TECHNICAL PAPER

Thermal and Electrical Breakdown Versus Reliability of Ta_2O_5 under Both – Bipolar Biasing Conditions

P. Vašina, T. Zedníček, Z. Sita
Czech Republic, s.r.o., Dvorakova 328,
563 01 Lanskroun, Czech Republic

J. Sikula and J. Pavelka
CNRL TU Brno, Technicka 8,
602 00 Brno, Czech Republic

Abstract:
Our investigation of breakdown is mainly oriented to find a basic parameters describing the phenomena as well as its impact on reliability and quality of the final product that is "GOOD" tantalum capacitor. Basically, breakdown can be produced by a number of successive processes: thermal breakdown because of increasing conductance by Joule heating, avalanche and field emission break, an electromechanical collapse due to the attractive forces between electrodes electrochemical deterioration, dendrite formation and so on. Breakdown causes destruction in the insulator and across the electrodes mainly by melting and evaporation, sometimes followed by ignition. An identification of breakdown nature can be achieved from VA characteristics. Therefore, we have investigated the operating parameters both in the normal mode, Ta is a positive electrode, as well as in the reverse mode with Ta as a negative one. In the reverse mode we have reported that the thermal breakdown is initiated by an increase of the electrical conductance by Joule heating. Consequently followed in a feedback cycle consisting of temperature - conductivity - current - Joule heat - temperature. In normal mode an electrical breakdown can be stimulated by an increase of the electrical conductance in a channel by an electrical pulse and stored charge leads to the sample destruction. Both of these breakdowns have got a stochastic behaviour and could be hardly localized in advance.

INTRODUCTION

Our investigation of breakdown in the thin Ta_2O_5 insulating films was mainly oriented to found a basic parameters controlling these phenomena. Breakdown can be produced by a number of different processes such as: a thermal breakdown due to an increase of the electrical conductance by Joule heating, avalanche and field emission breakdown, an electromechanical collapse of the insulator due to attractive forces of the electrodes, electrochemical deterioration, dendrite formation etc.

Breakdown causes destruction of the insulator and of the electrodes mainly by melting and by evaporation. The destruction is not only due to the breakdown event but also due to follow-up current, which make it to difficult to interpret origin and kinetics of breakdown.

Special conditions appear when self-healing processes are involved. In some special cases weak spots and bulk breakdown can be diminished. During laboratory experiments a thermal breakdown can be measured without destruction and electrical breakdown can be observed with a minimal destruction.

As a special healing process can be also taken a tantalum oxygen filling from manganese dioxide, which can eliminate weaker spots inside of the dielectric by a making tantalum dioxide thicker (like an electrical anodisation). This can be easily proved by a long time DCL measurement. The dielectric healing also increases capacitor reliability expressed by Weibull distribution.

Breakdown process is not a strictly deterministic one. Our experimental results for oxides films shown that electric breakdown does not occur at a sharply defined field. This is a result of the stochastic processes and breakdown corresponds to an absorption barrier of them.

The identification of the breakdown process, whether it is thermal or electrical, can be achieved from VA characteristic [1]. In this case the unit connected to power source with a series resistance smaller than unit resistance. In our experiments with Ta capacitors this resistance was larger than 20 kΩ. The value of this resistance was chosen experimentally to prevent successive breakdowns and varies from 10 kΩ to 1 MΩ.

Thermal breakdown

Thermal breakdown is in normal mode responsible for self-healing process of weak spots and destruction of a single hole type. This process eliminates weak spots and VA characteristic in normal mode is represented by mainly by PoolFrenkel conduction [2] and [3].

In reverse mode (for Ta electrode negative) VA characteristic is exponential up to maximum voltage V_{TB}, when negative resistance region appears. For a small series resistance, in our experiments less than 10 Ω for voltage close to V_{TB}, the thermal breakdown and current flow make a sample less reliable as well as easy-to-breakdown in forward mode, when a thermal runaway occurs. Current for this destruction has got a strictly defined value in contrast to the small single hole destruction appearing at the weak spots.

Electrical breakdown

Recent studies on amorphous thin film oxides grown on tantalum and aluminium give an information about electrical breakdown [1]. These results seem to be important for an interpretation of breakdown. The rate of breakdown events decreases with a time to a steady value. The rate becomes large in the vicinity of a breakdown voltage and the unit could be completely destroyed by separate single hole breakdown. Electric breakdown voltage depends on electric pulse duration. In some experiments was shown [1], that with increasing pulse length the breakdown voltage decreases. This process is not strictly deterministic, the breakdown occurs at random sites and at random time intervals. In reverse mode electrical breakdown is the final state of thermal breakdown, mainly due to the Joule heating.

CURRENT TRANSPORT IN REVERSE MODE

Experimental study of the thermal breakdown was done in reverse mode for tantalum electrode as a negative one. In this case current transport is different with respect to the normal mode. Negative differential resistance, with a specific resistance in series, was observed for several types of capacitors and manufacturers (see Fig.1.).

There are at least three different mechanisms to assist us explain the existence of negative differential resistance:

i) Field induced transfer of conduction band electrons from a low energy, high mobility valley to higher energy, low mobility satellite valleys (Gunn effect)

ii) Tunnelling

iii) Formation of high current filaments in current control negative differential resistance device

iv) Double injection

Experimental results on tantalum capacitors shown that negative differential resistance have a S shape type (Fig. 1.). In this case we suppose that instability of current controlled negative differential resistance is created by a random noise fluctuation or non-uniformity in doping and is related to thermal excitation of carriers. Such effect will be temperature dependent and device will be locally heated, which will finally turn into a conductance change. This kind of instabilities is related to the electric noise and than other noise measurement can give us more information about the origin of this effect.

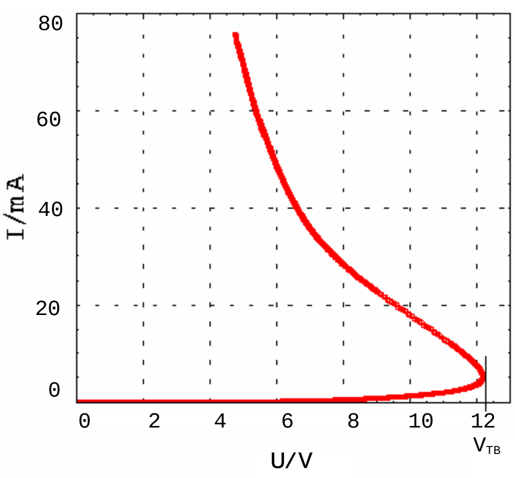

Fig. 1. VA characteristic in reverse mode

Tantalum capacitor can be generally considered in this case as a metal - insulator - semiconductor structure (MIS diode). Reverse mode with MnO_2 positive and Ta negative correspond to a MIS diode in forward direction and VA characteristic can be represented by an exponential - like dependence. In Fig.2. for voltage lower than thermal breakdown voltage V_{TB} in low injection region VA characteristic can be approximated by an exponential dependence. Thermal breakdown voltage V_{TB} on capacitor, where zero differential resistance appears, depends on the sample history and also on technology of production. The sample temperature increases with increasing current and for current 120 mA the temperature rise up to 100°C.

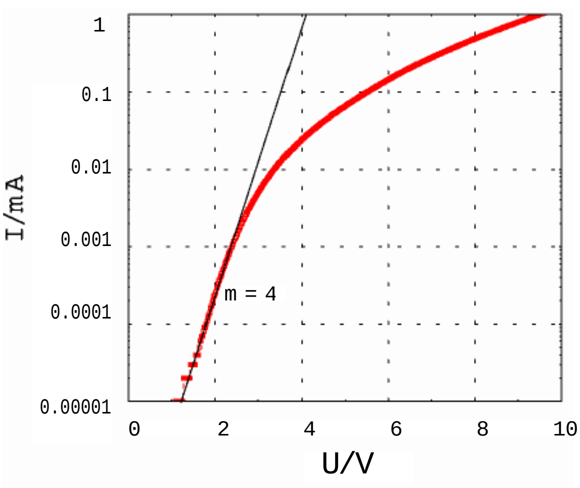

Fig.2. VA characteristic in reverse mode

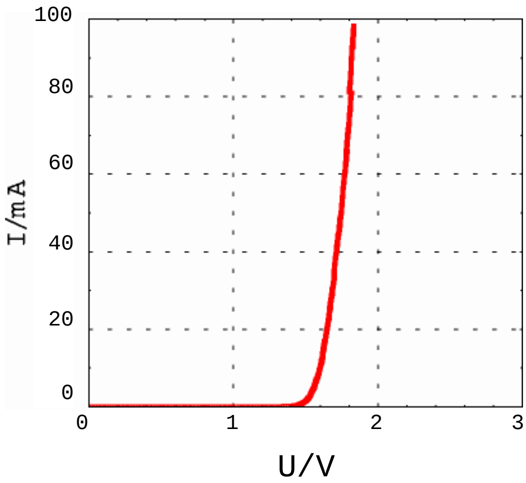

Fig.3. VA characteristic in reverse mode

For higher voltage current is not homogeneously distributed through all cross section and channels with high current density appear. This is due to feedback in cycle temperature - conductivity - current - Joule heat - temperature. In some cases this feedback changes the capacitance of this system and with increasing reverse mode voltage capacitance increases up to infinity.
High current density channels created due to Joule heating reveal some stability and VA characteristic in reverse mode can be due to long time heating changed into power dependence, as is shown in Fig.3.

2D MODELLING OF THE HEAT PROPAGATION

Thermal breakdown is initiated by an increase in the electrical conductance by Joule heat (see Fig. 4).

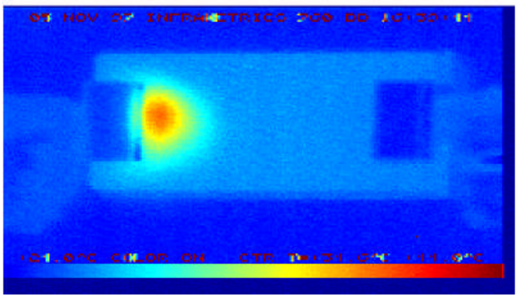

Fig. 4. The thermal breakdown under thermascope, in this case a self healing process took place.

In thin film without weak spots destruction occurs simultaneously in nearly the all insulator. If the discharge energy is enough not only to recreate the manganese into a dielectric, than a burn spot appears (see Fig. 5). This capacitor is after discharge shorted and further usage is impossible.

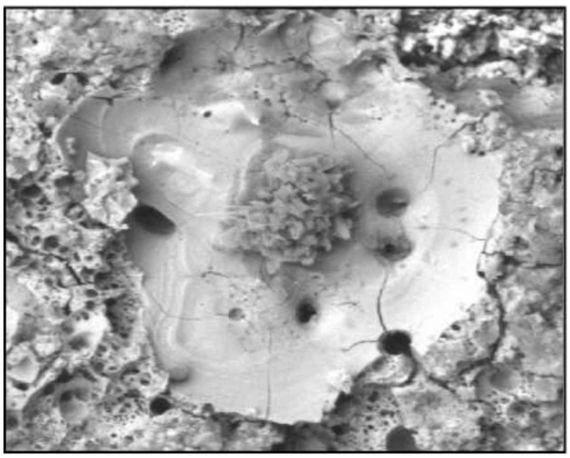

Fig.5. SEM analysis of the breakdown spot

Mathematical calculation of the thermal breakdown voltage requires a solution of the equation of heat conduction in the form

$$p.c. \frac{\partial T}{\partial t} = div(\lambda gradT) + \sigma E^2$$

and equation for the current continuity

$$\mathrm{div}(\sigma \vec{E}) = 0$$

where c is specific heat capacity, λ and σ thermal and electrical conductivity, T temperature, t time and E electric field intensity.

For calculation of V_{TB} relation for σ may be empirical in the form

$$\sigma = \sigma_o \exp(bE + a(T-T_o))$$

where σ_o, a and b are constants determined from VA characteristic of specimen and T_o is the ambient temperature.

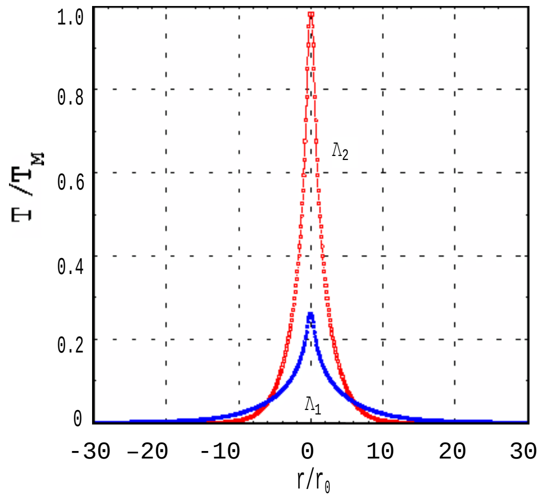

Fig.6. Normalised temperature distribution for a different thermal velocities λ_1 = 50 W/mK, λ_2 = 10 W/mK.

Numerical solution of given differential equation for two dimensional cylindrical approximation with λ=50 W/m.K and λ=10 W/m.K is shown in Fig.6. Here r_0 corresponds to dimension of the region, where the energy was dissipated. In out case r_0 was chosen 1 µm. Time evolution of temperature distribution is in Fig.7., where t_1 to t_3 denote time 1, 10 and 100 µs after pulse energy application with a power density 10^{16} W/m^3. This first approximation was performed for constant electrical conductivity σ, then the channel cross section will be smaller than we can estimate from this models. Due to the pinch effect of magnetic force the channel cross section will also diminish. Then the idea about thin channel creation can be.

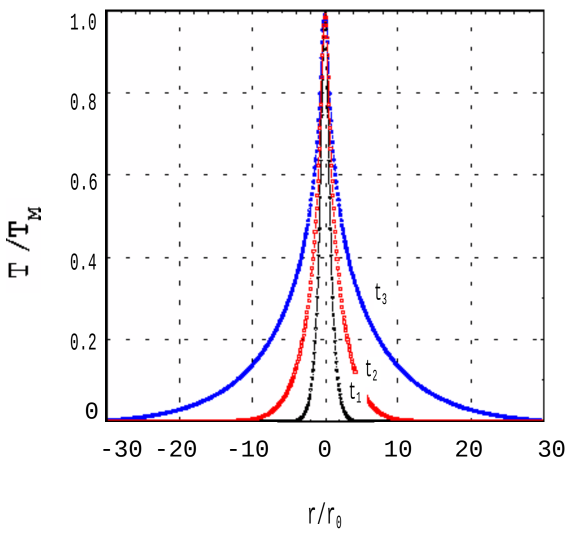

Fig.7 Normalise temperature distribution for λ = 10 W/m.K and time of heat generation t_1 = 1µs, t_2 = 10 µs, t_3 = 100 µs

CONCLUSION

The thermal breakdown, either in the normal mode or in the reverse mode, is initiated by an increase of the electrical conductance by Joule heat. There is a positive feedback among temperature - conductivity - current - Joule heat - temperature. To determine the breakdown voltage without destroying the sample, series resistance must be used. Not all of the breakdowns are harmful, e.g. selfhealing and tantalum additional oxidation coming from manganese dioxide are a tools, which can be used during assembly and successive testing as a tool for further capacitor healing. Knowledge of the breakdowns and their kinetics can show an additional site of the tantalum capacitors, which can build a product more robust and reliable.

A solid tantalum capacitor can be considered as a MIS (metal-oxide-semiconductor) diode and its reverse mode corresponds to a forward direction.

Modelling of temperature propagation in 2D approximation shows, that filaments with high current density and temperature can be created inside of the pellet.

REFERENCES

1. N. Klein, Electrical breakdown in thin dielectric films, J. Electrochem. Soc., Solid State Science, **116,** 963 (1969)
2. C. A. Mead, “Electron transport mechanisms in thin insulating films” Phys. Rev. **128,** 088 (1962)
3. S. M. Sze, Physics of Semiconductor Devices, J.Wiley & Sons New York (1981)

NORTH AMERICA
Tel: +1 864-967-2150

ASIA
Tel: +65 6286-7555

CENTRAL AMERICA
Tel: +55 11-46881960

EUROPE
Tel: +44 1276-697000

JAPAN
Tel: +81 740-321250

WWW.KYOCERA-AVX.COM