Ročník 2010 electroscope Číslo III

Charge Carrier Transport in Ta_2O_5 Oxide Nanolayers

M. Kopecky [1], , M. Chvatal[1], V. Sedlakova [1]
[1] Department of Physics, Brno University of Technology, Technicka 8, 616 00 Brno, Czech Republic
E-mail : xkopec31@stud.feec.vutbr.cz

Abstract:
The paper will present the modeling of charge transport in Ta_2O_5 nanolayers together with experimental verification of the model. MIS structure model for tantalum capacitors with conducting polymer cathode will be described on the base of the leakage current analysis. Ta_20_5 films show good electrical and dielectric properties for considered applications and low leakage current density value 10^{-4}A/m^2 for the electric field 100 MV/m. It is assumed that electrons tunnel from the localized states in the impurity band into the conduction band of the insulating Ta_2O_5 layer and, at low temperatures, from conducting polymer cathode to the conduction band of Ta_2O_5. The decreasing the thickness of the insulating Ta_2O_5 layer below 100 nm, the classical physical models are not able to give satisfactory descriptions of charge transport mechanism, and voltage and temperature dependences of electrical current. Dominant mechanism of charge carrier transport is ohmic conduction for the low electric field, while Poole-Frenkel mechanism becomes dominant for electric fields in the range 100 to 200 MV/m. Tunneling current becomes dominant for the electric field higher than 200 MV/m. Ohmic current component and Poole-Frenkel current component are thermally activated, while the tunnelling current component is temperature independent. We have observed that for temperatures above 250 K the leakage current is given predominantly by the ohmic and Poole-Frenkel mechanism. For temperatures below 250 K the tunneling is dominant charge carrier transport mechanism. VA characteristics measured for tantalum capacitor in the temperature range 10 to 300 K were analyzed.

1. INTRODUCTION

A tantalum capacitor consists of metallic Ta anode, amorphous Ta_2O_5 insulating layer produced mostly by anodic oxidation, and cathode made from semiconductor MnO_2 or conducting polymer. Capacitor structure can be in the first approximation considered as an ideal metal-insulator-semiconductor (MIS) structure [1 to 3]. Dominant mechanism of charge carrier transport is ohmic conduction for the low electric field, while Poole-Frenkel mechanism becomes dominant for electric fields in the range 100 to 200 MV/m. Tunneling current becomes dominant for the electric field higher than 200 MV/m. It is assumed that electrons tunnel from the localized states in the impurity band into the conduction band of the insulating Ta_2O_5 layer and, at low temperatures, from conducting polymer cathode to the conduction band of Ta_2O_5.
In normal mode (for Ta electrode positive) the VA characteristic for tunneling current is described by the relation:

$$I_T = G_T U^{\alpha} \exp\left(-\frac{U_T}{U}\right) \qquad (1)$$

Where U is the applied voltage, G_T and U_T are the constants, and the value of the exponent n depends on the barrier shape (for rectangular barrier $n = 2$).
Leakage current can be described as electron traveling wave with an amplitude A_1 in cathode with conducting polymer and amplitude A_2 in the conduction band of Ta_2O_5 the structure Ta-Ta_2O_5 or Ta_2O_5-CP conducting polymer. The wave amplitude exponentially decreases with the thickness t_0 of the potential barrier between cathode and insulating layer. The energy of the electron and the electron wave length λ are assumed to be constant during the transport. [4]

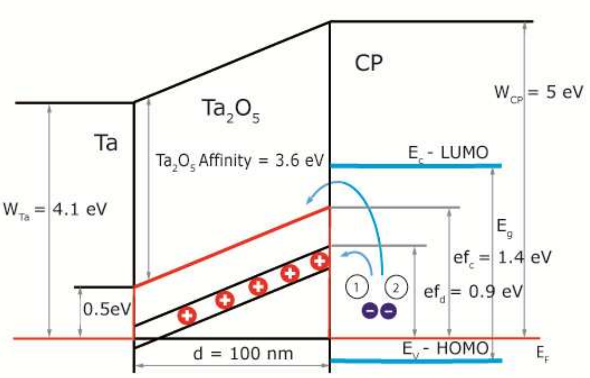

Fig. 1: A pproximate band diagram of MIS structure for tantalum capacitor with conducting polymer cathode

The traps rise during the anodic oxidation of Ta and create an impurity band in Ta_2O_5 layer. Oxide film contains oxygen vacancies with concentration of the order of 10^{18}/cm^3 [1]. They act as donors – deep traps which are charged during the electric field application. Activation energy of these traps is about 0.4 to 0.8 eV depending on the insulating layer preparation [2]. Approximate band diagram of MIS structure for tantalum capacitor with conducting polymer cathode is shown in Fig. 1. The value of the leakage current in normal mode depends on the potential barriers between the cathode and Ta_2O_5 insulating layer. In the reverse mode it depends also on the potential barrier between tantalum anode and tantalum pent-oxide. Charge carriers transport mechanism and charge storage in insulating layer are important parameters for the application in these devices. Ta_2O_5 films show good electrical and dielectric properties for considered applications and low leakage current density value about $4x10^{-8}$A/cm^2 for the electric field 2 MV/cm.

2. EXPERIMENT

2.1 Measurement in the temperature range 20 to 300 K

Experimental analysis of the leakage current in the wide temperature range can give the information on different current components as ohmic, Poole-Frenkel and tunneling. VA characteristics measured for tantalum capacitors with polymer cathode in normal mode (Ta electrode is positive) and the temperature range 10 to 300 K were analyzed. VA characteristics of capacitor TTC01 in the normal mode for low temperatures measured in the temperature range from 10 to 150 K are shown in Fig. 2.

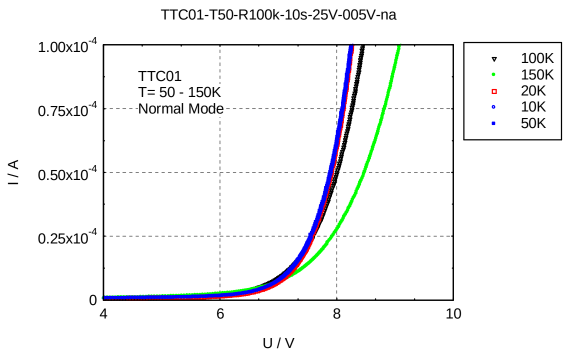

Fig. 2: VA characteristics of capacitor TTC01 in normal mode, T = 50 K (lowest) to 150 K (top curve)

We can see that the leakage current value increases with decreasing temperature up to 50 K and than the saturation of the leakage current value appears.

VA characteristics of capacitor TTC01 in the normal mode for high temperatures measured in the temperature range from 150 to 300 K are shown in Fig. 3. We can see that the leakage current value decreases with increasing temperature up to 250 K while slightly increases for the temperature 300 K. We expect the leakage current minimum value for the temperature about 250 K.

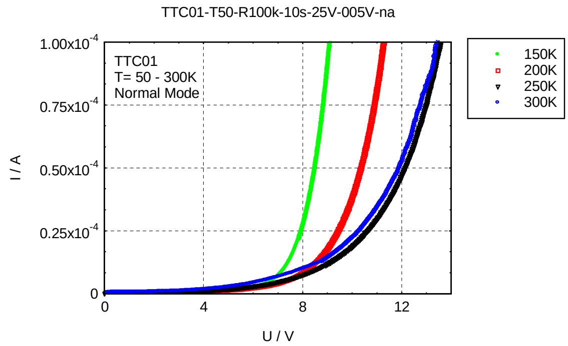

Fig. 3: VA characteristics of capacitor TTC01 in normal mode, T = 150 K (lowest) to 300 K (top curve)

VA characteristics of capacitor TTC01 in the reverse mode for the temperature range 20 to 300 K were measured. They are shown in Figs. 4 and 5.

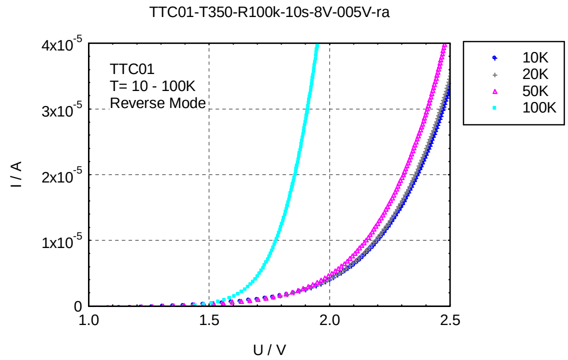

Fig. 4: VA VA characteristics of capacitor TTC01 in reverse mode, T = 10 K (lowest) to 100 K (top curve)

The leakage current value measured for the temperatures 10 and 20 K are equal. With increasing temperature the leakage current increases. The leakage current value decreases with decreasing temperature in the reverse mode similarly as for the capacitor with manganese dioxide cathode. For the temperature 300 K Schottky current is dominant, while for the temperature below 100 K VA characteristic can be fitted with the tunnelling component only [3].

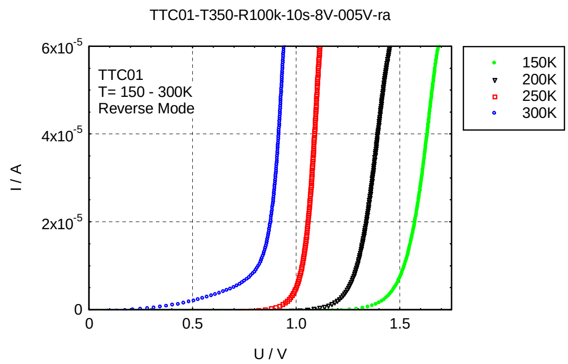

Fig. 5: VA characteristics of capacitor TTC01 in reverse mode, T = 150 K (lowest) to 300 K (top curve)

The potential barrier influencing the low temperature tunnelling process in reverse mode is the barrier on the Ta – Ta_2O_5 interface.

2.2 Fitting equations

The leakage current dependence on the applied voltage in the normal mode can be approximated by equation:

$$I(U) = G_{\Omega} U + G_{PF} U \exp\left(\beta_{PF} \sqrt{U}\right) + G_T U^{\alpha} \exp\left(U_T / U\right) \qquad (2)$$

Where G_{Ω} is Ohmic conductivity, G_P is Poole-Frenkel conductivity, β_{PF} is Poole-Frenkel coefficient, G_T is tunnelling current constant, exponent α depends on the potential barrier profile (α = 0 to 2), and U_T is a constant dependent on the barrier height.
Depending on the leakage current measurement speed also the polarisation current is observed in the VA characteristic. Polarisation current is given by

$$I_{pol} = b\ \left[1 - \exp\left(-c \cdot U\right)\right] \qquad (3)$$

Where b and c are constants. We have included polarisation current component into our fitting equation.
Ohmic current component and Poole-Frenkel current component are thermally activated, while the tunnelling current component is temperature independent. We have observed that the leakage current is given predominantly by the ohmic and Poole-Frenkel mechanism for the higher temperatures, while the tunnelling current component is dominant in the low temperature range.

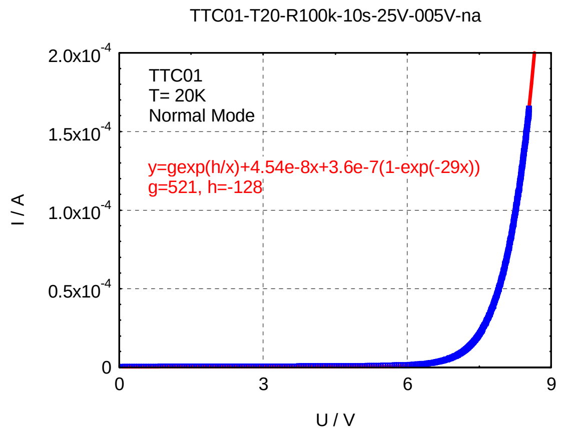

Fig. 6: Leakage current vs. applied voltage for capacitor TC01 in normal mode, T = 20 K, equation for ohmic and tunneling current component with polarization current

VA characteristic measured in the normal mode for the temperature 20 K and fitted characteristic including the ohmic, polarisation and tunnelling current component is shown in Fig. 6. Ohmic conductivity is G_{Ω} = 4.5 x 10^{-8} S, tunnelling current constant I_T = 521 A, and U_T = -128 V.
VA characteristic measured in the normal mode for the temperature 300 K and fitted characteristic is shown in Fig. 7 in the semi-logarithmic scale.

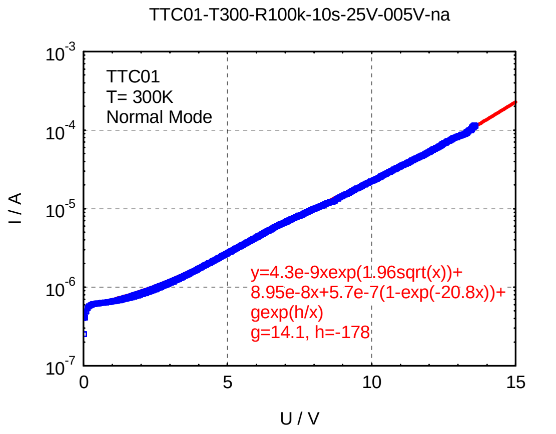

Fig. 7: Leakage current vs. applied voltage for capacitor TTC01 in normal mode, T = 300K, equation for ohmic, Poole-Frenkel and tunnelling current component with polarization current

You can see that VA characteristic can be with good accuracy approximated by ohmic and Poole-Frenkel and tunnelling current components. Ohmic conductivity is G_{Ω} = 8.9 x 10^{-8} S, Poole-Frenkel conductivity G_P = 4.3 x 10^{-9} S, Poole-Frenkel coefficient β_{PF} = 1.96 $V^{-1/2}$, tunnelling current constant I_T = 14.1 A, and U_T = -178 V.
Parameter U_T for the potential barrier of height Φ_0 with thickness t_0 is given by:

$$U_T = (8\pi\sqrt{2m^*} / 3eh)(e\Phi_0)^{1.5} t_0 \qquad (4)$$

Where m^* is effective electron mass, h is Planck constant, Φ_0 is the barrier energy in eV, and t_0 is effective thickness of potential barrier.
The tunnelling current component obtained from the VA characteristics fitting for the temperature 300 K is characterized by tunnelling constant U_T = -175 V, while the tunnelling current component obtained from the VA characteristics fitting for the temperature 20 K is characterized by tunnelling constant U_T = -128 V.
The difference between the low temperature and high temperature value of U_T corresponds to different potential barrier affecting the tunnelling process. We suppose that the potential barrier on the Ta_20_5 – conducting polymer interface is modulated with the temperature. With the decreasing temperature the barrier height decreases which leads to the increase of the leakage current for Ta capacitor with conducting polymer cathode.

3. CONCLUSIONS

The leakage current value for the various temperatures and applied voltage are frequently used as the reliability indicator for tantalum capacitors. Leakage current provides information on the insulating layer thickness, its homogeneity and the number of defects in tested sample. The investigation of the tantalum capacitors conducting polymer cathodes was performed in the temperature range 10 to 300 K.

Approximate band diagram of MIS structure for tantalum capacitor with conducting polymer cathode is presented. Leakage current in normal mode depends on the potential barriers between the cathode and Ta_2O_5 insulating layer.

VA characteristic for T = 300 K can be with good accuracy approximated by ohmic and Poole-Frenkel and tunnelling current components. For the temperature 20 K only the tunnelling current component must be considered.

For the capacitors with conducting polymer cathode we have measured that the leakage current value increases with decreasing temperature in the normal mode for the temperatures below to 250 K while slightly increases for the temperature 300 K. We expect the leakage current minimum value for the temperature about 250 K.

The difference between the low temperature and high temperature value of U_T corresponds to different potential barrier affecting the tunnelling process. We suppose that the potential barrier on the Ta_20_5 – conducting polymer interface is modulated with the temperature. With the decreasing temperature the barrier height decreases which leads to the increase of the leakage current for Ta capacitor with conducting polymer cathode.

The leakage current value decreases with decreasing temperature in the reverse mode similarly as for the capacitor with manganese dioxide cathode. For the temperature 300 K Schottky current is dominant, while for the temperature below 100 K VA characteristic can be fitted with the tunnelling component only. The potential barrier influencing the low temperature tunnelling process in reverse mode is the barrier on the Ta – Ta_2O_5 interface.

ACKNOWLEDGMENTS

This research has been partially supported by grants GACR No.102/09/H074 and GACR 102/09/1920 and under project MSM 0021630503.

REFERENCES

[1] Sedlakova, V., et al. *Noise and charge storage in Nb_2O_5 thin films. Noise and Fluctuations*, ICNF 2005, Salamanca, Spain, September 19-23, 2005. pp. 135-138.

[2] Sikula, J., et al. *Tantalum and Niobium Oxide Capacitors: Leakage Current, Anodic Oxidation and Reliability*. CARTS Europe 2007, Barcelona, Spain, October 29 – November 1, 2007. pp. 213-222. ISBN:0-7908-0117-5.

[3] Sikula, J., Hlavka, J., Sedlakova, V., Sita, Z. *Charge carrier transport in NbO and Ta capacitor in temperature range 100 to 300 K*. CARTS Europe, Bad Homburg, Germany, September 25-28, 2006, pp.189-198.

[4] Sedlakova, V. and Sikula, J., *Charge carrier transport in polymer based thick resistive films*. CARTS Europe, Prague, Czech Republic, October 17-20, 2005, pp.93-98.