Tantalum Capacitors

Design and Characteristics
Dielectric Materials

- Paper
- Ceramic
- Plastic Film
- Tantalum
- Aluminum
KEMET – Ta / Al Polymer Products

7 Manufacturing Plants*

3 billion Components Shipped per Year*

2 Innovation Centers

* Includes TOKIN

Carson City, NV
Ciudad Victoria, Matamoros, Mexico
Simpsonville, SC
Suzhou, China
Toyama, Japan
Chachoengsao, Thailand
Construction

Where:

\[ C = \frac{k \varepsilon_0 A}{d} \]

- \( C \) = capacitance, Farad
- \( k \) = dielectric constant, unitless; for \( \text{Ta}_2\text{O}_5 \), \( k = 27 \)
- \( \varepsilon_0 \) = permittivity in vacuum, \( 8.854 \times 10^{-12} \) Farad / meter
- \( A \) = surface area of conductive plate, meter
- \( d \) = dielectric thickness, meter; \( \text{Ta}_2\text{O}_5 \), thickness is \( 20 \times 10^{-10} \) meter per applied formation volt
Construction

Tantalum Wire
\( \rho_{\text{Tantalum}} = 16.69 \text{ g/cm}^3 \)

Tantalum Anode
(Porous Body)
\( \rho_{\text{Pressed Anode}} = 5.0 \text{ to } 7.0 \text{ g/cm}^3 \)

SEM Photo of Anode Surface

Interconnected Tantalum Particles

Ta Wire

MnO_2 or Polymer
Carbon Ink
Silver Paint

Tantalum Pentoxide Dielectric (Ta_2O_5)

Anode Tantalum Powder and Wire

Dielectric Ta_2O_5

Cathode MnO_2 or Polymer, Carbon, and Silver

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Construction

Standard Package

Detailed Cross Section

- Silver Paint (Fourth Layer)
- Wire
- Carbon (Third Layer)
- Polymer (Second Layer)
- Ta₂O₅ Dielectric (First Layer)
- Tantalum
- Leadframe (+ Anode)
- Molded Epoxy Case
- Silver Adhesive
- Weld (to attach wire)
- Leadframe (- Cathode)
- Polarity Stripe (+)
- Polarity Bevel (+)
Materials and Processes
Tantalum

- High ductility
- High corrosion resistance
- High melting point (3020°C)
- High resistance to heat and wear
- High biocompatibility

Tantalum has many Applications

Electronics
- Capacitors
- Resistors
- Hard Disk Drives
- Acoustic Fililters

Optics
- Camera Lenses
- Phone Display
- Ink Jet Printers
- X-Ray Film

Superalloys
- Aircraft Frames
- Turbine Blades
- Jet Engine Discs

Medical
- Joint Replacement
- Skull Plates
- Screws/clamps
- Wires

High Temp
- Rocket Nozzles
- Furnaces
- Cutting Tools
- Chemical Resistant

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Tantalum Pentoxide ($\text{Ta}_2\text{O}_5$)

- Dielectric constant: 27
- Dielectric breakdown: 470 volt/mm
- Dielectric thickness: 2.0 nm/volt
- Resistant to chemical attack

<table>
<thead>
<tr>
<th>$V_R$</th>
<th>Dielectric Thickness (nm)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Ta</td>
</tr>
<tr>
<td>2</td>
<td>20.7</td>
</tr>
<tr>
<td>4</td>
<td>27.6</td>
</tr>
<tr>
<td>6</td>
<td>36.8</td>
</tr>
</tbody>
</table>

Interference Color

Fractured Anode (Post Formation)

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Formation

**Traditional Anodization (Ta)**

Original Ta/Electrolyte Interface

- **Ta Substrate**
- **Diffusion**
- **Oxygen Diffusion**
- **Electrolyte**
- **Cathode**

**Half Reactions**

**Cathode:**

\[ 10H^+ + 10e^- \rightarrow 5H_2 \]

**Anode:**

\[ 2Ta \rightarrow 2Ta^{5+} + 10e^- \]
\[ 10H_2O \rightarrow 10H^+ + 10OH^- \]
\[ 2Ta^{5+} + 10OH^- \rightarrow 2Ta(OH)_5 \]
\[ 2Ta(OH)_5 \rightarrow Ta_2O_5 + 5H_2O \]

\[ 2Ta + 5H_2O \rightarrow Ta_2O_5 + 5H_2 \]

Dielectric (Ta$_2$O$_5$) grows inwardly and outwardly from the original surface of Tantalum particle
It is possible to isolate cap during formation depending on initial neck size and formation voltage.

Before Formation

Neck

Pore

Smaller neck sizes (higher resistance)

After Formation

Pore becomes smaller or even can close off.

It is possible to isolate cap during formation depending on initial neck size and formation voltage.

Small Neck of Effective Tantalum

Dielectric has formed completely through neck

SEM Photos (10,000x) of Anode Surface

50K Powder

150K Powder
Cathode forms the negative connection:

- Polymer is an intrinsically conductive polymer.
- MnO₂ is manganese dioxide.
Characteristics
Why Use Tantalum?

- Stable C (No Temp or Bias Effects), DCL (t)
- Reliable (Decreasing Failure Rate)
- Long Life (Exceeds Expected Life of All Hardware)
- Most Volumetrically Efficient (CV/cc, E/cc)

Military
Space
Medical
Automotive
Computers
Telecom

Ta Oxide Dielectric

SEM of a Sintered Ta Anode

Ta

Ta$_2$O$_5$
RC-Ladder Effect

RC-Ladder effects are factored by both capacitance and resistance.

\[ \text{tc1} = C_1 \times R_1 \]
\[ \text{tc2} = C_2 \times (R_1+R_2) \]
\[ \text{tc3} = C_3 \times (R_1+R_2+R_3) \]
\[ \text{tcn} = C_n \times (R_1+R_2+R_3...+R_n) \]
Capacitance vs. Frequency

Polymers are commonly used in applications up to 1MHz. Applications exceeding 1MHz typically call for MLCCs.
Applications Most Suitable For Polymer Capacitors
Most polymer caps are used in DC/DC power converter applications.
Reliability Models
KO-CAP capacitors have an average failure rate of 0.5 %/1,000 hours at category voltage, $V_C$, and category temperature, $T_C$. These capacitors are qualified using industry test standards at $V_C$ and $T_C$. The minimum test time (1,000 or 2,000 hours) is dependent on the product series.

The actual life expectancy of KO-CAP capacitors increases when application voltage, $V_A$, and application temperature, $T_A$, are lower than $V_C$ and $T_C$. As a general guideline, when $V_A < 0.9 \times V_C$ and $T_A < 85^\circ C$, the life expectancy will typically exceed the useful lifetime of most hardware (> 10 years).

The lifetime of a KO-CAP capacitor at a specific application voltage and temperature can be modeled using the equations on the next slide. A failure is defined as passing enough current to blow a 1-Amp fuse. **The calculation is an estimation based on empirical results and is not a guarantee.**
Reliability Model

**Lifetime**

\[
V_{AF} = \left(\frac{V_C}{V_A}\right)^n
\]

Inverse Power Law

where: \(V_{AF}\) – acceleration factor due to voltage, unitless
\(V_C\) – category voltage, Volt
\(V_A\) – application voltage, Volt
\(n\) – exponent 16

\[
T_{AF} = e^{\frac{E_a}{k}\left(\frac{1}{T_A+273} - \frac{1}{T_C+273}\right)}
\]

Arrhenius Equation

where: \(T_{AF}\) – acceleration factor due to temperature, unitless
\(E_a\) – activation energy, 1.4 eV
\(k\) – Boltzmann’s constant, 8.617E-5 eV/K
\(T_A\) – application temperature, °C
\(T_C\) – category temperature, °C

\[
A_F = V_{AF} \times TAF
\]

where: \(A_F\) – acceleration factor, unitless
\(TAF\) – acceleration factor due to temperature, unitless
\(V_{AF}\) – acceleration factor due to voltage, unitless

\[
Life_{U_A,T_A} = Life_{U_C,T_C} \times AF
\]

where: \(Life_{U_A,T_A}\) – guaranteed life at application voltage and temperature, years
\(Life_{U_C,T_C}\) – guaranteed life at category voltage and temperature, years
\(AF\) – acceleration factor, unitless

Constants (\(n\), \(E_a\)) were agreed upon by technical teams based on empirical results. These values can vary based on part type. For the product line, these are accepted values for the purpose of giving guidance.

<table>
<thead>
<tr>
<th>Ur</th>
<th>Equivalent Time (hours) at Specified Temperature (°C)</th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>45°C</td>
<td>65°C</td>
<td>85°C</td>
<td>105°C</td>
<td>125°C</td>
</tr>
<tr>
<td>1.00</td>
<td>6,587,826</td>
<td>321,712</td>
<td>22,011</td>
<td>2,000</td>
<td>231</td>
</tr>
<tr>
<td>0.90</td>
<td>35,551,833</td>
<td>1,736,149</td>
<td>118,785</td>
<td>10,793</td>
<td>1,248</td>
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<tr>
<td>0.80</td>
<td>234,046,611</td>
<td>11,429,505</td>
<td>781,992</td>
<td>71,054</td>
<td>8,215</td>
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<tr>
<td>0.67</td>
<td>3,995,262,380</td>
<td>195,105,889</td>
<td>13,348,893</td>
<td>1,212,923</td>
<td>140,238</td>
</tr>
<tr>
<td>0.50</td>
<td>431,739,793,834</td>
<td>21,083,715,712</td>
<td>1,442,520,611</td>
<td>131,072,000</td>
<td>15,154,549</td>
</tr>
</tbody>
</table>

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<thead>
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<tr>
<td></td>
<td>45°C</td>
<td>65°C</td>
<td>85°C</td>
<td>105°C</td>
<td>125°C</td>
</tr>
<tr>
<td>1.00</td>
<td>752</td>
<td>37</td>
<td>3</td>
<td>0.2</td>
<td>0.03</td>
</tr>
<tr>
<td>0.90</td>
<td>4,058</td>
<td>198</td>
<td>14</td>
<td>1.2</td>
<td>0.1</td>
</tr>
<tr>
<td>0.80</td>
<td>26,718</td>
<td>1,305</td>
<td>89</td>
<td>8</td>
<td>0.9</td>
</tr>
<tr>
<td>0.67</td>
<td>456,080</td>
<td>22,272</td>
<td>1,524</td>
<td>138</td>
<td>16</td>
</tr>
<tr>
<td>0.50</td>
<td>49,285,365</td>
<td>2,406,817</td>
<td>164,671</td>
<td>14,963</td>
<td>1,730</td>
</tr>
</tbody>
</table>

Baseline Condition

De-Rating Recommendations
Strengths And Weaknesses
By Dielectric
Dielectric Comparison

**Delivered Capacitance**

- **Cap vs Voltage**
  - Capacitance vs Voltage graph

- **Cap vs Temp**
  - Capacitance vs Temperature graph

- **Cap vs Time**
  - Capacitance vs Time graph

- **Cap vs Freq**
  - Capacitance vs Frequency graph

**Stable Capacitance**

- **No Piezo Noise**
  - Diagram showing no piezo noise

- **Non-Ignition Failure Mode**
  - Diagram showing non-ignition failure mode

- **Low Profile**
  - Diagram showing low profile

- **No Flex Cracks**
  - Diagram showing no flex cracks

**De-rating**

- **MnO2**
  - 50V

- **Polymer**
  - 24V

- **35V**

**High Ripple Handling**

- **Ripple Current (Amps)**
  - Chart showing ripple current with 360mΩ, 30mΩ, and 47uF/35V

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**MnO₂ vs. Polymer**

<table>
<thead>
<tr>
<th>Application Voltage</th>
<th>MnO₂ Voltage Rating</th>
<th>Polymer Voltage Rating</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.0 - 1.5</td>
<td>4.0</td>
<td>2.5</td>
</tr>
<tr>
<td>3.3</td>
<td>6.3</td>
<td>4.0</td>
</tr>
<tr>
<td>5.0</td>
<td>10</td>
<td>6.3</td>
</tr>
<tr>
<td>12</td>
<td>25</td>
<td>16</td>
</tr>
<tr>
<td>24</td>
<td>50</td>
<td>35</td>
</tr>
<tr>
<td>28</td>
<td>50(?)</td>
<td>35 &amp; 50</td>
</tr>
<tr>
<td>36</td>
<td>N/A</td>
<td>50</td>
</tr>
<tr>
<td>48</td>
<td>N/A</td>
<td>63 &amp; 75</td>
</tr>
</tbody>
</table>

**Replacing MnO₂ with Polymer**

- **MnO₂ Option**
  - 5V
  - 10V
  - 100uF
- **Poly Opt. #1**
  - 12V
  - 25V
  - 47uF
  - Low Profile
  - Higher Capacitance
  - Smaller Footprint
- **Poly Opt. #2**
  - 16V
  - 16V
  - 47uF
  - Low Profile
  - Smaller Footprint + Higher Capacitance

**Graphs**

- **Polymer (T52X/T530)**
  - % Rated Voltage vs. Temperature °C
- **MnO₂**
  - % Rated Voltage vs. Temperature °C
Polymers are much lower in ESR which result in a more efficient circuit. Polymer capacitors retain more actual capacitance than MnO$_2$. 
When Polymer Is Not the Ideal Choice

- Frequencies approach or exceed 1 MHz
- Temperatures exceed 150°C unless expected life time is short (within days).
- Voltage rails exceed 48 Volts.

- Ultra low ESR (<< 4 mΩ) is needed.
- Reverse bias occurs.
- Low cap (< 0.68 µF) is needed.
- Low leakage is needed for maximum battery life.
MLCC to Polymer Considerations

- Application Voltage
- Total Capacitance
- Leakage
- Switching Frequency
- ESR
WHAT IS THE CRITICAL DESIGN PARAMETER?

Total Capacitance

- Y >680nF? N
  - No KOCAP

  Y V>50V? N
  - No KOCAP

  - Y >10mΩ? N
    - No KOCAP

Voltage

ESR

- Y >10mΩ? N
  - No KOCAP

Frequency

- Y f>1MHz? N
  - No KOCAP

Reverse Bias

- Y OK? N
  - No KOCAP

KO-CAP may be an option, check the other critical parameters.

If you pass all the checks then you are in good shape for KO-CAP
A Common Buck

<table>
<thead>
<tr>
<th>Location (Ref Des)</th>
<th>Original MLCC</th>
<th>Description</th>
<th>KO-Cap Replacement</th>
<th>Description</th>
<th>Result</th>
</tr>
</thead>
<tbody>
<tr>
<td>Input (C1, C2, C3, C10)</td>
<td>C1206C225K5RAC</td>
<td>50V X7R 2.2uF 10%</td>
<td>T598V106M035ATE120</td>
<td>35V KO 10uF 20%</td>
<td>Layout change: 4 to 1</td>
</tr>
<tr>
<td>Support (C4)</td>
<td>C0402C104K4RAC</td>
<td>16V X7R 0.1uF 10%</td>
<td>None</td>
<td>None</td>
<td>DQ: Size</td>
</tr>
<tr>
<td>Support (C5)</td>
<td>C0603C472K3GAC</td>
<td>25V C0G 4.7nF 10%</td>
<td>None</td>
<td>None</td>
<td>DQ: Size</td>
</tr>
<tr>
<td>Support (C8)</td>
<td>C0402C470K3GAC</td>
<td>10V C0G 47pF 10%</td>
<td>None</td>
<td>None</td>
<td>DQ: Size</td>
</tr>
<tr>
<td>Output (C6, C7, C9, C11)</td>
<td>C1206C226K8RAC</td>
<td>10V X7R 22uF 10%</td>
<td>T520A226M006ATE100</td>
<td>6.3V KO 22uF 20%</td>
<td>Drop-in replacement</td>
</tr>
</tbody>
</table>
Input Side – Does it work as well?

KO-CAP has more effective delivered cap @ given conditions
## Input Side – What’s this going to cost me?

<table>
<thead>
<tr>
<th>Capacitor Part Number</th>
<th>No of Caps</th>
<th>Cap/pc (µF) @ 14V</th>
<th>Effective Cap (µF)</th>
<th>ASP/pc (Mouser)</th>
<th>ASP/Total Cap (Mouser)</th>
<th>Difference</th>
</tr>
</thead>
<tbody>
<tr>
<td>C1206C225K5RAC</td>
<td>4</td>
<td>1.75</td>
<td>7</td>
<td>$1.04</td>
<td>$4.16</td>
<td></td>
</tr>
<tr>
<td>T598V106M035ATE120</td>
<td>1</td>
<td>10</td>
<td>10</td>
<td>$3.10</td>
<td>$3.10</td>
<td>25%</td>
</tr>
</tbody>
</table>
Output Side – Does it work as well?

KO-CAP has more effective delivered cap @ given conditions
### Capacitor Part Number

<table>
<thead>
<tr>
<th>Capacitor Part Number</th>
<th>No of Caps</th>
<th>Cap/pc (µF) @ 5V</th>
<th>Effective Cap (µF)</th>
<th>ASP/pc (Mouser)</th>
<th>ASP/Total Cap (Mouser)</th>
<th>Difference</th>
</tr>
</thead>
<tbody>
<tr>
<td>C1206C226K8RAC</td>
<td>4</td>
<td>9.825</td>
<td>36.3</td>
<td>$1.95</td>
<td>$7.80</td>
<td>45%</td>
</tr>
<tr>
<td>T520A226M006ATE100</td>
<td>4</td>
<td>22</td>
<td>88</td>
<td>$1.07</td>
<td>$4.28</td>
<td>45%</td>
</tr>
</tbody>
</table>
C4, C5, C8 have no KO-CAP equivalent options. Their cap values are below the range of KO-CAP.
Other Considerations

- **ESR**
  - KO-CAP ESR is generally higher than ceramics, but the additional capacitance helps to mitigate the additional ripple.
  - Some series have ESR lower than 10mOhms, contact FAE if close to limit.

- **Voltage**
  - Derating rules may need to apply to extend life, if necessary.

- **Leakage**
  - Leakage mostly a major consideration with fixed, non-chargeable direct battery voltage is applied

- **Robustness**
  - KO-CAP will NOT tolerate reverse bias.

- **Supply**
  - KO-CAP supply chain is stable and KEMET capacity to be increased by 25%
  - KO-CAP capacity is currently below maximum for most series
  - KO-CAP can offer immediate and sustainable relief

- **Design**
  - The best value proposition is to replace banks of ceramics with fewer KO-CAPs
  - Drop-in replacements are possible but less likely

Contact a KEMET FAE for further support (www.kemet.com/ask)
Thank You!