Electrical Properties Of SiN_x Films Doped With CNTs for MEMS Capacitive Switches

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Abstract. The present paper aims to provide a better insight on the electrical properties of silicon nitride (SiN_x) dielectric films with embedded Multi-Walled Carbon Nanotubes (MWCNTs), that can be used in RF MEMS capacitive switches. The effect of the embedded MWCNTs on the leakage current density, on the discharging processes and on dielectric charging phenomena of the films has been probed with the aid of *Metal-Insulator-Metal* (MIM) capacitors

1. Introduction

Capacitive RF MEMS switches are quite promising devices for RF applications, since they offer several advantages over the conventional semiconductor counterparts [1]. They exhibit very attractive performance in terms of linearity, power consumption, losses and isolation. Despite these, MEMS switches suffer from reliability issues [1] that still remain unsolved. One of the most important reliability problem is the effect of dielectric charging, which causes erratic device behaviour and limits the device lifetime [1 – 3].

On the way to solve this problem and prevent dielectric charging phenomena the electrical properties of different dielectric materials [4 – 12] have been intensively investigated. Moreover, several approaches have been proposed up to now, such as the fabrication of MEMS switches with dielectric-dielectric contact [13], the dielectric film removal and replacement with pillars [14] or the introduction of side actuation pads and the exposure of the CPW capacitor only to RF signal [15]. Despite these, dielectric charging remains an unsolved issue for RF MEMS switches. Meanwhile different theoretical models have been derived that take into account the distribution of injected charges in the insulating film band gap assuming either band tails DOS [16] or a single level of traps [17].

In the case of non-stoichiometric $\mathrm{SiN}x$, it has been found that beyond the percolation threshold at x c = 1.0 the Si-Si bonds fail to form continuous percolation paths across the network [18] and thus the Si-rich material has been intensively investigated [4 - 9] in the view of providing a potential solution to mitigate the dielectric charging. An attempt to further increase the percolation paths and therefore the draining of injected charges has been reported by using gold nanorod array structured silicon nitride films [19]. Moreover, the use of carbon nanotubes (CNTs) doped silicon nitride films for RF MEMS switches was presented by C. Bordas *et al* in [20]. This nanostructured dielectric film exhibited a higher *Figure of Merit* [20] that was found to increase with increasing the CNTs density towards the percolation threshold [21]. Finally, the electrical behaviour of multi-walled CNTs (MWCNTs) network embedded in amorphous silicon nitride films of 8 μm thickness has been investigated by Stavarache *et al.*[22], proving the metallic behaviour of the MWCNTs network in silicon nitride matrix.

In view of these, this paper aims to present a different nanostructured dielectric material that consists of silicon nitride with incorporated MWCNTs. The electrical properties of these films have been investigated with the aid of *Metal-Insulator-Metal* (MIM) capacitors by measuring current-voltage (I-V) characteristics and by using *Thermally Stimulated Depolarization Current* (TSDC) and *Kelvin Probe* (KP) assessment methods. A reference $\mathrm{SiN}x$ material (without MWCNTs) has been also fabricated in order to investigate the impact of the embedded MWCNTs on the leakage current density, on the discharging processes and on the dielectric charging phenomena of the films.

2. Experimental Details

The utilized MIM capacitors (Fig. 1) have been fabricated with symmetric metal contacts (Pt/Au) of 1 mm diameter and the dielectric film was $\mathrm{SiN}x$ with embedded MWCNTs. The dielectric film has been fabricated with the following steps: First, 100 nm $\mathrm{SiN}x$ has been deposited on the bottom electrode with PECVD method. After that a solution of MWCNTs with propanol was deposited via spin coating and then a final layer of 100 nm $\mathrm{SiN}x$ was grown by PECVD to embed the MWCNTs. We mention that the diameter of the MWCNTs used in the present work is 1 nm and their length is 2 – 3 μm. Apart from these, a reference sample with SiN_x has been fabricated by PECVD method in two steps (100 nm each step)

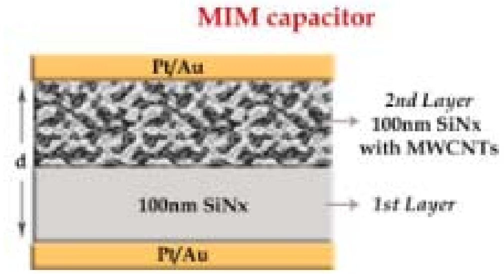
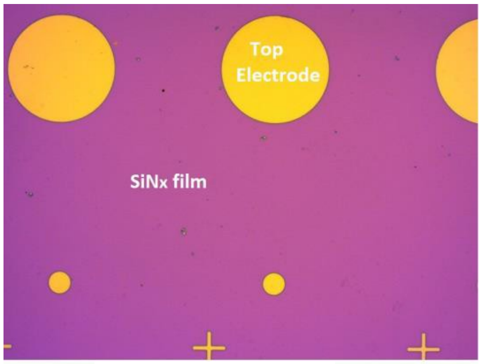
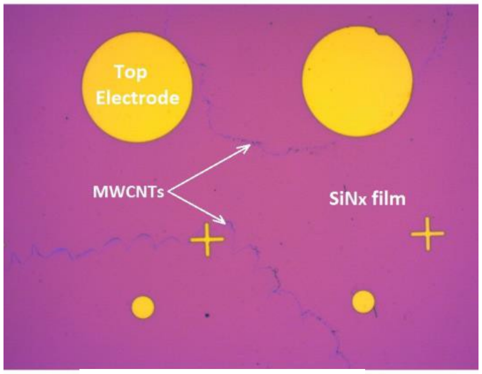


Fig. 1. Schematic representation of utilized MIM capacitors.



Reference SiN$_x$



SiN$_x$ *with MWCNTs*

Fig. 2. (Color on line). Photos of utilized samples with reference SiNx films (top) and SiNx films with embedded MWCNTs (bottom). White arrows show the embedded MWCNTs.

without using MWCNTs solution. Fig. 2 shows a photo of utilized MIM capacitors with reference SiN_x films and with SiN_x films doped with MWCNTs.

The capacitance of the samples has been measured with the aid of a Boonton 72B capacitance meter with a resolution of 0.05 fF.

Current-voltage (I-V) characteristics have been obtained for fields up to 2 MV/cm with the aid of a Keithley 6487 source-meter/electrometer. The DC bias was applied to the top electrode and the voltage ramp on I-V measurement was performed with a rate of 100 mV/s. We also mention that I-V measurements were performed in a vacuum cryostat and at room temperature.

The MIM capacitors have been also assessed with Thermally Stimulated Depolarization Currents (TSDC) technique in order to investigate dielectric charging phenomena. The polarization field's intensity was 2 MV/cm and the polarization bias has been applied to the top electrode of MIM capacitors at 450 K. The TSDC current has been measured under vacuum with the aid of a Keithley 6487 voltage source – picoampere meter, in the temperature range of 200 – 450 K and with a heating rate of 2.5 K/min.

Finally, the discharging process through the bulk material has been investigated with the aid of a single-point Kelvin Probe system (KP010), at room temperature and at ambient conditions. The Kelvin Probe is a non - contact, non-destructive vibrating capacitor device used to measure contact potential difference between a conducting specimen and a vibrating probe tip which is placed near the surface of interest. The surface potential of the utilized devices is thus directly measured during discharge, while the device is not in contact with the measuring system. A polarization field with intensity 1 MV/cm and 2 MV/cm has been applied for 5 min at room temperature. The following discharging process has been assessed by measuring the decay of surface potential using a Single Point Kelvin Probe system (KP010) for a time period of about 10^4s.

4. Results and Discussion

The capacitance of the utilized samples has been found to increase about 2% when MWCNTs are embedded into SiN_x matrix.

Figure 3 shows the I-V characteristics of MIM capacitors with reference SiN_x material and with SiN_x material doped with MWCNTs. It is thus interesting to notice that the leakage current of SiN_x/MWCNTs films is quite larger (*i.e.* almost two orders of magnitude) than the reference material.

In order to understand this behavior, it is important to bear in mind the following: The length of the incorporated MWCNTs is quite larger than the thickness of the second SiN_x layer (100 nm) and so it is expected that the MWCNTs will be distributed along the second SiN_x layer, thus producing an inhomogeneous electric field across this layer. Taking these into account and neglecting any interfacial phenomena that may be present between the two SiNx layers (due to the step deposition process of the SiNx material), we expect that when we apply a potential difference V across the metal electrodes of the MIM capacitor the applied electric field on the reference material will be homogeneous and its intensity will be V/d (d is the thickness of SiNx film). On the contrary, the applied electric field across the SiNx film with MWCNTs is expected to be inhomogeneous and its intensity is expected to vary between V/d and $2V/d$, since

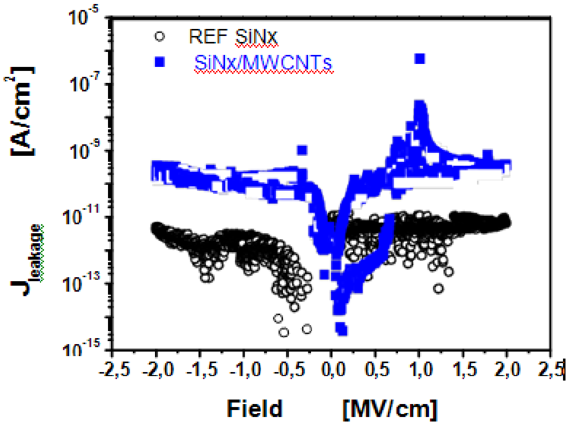


Fig. 3. I-V characteristics for reference SiNx material and SiNx with embedded MWCNTs.

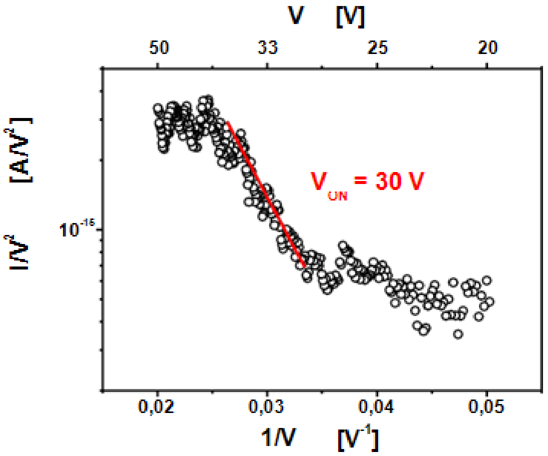


Fig. 4. FN signature plot for SiNx with embedded MWCNTs films, in agreement to Eq. 1.

it is possible that some MWCNTs may extend across the second SiNx layer up to the top electrode.

Apart from these, I-V characteristics revealed that field emission processes between CNTs arise on SiNx films when MWCNTs are present, for applied electric field intensities larger than 1.5 MV/cm. Figure 4 presents the characteristic signature plot of *Fowler-Nordheim* (FN) mechanism that describes field emission processes. *Fowler–Nordheim* (FN) theory describes the emission of electrons from a metal due to very high electric field and it takes place through sharp asperity paths, where the electric field is locally enhanced by several orders of magnitude. In terms of measured current (I) *versus* applied bias (V) the Fowler–Nordheim equation is expressed as [23]:

$$I = A \cdot V^2 \cdot \exp\left(-\frac{B}{V}\right), \tag{1}$$

where A is a parameter proportional to effective emitting area (α) and the parameter B is inversely proportional to field enhancement factor (β) [23]. Assuming that the work function of the MWCNTs in our case is $\Phi = 4.5$ eV [24] we thus obtain that the effective emitting area is $\alpha = 4.3\mathrm{x}10^{-20}\mathrm{cm}^2$ and the field enhancement factor is found to be $\beta = 2.2\mathrm{x}10^6\ \mathrm{cm}^{-1}$. We mention that field emission has been also found to dominate conductivity on CNTs filled Polydimethylsiloxane composites [25].

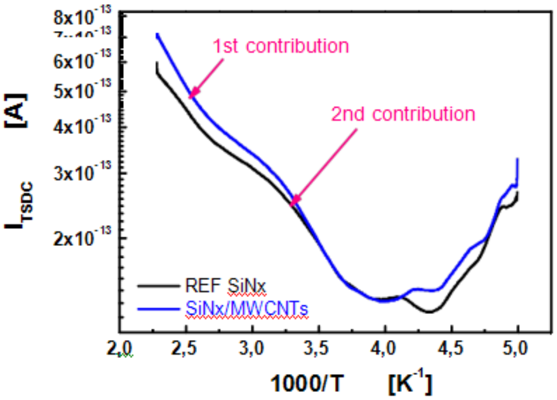


Fig. 5. TSDC spectra for reference SiNx material and SiNx with embedded MWCNTs.

TSDC assessment revealed that there is a minimum number of two contributing charging mechanisms on SiNx films (Fig. 5) that have been measured. Moreover, dielectric charging is enhanced when MWCNTs are incorporated in the SiN_x matrix. This may be attributed to the fact that the polarization field intensity on SiN_x/MWCNTs films is expected to be inhomogeneous and with larger intensity than the corresponding values that apply on the reference SiN_x material, as mentioned previously.

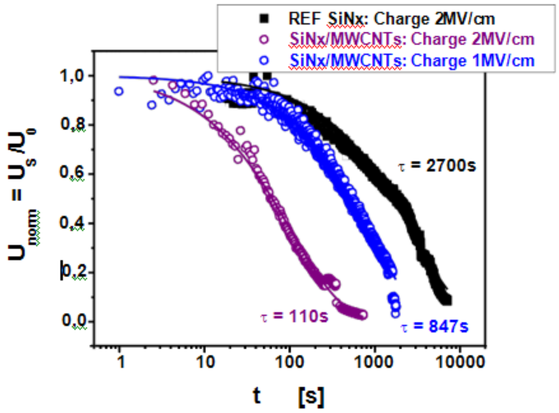


Fig. 6. Normalized values for the surface potential decay during discharge measured with KP system, for reference SiN_x material and SiN_x with embedded MWCNTs after charging the films for 5 min with electric field intensities of 1 MV/cm and 2 MV/cm.

Field emission processes that arise on SiN_x/MWCNTs films may also be responsible for enhanced dielectric charging phenomena on these films.

Finally, the discharging process through the bulk material has been investigated with the aid of KP method. The decay of surface potential (U_S) has been found to obey a stretched exponential law of the form:

$$U_s(t) = U_0 \cdot \exp\left[-\left(\frac{t}{\tau}\right)^{\beta}\right], \tag{2}$$

where U_0 is the surface potential immediately after charging (*i.e.* at t = 0 s), τ is the characteristic time of the discharging process and β is the stretched exponential factor with $0 < \beta < 1$. As presented on Fig. 6, it has been found that the incorporation of MWCNTs results to a decrease of the relaxation time to almost one order of magnitude. Further decrease of the discharging relaxation time has been observed on SiN_x/MWCNTs films as the intensity of the polarization field increases (Fig. 6). The increase of polarization field intensity is expected to shiftthe injected charges centroid deeper inside the film and thus facilitating charge collection from the bottom electrode.

6. Conclusion

A nanostructured dielectric material for RF MEMS capacitive switches has been fabricated by doping PECVD SiN_x films with MWCNTs. The fabrication process is quite simple and it takes place in two steps, in order to incorporate MWCNTs on the upper SiN_x layer. The electrical conduction processes of these films have been probed with the aid of MIM capacitors by measuring I-V characteristics and dielectric charging phenomena have been investigated with the aid of TSDC method. It has been then found that films with embedded MWCNTs exhibit larger leakage current density and field emission processes arise on these films when the intensity of the polarization field becomes larger than 1.5 MV/cm. The capacitance of the samples has been found to increase about 2% when MWCNTs are incorporated into SiN_x matrix and dielectric charging is also enhanced on SiN_x/MWCNTs films. Finally, the discharging process due to charge displacement through the bulk material and towards the bottom electrode has been probed with the aid of a Kelvin Probe single-point system and it has been found to be accelerated when MWCNTs are embedded into SiN_x material.

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