Transport and charging mechanisms in Ta$_2$O$_5$ thin films for capacitive RF MEMS switches application

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The potential of sputtered Ta$_2$O$_5$ thin films to be used as dielectric layers in capacitive radio frequency microelectromechanical system switches is evaluated by investigating two factors of crucial importance for the performance of these devices which are the transport mechanisms and the charging effects in the dielectric layer. We find that Ta$_2$O$_5$ films show good electrical and dielectrical properties for the considered application in terms of a low leakage current density of 4 nA/cm$^2$ for $E=1$ MV/cm, a high breakdown field of 4 MV/cm and a high dielectric constant of 32. For electric fields lower than 1 MV/cm the conduction mechanism is found to be variable-range hopping in the temperature range 300–400 K, while nearest-neighbor hopping is observed at higher temperatures. For fields in the range 1–4 MV/cm Poole–Frenkel becomes the dominant conduction mechanism. Current and capacitance transients used to investigate the charging effects show a decay which is well described by the stretched-exponential law, thus providing further insights on capture and emission processes. © 2010 American Institute of Physics. [doi:10.1063/1.3407542]

I. INTRODUCTION

Radio frequency (RF) microelectromechanical system (MEMS) switches have emerged as a serious alternative to solid-state GaAs or Si based devices thanks to several advantages such as the low power dissipation and insertion loss, high isolation, and linearity. However, in spite of the attractive capabilities, the reliability of RF MEMS components is still of major concern for long-term and broad-based applications and it is currently an area of intense research. To date, for capacitive RF MEMS switches the major reliability problem is the charging of the dielectric layer which covers the actuation electrode. This charging occurs in the down state when the membrane comes in contact with the dielectric layer and it is possible for charges to be injected and then to be trapped in the dielectric film. Even though the exact mechanisms for the transfer and trapping of charge are not known, the effects are measurable resulting in a change in the pull-down voltage and/or in the phenomenon of “stiction” which seriously limits the functionality of the device. This is because when charge becomes trapped within the dielectric, it tends to screen the applied electric field that is used to control the actuation and release of the switch. More specifically, as the charge builds up, the screening voltage detracts from the actuation voltage until there is no longer enough force pulling down the membrane to cause it to actuate. The opposite occurs when the actuation voltage is removed and the trapped charge provides enough potential to stick down the membrane.

In order to overcome the limitations of RF MEMS switches reliability, the evaluation of materials alternative to the ones commonly used as well as the investigation of the transport and charging mechanisms in the dielectric layer are required.

Ta$_2$O$_5$ is a good candidate for the application in RF MEMS switches thanks to its low leakage current density, high breakdown fields, high dielectric constant, and excellent step coverage characteristics which can be obtained by a number of methods compatible with both Si and GaAs technologies. In particular, the Ta$_2$O$_5$ dielectric constant (25–30) is much higher than that of SiN (6–7) and SiO$_2$ (2–4) which are the conventional dielectric materials used in RF MEMS switches. This aspect offers the important advantage that a higher capacitance ratio, $C_{down}/C_{up}$, can be achieved in RF MEMS capacitive switches with Ta$_2$O$_5$ as dielectric layer, thus improving the switch performance.

To the best of our knowledge, a general understanding of the leakage current in Ta$_2$O$_5$ films is gained but detailed information about the physics behind the transport properties and charging effects in Ta$_2$O$_5$ films under the application of external electric fields, as in the down state of capacitive RF MEMS switches, is still missing.

In this work a comprehensive investigation of the transport mechanisms and the charging effects in thin films of Ta$_2$O$_5$ in view of their application as dielectric layers in capacitive RF MEMS switches is presented. The investigated Ta$_2$O$_5$ films show a low leakage current density $J$ of few nA/cm$^2$ at the field $E$ of 1 MV/cm, a high breakdown field of 4 MV/cm and a high dielectric constant of 32 which are interesting values for the considered application. Furthermore, the analysis of $J$-$E$ characteristics performed as a function of the temperature allows the identification of the different conduction mechanisms. For low electric field values ($E\leq 1$ MV/cm) the current is observed to be due to variable-range hopping (VRH) in the temperature range 300–400 K, while nearest-neighbor hopping (NNH) is observed at

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higher temperatures. For high fields ($E$ in the range 1–4 MV/cm) Poole–Frenkel becomes the dominant conduction mechanism. Charging effects are investigated by current and capacitance transients finding that they are well described by a stretched-exponential law. The electric field-dependence of the stretched exponential fitting parameters is thus discussed providing information on the charging and emission processes.

II. EXPERIMENTAL DETAILS

Test capacitors with a metal-insulator-metal (MIM) structure were fabricated on (100) semi-insulating GaAs substrates. Ta$_2$O$_5$ thin films were deposited by RF-magnetron reactive sputtering from a high purity tantalum metal target (4 in. diameter). The Ta$_2$O$_5$ films were prepared at a fixed power of 200 W and a constant chamber pressure of 9 mTorr which was maintained by a mixture of argon and oxygen at a flow ratio of 1:2. The substrates were not intentionally heated during the deposition process. Both bottom and top MIM metallizations were deposited by magnetron reactive sputtering in a separate vacuum system. The bottom contact is a continuous multilayer Ti/Au/Ti (10/100/10 nm) over the wafer. The top electrode consists of square Ti/Au (10/300 nm) contacts with size of 180 \( \mu \)m which were realized by standard optical lithography. The Ta$_2$O$_5$ film thickness was measured by using an Alpha–Step IQ and results to be 324 ± 5 nm.

The structure and the composition of the deposited Ta$_2$O$_5$ films were analyzed by using x-ray diffraction and x-ray photoelectron spectroscopy, respectively. The films were found to be amorphous with a composition almost stoichiometric (ratio O/Ta = 2.46).

Ta$_2$O$_5$ film morphology was investigated by performing plan-view and cross-sectional scanning electron microscopy (SEM) images. In particular, the cross-sectional SEM images were recorded on cleaved surfaces obtained by using a focused ion beam (FIB). A typical cross-sectional SEM image of the investigated MIM capacitors is shown in Fig. 1. The different morphology of the various layers in the MIM structure is clearly observed with the Ta$_2$O$_5$ film which is noted to be dense and continuous over the whole surface.

All electric measurements were performed in an electromagnetically shielded K. Suss PM5 Probe Station. The leakage currents were measured by using two low-noise preamplifiers connected to a 4200 Keithley parametric system in order to apply a positive bias voltage at the upper contact of MIM structures and measure the current at the bottom electrode. The current detection limit in our measurements was ~2 fA. For stationary $J$-$E$ characteristics the voltage was stepped in 1 V increments and the data points were recorded after a delay time of 2 s. This delay time was chosen short enough in order to minimize the charging processes.

The capacitance transients were measured by using a HP4284A precision LCR-meter with a sinusoidal excitation voltage having an amplitude of 30 mV at the frequency of 1 MHz.

III. RESULTS AND DISCUSSION

A. Transport mechanisms

Figure 2 shows the typical $J$-$E$ curve measured at room temperature for the Ta$_2$O$_5$-based MIM capacitors. In the electric field range 0.2–1 MV/cm the current density increases approximately linearly with the field and the conductivity is very low. For these low electric field values, the current in dielectric films is expected to be due to the hopping conduction mechanism, i.e., the thermal excitation of trapped electrons from one trap site to another dominates transport in dielectric films. This hopping process leads indeed to a linear $J$-$E$ characteristic with conductivity exponentially dependent on temperature. For fields higher than about 1 MV/cm a kink in the current density is observed, which is indicative that a conduction mechanism different from hopping dominates. Irreversible dielectric breakdown occurs for $E$=4 MV/cm, consistently with the highest breakdown field values reported for Ta$_2$O$_5$ films.

The inset of Fig. 2 displays the $J$-$E$ characteristic under reverse applied voltage. No asymmetry is observed in the characteristic for both forward and reverse electric field.

In order to get deeper insight into the conduction mechanisms, $I$-$V$ characteristics at different temperatures in the range 300–480 K were performed. Figure 3 shows the Arrhenius plot of the conductivity, $\sigma$, in the low field regime ($E$=0.3 MV/cm). In particular, it is observable that no single law conduction can fit the entire curve of the conductivity. For the high temperatures ($T>$ 400 K), the conductivity data are well fitted in the Arrhenius plot by a straight-line with a slope of 934 meV, thus indicating that a simple thermal activation process describes the electrical conduction.

FIG. 1. SEM image of a MIM capacitor. The cross section on a cleaved surface was obtained by using a FIB.

FIG. 2. (Color online) Typical $J$-$E$ characteristic at room temperature. An 1-mA value is set as compliance level of the measurement. The inset shows the $J$-$E$ characteristic at room temperature under reverse applied voltage.
This result strongly suggests that the hopping process occurring for $T > 400$ K is the NNH in which electron hops to the nearest neighboring empty site with an activation energy almost corresponding to the magnitude of potential fluctuation of the hopping sites.\textsuperscript{12}

For temperatures lower than 400 K, a deviation from the linear dependence observed for $T > 400$ K is evident in the Arrhenius plot, while the conductivity data show a better linear behavior in the $\ln(\sigma)$ versus $T^{-1/2}$ plot (see inset of Fig. 3).

Similar changes in the temperature dependence of the conductivity have been observed in many amorphous materials and attributed to the transition from NNH to Efros VRH.\textsuperscript{13,14} In a disordered insulator, Mott first pointed out that electron hopping between nearest neighbor sites is not always favored with decreasing the temperature as the levels may be significantly different in energy. It is then possible that electrons prefer to move to a more energetically similar remote site, leading to a VRH mechanism.\textsuperscript{15} Hence, at a given cross-over temperature, the transition between the NNH and VRH occurs. In Efros VRH regime, the expected law for the variation of the conductivity is:\textsuperscript{16}

$$
\sigma = \sigma_0 \exp \left( - \frac{T_0}{T} \right)^{1/2},
$$

where $\sigma_0$ is a pre-exponential factor and $T_0$ is a characteristic temperature given by the slope of data in the plot $\ln(\sigma)$ versus $T^{-1/2}$. When the transition from NNH to VRH occurs, the characteristic temperature, $T_0$, can be also calculated by the relation $T_0 = (\Delta E_a)^2/T_c$, which involves the NNH activation energy, $\Delta E_a$, and the cross-over temperature, $T_c$. This relation is obtained by combining the equations $T_0^{NNH} = 4\Delta E_a \alpha$,\textsuperscript{14} and $\alpha = \Delta E_a/4T_c$,\textsuperscript{15} where $\alpha$ is the ratio between the nearest-neighbor distance and the localization length of hopping electrons. By using the experimental value, $\Delta E_a = 934$ meV and $T_c = 400$ K, the theoretically expected value $T_0^{NNH} = 2.9 \times 10^5$ K is calculated which is very close to the experimental value $T_0^{exp} = 2.8 \times 10^5$ K, obtained from the slope of the linear fit of conductivity data in the plot $\ln(\sigma)$ versus $T^{-1/2}$.

For electric field values higher than about 1 MV/cm, the $J$-$E$ curve of Fig. 2 shows a behavior which can be described in terms of electrode-limited or bulk-limited processes.\textsuperscript{17}

However, for Ta$_2$O$_5$ films of a thickness of about 140 Å or greater, evidence for a Poole–Frenkel (bulk-limited) conduction process has been reported for MIM structures.\textsuperscript{18} Charge transport via Poole–Frenkel emission is a process of bulk trap-regulated, electric field-enhanced, thermionic emission. Under the influence of an external electric field, asymmetric barrier lowering of the Coulombic potential enhances the probability for thermal emission. This gives rise to an exponential increase in the conductivity with field. Quantitatively, the Poole–Frenkel effect is described by:\textsuperscript{10}

$$
J(E, T) = C_1 E \exp \left[ - \frac{q(\phi_t - qE/\pi\varepsilon_0\varepsilon_d)}{KT} \right],
$$

where the preexponential factor, $C_1$, is a parameter dependent upon the carrier mobility and charge trap density, $q\phi_t$ is the charge trap potential depth (assumed to be monoenergetic), $\varepsilon_0$ the permittivity of free space, $\varepsilon_d$ the dynamic dielectric constant of the insulator.

Hence, according to Eq. (2), a linear dependence in the plot $\ln(J/E)$ versus $E^{1/2}$ is observed when the current is dominated by the Poole–Frenkel effect. Figure 4 displays the experimental $\ln(J/E)$ versus $E^{1/2}$ data and the corresponding linear fits for different temperatures. It is observable that at room temperature a linear dependence is observed for fields higher than 1.2 MV/cm, while at higher temperatures Poole–Frenkel effect becomes effective at lower field values. As shown in Fig. 4, the fits of the data linear portions were performed. The extrapolated slopes $[-q\phi_t/KT+\ln C_1]$ and intercepts $q\sqrt{\pi\varepsilon_0\varepsilon_d/2KT}$, when reported as Arrhenius plots [Figs. 5(a) and 5(b), respectively], follow a linear behavior which confirms Poole–Frenkel as the conduction mechanism in the considered field range, thus allowing to extract both the trap level and the so-called dynamic dielectric constant.\textsuperscript{10,19}

From the slope values, $\phi_t = 0.87$ eV is estimated, which is a value comparable with the trap levels of about 1 eV which have been recently reported to be involved in the Poole–Frenkel effect for Ta$_2$O$_5$ thin films.\textsuperscript{20}

From the intercept values, a dynamic dielectric constant ($\varepsilon_d$) of 13 is found. The dynamic dielectric constant should\textsuperscript{10,19} fall between the optical dielectric constant ($\varepsilon_{opt} \sim n^2$), which is typically lower than 5 for Ta$_2$O$_5$,\textsuperscript{19} and the static dielectric constant ($\varepsilon_s$). In our case, the static di-
The electric constant is estimated to be 32 by independent capacitance measurements performed at 1 MHz (as shown in Sec III B). Hence, the value of the dynamic dielectric constant, \( \varepsilon_d \), obtained from the linear fits of the \( \ln(J/E) \) versus \( E \) data satisfies the relation
\[
\varepsilon_{\text{opt}} = \frac{5}{\varepsilon_d} = \frac{13}{32}
\]
and, consequently, is consistent with the Poole–Frenkel effect.

**B. Charging effects**

In order to investigate the charging effects, current transients under a constant applied electric field in the range 0.3–4 MV/cm were measured, as shown in Fig. 6. The current is observed to decay, as already reported in charging studies on SiN films for capacitive RF MEMS switches. These transient currents are attributed to the fact that the charge injected under the application of the electric field can be trapped in the large density of defect states contained in the dielectric film, causing a screening of the electric field across the dielectric and thus a reduction in the leakage current. It is worth noting that even if the electric field distribution can be affected by the charging process, the Poole–Frenkel analysis remains valid for thin films like those investigated here, as it has been calculated in Ref. 22.

The dielectric polarization is expected to change with time because of the trapping process, according to a stretched exponential law:23
\[
P(t) = P_0 \exp \left( -\frac{t}{\tau} \right) \left( \frac{\beta - 1}{\beta} \right),
\]
where \( P_0 \) is the initial polarization, \( \tau \) is the process time constant, and \( \beta (0 \leq \beta \leq 1) \) is the stretch factor. The stretched exponential law fits many relaxation processes in a variety of electronic and molecular systems which have the common characteristic to exhibit disorder of some type. This disorder leads to a distribution of parallel rates due to the random distribution of active centers and microscopic distance-dependent interactions.24,25 The temporal variation of the polarization expressed by Eq. (3) has been found to cause a transient current given by:26
\[
I(t) \approx P_0 \exp \left( -\frac{t}{\tau} \right) \left( \frac{\beta - 1}{\beta} \right),
\]
where \( \beta \) and \( \tau \) are reported in (a) and (b), respectively.

Figure 6 shows that, with increasing the electric field, the experimental \( I(t) \) curves are well fitted by Eq. (4). The values of the fitting parameters \( \tau \) and \( \beta \) with increasing the electric field are reported in Figs. 7(a) and 7(b), respectively.
With increasing $E$, a reduction of $\tau$ is observed. According to the previous interpretation of the decay as due to a charging process in the dielectric film, the reduction of $\tau$ points out that the charging becomes faster as the electric field raises probably due to the increase in the injected charge. In particular, two regions can be distinguished in the field-dependent reduction of $\tau$: for $E \leq 1$ MV/cm $\tau$ rapidly decreases by three orders of magnitude, while for $E$ in the range 1–4 MV/cm a much slower reduction of $\tau$ is observed.

A possible explanation for this result is that the conduction mechanisms of VRH and Poole–Frenkel effect differently compete with the charging process. Accordingly, the reduction of $\tau$ and, hence, the increase in the charging effect, is much slower in the range 1–4 MV/cm, where the Poole–Frenkel emission, which is a mechanism opposite to the charging process, is effective.

With regard to $\beta$, a monothonic increase from 0.04 to 0.56 is observed with $E$ increasing from 0.3 to 4 MV/cm. In general, in the experimental works $\beta$ constitutes an index of charge relaxation complexity and no specific microscopic meaning can be assigned to it. Hence, the observed increase of $\beta$ with raising $E$ can indicate that the complexity of the relaxation process reduces or, equivalently, the distribution of the relaxation times becomes smaller as the field increases.

According to $J$-$E$ characteristics (see Fig. 2), an irreversible dielectric breakdown is observed in the current transient recorded at $E=4$ MV/cm. For the investigated Ta$_2$O$_5$ films, breakdown was manifested by the formation of a conductive path through the oxide initiated by the presence of weak spots, as already observed for Ta$_2$O$_5$ films. More specifically, the percolation model predicts that microscopic defects randomly-distributed are created in the dielectric under electric stress due to the interaction of energetic electrons and lattice. The defects accumulate in the film until a critical defect density is reached. At this point a conduction path is created between the electrodes, which results in an abrupt increase in the leakage current through the dielectric. Hence, the breakdown is a direct consequence of the interaction of the leakage current flowing through the dielectric and the dielectric itself. It is known that breakdown occurs, under a given electric field, after a certain charge has been forced through the dielectric. This critical charge can be calculated as the integral of the leakage current over the time to breakdown: $Q_{BD} = \int_0^{t_{BD}} I(t) dt$. Here, $t_{BD}=440$ s for $E=4$ MV/cm and it is found $Q_{BD} \sim 2.2 \times 10^{-5}$ C/cm$^2$ which is a value much lower (about four orders of magnitude) than that reported in Ref. 27 for ~60-nm thick SiN films. This large discrepancy can be due to the different material properties and/or to the fact that the trap generation rate significantly increases with increasing the dielectric thickness.

Finally, capacitance transients during the application of a constant electric field were measured, as shown in Fig. 8. When the applied field is zero ($E=0$) the capacitance value is 28.77 pF. Under the assumption that the MIM capacitance is given by the geometric expression $C = \varepsilon_0 \varepsilon_r A/d$, where $\varepsilon_r$ is the static dielectric constant of the insulator, $\varepsilon_0$ is the permittivity of free space, $A (180 \times 180 \ \mu m^2)$ is the active area and $d$ is the film thickness, it is found a static dielectric constant value of 32 which is pretty high, in agreement with the values reported for Ta$_2$O$_5$ films.

When a constant electric field is applied, the capacitance initially increases and then a very small decay is recorded toward a stationary value. This result is consistent with the dielectric charging as caused by a charge injection under the application of the electric field. Specifically, the increase in the stationary value of the capacitance with the field suggests that the charge trapped in the dielectric film gives rise to a capacitance in parallel with the geometric capacitance measured for $E=0$.

The temporal decay of capacitance has been already observed for dielectric layers of capacitive MEMS switches under actuation voltage. We find that the capacitance follows the polarization transient expressed by Eq. (3), resulting in

$$C(t) = C_s + \Delta C_0 \exp \left[ -\left( \frac{t}{\tau} \right)^{\beta} \right],$$

where $C_s$ is the steady-state capacitance after the application of the voltage and $\Delta C_0$ is the transient amplitude.

In Fig. 8 the fit lines of Eq. (5) to the experimental $C(t)$ transients are shown. The fitting parameters $\tau$ and $\beta$ are found to be $1.24 \times 10^8$ s and 0.18 for $E=0.9$ MV/cm and $5.8 \times 10^7$ s and 0.22 for $E=1.2$ MV/cm, which are values very close to those obtained from the fitting of current transients [see Figs. 7(a) and 7(b)]. Hence, capacitance measurement results to be able to detect the same charging process which is responsible for the current transients.

IV. CONCLUSIONS

Conduction mechanisms and charging effects were investigated for Ta$_2$O$_5$ thin films in order to value their application in capacitive RF MEMS switches.

Ta$_2$O$_5$ films show at room temperature an interesting low leakage current density of 4 nA/cm$^2$ for $E=1$ MV/cm, a high breakdown field of 4 MV/cm and a high dielectric constant of 32. The different conduction mechanisms were distinguished by performing $J$-$V$ curves as a
function of the temperature. For low electric field values ($E \leq 1$ MV/cm) the temperature-dependence of the conductivity is found to follow the VRH law in the temperature range 300–400 K, while the NNH behavior is observed at higher temperatures. For $E$ ranging from 1 to 4 MV/cm, Poole–Frenkel effect becomes the dominant conduction mechanism, as confirmed by the self-consistent value found for the dynamic dielectric constant.

Charging effects due to the trapping in the Ta$_2$O$_5$ films of the injected charge were investigated by performing current and capacitance transients. The charging process is found to follow the stretched exponential law with the characteristic time $\tau$ which significantly reduces as the electric field increases.

In summary, the results presented here, demonstrate that the studied Ta$_2$O$_5$ films are a valid alternative to the dielectric layers commonly used for the realization of capacitive RF MEMS switches. Moreover, in this work important information are provided for the deeper understanding and controlling of the conduction and charging mechanisms which are still now the most critical issues for the reliability of capacitive RF MEMS switches.

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