Temperature Dependence of Leakage Current Degradation of Tantalum Capacitors at High Electric Field

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Abstract

Tantalum capacitors have been the preferred capacitor technology in long lifetime electronic devices thanks to the stability of its electric parameters and high reliability. However, long time application of elevated temperature and high electric field can result in capacitor leakage current increase in time. In this paper the effect of ions drift and diffusion at different temperatures on DCL degradation is analysed. DCL vs. time characteristics at temperatures from 65°C to 155°C were studied in order to determine the parameters of leakage current ageing. Results for four technologies are presented and it is shown that capacitor technology has crucial impact on DCL vs. time characteristics. These experiments are used to determine the background temperature at which DCL degradation starts with respect to the value of electric field. There exists background temperature under which the thermal excitation is not sufficient for give rise to the ions movement. This background temperature is higher than 105°C for technology IS4 while for technology IS3 this temperature is 65°C only.

Introduction

The thick amorphous insulating layer is not stable and at high temperature and high electric field the ions motion and recrystallization of Ta_2O_5 oxide layer can start [1 to 10]. It is important that oxygen ions transport needs temperature excitation. Main aim is to answer the question what is the background temperature under which the thermal excitation of ions in Ta_2O_5 oxide layer is not sufficient to move ions from one potential well to the second one and then to start the ions transport. DCL vs. time characteristics at temperatures from 65°C to 155°C were studied in order to determine the DCL ageing parameters. Results of four technologies are presented and it was found that the background temperature can be higher than 120°C and that it is influenced by the capacitor technology.

Experimental

Experiments were performed on tantalum capacitors with MnO_2 cathode prepared by four different technologies denoted as IS1, IS2, IS3, and IS4. Ten samples were evaluated within each of technology IS1 (No. 1 to 10), IS2 (No. 11 to 20), and IS3 (No. 11 to 20), respectively. Six samples were evaluated within the technology IS4 (No. 33 to 38). The parameters of all evaluated samples are following: nominal capacitance 10 μF, rated voltage 35 V, Ta_2O_5 oxide layer thickness d = 210 nm, electrode effective area A = 85 cm^2 and the volume of Ta_2O_5 oxide layer $V_{vol} = 1.8$ mm^3.

The dependence of leakage current on time and applied voltage were monitored using a PC-based data acquisition system. Temperature was varied in the range from 105°C to 155°C and voltage was varied in the range 25 to 45 V. Typical duration of the experiment was 340 hrs. After the measurement on each temperature the samples were shorted for 24 hours at this temperature in order to restore initial conditions.

Leakage current vs. ageing time

We will show how characteristics of DCL vs. time at different temperatures vary with the technology of samples preparation. The electron transport is controlled by drift and diffusion of ions in the Ta_20_5 insulating layer.

DCL vs. time characteristic after the voltage application consists from two processes. For the first one is characteristic the DCL lowering in the time interval 30 minutes (see. Fig. 1 -samples IS1-1 and IS2-12) up to 10 hours (see Fig. 2 - sample IS4-37). We suppose that potential barrier on the Ta_2O_5 oxide layer/MnO_2 cathode interface increases in this time interval. This effect depends on technology and length of ageing. We suppose that this process can be influenced by deep traps or double layer formed on the Ta_2O_5 oxide layer/MnO_2 cathode interface.

The second process is characterised by DCL increase probably due to ions (oxide vacancies) drift/diffusion in Ta_2O_5 oxide layer. The ions movement results in the decrease of potential barrier on the interface of Ta_2O_5 oxide layer/MnO_2 cathode. The changes induced by this second process are discussed further.

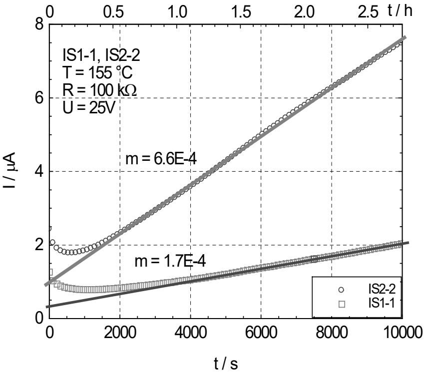

Fig. 1. DCL vs. time for $U = 25$ V at $T = 155$ °C during the time interval 2.5 h for samples IS1-1 and IS2-12

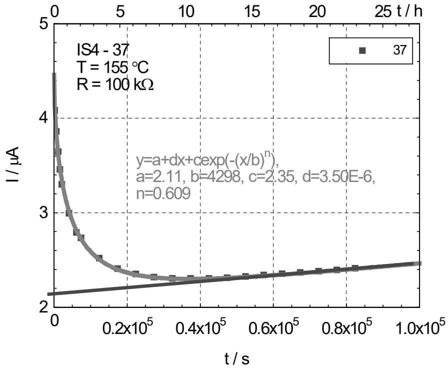

Fig. 2. DCL vs. time for $U = 25$ V at $T = 155$ °C during the time interval 13 h for sample IS3-15

Technology IS1

DCL vs. time characteristic at temperature 155ºC for applied voltage $U = 25$ V for tantalum capacitor IS1-1 is shown in Fig. 3. DCL vs. time characteristic has linear progression at first with a slope 130 pA/s. Second part of the characteristics is described by the exponential stretched law for all samples from technology IS1:

$$I = I_0 + I_1(1 - \exp(-t/\tau_1)^n) \qquad (1)$$

Where I_0 is DCL value at the beginning of aging, I_1 is a change of DCL and τ_1 is the time constant. Exponent n varies in the interval $n = 1$ to 0.9. Average value of DCL increases about 4times for all samples of ensemble IS1 during the ageing. The parameters of DCL vs. time dependence fit by equation 1 are shown in Tab. 1.

Tab. 1 Values of parameters I_0, I_1, n and τ_1 from eq. 1 for IS1-1 in time interval 340 h

Sample No	I_0 / µA	I_1 / µA	n	τ_1 / s
IS1-1	0.478	36.6	1.0	2.38×10^5

The electron transport is mostly controlled by ions drift from anode to cathode in the Ta_20_5 insulating layer for samples of technology IS1.

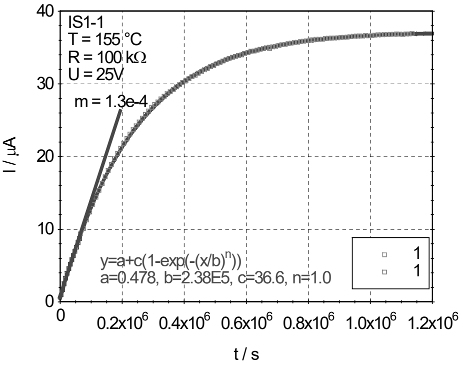

Fig. 3. DCL vs. time for *U* = 25 V at *T* = 155 °C during the ageing time interval 340 h for sample IS1-1

Technology IS2

DCL vs. time characteristic at temperature 155°C for applied voltage *U* = 25 V for tantalum capacitor IS1-12 is shown in Fig. 4. The parameters of DCL vs. time dependence fit by equation 1 are shown in Tab. 2.

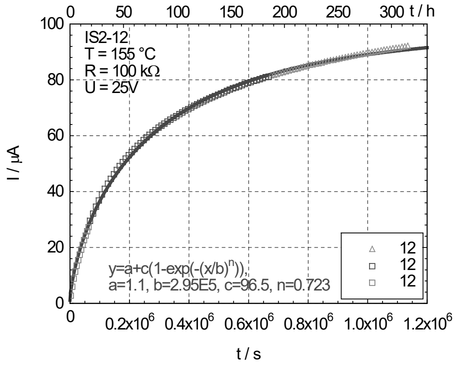

Fig. 4. DCL vs. time for *U* = 25 V at *T* = 155 °C during the ageing time interval 340 h for sample IS2-12

Tab. 2 Values of parameters I_0, I_1, n and τ_1 from eq. 1 for IS2-12 in time interval 340 h

Sample No	I_0 / μA	I_1 / μA	n	τ_1 / s
IS2-12	1.1	96.5	0.723	$2.95 \text{x} 10^5$

Exponent *n* varies in the interval *n* = 0.7 to 0.8. Here the electron transport is controlled by both ions drift and diffusion from anode to cathode in the Ta_20_5 insulating layer. The average value of DCL increases about 37 times during the ageing of samples of technology IS2.

Technology IS3

DCL vs. time characteristic at temperature 155°C for applied voltage *U* = 25 V for tantalum capacitor IS3 – 15 is shown in Fig. 5. Sample IS3 – 15 had the lowest value of DCL during the ageing at temperature *T* = 155°C within all samples of IS3 technology.

The parameters of DCL vs. time dependence fit by equation 1 are shown in Tab. 3. Exponent *n* is equal to 1 for all samples of technology IS3. Evaluation of DCL vs. time characteristics of samples IS3 shows that potential barrier on Ta_2O_5 insulating layer/cathode interface decreases linearly with time of ageing.

Tab. 3 Values of parameters I_0, I_1, n and τ_1 from eq. 1 for IS3-15 in time interval 340 h

Sample No	I_0 / µA	I_1 / µA	n	τ_1 / s
IS3-15	0.119	1.42	1.0	$8.87\text{x}10^5$

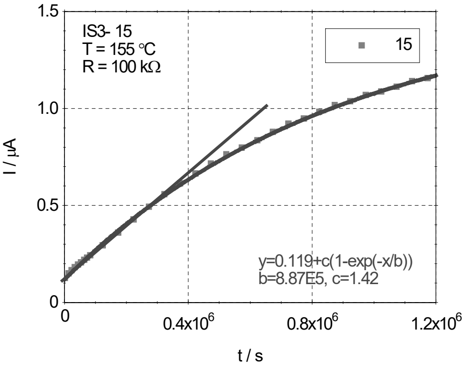

Fig. 5. DCL vs. time for U = 25 V at T = 155°C during the ageing time interval 340 h for sample IS3-15

The value of time constant τ_1 decreases for increasing value of DCL at the beginning of ageing. The samples with higher value of DCL before ageing exhibit lower relative change of DCL during ageing (ratio I_1 / I_0).

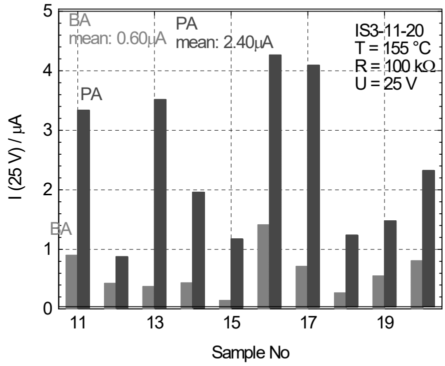

Fig. 6. Bar chart diagram of DCL for applied voltage U = 25 V at T = 155°C for ensemble IS3

There is homogeneous distribution of oxygen vacancies in Ta_2O_5 insulating layer before ageing and then theirs drift motion is dominant. It is the first experimental result which shows that the ageing is controlled by drift of oxygen vacancies only during the time interval of 340 hrs at temperature 155°C. DCL reaches saturation value after 3 time constants which is after about 400 h.

Effect of ageing on DCL for applied voltage U = 25 V at temperature T = 155°C of all samples of technology IS3 is shown in Fig. 6.

Average value of DCL before ageing is $\boldsymbol{I_{avB}} = \mathbf{0.60}$ **µA**. DCL increases during ageing the average value after the ageing is $\boldsymbol{I_{avA}} = \mathbf{2.40}$ **µA**. Average value of DCL increases 4times during the ageing for time interval 340 h.

Technology IS4

DCL vs. time characteristic at temperature 155 ºC for applied voltage U = 25 V for tantalum capacitor IS4-37 is shown in Fig. 7. The parameters of DCL vs. time dependence fit by equation 1 are shown in Tab. 4. Exponent n varies in the interval n = 0.75 to 0.85 for all samples of technology IS4. The value of time constant is of the same order as for ensembles IS1 to IS3.

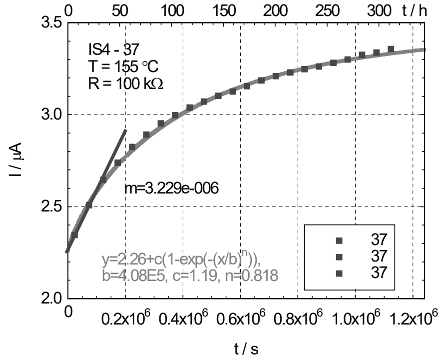

Fig. 7. DCL vs. time for $U = 25$ V at $T = 155$ °C during the ageing time interval 340 h for sample IS4-37

Tab. 4 Values of parameters I_0, I_1, n and τ_1 from eq. 1 for IS4-37 in time interval 340 h

Sample No	I_0 / µA	I_1 / µA	n	τ_1 / s
IS4-37	2.26	1.19	0.818	$4.08\text{x}10^5$

It need to be highlighted, that samples of technology IS4 exhibited high decrease of leakage current within initial 10 hours of ageing (see Fig. 2). Considering both discussed processes the values of DCL of ensemble IS4 are lower past ageing for 340 hrs than before the ageing as is shown in bar chart diagram in Fig. 8.

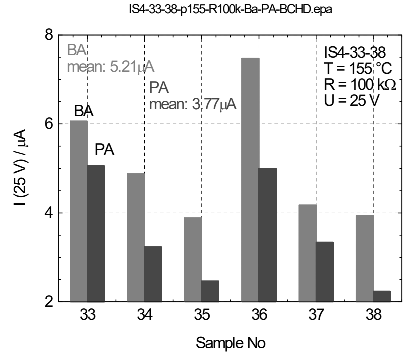

Fig. 8. Bar chart diagram of DCL for applied voltage $U = 25$ V at $T = 155$°C for ensemble IS4

Average value of DCL before ageing is $\boldsymbol{I_{avB}}$ **= 5.21 µA,** while after the ageing for time interval 340 h it is $\boldsymbol{I_{avA}}$ **= 3.77 µA**.

Effect of temperature and electric field on leakage current vs. time characteristic

Ions transport in Ta_2O_5 oxide layer is influenced by the temperature excitation, value of electric field and ions gradient concentration. Aim of these experiments is to show that exist background temperature at which the temperature excitation of ions is not sufficient to release them from the bound states - potential wells. In this case ions are at rest even in high electric field and for high ions concentration gradient.

Influence of Temperature on DCL vs. Time Characteristic for Applied Voltage $V = 25$V

The measurements on ensemble IS4 was performed for temperatures 105°C, 125°C, 145°C and 155 °C, respectively, for applied voltage $U = 25$ V (see Fig. 9).

DCL vs. time characteristics can be fitted for temperatures 145°C and 155°C by equation 1, and for temperatures 105°C and 125°C the characteristics can be fitted by equation:

$$I = I_0 + Dt \qquad (2)$$

Where I_0 is leakage current for $t = 0$ s and $D = dI/dt$ is the slope of DCL vs. time dependence. Fitting parameters are given in Tab. 5.

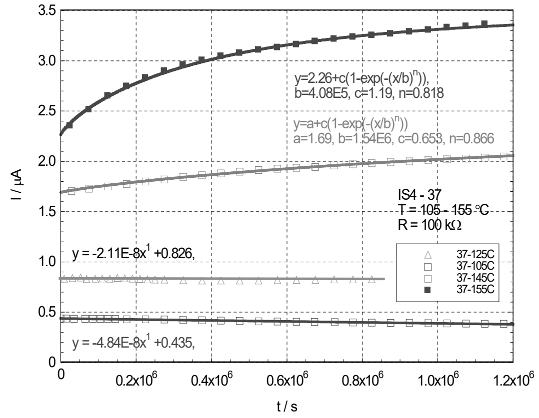

Fig. 9. DCL vs. time for $U = 25$ V at $T = 105$, 125, 145 and 155 °C during the ageing time interval 340 h for sample IS4-37

Tab. 5. Values of parameters I_0, I_1, n and τ_1 for IS4-37 in time interval 340 h

Sample	Temperature / °C	I_0 / μA	I_1 / μA	n	τ_1 / s	D / μAs^{-1}
IS4-37	105	0.435				-4.84 x10^{-8}
	125	0.826				-2.11 x10^{-8}
	145	1.69	0.53	0.866	1.54x10^{6}	
	155	2.26	1.19	0.818	4.08x10^{5}	

Leakage current vs. applied voltage at temperature 125°C

Similar experiment was performed for selected samples of all technologies in the time interval 340 hrs at temperature 125°C (see Fig. 10 and Tab. 6). Ions in these samples have the same thermal excitation energy and they are subjected to the same electric field. It is shown here that technology can influence the depth of ion potential well in Ta_2O_5 oxide layer.

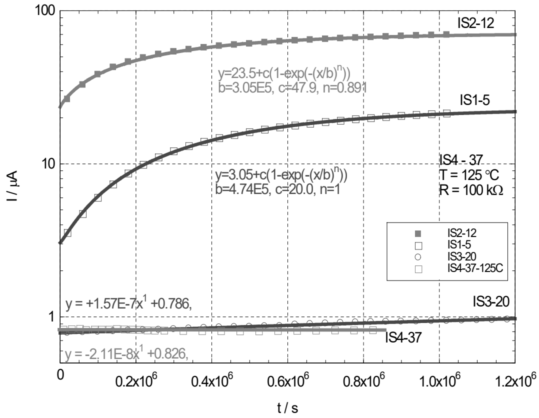

Fig. 10. DCL vs. time at $U = 25$ V and $T = 125$ °C in time interval 340 h for samples IS1-5, IS2-12, IS3-20 and IS4-37

Tab. 6. Values of parameters I_0, I_1, n and τ_1 for temperature 125°C in time interval 340 h

Sample	I_0 / µA	I_1 / µA	n	τ_1 / s	D / µAs^{-1}
IS1-5	3.05	20.0	1	4.74 x10^5	
IS2-12	23.5	47.9	0.89	3.05 x10^5	
IS3-20	0.786				+1.57 x10^{-7}
IS4-37	0.826				-2.11 x10^{-8}

DCL slightly decreases with time for technology IS4 while DCL increase with very low slope is observed for technology IS3. DCL increases with time of ageing according to exponential stretched law with exponent n = 0.9 to 1 for both technology IS1 and IS2. Time constants are of the order 1 x10^5 s.

Influence of Electric Field on DCL vs. Time Characteristic for Temperature 105°C

The effect of electric field on the DCL vs time characteristic for fixed temperature is shown in Fig. 11 for ageing time interval 170 h. Here the results measured on sample IS3-15 are shown. All the experiments were done on temperature 105°C. Applied voltage was changed from 25 V to 45 V. When electric field is applied then the ions - oxygen vacancies move in the direction of electric field due to that potential wells are effectively lowered. The higher is electric field the higher change of DCL value.

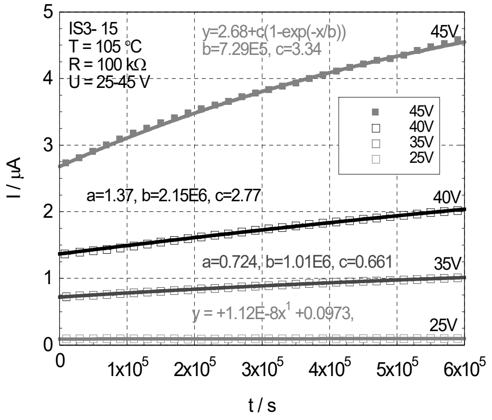

Fig. 11. DCL vs. time for applied voltage U = 25 to 45 V and T = 105 °C during time interval 170 h for IS3-15

Tab. 7. Values of parameters I_0, I_1, τ and D for IS3-15 in time interval 170 hrs

Voltage/V	I_0 / µA	I_1 / µA	τ_l/ s	D / µAs^{-1}
25	0.0973			1.12x10^{-8}
35	0.724	0.661	1.01x10^6	
40	1.37	2.77	2.15x10^6	
45	2.68	3.34	7.29x10^5	

Values of parameters I_0, I_1, τ_l and D for IS3-15 in time interval 170 hrs are in Tab. 7. Background temperature is for this sample lower than 105°C. DCL slightly increases with time of ageing for applied voltage 25 V while for voltage 30 to 45 V exponential increase according to eq. 2 is observed.

Results measured on sample IS4-37 show, that technology 4 has higher background temperature than 105°C. Thermal energy at temperature 105°C is not sufficient for the excitation of ions from potential wells at higher applied voltage up to 45 V (1.5 of rated voltage) and then DCL is constant or slightly decreases with time of ageing (see Fig 12).

Results measured on sample IS3-15 show, that technology T3 has background temperature about 65°C (see Fig 13). DCL for temperature $T = 65$ °C decreases with slope -4.11x10^{-7}μA/s while for temperature $T = 85$ °C increases with the slope 4.45x10^{-7}μA/s.

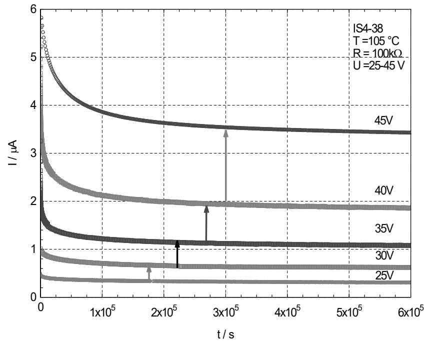

Fig. 12. DCL vs. time for applied voltage $U = 25$ to 45 V and $T = 105$ °C during time interval 170 h for IS4-37

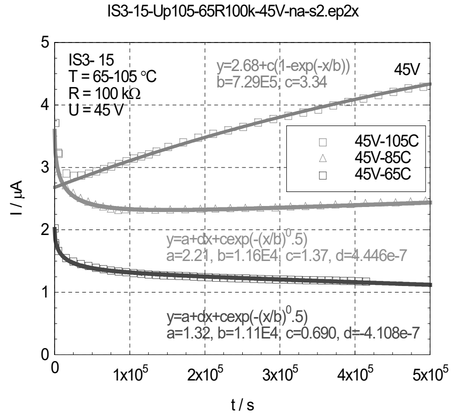

Fig. 13. DCL vs. time for applied voltage $U = 45$ V and T =65 to 105 °C during time interval 140 h for IS3-15

Conclusions

DCL vs. time characteristic after the voltage application consists from two processes. For the first one is characteristic the DCL lowering in the time interval 30 minutes up to 10 hours. We suppose that potential barrier on the Ta_2O_5 oxide layer/MnO_2 cathode interface increases in this time interval. We suppose that this process can be influenced by deep traps or double layer formed on the Ta_2O_5 oxide layer/MnO_2 cathode interface. The second process is characterised by DCL increase probably due to ions (oxide vacancies) drift/diffusion in Ta_2O_5 oxide layer. Both absolute and relative increase of DCL value depends on the capacitor technology. Determined relative increase of DCL varies from 4times (technology IS3) up to 37 times (technology IS2). Capacitors of technology IS4 exhibited high decrease of leakage current within initial 10 hours of ageing due to the first mentioned process. Considering both discussed processes the values of DCL of ensemble IS4 are lower past ageing than before the ageing. Ions transport in Ta_2O_5 oxide layer is influenced by the temperature excitation, value of electric field and ions gradient concentration. There exists background temperature at which the temperature excitation of ions is not sufficient to release them from the bound states - potential wells. In this case ions are at rest even in high electric field and for high ions concentration gradient. Background temperature depends on the technology. It is lower than 105°C for technology IS3 while higher than 105°C for technology IS4. For the technology IS3 the background temperature is as low as 65°C.

Acknowledgments

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