TANTALUM CAPACITOR AS A MIS STRUCTURE: TRANSPORT CHARACTERISTICS TEMPERATURE DEPENDENCIES

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Abstract: Temperature dependencies of a leakage current in normal mode are explained on the basis of a model, in which the solid state tantalum capacitor is considered as a metal-insulator-semiconductor (MIS) heterostructure. The measurement was performed in temperature range from 105 to 155°C. Ohmic conductivity increases exponentially with increasing temperature with activation energy 0.94 eV. Tunneling voltage parameter and tunneling energy barrier decreases with increasing temperature, reaching values 0.45 to 0.26 eV.

Keywords: tantalum capacitor, MIS structure, *I-V* characteristics, tunneling energy barrier, activation energy

1. INTRODUCTION

A tantalum capacitor consists of a metallic Ta anode, insulator-Ta_2O_5 film and a semiconductor-MnO_2 cathode, which is made of carbon and dipping silver layers. The ideal metal-insulator-semiconductor (MIS) structure theory [1], to be considered in this paper, serves as a foundation for understanding the real tantalum capacitor characteristics. Current through an amorphous insulating film increases roughly exponentially with applied voltage [2].

Mechanisms, which may explain the observed characteristics, are: Ohmic electron transport, Poole-Frenkel electron transport with distributed traps, and tunneling electron transport.

Leakage current in our samples may be described as an electron transport with Ohmic, Poole-Frenkel, and tunneling components.

I-V characteristics have three components given by:

$$I = G_{\Omega}V + G_{PF}V\exp(\beta_{PF}\mathrm{sqrt}(V)) + G_T V^2 \exp(-V_T/V)\ , \tag{1}$$

where G_{Ω} is Ohmic conductivity, G_{PF} is Poole-Frenkel conductivity, β_{PF} is Poole-Frenkel coefficient, G_T is tunneling transparencies or tunneling conductivity per volt in S/V, and V_T is tunneling voltage parameter.

Ohmic conductivity G_{Ω} is given by:

$$G_{\Omega} = Ae\,\mu n/d\ , \tag{2}$$

where A is the area of capacitor, e is its elementary charge, μ is electron mobility, n is electron concentration and d is insulating layers thickness.

Electron concentration is exponential function of reciprocal given by:

$$n = n_0 \exp(-E_a/kT) , \quad (3)$$

where n_0 is electron concentration at temperature T_0, E_a is activation energy and kT is electron thermal energy. Electron mobility and other quantities can be in short temperature range considered to be constants.

Then we can write that:

$$G_\Omega = G_{\Omega 0} \exp(-E_a/kT) , \quad (4)$$

where

$$G_{\Omega 0} = Ae\, \mu n_0 /d. \quad (5)$$

Activation energy E_a can be obtained from temperature dependence of Ohmic conductivity.

Poole-Frenkel coefficient β_{PF} is given by

$$\beta_{\mathrm{PF}} = 2(e^3 / \pi\varepsilon_0\varepsilon_r d)^{1/2} / kT , \quad (6)$$

where e is elementary charge, ε_0 is permittivity of vacuum, ε_r is Ta_2O_5 layer permittivity.

Poole-Frenkel coefficient vs. temperature for insulating layer thickness d = 210 nm is given by:

$$\beta_{PF} = 362.12 / T , \quad (7)$$

where T is temperature in Kelvin.

Table 1: Poole-Frenkel coefficient vs. temperature

T / °C	23	85	105	125	135	145	155
T / K	296.15	358.15	378.15	398.15	408.15	418.15	428.15
β_{PF} /V $^{-1/2}$	1.21	1.0	0.96	0.9	0.88	0.86	0.84

The impurity states in the forbidden energy gap

Insulating Ta_2O_5 films always contain impurities like oxygen vacancies and traps. These impurities form localized states for charge carriers in the forbidden energy gap. When the localized electronic wave functions of such impurities overlap, an electron bound to one impurity state can tunnel to an unoccupied state without involving activation into the conduction band. This tunneling process between impurity sites is referred to as impurity conduction.

Electrical transport by hopping and tunneling

The mobility of an electron moving through impurity states is small especially at low temperatures. Then, the conduction mechanism is mainly influenced by electron hopping between neighboring impurity site. This type of conduction process depends on impurity concentration and the energy depths of impurity states. The concept of hopping transport has been used for a long time in connection with ionic conduction; ions move essentially by hopping, whether through interstices or vacancies.

The leakage current is at high electric fields mainly influenced by electron tunneling through a potential barrier between Ta_2O_5 insulating layer and cathode or anode. The potential barriers can be approximated by a square or triangular shapes (see Figure 1). The triangular shape facilitates an inter-molecular electron transfer, since the barrier width at higher fields becomes effectively smaller for high energy electrons.

Tunneling current

The charge carrier transport in tantalum pentoxide thin film at high electric fields becomes mainly given by the tunneling current [3 and 4]. The barrier hight depends on the work function of the cathode material and the electron affinity of the Ta_2O_5 insulating layer, as it is shown in Figure 1 for a triangular potential barrier.

In normal mode (for Ta electrode positive) the *I-V* characteristic for tunneling current is described by the relation:

$$I = G_T V^n \exp\left(-\frac{V_T}{V}\right) \tag{8}$$

where V is the applied voltage, G_T and V_T are the constants, and the value of exponent n depends on the barrier shape (for triangular barrier n = 2).

The tunneling parameter V_T can be expressed for the energy barrier $e\Phi_T$ and the thickness t_0 of the insulating layer as

$$V_T = \left(\frac{8\pi\sqrt{2m^*}}{(3eh)(e\Phi_0)^{1.5}t_0}\right), \tag{9}$$

here, m^* is the electron effective mass, h = 6.6x10 $^{-34}$ Js is the Planck constant.

Evaluating the potential barrier from *I-V* characteristic we can further determine the parameter V_T for the potential barrier height Φ_0.

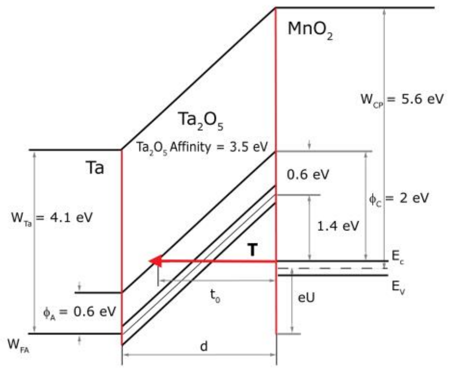

Figure 1: The triangular potential barrier model for Ta capacitor with MnO_2 cathode

2. EXPERIMENTAL

To get more information on the current transport processes, the *I-V* characteristics were measured in normal mode (Ta electrode is positive) in the temperature range from T = 105 to 155 °C. The fitting of experimental dependencies were performed in order to find the parameters important for the construction of the energy diagram of the MIS structure. Studied capacitors have Ta_2O_5 layer prepared by anodic oxidation. Measured sample TaS4 – 37 has oxide thickness d = 210 nm, AC capacitance C = 10 uF/25V, and rated voltage 35 V.

3. DISCUSSION

I-V characteristics of sample TaS4 - 37 measured at temperatures T = 105 to 155 °C are shown in Figures 2 to 5. *I-V* characteristics were measured with voltage step 0.1 V and time delay between two successive steps 20 s to have low value of polarization current component, which was removed from measured data. Analysis was performed by fitting of experimental data using equation (1). This equation contains 6 parameters. Therefore the best coincidence of fitting curve with experimental data in all voltage ranges is difficult. For this reason we have used theoretical value of Poole-Frenkel coefficient β_{PF} to decrease the number parameters. It is due to that Poole-Frenkel current component is at rated voltage lower than tuneling one at all measured temperature ranges.

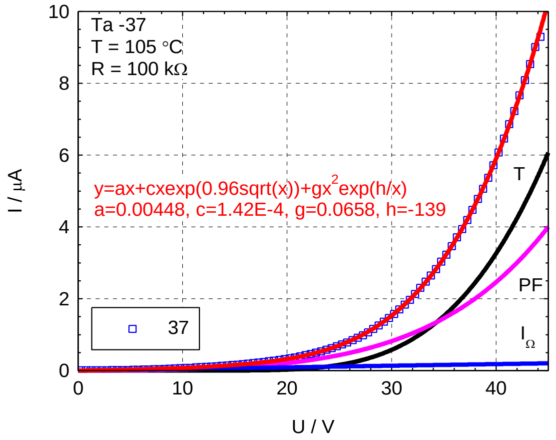

Figure 2: *I-V* characteristics of sample TaS4 - 37 measured at temperature T = 105 °C

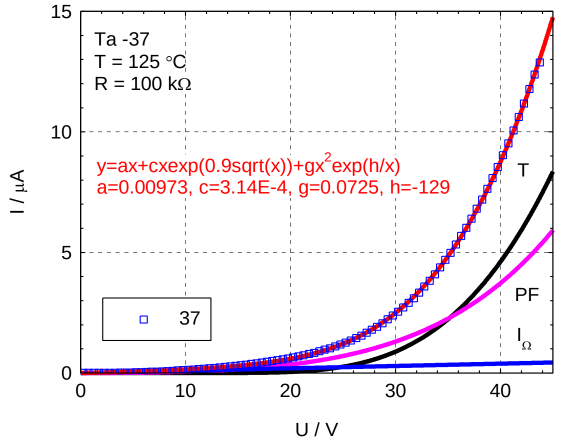

Figure 3: *I-V* characteristics of sample TaS4 - 37 measured at temperature T = 125 °C

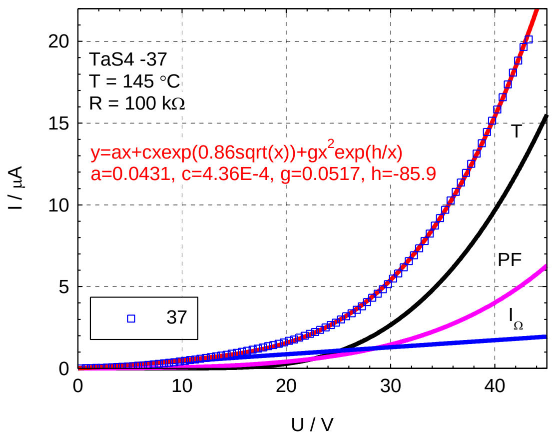

Figure 4: *I-V* characteristics of sample TaS4 - 37 measured at temperature T = 145 °C

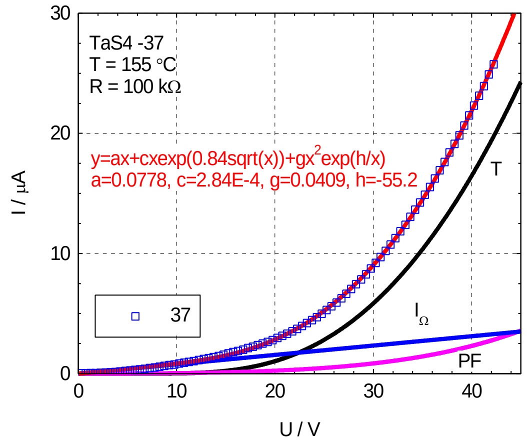

Figure 5: *I-V* characteristics of sample TaS4 - 37 measured at temperature T = 155 °C

Table 2: *I-V* characteristics parameters of sample TaS4-37

Temperature: T / °C	105	125	145	155
Absolute temperature: T / K	378.15	398.15	418.15	428.15
Ohmic conductivity: G_{Ω} / nS	4.48	9.73	43.1	77.8
P-F conductivity: G_{PF}/ pS	142	314	436	284
P-F coefficient: G_{PF} /$V^{-0.5}$	0.96	0.9	0.86	0.84
Tunel transparences: G_T / nS/V	65.8	72.5	51.7	40.9
Tunneling voltage: V_T /V	139	129	85.9	55.2
Barrier energy: Φ_T / eV	0.45	0.41	0.35	0.26

We will give graphical evolution of Ohmic conductivity vs. reciprocal temperature (see Figure 6) and in Figure 7 tunneling barrier energy Φ_T vs. temperature.

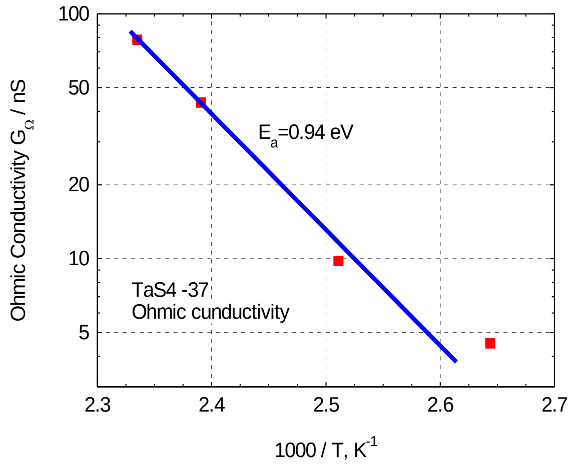

Figure 6: Activation energy of Ohmic conductivity for sample TaS4 - 37

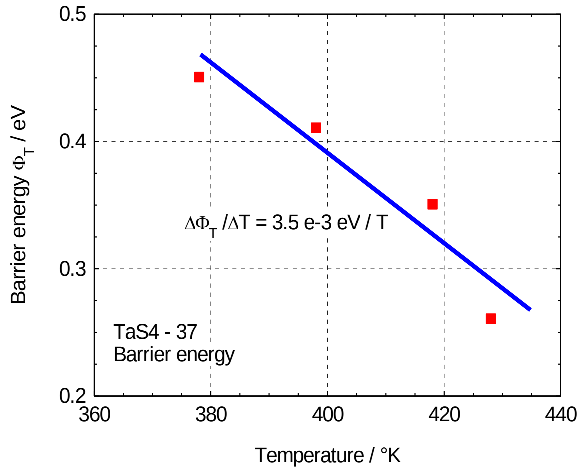

Figure 7: Tunneling barrier energy Φ_T vs. temperature for sample TaS4 - 37

4. CONCLUSION

Ohmic conductivity vs. reciprocal temperature give an activation energy E_a = 0.94 eV which is equal to the energy of oxygen vacancies band below conduction band of Ta_2O_5 insulating layer. This value is very near to that of other experiments (see [3 and 4]).

Tunneling voltage parameter and tunneling barrier energy decrease with increasing temperature. It means that with increasing temperature tunneling current components increases while Poole-Frenkel current component decreases.

Poole-Frenkel conductivity increases with increasing temperature. Some new effect at temperature 155 °C where Poole-Frenkel conductivity is lower than at temperature 125 °C is described. Similar effect is obtained for the tunneling barrier energy Φ_T at temperature 155 °C. It can be caused by some change in oxygen vacancies distribution. Single *I-V* characteristics measurement was performed during 2.5 h, then at high temperature ionic motion can affect value of current at high voltage range.

ACKNOWLEDGEMENT

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