FAILURE MODES OF TANTALUM CAPACITORS MADE BY DIFFERENT TECHNOLOGIES

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ABSTRACT

Generally, tantalum capacitor failure modes have been discussed both for the standard manganese dioxide cathode and the new conductive polymer (CP) type. For standard tantalum in the normal operation mode, an electrical breakdown can be stimulated by an increase of the electrical conductance in channel by an electrical pulse or voltage level. This leads to capacitor destruction followed by thermal breakdown. In the reverse mode, we have reported that thermal breakdown is initiated by an increase of the electrical conductance by Joule heating at a relatively low voltage level. Consequently, a feedback cycle consisting of temperature - conductivity - current - Joule heat - temperature, ending with electrical breakdown was created. Both of these breakdown modes possess a stochastic behavior and can be hardly localized in advance. Conductive polymer capacitors have shown a slightly different current conductivity mechanism compared to standard tantalum capacitors. The breakdown of CP dielectrics is similar to avalanche and field emission breaks. It is an electromechanical collapse due to the attractive forces between electrodes, electrochemical deterioration, dendrite formation, and so on. However, some self-healing of the cathode film has been reported. This can be attributed to film evaporation, carbonizing or reoxidation. Not all of the breakdowns of CP capacitors can lead to self-healing or an open circuit state. Short circuits can also occur.

INTRODUCTION

Our investigation of dielectric breakdowns was oriented toward finding a basic set of parameters that would describe this phenomenon and its relation to the reliability and quality of the final product. Basically, dielectric breakdown can be produced by a number of successive physical processes: thermal breakdown brought on by increasing conductance from Joule heating, avalanche and field emission break, an electromechanical collapse due to the attractive forces between electrodes, electrochemical deterioration, dendrite formation and so on. Dielectric breakdown causes destruction in the insulator and across the electrodes mainly by melting and evaporation, sometimes followed by thermal runaway. To obtain more information about the tantalum MIS (metal-insulator–semiconductor) heterostructure and find a correlation between the dielectric breakdowns, we investigated operating parameters which were current and voltage dependent, both in the normal mode where the tantalum electrode is positively biased, and in the reverse mode where the tantalum electrode is negatively biased.

Breakdown destruction is not only due to a sudden breakdown event, but is also due to subsequent current flow, which makes it difficult to interpret the origin and kinetics of the breakdown.

Special conditions appear when self-healing processes are involved. In some cases, the incidence of weak spots and bulk breakdown areas can be reduced. During laboratory experiments, thermal breakdown can be measured without destroying the device, and electrical breakdown can be observed with minimal damage occurring. An additional healing process can also be inferred; oxygen can be released from the manganese dioxide counter-electrode, which then reduces weak spots inside the dielectric by allowing local regeneration of tantalum dioxide or eliminating charge traps (similar to an electrical anodization and/or passivation process).

There are two possible self-healing methods reported on conductive polymer materials. The first theory is based on an evaporation process. Polymers tend to have fairly low melting and evaporation temperatures. If the current into the fault is sufficient to heat the polymer, it can evaporate and eliminate

connection to that site. The secondary theory of self-healing proposes that the polymer absorbs oxygen as it is heated at the fault site, thereby creating a high resistance cap and sealing the current to the fault site, in the much the same manner as the MnO_2 healing. [1]

The dielectric breakdown processes are not strictly deterministic ones. Our experimental results for thin oxide films show that electric breakdown does not occur at a sharply defined value of the applied electrical field. The breakdown is a result of stochastic processes, and the final breakdown corresponds in many cases to the sum of independent events.

EXPERIMENTAL

Identification of the breakdown process, whether it is thermal or electrical, can be determined by V-A (voltage / current) characteristics coupled with measurements in the time domain [2], in the normal mode and in the reverse mode as defined above. In these cases, the device must be connected to a power source with a series resistance smaller than the resistance of the device itself. The value of this resistance was chosen experimentally to prevent successive breakdowns as well destruction, the range being from 10 Ω to 1 MΩ.

A breakdown test was performed in order to evaluate self-healing processes of both the MnO_2 and conductive polymer technologies. Current step-up sweep was used to increase load voltage by small increments until electrical breakdown occurred. The ability of the capacitor to recover / self-heal the breakdown failure spot was monitored by voltage drop and IR camera check.

MnO_2

CURRENT TRANSPORT IN NORMAL MODE

Current transport in normal mode through an MIS heterostructure (in this case, the Ta-Ta_2O_5-MnO_2 system) has been reported in many papers [for example see 3,4]. Therefore, we will consider only the physical mechanism and basic theory of transport. Electron transport through the Ta capacitor in normal mode follows the Poole-

Frenkel and Schottky mechanism. One can assume that electrons may tunnel from the MnO_2 electron level through the interface barrier inside the Ta_2O_5 dielectric layer. The electric field in the Ta_2O_5 assists in the release of electrons from the traps, suggesting that electrons are hopping from one trap to the other with low mobility. The Schottky effect is frequently considered to be an interface effect, while the Poole-Frenkel effect is a bulk effect.

One can say primarily that electrical breakdowns appear at high electrical field, at random sites and time.

CURRENT TRANSPORT IN REVERSE MODE

Negative differential resistance, with a specific series resistance, was observed for several types of capacitors and manufacturers (see example in Fig.1.).

There are at least four different mechanisms to help us explain the presence of the negative differential resistance:

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

ii) Tunnelling

iii) Formation of high current

iv) Double injection

Experimental results on tantalum capacitors show that negative differential resistance has an "S" shaped V-A curve (Fig.1.).
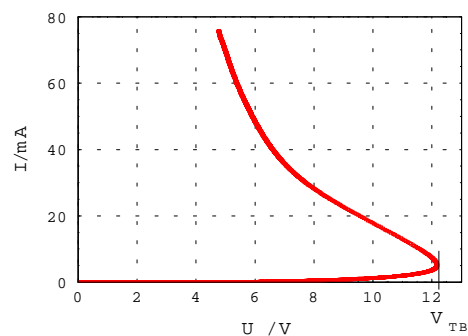

Fig.1. V-A characteristic in reverse mode of MnO_2 tantalum capacitor system.

In this case, we believe that the instability of current controlled negative differential resistance is created by either a random noise fluctuation or non-uniformity in doping, and is related to thermal excitation of the carriers. Such an effect should be temperature dependent, and local heating will take place within the device. This will, in turn, lead to a conductance change. This kind of instability is related to the electrical noise. Additional noise measurements will give us more information about the origin of this phenomenon.

A tantalum capacitor is generally considered to be a metal – insulator – semiconductor heterosystem (MIS diode). The reverse mode (where the MnO_2 counter-electrode is positively biased and tantalum anode negatively biased) corresponds to an MIS diode operating in forward direction and the V-A characteristic will exhibit an exponential dependence. In Fig.1, for voltages lower than the thermal breakdown voltage V_{TB}, the V-A characteristic in the low injection region can be approximated by an exponential curve. The thermal breakdown voltage V_{TB} of the capacitor, where zero differential resistance appears, depends on the sample history and production technology used. The sample temperature will increase with increasing current and for a current of 120 mA temperature rises up to 100°C can occur.

At higher voltages or for devices with internal defects, the current is not homogeneously distributed through the bulk of the capacitive element, and channels with high current density occur. This is due to feedback in the temperature - conduction - Joule heating – increased temperature cycle. High current density channels that are created by Joule heating exhibit some stability, and the reverse mode V-A power dependence characteristic is likely due to constant heating over time.

Thermal breakdown

Controlled thermal breakdown in the normal operating mode gives rise to self-healing of weak spots and a reduction in the generation of local defect sites.

On the other hand, uncontrolled thermal breakdown can cause shorts, resulting in thermal runaway that can ultimately destroy the capacitor.
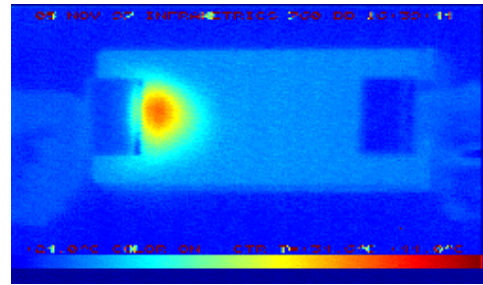

Fig. 2. Self-healing process under IR camera

In reverse mode, the V-A characteristic is exponential up to maximum voltage V_{TB}, at which point it enters the negative resistance realm.

Our experiments showed that, for a small series resistance (~10 Ω) for voltages close to V_{TB}, the thermal breakdown and current flow make the device less reliable and more prone to thermal breakdown in the forward mode. The current associated with this failure mechanism has a more defined value, in contrast to the range of values associated with smaller, single-site failures occurring at the weak spots.

Electrical breakdown

Studies on amorphous thin film oxides grown on tantalum and aluminium have yielded information about electrical breakdown [2]. The rate that breakdown events occur decreases with time to a steady value. The rate increases as breakdown voltage is approached. With this increase in voltage, the likelihood the device will fail from thermal runaway at a single defect site increases. The breakdown voltage is dependant on pulse duration. In some experiments [2] it was seen that the breakdown voltage decreases with increasing pulse length. This process is not strictly deterministic; the breakdowns occur at random sites and at random time intervals. In reverse mode, electrical breakdown is the final state of thermal breakdown, mainly due to Joule heating.

Conductive polymer

CURRENT TRANSPORT IN NORMAL MODE

The first section of the V-A characteristic curve (see Fig. 3.) can be described as a square

law dependency that is related to the injection of current into the insulating layer with trap-fillet-limit. The second section is a quadratic dependence due to space charge limited current injection with uniform trap distribution. The transition point between these two processes depends on Fermi level energy with respect to trap activation energy. The Poole-Frenkel mechanism is overlapped with current injection into insulator limited by space charge. Electric field intensity is not homogeneous and is extremely high near the injection electrode; thus, it is critical for cathode material requirements.
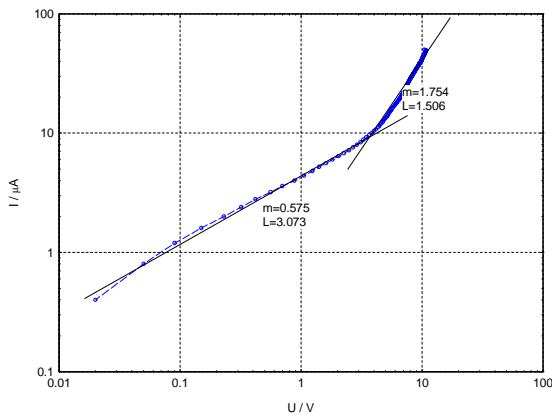

Fig. 3. Tantalum capacitor with conductive polymer in normal mode.

CURRENT TRANSPORT IN REVERSE MODE

Negative differential resistance, with a specific series resistance, was not observed for conductive polymer technologies (see example in Fig.4.). This is due to the feedback in the temperature - conduction - Joule heating – increased temperature cycle in high current density channels via dielectric.

Because the mechanism of transition in the reverse mode is significantly proportional to the dielectric performance, the same result should be attained. Another difference can be found in the lower level of breakdown voltage because of the different function of cathode material.
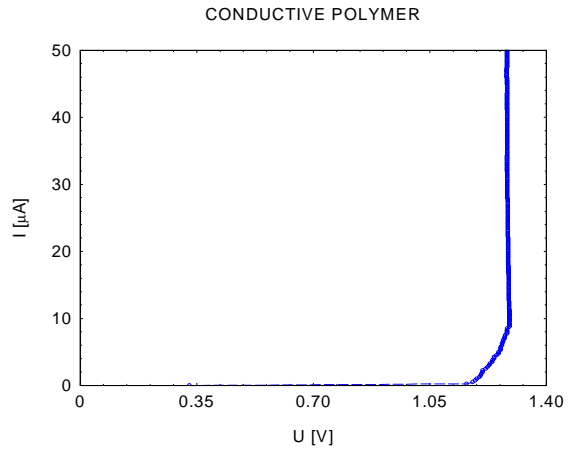

Fig. 4. Tantalum capacitor with conductive polymer in reverse mode.

Conductive Polymer breakdowns

There have been significant differences reported between individual CP manufacturer technologies. Capacitors made by the first technology have shown breakdowns without record of any self-healing processes and short circuit of the capacitor after dielectric breakdown (see Fig. 5.). No single breakdown voltage has been found in the case of the second technology. During the test, the current was continuously increased up to thermal breakdown with no self-healing observed.
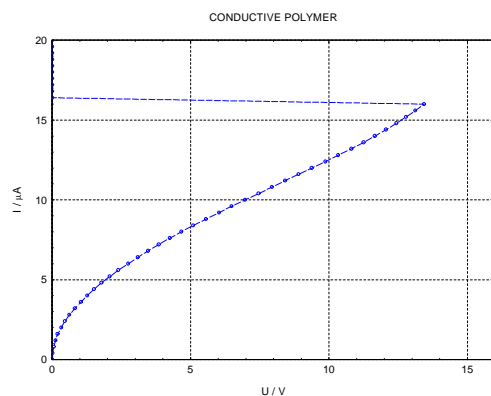

Fig. 5. Dielectric breakdown results in short for conductive polymer made in the first technology.

CONCLUSION

According to V-A characteristics, a solid tantalum capacitor made with either MnO_2 or conductive polymer technology can be considered as an MIS (metal-oxide-semiconductor) diode, and its reverse mode corresponds to an MIS diode operated in a forward direction.

With MnO_2 as the cathode material, thermal breakdown in the normal mode follows electrical breakdown due to energy dissipation. However, in the reverse mode, breakdown is initiated by an increase of the electrical conductance by Joule heating. A positive feedback cycle of temperature - conduction - - Joule heating – increased temperature then occurs.

The V-A characteristic of the conductive polymer capacitor, on the other hand, has a first section, the low intensity region, that is described as a square law dependency. It is related to the current injection into the insulating layer with trap-fillet-limit. This is consequently followed by a section of quadratic dependence due to space charge limited current injection with uniform trap distribution.

Electrical breakdown of MnO_2 capacitors initiated by the test started at about $25 - 35V$ (three times rated voltage). Conductive polymer dielectric breakdown occurred at lower voltage, about $10 - 20V$ (one to two times rated voltage).

MnO_2 parts were found to be more capable of self-healing during the electrical breakdown experiment than either of the conductive polymer technologies tested. No efficient self-healing processes were found during the test to confirm the theories on conductive polymer materials. Some additional work on conductive polymer materials may be required in order to understand their physical properties and potentials for future applications.

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