Breakdown in Tantalum Capacitors

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List of Acronyms

BI	burning-in	ESR	equivalent series resistance
CCS	constant current stress	MC	molding compound
CPTC	chip polymer tantalum capacitor	PS	power supply
DCL	direct current leakage	SEM	scanning electron microscopy
DF	dissipation factor	VBR	voltage breakdown
DUT	device under test	VR	voltage rating
EDS	energy dispersive analysis	WGT	Weibull grading test

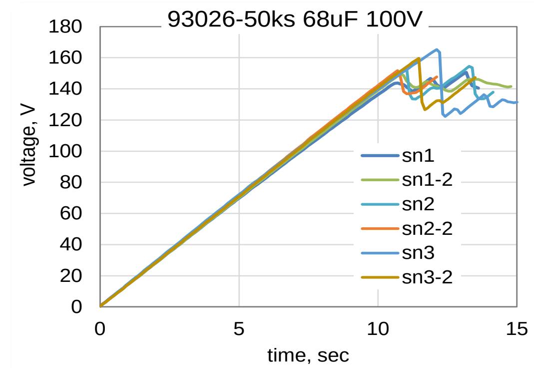
Abstract

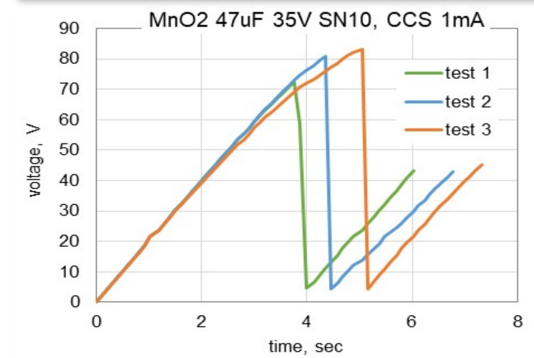
Failures in tantalum capacitors can be considered as a time-dependent-breakdown and reliability of all types of capacitors, including wet, MnO2 and polymer cathode parts, depends on the efficiency of self-healing that can mend parts after breakdown. A mechanism of self-healing in MnO2 capacitors is associated with oxygen reduction in the cathode layer and isolation of the breakdown site with high-resistive Mn2O3/Mn3O4 compositions. Although this mechanism is commonly accepted, details of self-healing have not been analyzed sufficiently yet, and the effects of scintillations on behavior of the parts has not been fully understood. There is a lack of data on the self-healing efficiency in different lots of capacitors. Even less is known about self-healing in polymer tantalum capacitors. In this work, different types of polymer and MnO2 capacitors have been tested for scintillation breakdown using a constant current stress (CCS) technique modified to allow detection of the amplitudes and durations of current spikes during breakdown. Characteristics of the parts and in particular leakage currents were measured to assess the efficiency of self-healing and improve screening processes for tantalum capacitors. Damaged sites were localized using infrared camera and their appearance analyzed after deprocessing and cross-sectioning. Thermal effects during scintillations have been modeled, self-healing processes in polymer and MnO2 cathode capacitors discussed, and mechanisms of breakdown based on the growth of conductive filaments in the dielectric suggested.

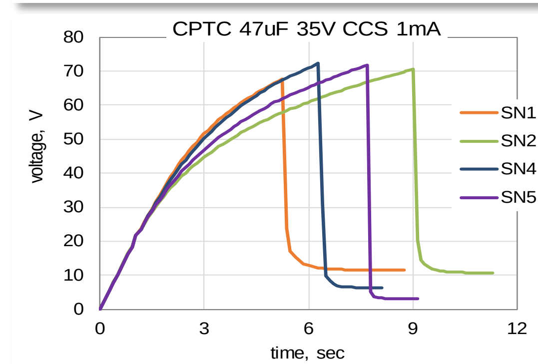
Outline

- A technique to characterize scintillation breakdown and self-healing.
- Breakdown in MnO2 and polymer capacitors.
- How effective is self-healing?
- Location of damaged sites.
- Energy and power of breakdown.
- Mechanisms of breakdown and self-healing.
- Conclusion.

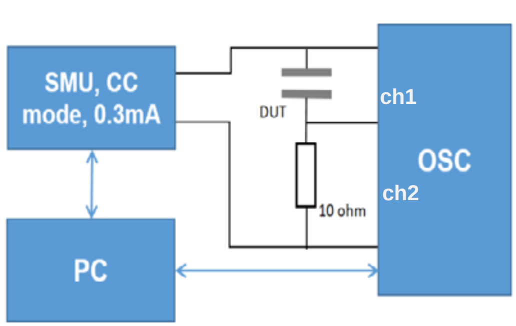
Examples of CCS testing for different types of capacitors





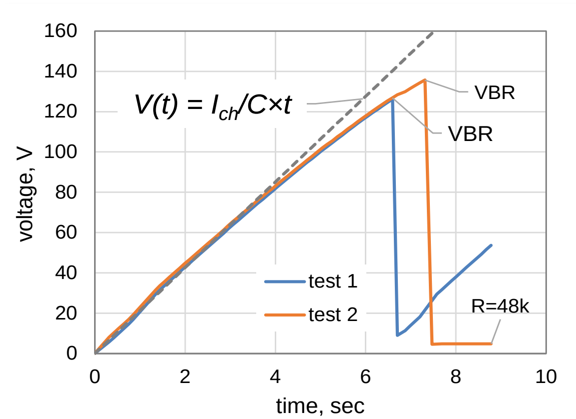


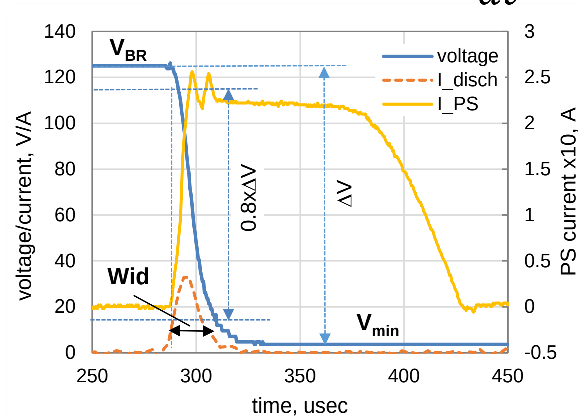
Technique

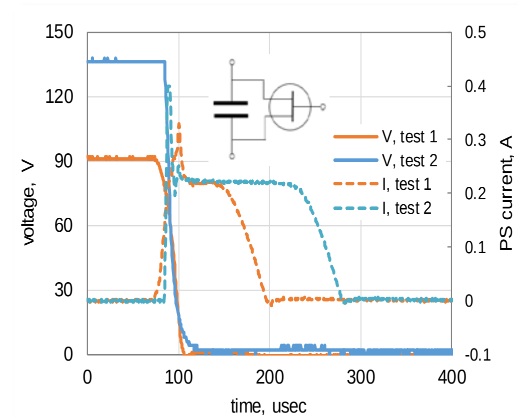


- Voltage across DUT is monitored during charging at a constant current;
- Oscilloscope is trigged at breakdown to record discharging process and PS current spike.
- Multiple lots of MnO_2 and polymer tantalum capacitors rated from 6.3 to 35 V were tested.

$$I_{disch}(t) = C \times {dV(t)}/{dt}$$

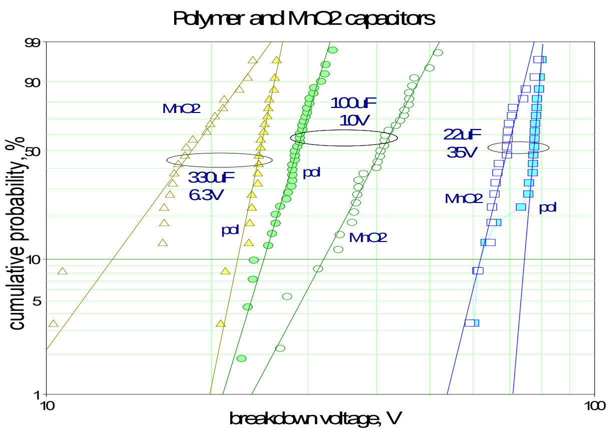




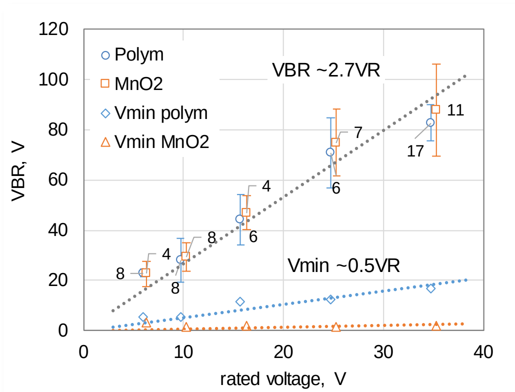


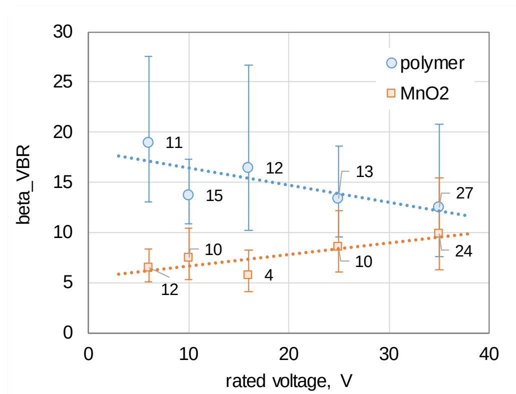
- ✓ Major characteristics of a scintillation are VBR, V_{min}, and *Wid*.
- ✓ Amplitude and duration of PS current spikes depend on dynamic characteristics of PS used and do not characterize breakdown.
- ✓ Self-healing can be characterize by the proportion of damaged parts and R_d.

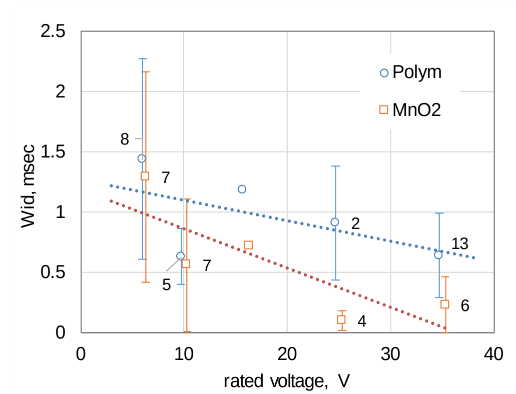
Distributions of Breakdown Characteristics



- No significant difference in VBR between CPTC and MnO_2 capacitors with similar ratings.
- The slopes of Weibull distributions of VBR, β, are larger for polymer than for MnO2 capacitors.
- Scintillation times vary from ~100 μsec to ~2 msec and are smaller for MnO2 than for polymer capacitors.



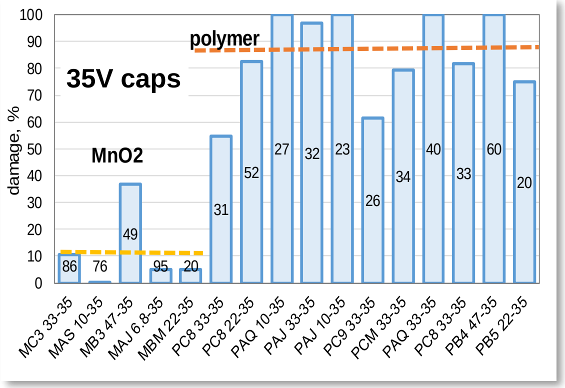


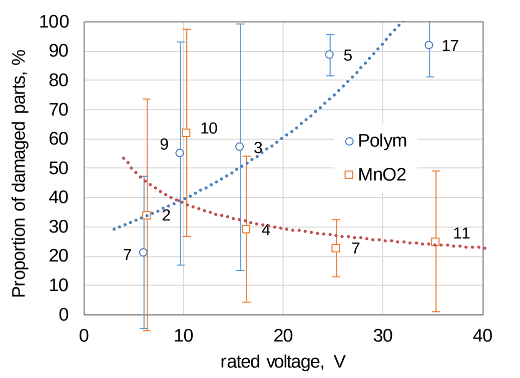


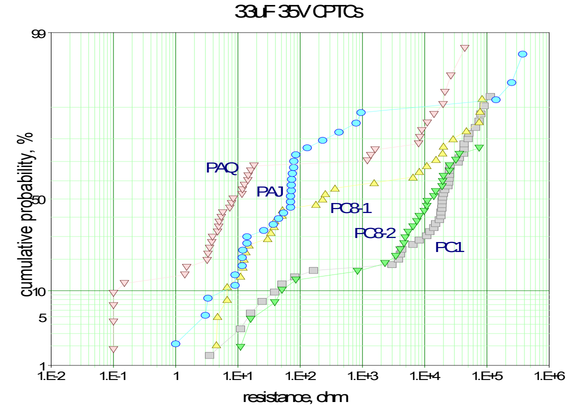
✓ Formation of polymer cathodes occurs at much lower temperatures (≥ 180ºC) compared to MnO2 cathodes (pyrolysis of manganese nitrate at 250 to 350ºC) → more oxygen vacancies and defects in the structure of the dielectric is generated in MnO2 than in polymer capacitors.

Self-Healing Characteristics

- Proportion of damaged parts varies from lot to lot substantially, but on average, is much greater for CPTCs than for MnO2 capacitors.
- The difference is significant for VR ≥ 16V.
- Wide distributions of resistances for damaged capacitors – from ohms to Mohms.



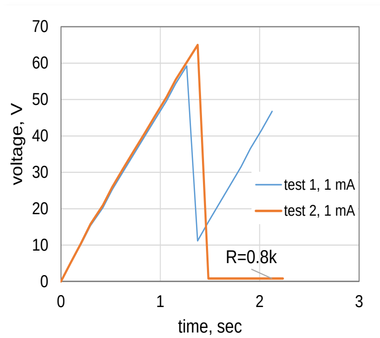


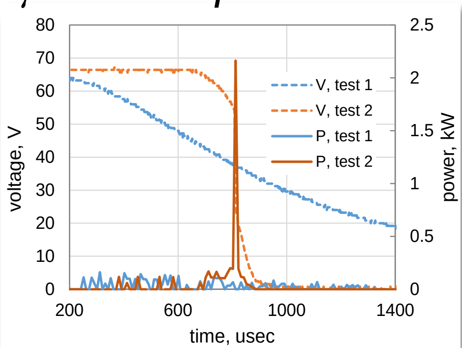


- ✓ On average, self-healing capability is greater for MnO2 than for CPTCs.
- ✓ Some CPTCs might fail in high-resistive mode that cannot be detected by blown 1A fuses.
- ✓ Due to large DCL margin for CPTCs (DCLmax= 0.1CV), capacitors with relatively low resistances (R_{cr} = 10/C) might pass the screening.

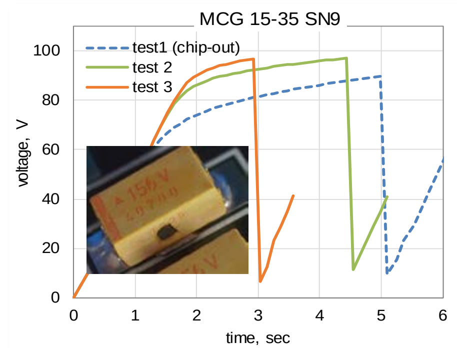
Discharge in MnO2 Capacitors

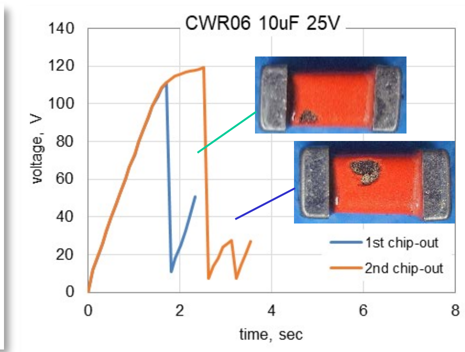
Damaging and non-damaging breakdowns in 22μF 35V capacitors



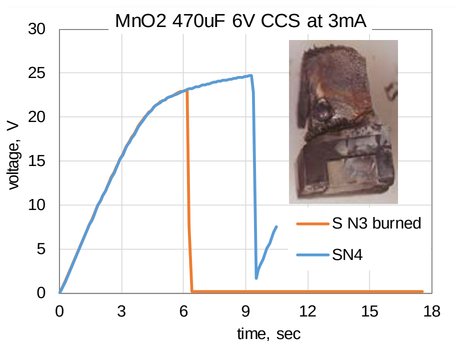


Chip-outs during scintillation testing



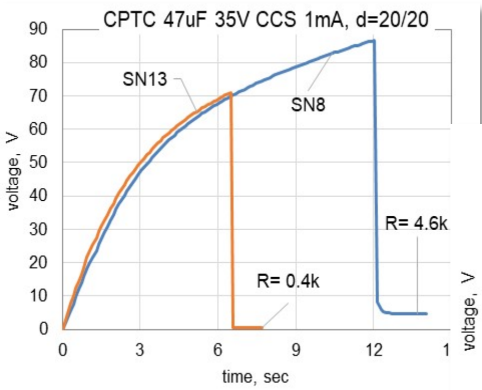


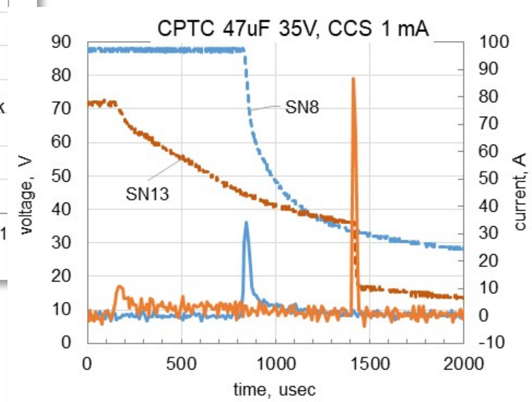
Burning during scintillation testing

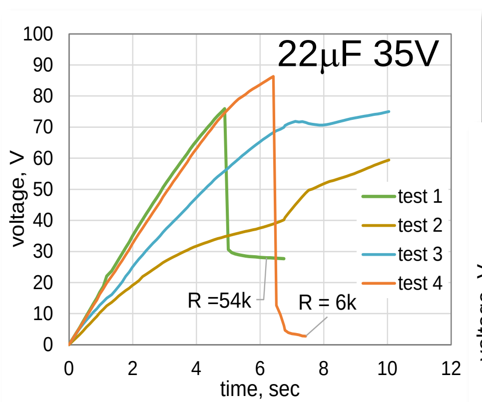


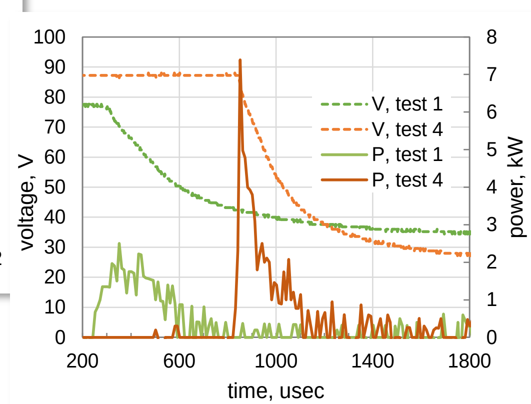
- ✓ The rate of discharge might vary substantially during breakdown.
- ✓ Damage is typically associated with significant spikes of discharge currents.
- ✓ MnO2 capacitors might remain functional even after physical damage (chip-outs).
- ✓ Consecutive tests might result in damage at a different location.
- ✓ Large value MnO2 capacitors might burn in high impedance circuits (burning continues after circuit disconnection).

Discharge in Polymer Capacitors





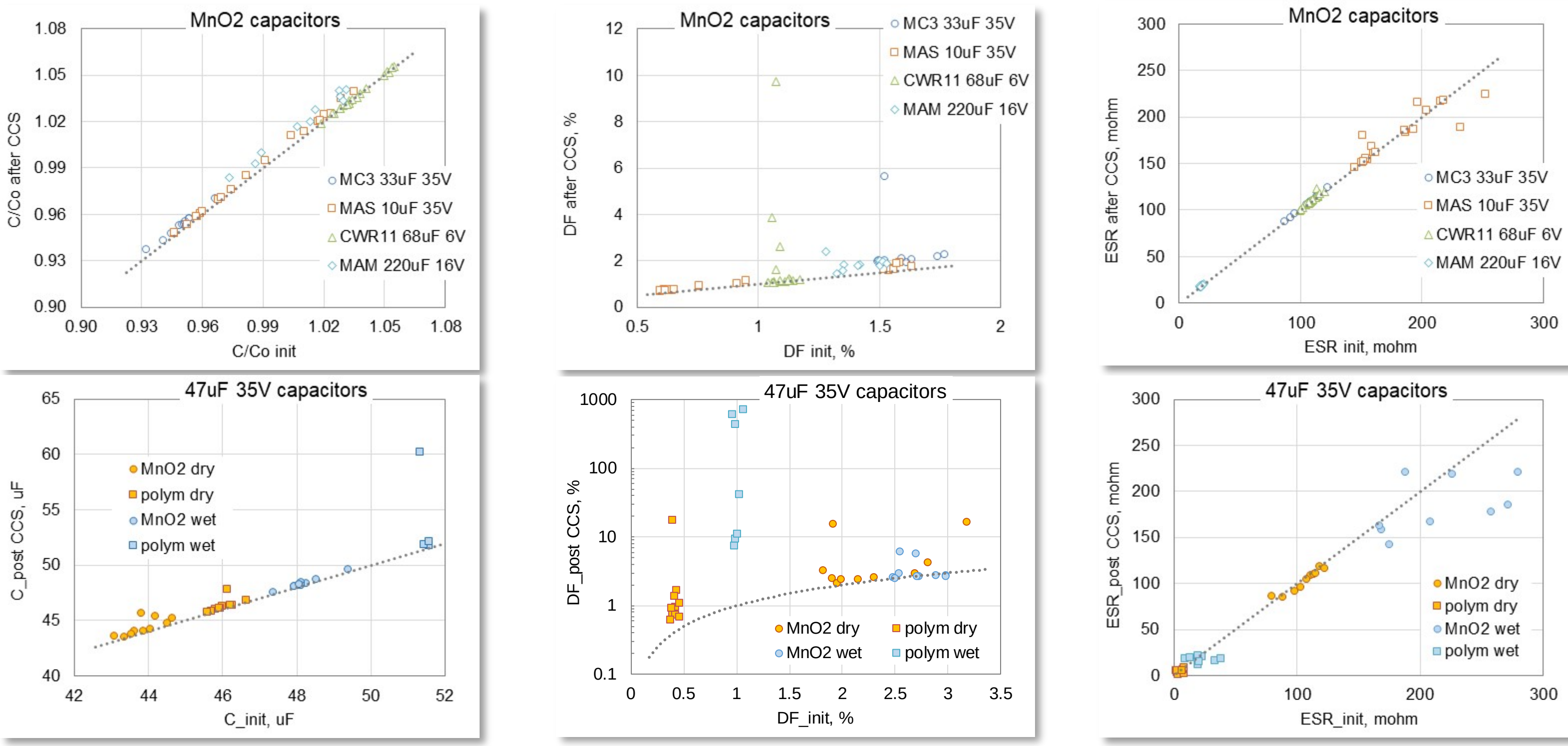




- ✓ Larger discharge times indicate smaller average discharge currents in CPTCs.
- ✓ However, similar to MnO2 parts, damage in CPTCs is due to presence of high-current spikes that correspond to kilowatts range power.
- ✓ Several spikes can occur during the same discharging process.
- ✓ Repeat tests might self-heal or further damage the part.
- ✓ Scintillations might not cause fuse blowing and damaged parts can pass BI or life testing.

Effect of Scintillations on AC Characteristics

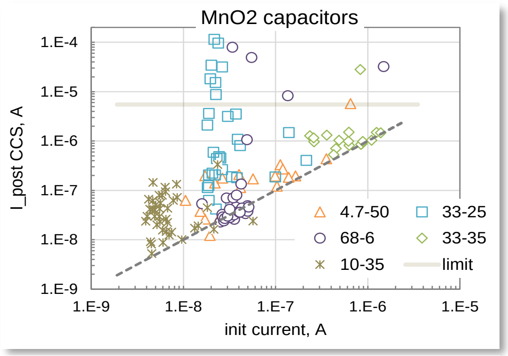
Correlations between AC characteristics measured before and after CCS testing

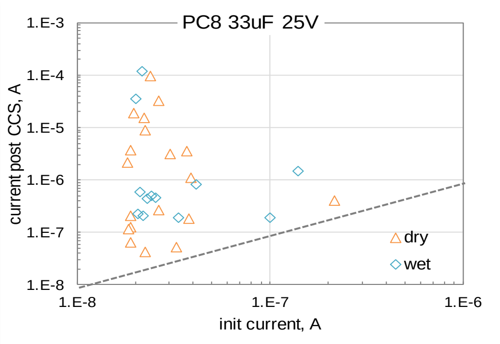


- ✓ Capacitance and ESR do not change substantially after CCS testing, but DF might increase significantly.
- ✓ Due to a large margin, parts with increased DF might pass screening.
- ✓ Scintillations might happen during WGT and parts with the out-of-family DF values should be screened out.

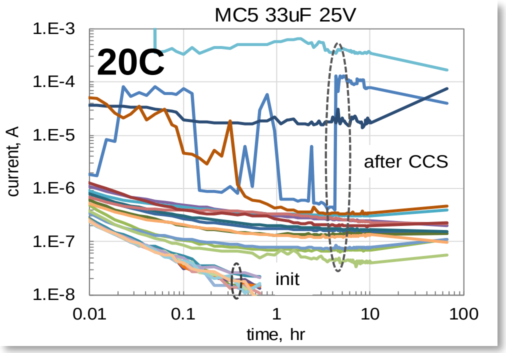
Effect of Scintillations on Leakage Currents

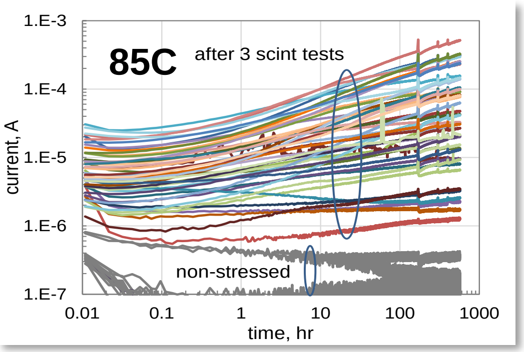
Correlations between initial and post-CCS leakage currents

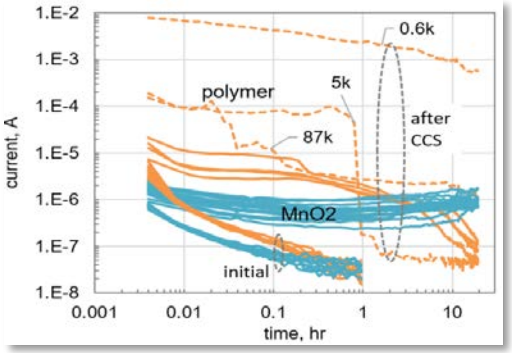


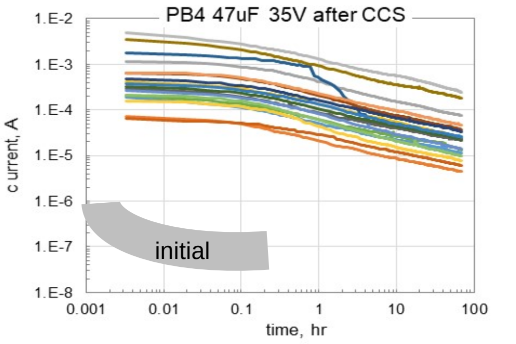


Variations of leakage currents with time





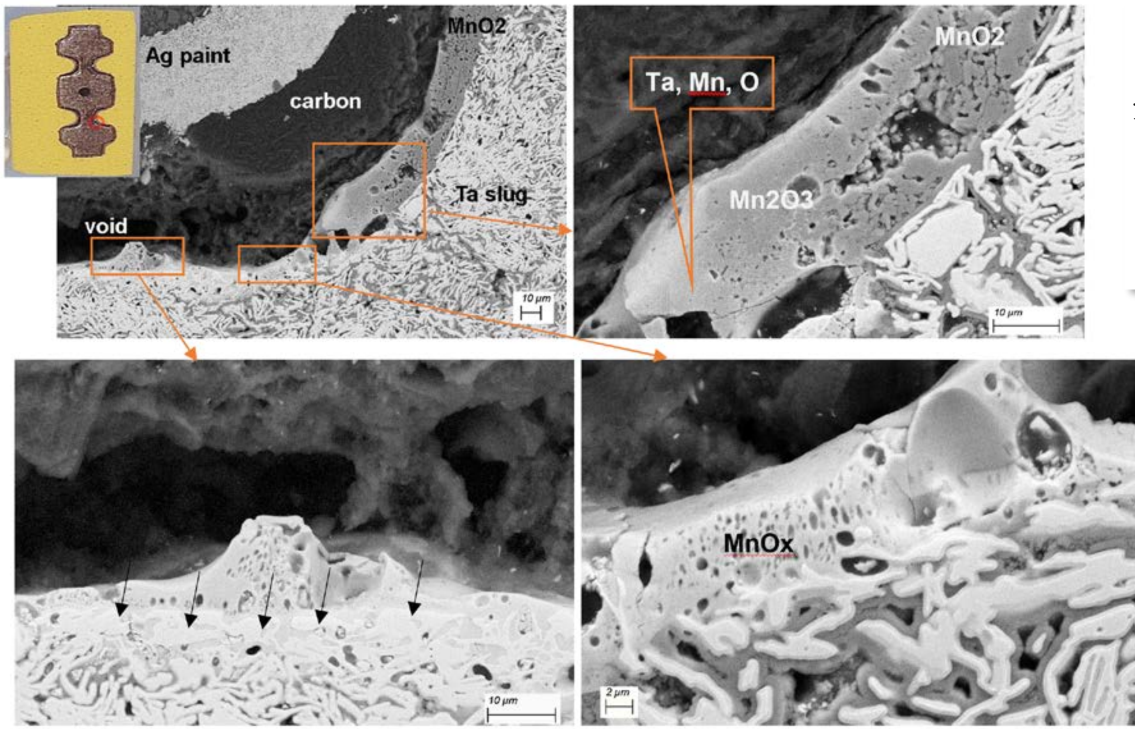




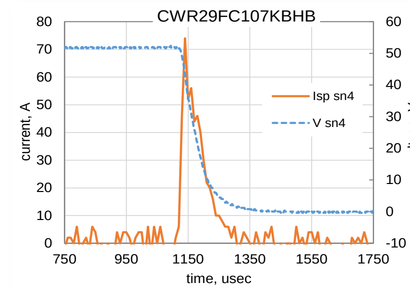
- ✓ Scintillations result in substantial increasing of currents even for self-healed caps.
- ✓ Erratic behavior indicates additional scintillations occurring with time under bias.
- ✓ At VR, scintillations might occur after dozens and hundreds of hour of testing.
- ✓ Degradation of currents for MnO2 parts after CCS testing increases substantially.
- ✓ For CPTCs, contrary to MnO2 parts, currents after CCS might decrease with time.

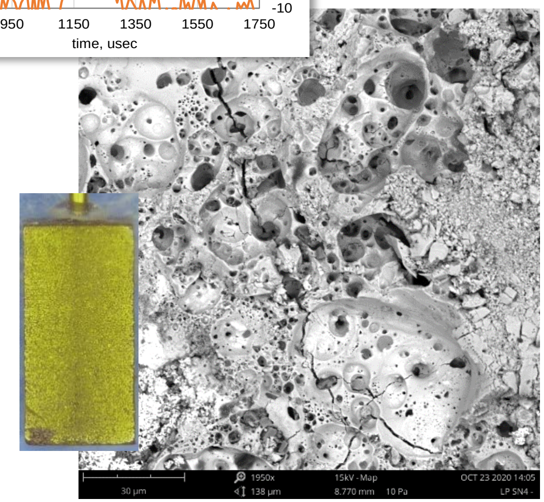
Damage in MnO2 Capacitors

A 6.8μF 35V capacitor that failed CCS testing at 240ohm



100μF 10V capacitor that failed at 63ohm

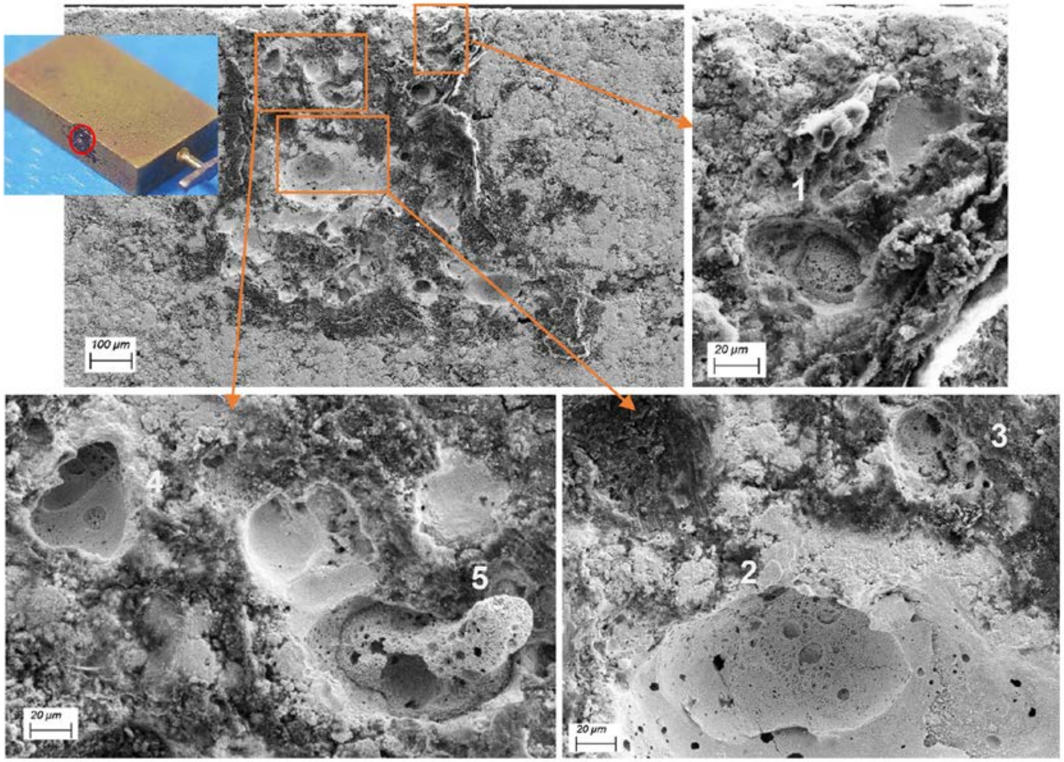




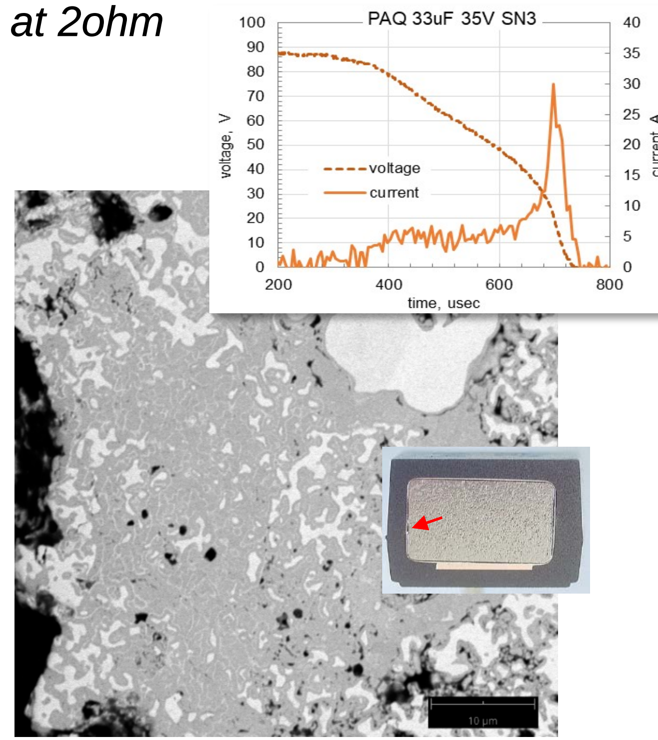
- ✓ Damaged sites were on the surface of the slugs and had a size of ~200 μm.
- ✓ SEM and EDS analysis showed evidences of formation of areas with mixed TaOx/MnOx oxides adjacent to voids in MC.
- ✓ The oxide areas comprised of a mixture of non-stoichiometric MnO_x and TaO_y.
- ✓ Morphology of breakdown damage indicates multiple scintillation events.

Damage in Polymer Capacitors

A 47μF 35V capacitor that failed CCS testing at 1ohm



A 33μF 35V capacitor failed CCS at 2ohm

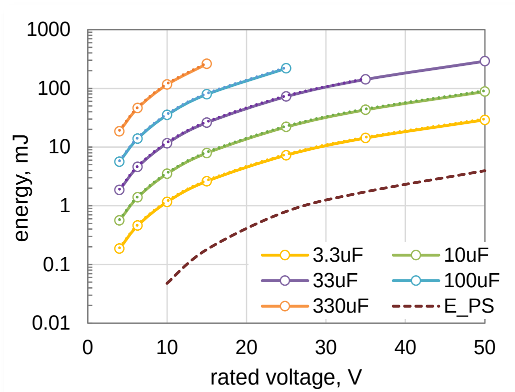


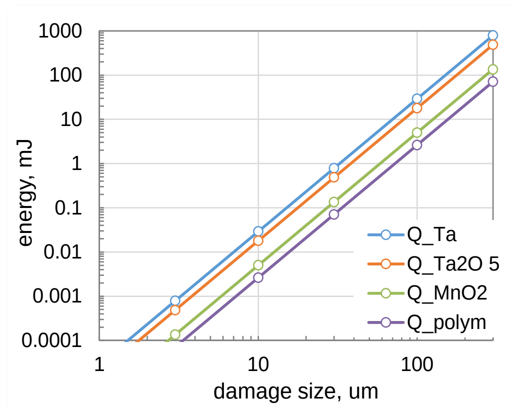
- ✓ Damage in CPTCs had similar size and appearance as in MnO2 parts and has also multiple impact areas.
- ✓ SEM and EDS examinations suggest oxide diffusion, fusion of the oxidized tantalum particles, and a substantial reduction of the size of pores.
- ✓ Oxide diffusion formed non-stoichiometric tantalum oxide TaOx, x < 2.5, that might have higher conductivity compared to Ta2O5 layers.

Energy of Scintillation Events

- High discharge current during breakdown can cause local overheating and physical damage to the structure.
- Assuming damage size *r* and volume υ, at adiabatic conditions:
  $\upsilon \times \rho \times (c \times \Delta T + Cf) = {}^{C}/_{2} \times (V_{BR}^{2} - V_{min}^{2})$

Characteristic	unit	Ta	Ta2O5	MnO2	polym
specific heat capacity, c	J/(kg×K)	140		630	
specific density, ρ	g/cm^3	16.7	8.2	5	~1
heat of fusion, C_f	J/kg	176			
Thermal conductivity, k	W/(m×K)	58		~0.35	~0.2
Critical temperature	ºC	3017	1870	535	290

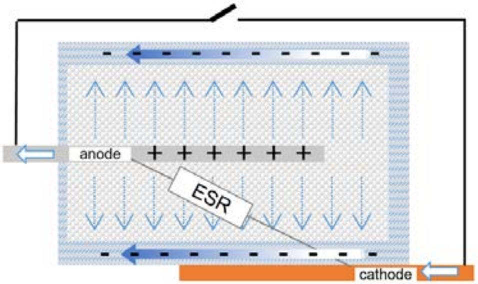


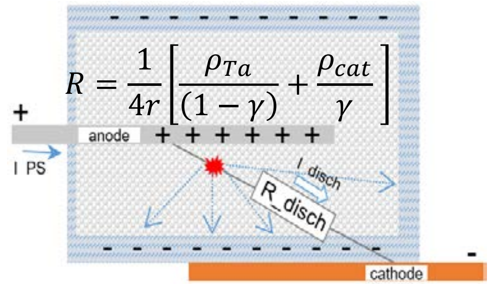


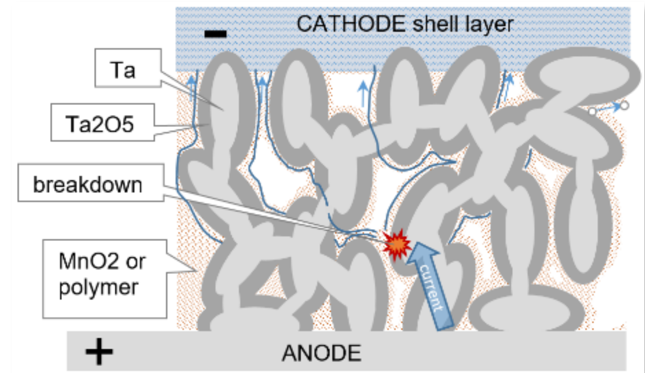
- ✓ Most energy during breakdown goes to heat-up tantalum areas of the damage.
- ✓ Breakdown in 33μF 35V capacitors has energy ~150 mJ that is sufficient to melt a sphere of tantalum ~200 μm.
- ✓ Estimations are in agreement with results of failure analysis: in most cases, damages had sizes in the range from 100 to 200 μm.

Discharge Times During Scintillations

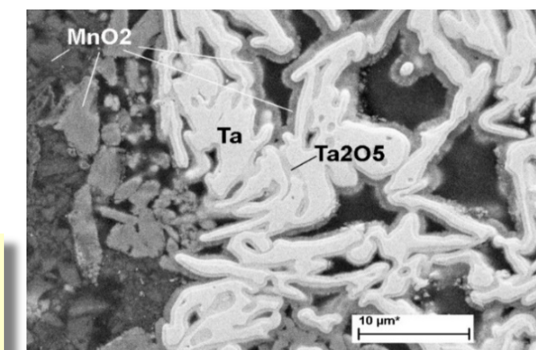
Transients during external and internal shorts, $\tau = C \times R$

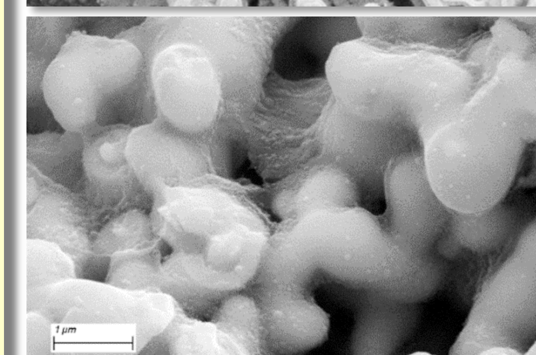






- ❑ Discharge based on ESR predict a faster breakdown in CPTCs.
- ❑ Discharge conditions for a capacitor shorted externally and internally are different.
- ❑ Calculations show that R_{disch} for r ~a few μm are relatively large, ~0.5 to 50 kohm, so a substantial portion of the discharge energy will be lost.

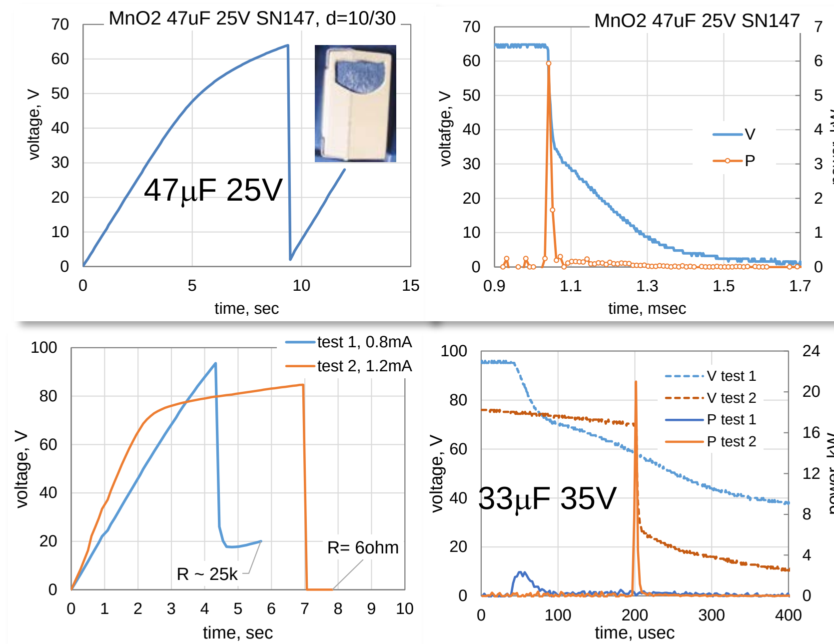




- ✓ Formation of damage with size < ~ 10 μm in the bulk of the pellet is unlikely.
- ✓ The assumption that cathode materials fill pores completely might be reasonable for MnO2, but is not realistic for CPTCs.
- ✓ Constriction resistance during breakdown is much lower for surface areas of the pellet.
- ✓ A higher risk of breakdown for multianode capacitors requires a better quality control.

Power of Scintillation Events

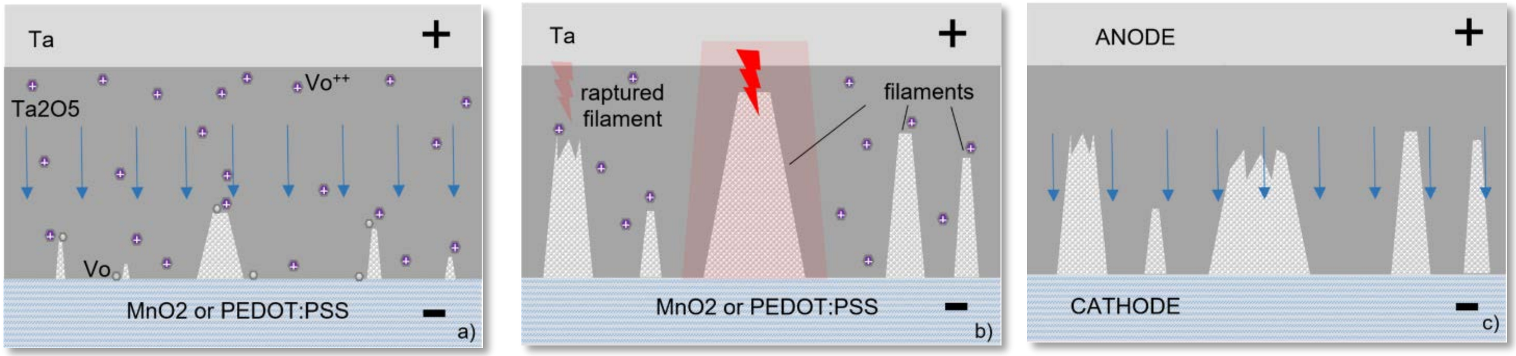
- The severity of damage depends on temperature rise that is controlled by power.
- Damaging scintillations are often associated with a high current spikes.
- Power spikes vary from hundreds of watts to dozens of kilowatts, and their duration is in the range from 2 to 5 μsec.
- Less powerful spikes that did not cause shorting failures had typically amplitudes below a few hundreds of watts and durations exceeding 1 msec.
- A simple one-dimensional model allows for the assessment of temperature on the surface of a sample that experienced an instant energy pulse.



$$\Delta T = \frac{P_0 \Delta t^{0.5}}{\pi r^2 (\gamma \pi k \rho c)^{0.5}}$$

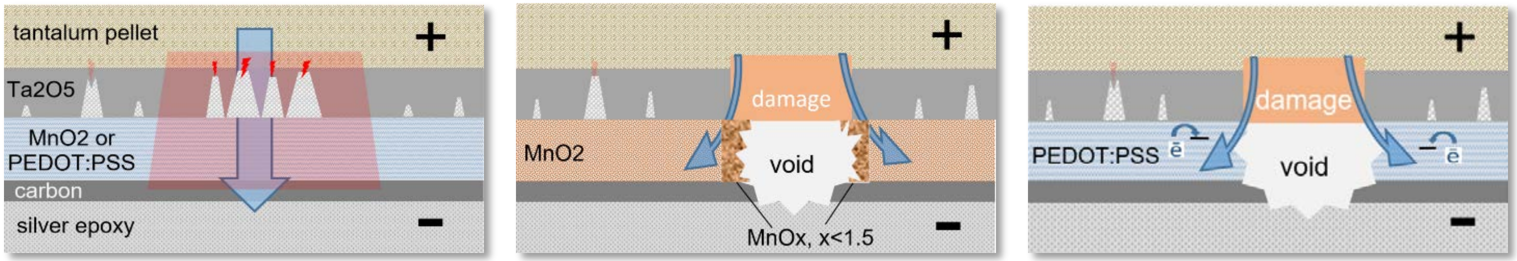
- ✓ For a given size of the damage, same energy spikes (*P×Δt = const*) result in substantially greater temperatures for shorter spikes.
- ✓ Energy to cause damage during BI or life testing is delivered from neighboring capacitors, rather than from the power supply.

Mechanism of Breakdown



- At V ≈ VBR, an intensive growth of conductive filaments in the Ta2O5 dielectric occurs.
- The process is similar to switching in ReRAM elements and is related to reversible formation and rupture of nano-size filaments composed of oxygen vacancies (V_O).
- The rupture occurs due to thermal destruction by joule heating and does not cause physical damage.
- Formation of filaments is a stochastic process and multiple filaments in Ta2O5 are formed and destroyed before breakdown occurs.
- Micro-scintillations might facilitate discharging at the close-by filaments due to increased temperature in the area and voltage oscillations.
- Progressive micro-scintillations result in a relatively soft breakdown that do not damage the structure of the pellet unless multiple micro-scintillations occur at a defect site.
- A partial destruction of the filaments increases local electric field, facilitates injection of electrons, and increases post-CCS leakage currents.
- Increasing rate of degradation is due to generation/activation of oxygen vacancies during scintillation events.

Mechanism of Self-Healing



- Self-healing in MnO_2 and CPTCs is due to a combination of different mechanisms.
- MnO2 capacitors:
  - Thermo-oxidative destruction of the conductive filaments.
  - Conversion of MnO_2 areas at the damaged site into high-resistive oxides.
  - Formation of voids in the cathode layers.
- Polymer capacitors:
  - Thermal destruction of the filaments.
  - Formation of voids in the cathode layers.
  - Trapping of electrons into states in conductive polymers.
- Different processes self-heal capacitors to a different degree and require different times.
  - Destruction of the filaments occurs within dozens of nanoseconds.
  - Oxygen reduction of MnO_2 requires from 0.1 to 1 msec.
  - Formation of voids occurs when a large enough area of the pellet exceeds the critical temperature of polymer or MnO2 destruction and requires more than 1 msec.
  - Reduction of the anomalous conduction of the Ta_2O_5 dielectric in CPTCs might take from seconds to hours.

Conclusion

- Breakdown voltages in MnO_2 CPTCs with the same ratings are close, but CPTCs have tighter distributions indicating a lesser concentration of defects in the dielectric.
- Several short, microsecond range high-power spikes might happen during breakdown creating multiple sites with structural damage on the surface of the pellet.
- The proportion of damaged by scintillations parts varies from lot to lot, but on average is greater for polymer than for MnO_2 capacitors.
- Capacitors that appear self-healed have significantly increased leakage currents. Contrary to MnO_2 capacitors, where leakage currents increase with time under bias, CPTCs have a tendency of decreasing currents.
- Energy stored in capacitors is sufficient to create damage in the range from 100 to 200 μm. The surface location of damage is due to lower constriction resistances for discharge currents.
- Breakdown is due to progressive micro-scintillation events caused by growth of conductive filaments composed of oxygen vacancies. A combined effect of multiple micro-scintillations at a defect site results in structural changes in the pellet and damage to cathode layers.
- Self-healing is due to several mechanisms.
  - MnO_2: (i) thermo-oxidative destruction of the filaments, (ii) conversion of MnO_2 into high-resistive oxides, and (iii) formation of voids in the cathode layers.
  - CPTCs: (i) thermal rupture of the filaments, (ii) formation of voids in the cathode layers, and (iii) reduction of the anomalous conductivity of Ta2O5.