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Electrical properties in low temperature range (5 K–300 K) of Tantalum Oxide dielectric MIM capacitors

E. Deloffre [a,b,*], L. Montès [a], G. Ghibaudo [a], S. Bruyère [b], S. Blonkowski [c], S. Bécu [b], M. Gros-Jean [b], S. Crémer [b]

[a] IMEP, ENSERG, 23, rue des martyrs, BP 257, 38016 Grenoble Cedex 1, France
[b] STMicroelectronics, Central RD Labs, 850 rue Jean Monnet, BP16, 38926 Crolles, France
[c] CEA-Leti, 17 rue des martyrs, 38054 Grenoble Cedex 9, France

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Abstract

Tantalum oxide (Ta_2O_5) is widely used for MIM (Metal-Insulator-Metal) capacitor owing of its high dielectric constant. This work examines current–voltage and capacitance–voltage characteristics in the 5 K–300 K temperature range. Working at low temperature was chosen in order to freeze trapping mechanisms of the MIM capacitor. The curvature of *C–V* characteristics radically changes from 5 K to 300 K. The capacitance variation under voltage at 50 K and below can be investigated using the Langevin theory. From this model the permanent dipole moment and the number of dipoles have been extracted. From Poole–Frenkel identification curves, activation energy around 0.20 eV and a dielectric constant of 26 were found for positive polarisation. However, conduction mechanisms cannot be reduced to strick Poole–Frenkel modelling.

1. Introduction

MIM (Metal-Insulator-Metal) capacitors are widely used in BiCMOS, mixed-signal and logic technologies. The applications range from filters, which require excellent linearity, high quality factor and good matching, to blocking application, where the leakage current is a key parameter. In this context, it appears to be particularly important to better understand the origin of capacitance non-linearity and leakage current. In this study, we analyzed the capacitance and leakage current characteristics of 5 fF/μm^2 MIM capacitor with Ta_2O_5 ($\varepsilon = 25$) as dielectric at low temperatures, from 5 K to 300 K. Similar measurements have been done with a MIM capacitor with Si_3N_4 ($\varepsilon = 7$) as dielectric for comparison.

2. Experimental details

Ta_2O_5 films are amorphous and are about 45 nm thick. They are produced by MOCVD (Metallo-Organic Chemical Vapour Deposition) and an annealing step follows the deposition. This post-treatment may reduce impurity concentrations and repair the oxygen vacancies of the as-deposited Ta_2O_5 films [1]. TiN films were chosen as electrodes for their barrier height and their thermodynamical stability with Ta_2O_5.

* Corresponding author. Tel.: +33 476 926 226; fax: +33 476 926 814.
E-mail address: deloffre@enserg.fr (E. Deloffre).

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The MIM structures were electrically characterized by means of current–voltage ($J(V)$) and capacitance–voltage ($C(V)$) measurements. These measurements were performed from 5 K to 300 K, directly on 200 mm wafer and on monted samples.

3. Results and discussion

3.1. Capacitance versus voltage and temperature

Fig. 1 depicts the $C(V)$ characteristics of a MIM capacitor from 50 K to 300 K for two dielectrics: (a) Si_3N_4 and (b) Ta_2O_5. As expected the capacitance is found to increase with temperature for both dielectrics. An original result can be remarked for MIM capacitor with Ta_2O_5 as dielectric. Indeed, the curvature radically changes between 5 K and 300 K.

$C(V)$ plots can be fitted with a polynomial law:

$$C(V) = C_0 \cdot (1 + C_1 V + C_2 V^2), \tag{1}$$

where C_0 is the capacitance value at 0 V and C_1 and C_2 the coefficients of non-linearity.

We extract C_0 and the quadratic coefficient C_2 as a function of temperature (Figs. 2 and 3) for Ta_2O_5 as dielectric. We found that these two parameters increase linearly with temperature in the 50–300 K range.

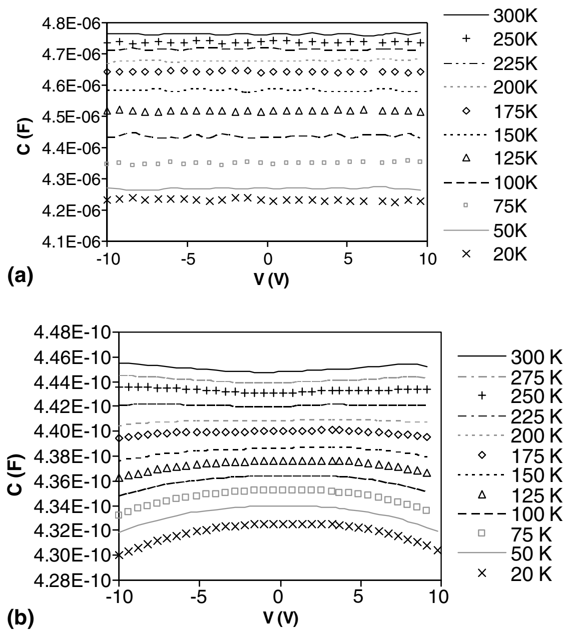

Fig. 1. C–V characteristics for MIM capacitor from 50 K to 300 K at 100 kHz for (a) Si_3N_4 and (b) Ta_2O_5 as dielectric. At 300 K, C_1 and C_2 are equal to 11 ppm/V and 4 ppm/V^2 for Si_3N_4 and 100 ppm/V and 35 ppm/V^2 for Ta_2O_5 as dielectric. These values are perfectly suitable for all MIM applications.

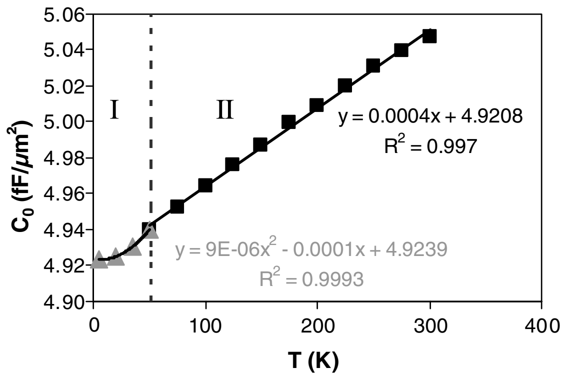

Fig. 2. C_0 versus temperature, from 50 K to 300 K fitted by a linear trend line. Two regions (I and II) can be distinguished.

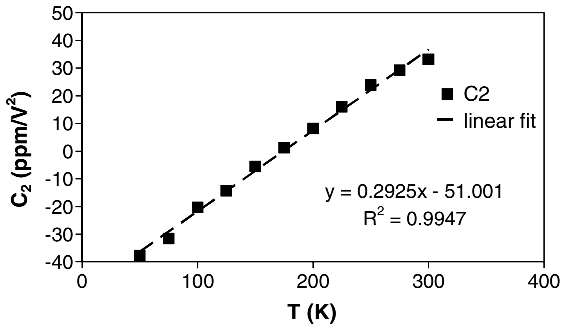

Fig. 3. C_2 extracted between −5 V and 5 V versus temperature, from 50 K to 300 K.

From Fig. 2 the temperature coefficient of capacitance (Tcc) is extracted. Tcc is around 86 ppm/K in agreement with other study [3].

However, we can distinguish two regions (I and II) in the C_0 (T) plot. Indeed, from 50 K to 300 K (II), a linear fit can be used whereas a polynomial curve is needed below 50 K (I). Afterwards, we will conclude that these two regions correspond to different mechanisms.

The quadratic coefficient C_2 value (Fig. 3) reached a value of 35 ppm/V^2 at 300 K, which leads to good performance for linearity sensitive application as shown previously [2].

To investigate in more details the change in the capacitance versus voltage curvature with temperature as parameter we use the Langevin theory that describes dipoles randomly distributed in an homogenous medium, in order to check the order of magnitude of such dipoles.

The dipole moment μ can be expressed from the Langevin's Law by:

$$\mu = \mu_0 \left[\coth(x) - \frac{1}{x}\right], \tag{2}$$