond [5-7]. The reduced dielectric charging effects have been initially reported in ultra-nanocrystalline diamond MEMS in [6] where the time constants for the bridge release, revealed by monitoring the switch recovery, time were found to be 5-6 orders of magnitude faster than those for the conventional insulating films. Similar results have been also reported for nanocrystalline diamond films where the discharging current recorded in MIM structures revealed a very fast relaxation process in comparison to silicon nitride while in the case of MEMS the short term cycling test had only minor effect on the pull-in voltage [7]. In spite of these efforts the long term dielectric charging still has not been investigated in diamond based MEMS.

The present paper shows for the first time the long term discharging process in nanocrystalline diamond film MEMS capacitive switches. The study has been performed by the simultaneous assessment of both MEMS switches and MIM capacitors fabricated on the same chip. The stressing time has been progressively increased up to observation of onset of saturation. The discharging process has been monitored through the shift of the bias for minimum up-state capacitance. Complementary information has been obtained by the analysis of both the steady state and transient response of MIM capacitors.

II. THEORY – THE DISCHARGE IN MEMS SWITCHES

The charging of dielectric film in MEMS capacitive switches affects the capacitance-voltage characteristic of the devices. Theoretical analysis of the charging effect has revealed that its impact is twofold: i) the shift of the C-V characteristic directly determined by the net charge at the dielectric film surface and ii) the narrowing of the pull-down and pull-up windows that is caused from the non uniform distribution of charge, arising from asperities or non flat electrode/dielectric surfaces [3]. The later is also caused by creep and the separation of the two contributions is not always easy. Here it must be pointed out that the proper selection of a switch with almost parallel armatures diminishes significantly the error of the calculation of net charge at the surface of the dielectric film during electrical stress. This procedure has been successfully applied and allowed the calculation of the

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dielectric film surface charge and the discharge current arising from charge collection through the dielectric film [8].

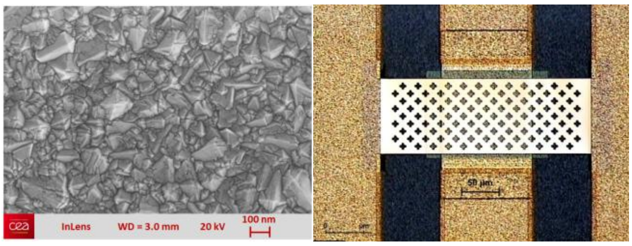
In principle the bias at which the up-state capacitance attains minimum (V_{min}) is the one for which the electrostatic force becomes minimum independently of the uniformity of charge and air gap distributions as well as the bridge deformation. Assuming that the deformation of moving armature in the up-state is minimal then the relation between V_{min} and the net charge density μ_{ψ} at the surface of the dielectric film is given by:

$$V_{\min} = \frac{d_e}{\varepsilon_r \varepsilon_0} \mu_{\psi} \quad (1)$$

where d_e is the film thickness and ε_0 and ε_r the dielectric constants.

III. EXPERIMENTAL

The tested devices were bridge type RF MEMS capacitive switches with 500 nm nanocrystalline diamond dielectric film as well as MIM structures fabricated on the same chip under the same conditions.



(a) (b)

Fig.1 (a) HRSEM of the diamond film surface and (b) RF MEMS capacitive switch

Nanocrystalline diamond films deposited by Microwave Plasma assisted Chemical Vapor Deposition (MPCVD) on Si(100)/TiW/Au substrate. Plasma treatments were performed in a home made designed MPCVD reactor equipped with a 2.45 GHz – 2 kW SAIREM microwave generator. The base pressure inside the chamber was about 10^{-9} mbar. High nucleation density is needed for the early stage of diamond growth in order to form rapidly a continuous diamond film. Nanoseeding technique [9], which consists in the deposition of diamond nanocrystals by spin coating on the substrate, was used to obtain crystal density higher than 10^{11} cm^{-2}. Then synthesis of the nanocrystalline diamond film with columnar structure was performed by MPCVD with a mixture of methane (CH_4) at 0.6% diluted in hydrogen (H_2). The total pressure, total gas flow rate, and microwave power during the growth were maintained at 35 mbar, 250sccm, and 900 W. During growth the film thickness is monitored by a home-made laser interferometry system [10]. This system is used to stop the experiment at the desired thickness. The surface morphology was characterized by SEM (fig. 1a) and AFM images and shows a nanocrystalline structure with a grain size around 90nm and a RMS of 20 nm on 2x2μm^2.

The capacitance voltage characteristics have been obtained by a Boonton 72B offer sub-fF resolution while the applied bias provided by the voltage source of a Keithley 6487. The latter has been also used to measure the static and transient current across the MIM structures. Both the charging and discharging processes were monitored by recording the shift of the bias for minimum up state capacitance as obtained by the continuously recording of the C-V characteristics [8] in the up-state. The charging was performed by applying an electric field intensity of 1.2 MV/cm that corresponded to 60 V (about 1.4xVpi) and increasing progressively the charging time up to the point where onset of saturation was observed (3600 sec).

Finally, all measurements have been performed at room temperature in vacuum after annealing at 140^{o}C, in order to avoid any interference from humidity.

IV. RESULTS AND DISCUSSION

Metal – Insulator – Metal (MIM) capacitor is the simplest device to study the dielectric charging and asses the material properties it self. However the metal to insulator contact in a MIM capacitor is almost perfect a fact that does not occur in a real MEMS switch. Moreover as it has been theoretically calculated [11] and recently practically confirmed the injected charges are confined near the injected electrode. Thus all methods applied in MIM are leading to assessment of injection/collection from the injecting electrodes. In consequence no information on the discharging through the different electrode may be obtained from the analysis of MIM behavior. For this reason a comprehensive study must include experimental observations in both MIM capacitors and MEMS switches.

A. *Assesment of MIM capacitors*

The MIM assessment includes the recording of current voltage characteristics (I-V) as well as the transient device response. The analysis of I-V curves provide the corresponding conduction mechanism under various operation conditions and can lead to conclusions correlating the conduction paths to material properties.

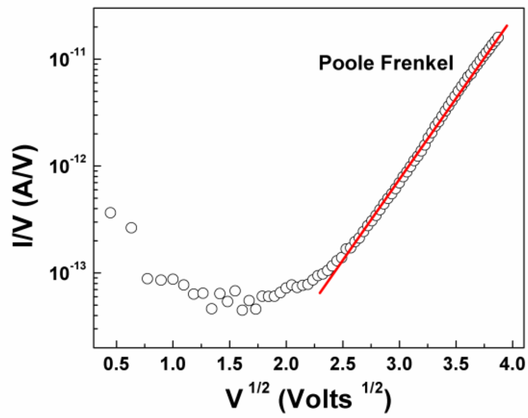


Fig. 2 Signature of Poole Frenkel conductivity for field intensities higher than 150 KV/cm

The straight line that is obtained in the I/V vs √V plot in figure 2 corresponds to Poole Frenkel conduction above 150 KV/cm, while at lower fields the conduction mechanism at room temperature is either due to hopping or thermal generation depending on the energy distribution of band gap states.

Regarding the transient device response, the discharging current transient after charging up to saturation at 250 KV/cm is presented in figure 3.

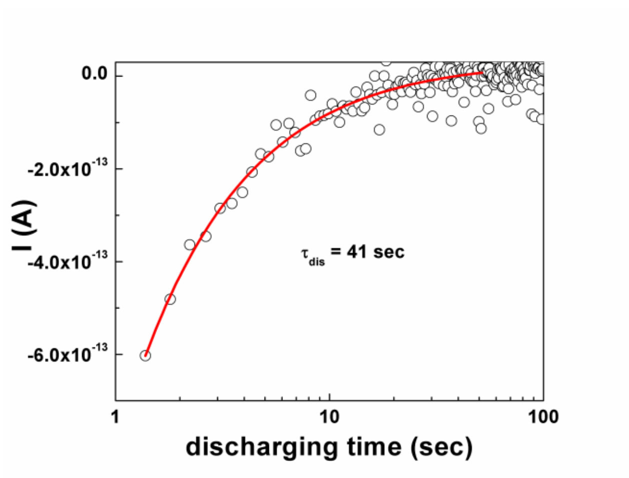


Fig. 3 Stretched exponential discharging relaxation is obtained in MIM structures

The decay is found to obey the stretched exponential relaxation rather than a single exponential one.

$$I_{dis} = I_0 \exp\left[-\left(\frac{t}{\tau_{dis}}\right)^{\beta}\right] \qquad (2)$$

The stretched exponential relaxation has been associated to the emission of trapped charges from a distribution of trap states mainly located to the boundaries of polycrystalline materials. The obtained time constant for the discharging process is τ_{dis} = 41 sec. The latter result clearly supports the use of nanocrystalline diamond films as dielectric in RF MEMS capacitive switches since the typical values for the discharging process obtained in MIM structures with the commonly used Si_3N_4 extends to hundreds of seconds [12].

B. Assesment of MEMS capacitive switches

The charging characteristics of nanocrystalline diamond MEMS switches have been obtained by recording the shift of bias for minimum up state capacitance between the virgin curve and the first of the curves recorded just after the end of the charging. The voltage shift (ΔV_{min}) corresponds according to Eq.1 to the accumulated charge at the film surface. The results reveal that the long term charging process in diamond MEMS tend to saturate in about an hour. The extracted saturation voltage shift is ΔV_0 = 2.24 V correspond to equivalent surface charge density of (Eq. 1) μ_ψ = 21.8 nC/cm^2.

In MEMS switches the charging process is mainly determined by the microstructure near the surface of the film [11]. The space charge is determined by simultaneous charge injection from the metallic electrodes via trap assisted tunneling (TAT) and/or field emission process in non contacting areas [13] and the charge redistribution. The latter as revealed from the I-V analysis (Fig. 2) of MIM capacitors in our case occurs through Poole Frenkel emission of already trapped charges.

Regarding the discharging process, this was monitored from the shift of bias for minimum capacitance versus time after 3600 sec down state stress. Figure 4 presents the typical behavior of the C-V curves during the discharging process.

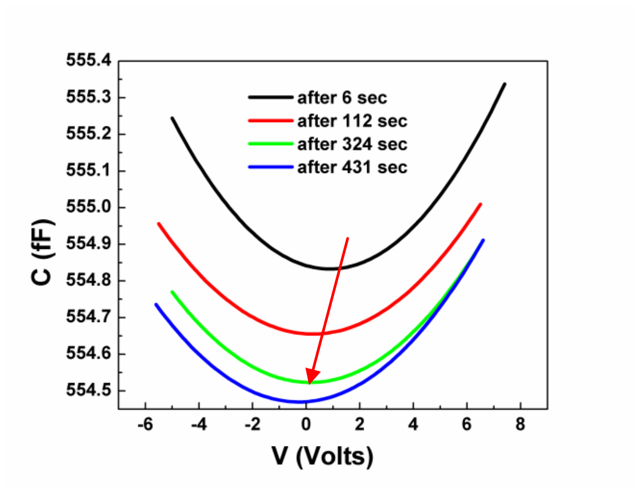


Fig. 4 C-V curves during the discharge

The shift of bias for the minimum capacitance (ΔVmin) corresponds to the discharging decay and presented in figure 5. The discharge in nanocrystalline diamond MEMS switches has been also found to obey the stretched exponential relaxation as in the case of MIM capacitors.

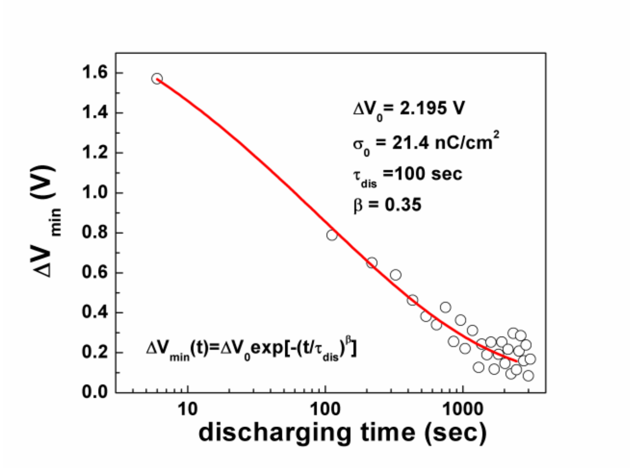


Fig. 5 Shift of V_{min} vs discharging time

In this point it is important to notice that the extracted parameters correspond to equivalent surface charge density of μ_ψ = 21.4 nC/cm^2, that is very close to the values estimated from the analysis of the charging process, presented above. Moreover the relaxation time constant in this case is τ_{dis} = 100 sec revealing a slower relaxation process in comparison to MIM capacitors. The latter is an expected result due to differences in the collection mechanisms. In order to get a better insight on the different mechanisms it is essential to bear in mind that the discharge in MEMS switches occurs in the up-state under the presence of a low intensity electric field that is generated by the trapped injected charges. Thus the injected charges are collected by the bottom electrode, and not from the injecting one, the moving armature, in contrast to MIM capacitors. The discharging current in MEMS occurs mainly through hopping of carriers via gap states, related to the presence of extended defects [14]. Specifically, the conductivity in diamond films is directly related to grain boundary defects and more precisely to the ratio of sp^2/sp^3 bonded carbon, which is directly related to the ratio of non diamond carbon over diamond carbon phase [15]. For the material used in present work electron microscopy analysis revealed that the dielectric film is more defective near the bottom electrode. Thus an enhanced conductivity is expected at the film/bottom electrode interface. The increase of grain size close to the top surface gives rise to a percolative conduction that can be considered to be responsible for the stretched exponential relaxation in the discharging mechanism.

Finally, the short time constant, compared to conventional dielectric materials such as Silicon dioxide or Nitride [2], indicates that the nanocrystalline diamond is a promising material for fabrication of reliable RF MEMS switches.

V. Conclusions

The long time discharging process is presented for the first time for nanocrystalline diamond RF MEMS capacitive switches. The charge collection has been monitored through the shift of bias for minimum up state capacitance as well as by analyzing the steady state and transient response of MIM capacitor fabricated on the same chip. The results revealed that the discharging processes obey the stretched exponential relaxation. The time constants in both MIM and MEMS structures are found to be in the range of seconds. The short time constants are attributed to the important role of the conductivity at grain boundaries to the collection of the injected charges. The specific electrical properties of nanocrystalline diamond with columnar structure obviously indicate that this dielectric material can be considered of being a potential solution for the issue of dielectric charging in MEMS capacitive switches.

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