

New Tantalum Capacitors in Power Supply Applications

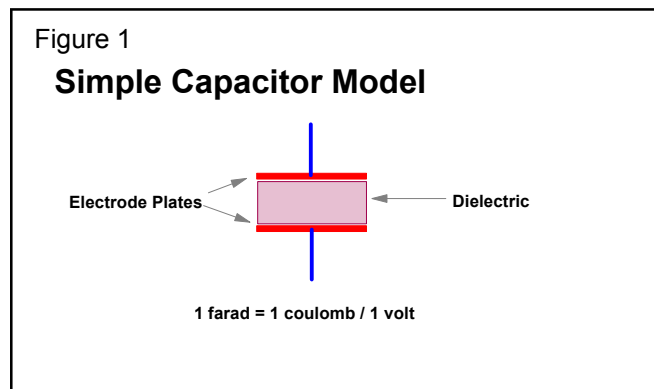
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Abstract—Capacitors used in various applications are usually selected for the usage by the type of capacitor. This selection process is most visible in the selection of the aluminum electrolytic for power supply applications. Developments related to improve performance of an alternative type of capacitor is sometimes lost to the user because of the narrow focus given to the one type. It is of the designer's best interest to be aware of the developments of all types for all applications. It is the intent of this paper to present the latest developments for power applications with the tantalum capacitor.

Introduction

All capacitors adhere to the *simple model* (Figure 1) depicted by the plate-dielectric-plate model. With some types of capacitors this is easy to see, while with others this is not that easy to see. The dielectric material between the plates has two major properties: it is insulative and it enhances an electric field between the plates. This enhancement is depicted in the dielectric constant of the material, with the reference being a vacuum with a constant of 1. The capacitance is proportional to the dielectric constant and the plate area, and inversely proportional to the dielectric thickness. The various types of capacitors are divided into groups of common materials for the dielectric. Understanding the differences in construction and materials helps to define their performance differences.



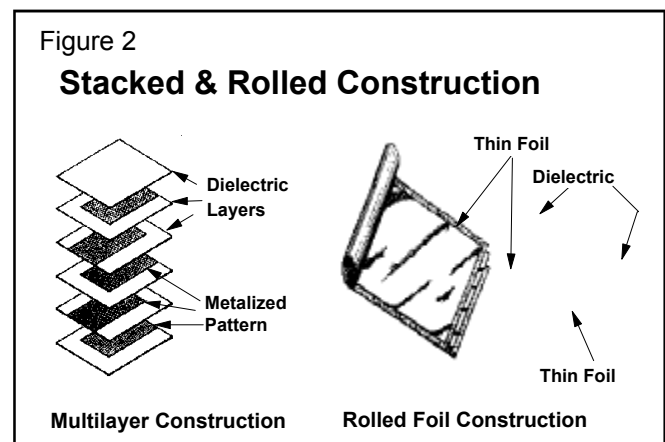
Constructions

The multilayer ceramic and film capacitors utilize stacked plates separated by a dielectric layer, allowing a quick comparison to the simplistic model. Each layer of

these types constitutes a single capacitor, and the multiple stacks can be viewed as capacitors connected in parallel. The total capacitance is additive.

Even the earlier film capacitors that utilized the rolled foil construction, could be seen as a single *simple model* capacitor, elongated in length, and rolled up to provide a more compact package. Earlier ceramic disk capacitors were the perfect epitome of the *simple model* as they physically duplicated the model utilizing circular plates separated by a cylindrical button of ceramic material. The stacked arrangements used in both ceramic and film represent parallel or stacked single plate capacitors.

The aluminum electrolytic capacitor may be seen as using the rolled foil technique, but the similarity ends there. The dielectric in this capacitor is not the electrolyte solution or material between plates, but is created as a thin insulative film on one of the plates. It is a similar creation of this thin film on one plate that forms the dielectric in the tantalum capacitor, as well.

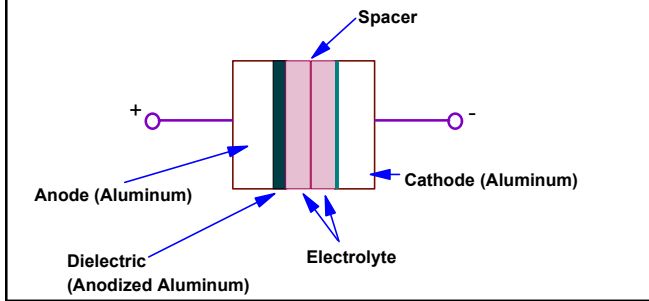


Electrolytic Capacitors

The metal plates in the aluminum and tantalum capacitors are of a group denoted as valve metals. These metals have the property such that a thin insulative film of the metal's oxide can readily be grown through an electrochemical process. These oxides, aluminum oxide (Al_2O_3) for the aluminum and tantalum pentoxide (Ta_2O_5) for the tantalum, are superb insulative materials. They do not have large dielectric constants (~ 12 for Al_2O_3 , and ~ 17 for Ta_2O_5), but their ability to be formed to such thin layers, allows a large capacitance capability.

Figure 3

Aluminum Electrolytic Construction



The electrochemical process applies a bias while the metal is in an acid solution such that oxygen is released by the solution, and absorbed by the metal. The polarity of the bias is such that the oxygen atoms are held at the outer surface of the metal. The depth of the oxygen penetration and mixture with the base metal is controlled by the bias applied during formation. The thickness of the oxide formation for the tantalum capacitor is approximately 1.7 nm/V (1.7×10^{-9} m/V) for the tantalum. Because the dielectric is an oxide of the base metal, these devices must maintain this same polarization in use. If not, the oxygen atoms are free to travel into the depths of the base metal, leaving a depleted dielectric behind.

The contact to this dielectric layer that now coats the previously exposed surface of the base metal, was initially made through some type of liquid electrolyte solution or paste. The dielectric (metal oxide) is extremely thin, and trying to use another metal to contact the dielectric is impossible. The rough surface of the base material as well as any other material brought into contact with the dielectric — at most, singular point contacts would be made. If singular point contacts are made, the capacitance is minuscule and there becomes a focal point of mechanical contact on this very thin layer, eventually rubbing it away to create a direct contact and short. The liquid material freely moves along the undulations of the surface to contact the dielectric.

Another consideration, that some might hold as the primary consideration, for using an electrolyte solution has to do with the faults that reside in the created dielectric. Impurities in the base metal or introduced through handling or the electrolyte solution for formation, will create faults at distributed points within the dielectric layer. These faults can reside as inclusions of a conductive element within the dielectric, or as a thinner creation of the dielectric. In either case, these faults can lead to breakdown of the dielectric at voltages below the rating. In application, the electrolyte solution is formulated in a manner to allow a reformation of the dielectric layer at these fault sites. Remember, the use polarization is the same as formation polarization.

Solid Electrolyte

The liquid electrolyte utilizes penetration and reformation properties in its activity as the cathode plate contact in an electrolytic capacitor. The drawback in using this contact is that it is caustic, can lead to the generation of gasses, and cannot withstand the thermal cycles required of surface mount assembly.

In the earlier days of the transistor development, Bell Labs was first to use a solid material in an electrolytic capacitor as the cathode plate connection. This material is formed within the tantalum anode through a series of dips in manganese nitrate solution $Mn(NO_3)_2$, with drying cycles in between dips. This results in a film or coating of MnO_2 to form on the exposed surfaces of Ta_2O_5 .

This material formed on the dielectric, is in a liquidous form during the dips, allowing full penetration along the channels and crevices of the device. As it dries on the surface of the dielectric, it loses its liquid properties and attains a solid, undulating coverage as would the liquid electrolyte.

The MnO_2 material is semi-conductive in nature, with resistivity in the range of 2 to 6 ohm-cm. This is the conductor that forms the cathode plate connection to the capacitor. As a solid material, leakage of caustic electrolytes is eliminated, and thermal robustness to withstand the solder reflow temperature is attainable.

With the liquid electrolyte there is a healing mechanism in that faults developed or uncovered within the dielectric layer, can be reduced by reformation of the oxide layer in circuit bias conditions. The solid state nature of the MnO_2 cannot activate this effect; but it does bring another healing mechanism to the device.

The MnO_2 material has a propensity to release oxygen and move to a lower oxide state, under concentrated heat. With the current into a fault in the dielectric emanating from a localized point within the MnO_2 , there is a concentrated heat buildup in the MnO_2 at that point. The MnO_2 readily changes to a reduced oxygen state like Mn_2O_3 . The reduced oxide states of manganese are of much higher resistance, thus effectively shutting the current down.

Polar vs. non-Polar

Because the electrolytic capacitors utilize a dielectric that is an oxide of the valve metal anode, these devices require polar consistency in their application. The circuit application of voltage must be in the same polarity as that utilized in the dielectric formation. The oxide portion of the molecular structure of this dielectric can move further into the pure metal anode region with some assistance of incorrect polarity. If the oxide portion of this surface is depleted, the conductivity increases, leading to early failures.

The ceramic and film capacitors utilize dielectric materials distinct from their electrode materials. As such, there is no polarity considerations for these devices. Other less popular capacitors with dielectric such as glass, mica, and air, are also bipolar capacitors.

ESR and ESL

A capacitor does not always behave as an ideal capacitor. The ideal capacitor has only a reactive element that is inversely proportional to frequency. All the energy put into the ideal capacitor, is eventually returned to the circuit.

It may appear less than ideal because it causes power loss — a perfect capacitor has no power loss as the voltage and currents are totally reactive. A distinct measurement of this non-ideal property is commonly given as dissipation factor (DF). This represents a measurement of the loss component or resistance, expressed as a ratio of the resistance to reactance magnitudes. Because it includes reactance, it is factored by frequency.

A more direct measurement of this loss component is accomplished as a measurement of its effective series resistance, or ESR. The resistance denoted as effective or equivalent is not a constant — in the same manner as reactance is frequency dependent, this resistive element is also frequency dependent. With the ceramic capacitor, the ESR reaches a minimum at, or very near, the self-resonance frequency. With these devices, the ESR response on a log-log display, appears parabolic, increasing as it moves above or below the self-resonance frequency.

With the electrolytic capacitors, both tantalum and aluminum, the ESR variance with frequency appears to have at least a two tier effect. Also, the magnitudes of resistance are much higher than those of the ceramic. Figure 4 shows the frequency plot of both impedance and ESR for equal capacitance values of tantalum and ceramic devices. Both of these 4.7 uF devices have impedances that overlap each other in the lower frequency ranges below 20

kHz. As the frequency moves above this point, the impedance of the ceramic capacitor continues to decay, while that of the tantalum capacitor reaches a certain level then maintains that value.

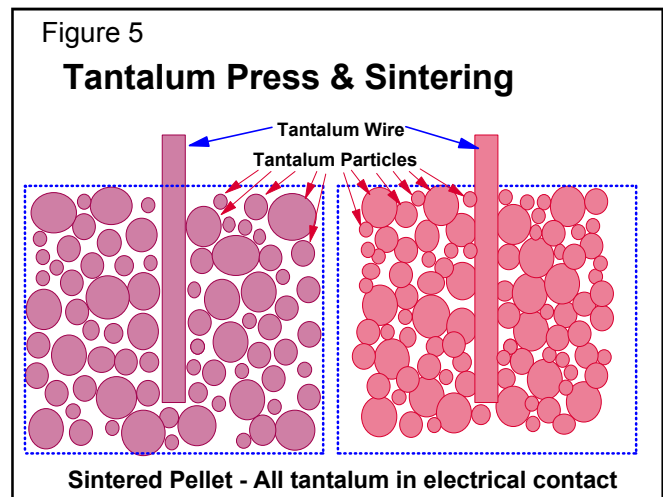
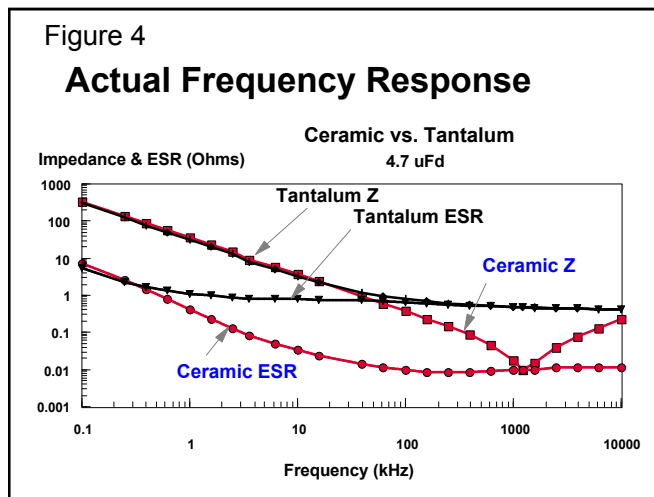
The other parasitic element, the ESL, or effective series inductance, is controlled by physical parameters. The current path, or how constrictive the path is, goes a long way in determining the ESL of a capacitor. Unlike the ESR, which varies with the capacitance attainable in a given structure, the ESL is fairly constant across capacitance for a given chip size.

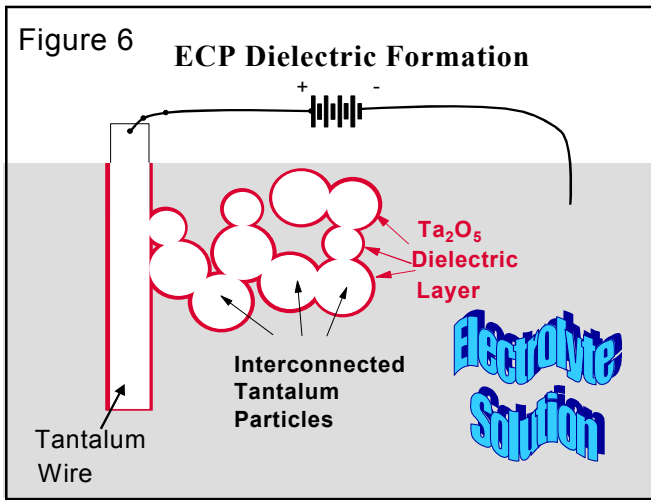
Tantalum Construction

Improving the ESR within a tantalum capacitor requires an in-depth understanding of where the ESR is created from a physical and material point of view. The construction of this device is like no other that has been reviewed to this point. The solid-state tantalum capacitor utilizes a slug construction started when the tantalum powder is placed in a cavity and pressed to form a cylindrical or rectangular block. A small riser wire is inserted in the powder prior to pressing, with allowance in the die to permit the wire to extend out of the pressed slug. In order to facilitate a consistency of powder density within the volume of the slug, an organic material is usually included to act as a lubricant during the pressing.

The powder's physical size and shape determine the volumetric capability of the tantalum slug. For a given slug size, smaller and flakier powder allow greater surface area totals within a given slug. The capacitance per unit volume is a method of defining a powder's capacitance capability.

The pressed slug now has tantalum powder surrounding the tantalum wire. In many cases there is a finite contact, both electrical and physical, among all the particles. These contacts are weak at this point. The slug is then heated in a vacuum oven, to temperatures below the melting point of the tantalum to allow these intimate contacts





to fuse and grow to stronger bonds. The organic lubricant is also removed during this process. (Figure 5)

After sintering, the slug is basically a pure tantalum slug. The points of contact have grown, but this slug has a tremendous amount of voids and channels between tantalum particles. It is this porosity that gives the tantalum capacitor a volumetric advantage over all other types of non-chemical capacitors. There is a tremendous amount of tantalum surface area within this slug — likened many times to a sponge.

The dielectric, Ta₂O₅, is now grown on all the exposed surfaces of the tantalum, utilizing an electrochemical process. The slug is immersed in an acidic solution with a bias applied to oxidize the exposed tantalum surfaces. The depth of the oxide layer is controlled by the voltage and current and time parameters. The dielectric thickness is proportional to the voltage capability of the tantalum capacitor, and the capacitance available within a given slug and tantalum powder, is inversely proportional to the thickness. (Figure 6)

Now we have one plate (the tantalum), and the dielectric (the Ta₂O₅), and what we need to finish this capacitor

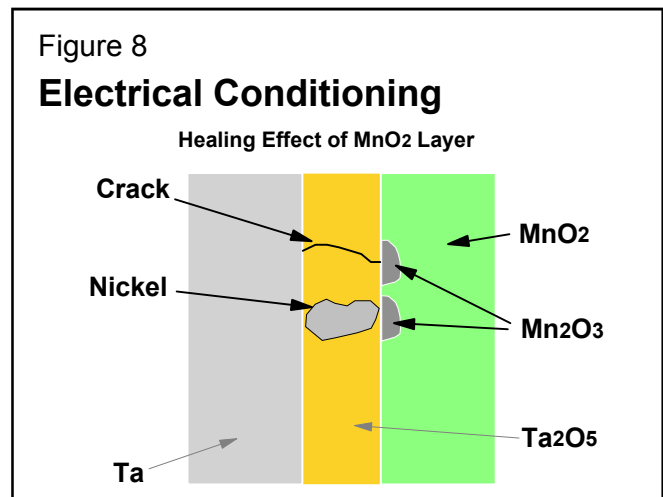
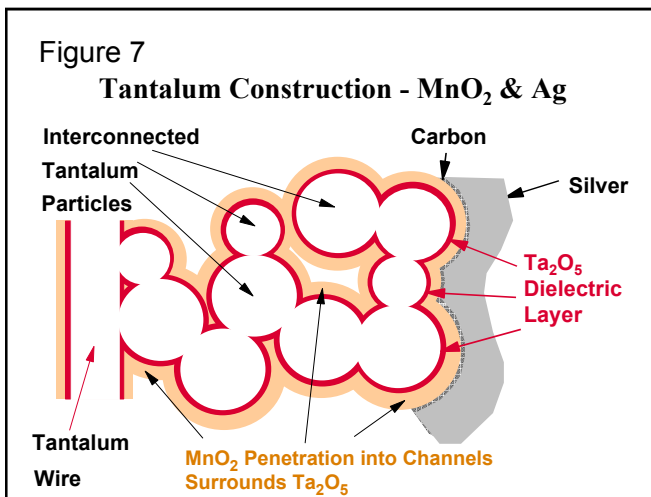
construction is another plate. Remember though that the dielectric is grown on the irregular surface of the tantalum, stretching from the outside surfaces of the slug, to deep within the slug through the porous channels. The second plate contact must penetrate deep within these channels of the slug to contact the now exposed dielectric surface area. A wet electrolyte solution that easily penetrates these channels is used in the wet tantalum capacitor, but we want a solid state capacitor. This is accomplished with a deposition of conductive material within the channels, along the exposed dielectric surfaces through a dip and dry process.

The slug is dipped into solutions of Mn(NO₃)₂ and dried, to allow a film deposition of MnO₂ to form the secondary plate contact. This impregnation scheme starts out with very fine solution of the Mn(NO₃)₂ and gets thicker with successive dips. The resulting contact is with channeled MnO₂. Now MnO₂ is a semiconductor with resistivity of 6 to 2 ohm-cm. This might be looked on as an obvious candidate for replacement with a more conductive compound in order to lower the ESR; but it has a property that cannot be found in other materials. (Figure 7)

Self-Healing in Tantalum Capacitors

Every tantalum capacitor built has defects within the dielectric created. There is tremendous effort to eliminate impurities from the tantalum metal during its process, and during its use, but not all impurities are removed. The process itself, also lends itself to the introduction of impurities in the early manufacturing steps of this capacitor.

The wet electrolyte solutions used for the secondary plate in some capacitors, are chemically adjusted to allow a re-anodization at a fault site to occur. With the solid state secondary plate, no chemical exchange can heal these developed or uncovered fault sites. The benefit of using the semiconductor MnO₂ for the secondary plate is realized in a combined electrical and thermal property of this material. If a defect site occurs, then the current into that



defect site is concentrated in a small area of the MnO_2 . This current concentration through this poor conductor causes the heat to increase locally at this point. The MnO_2 material is unstable at the increased temperature and gives up oxygen to change its composition to a lower oxide state, such as Mn_2O_3 . This reduced oxide state has a much greater resistivity, and shuts the current down to the fault site. (Figure 8)

If the fault occurs with unrestricted current available, the tantalum will start to heat, feeds voraciously on the oxygen in the MnO_2 , and an exothermic reaction occurs. By keeping the current restricted, the time for the heat to develop and convert the MnO_2 to another state is long enough for this reaction to take place. For all the theories that were purported as to why tantalum capacitors could not take high surge, this solution of using series resistance and limiting the current, enabled the healing mechanism the time to clear the fault.

Tantalums in Power Applications

In order to support this application, the restrictions requiring series resistance had to be eliminated. In power applications, the resistance in series with the capacitors adds its own magnitude of noise to the circuit. In the new DC-DC converters, the output currents are periodic bursts from a switch device. These currents supply energy directly to the circuit, and also store energy as charge in the output filter capacitors. During the brief times that the current is switched off, the capacitor then becomes the sole source of energy for the circuit.

In Figure 9, a timing diagram depicts the current state of the switching circuit and the resulting current and voltage traits of the capacitor. The saw-toothed wave form is idealistic in that this capacitor has no ESR or ESL adding elements to the voltage generated. The voltage rises and falls solely based on the charge maintained by the capacitor.

Realistically, the resistance appears as a voltage loss

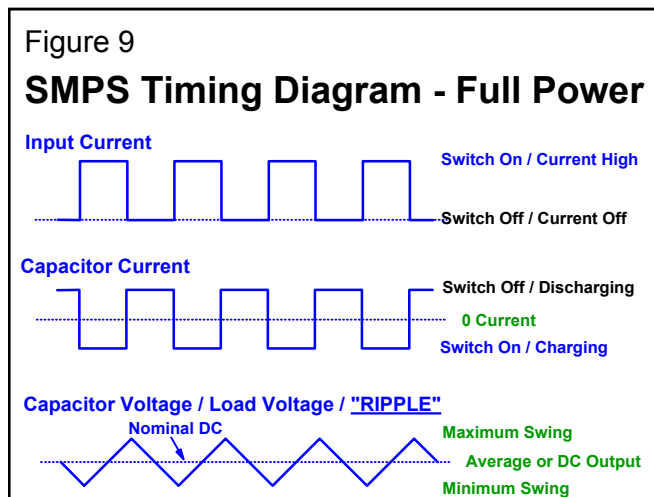
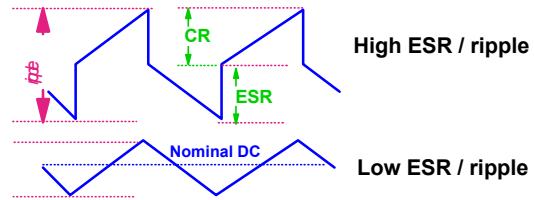


Figure 10
CR & ESR Ripple

The magnitude (peak-to-peak) of the ripple is proportional to the magnitude of the ESR above a critical level.



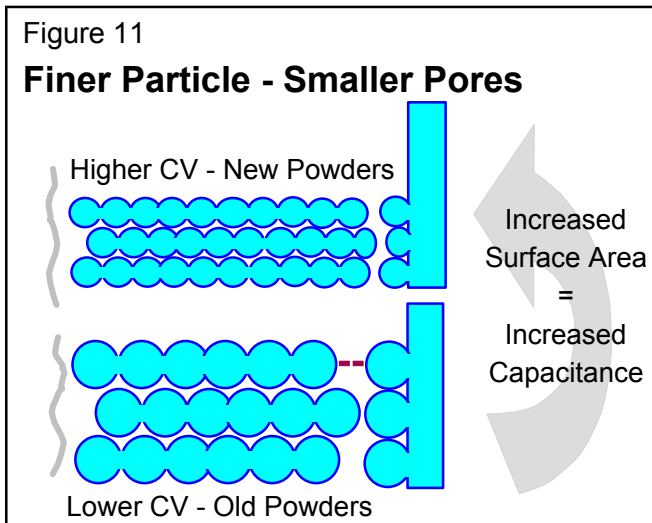
element in series with the capacitor. It prevents the capacitor from achieving the exact same potential as the load during its charge cycle, and robs again from the capacitors depleted voltage during the discharge. Figure 10 is a simplistic view of this occurrence. The ideal capacitor or one with insignificant ESR appears as the bottom trace, simply changing voltage as the charge across its place changes. The trace on the top represents the ESR effects. The slopes of discharge and discharge are exactly the same as the ideal, because this slope is a property of the capacitance. The step in the voltage trace is caused by the voltage dropped across the series resistor. The magnitude of the voltage is directly proportion to the current and the resistance — the larger the ESR the greater the ESR step voltage.

Moving Against Development

The industry trend in the tantalum capacitor industry has been to higher capacitance in smaller packages. In order to accomplish this trend, the surface area within a given volume has to be increased, because the dielectric constant is not changing, and the voltage stress capability cannot be pushed further. This increase in surface area is attained with finer particles, and particle shapes that are more like flakes instead of spheres.

This general trend is shown in Figure 11. Higher capacitance in a given volume (the anode pellet within the molded case) is dictated by surface area and particle size and shape.

At the same time this development is taking place, materials and processes are constantly being refined to improve the density and consistency of the application of the cathode plate layer (MnO_2) within the porous anode. Yet with each development of finer powder anodes, the size of the channels into the core structure are decreasing in cross sectional area, but maintaining the same distance to the center corer. To overcome this depleting path, accelerated developments had to be made in the process of depositing the MnO_2 .



Basically, the finer channel structures dictated that the impregnation process for the MnO_2 be extended over many more steps, with finer initial solutions of $Mn(NO_3)_2$. The movement to structures with finer pores should have caused the ESR to increase, but because this step was offset by refinements in materials and processes, the ESRs have actually dropped.

The recommended series resistance for the commercial lines have reduced over the years from 3 ohms per volt, down to one ohm per volt, down to today's recommendation of 0.1 ohms per volt. Yet even this resistance is ridiculous in face of power supply applications.

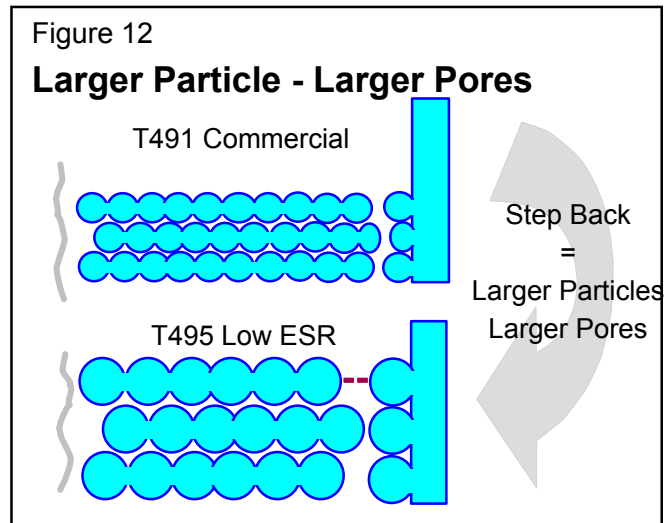
Building the Power Supply Tantalum

For this application, there could be no recommended series resistance. The internal ESR would have to be reduced to eliminate its contribution to the noise effects, and the application of the MnO_2 must be as consistent as possible. Both of these requirements dictated moving back in powder technologies to coarser powders with the inherent larger channel widths. This step is opposite that taken by the industry in moving to higher capacitance densities. For this line of capacitors, we would have to sacrifice the maximum capacitance. (Figure 12)

The product line, T495 was built following the guidelines of lower ESR with greater consistency of the MnO_2 deposition. Because the finer powders invariably required additional process steps with finer solutions to achieve total coverage, we did not go back to thicker solutions for this device. We started with the finer solutions, working up to thicker solutions, with additional steps to guarantee complete and denser coverage.

Frequency Response

The effects on ESR are readily seen in the frequency graphs of Figure 13. These are equal capacitance and voltage devices, constructed with different means. The T495 product is not selected from the commercial prod-



uct, but is entirely different in construction.

Electrolytic capacitors have an RC-Ladder behavior (Figure 14). In the frequency domain, this behavior causes a loss of capacitance as frequency increases. The degree of loss is dependent on the size of the capacitive elements of the RC-Ladder, as well as the size of the resistive elements. For low frequency, all capacitive elements respond. As frequency increases, the additive resistance to the deeper capacitive elements, cause its RC time-constant to prohibit response to increasing frequencies. Increasing the frequencies further still, progressively eliminates additional capacitive elements, moving from the deep to those near the contact. In Figure 14, this would eliminate capacitive elements starting with the rightmost (C_n), out to the leftmost, or C_2 .

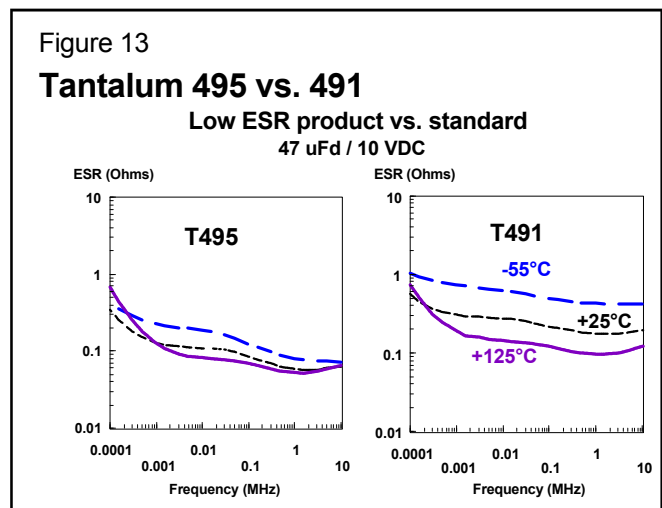
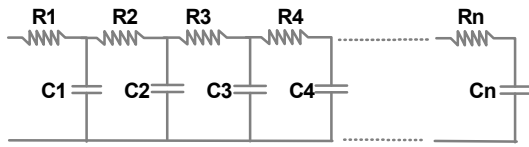


Figure 15 shows the effect the lower ESR has on the capacitance roll-off. Since the ESR decreases with increasing temperature, the effects at $-55^\circ C$ are most pronounced, and at $+125^\circ C$, least. The change from the commercial to the power supply capacitors has a reduced capacitance roll-off effect. The deliverable capacitance is

Figure 14

RC Ladder Network



$$tc1 = C1 \times R1$$

$$tc2 = C2 \times (R1+R2)$$

$$tc3 = C3 \times (R1+R2+R3)$$

$$tcn = Cn \times (R1+R2+R3...+Rn)$$

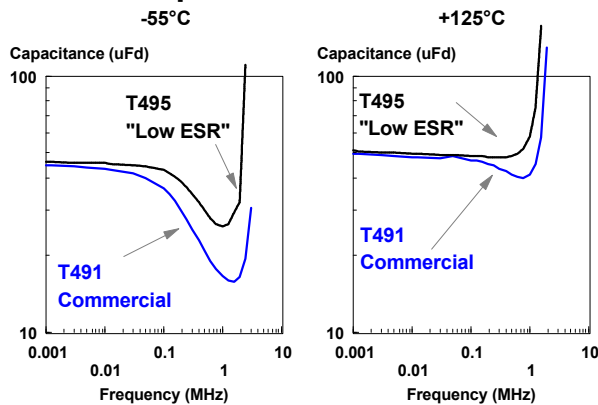
higher for the higher frequencies than the commercial.

Anode Penetration

We reduced some of the RC-Ladder effects, but we have not eliminated them. There is still some capacitance roll-off that we wanted to reduce further still. If the penetration of the RC-Ladder was presented as a physical diagram of the anode structure, at any of the higher frequencies, we would see that the depth of penetration has increased for the T495. Yet at higher frequencies, we still end up with the center portion of the anode being dormant to the circuit.

Figure 15

Reduced Capacitance Roll-off



If the depth of penetration is fixed by the materials used, then one way of realizing a greater percentage of the anode would be to make the anode thinner. Figure 16 shows equal penetration depths for an anode almost cubic versus one much thinner. In the figure, the capacitance realized at a fixed frequency may result in only 20% of the original, but with the reduced thickness anode, the capacitance is ~ 17% of the original. With an anode that started 67% lower, it now ends up as only 3% lower. (Figure 16)

Figure 16

Anode Penetration vs. Thickness

High frequency loss of penetration



Approximately 80% of volume lost resulting in ~20% of Reference Cap

About 50% of volume lost, or 50% of 1/3 ~ 17% of Reference Cap

Nobody wants to start out with 67% lower capacitance. By using three anodes of 1/3 the thickness of the original, the same initial capacitance is achieved. Now, instead of achieving 17% of the original capacitance, this structure can now achieve 50% of the original capacitance at this fixed high frequency point. This is a 150% increase in capacitance over the single anode design. (Figure 17)

Multiple anode construction is the basis of the T510 series power supply capacitors. They utilize the same material and process capabilities of the T495, but there are three anodes in the case, instead of one. These additional faces for the anode penetration effectively increase the cross sectional area of the capacitor, and this results in additional decreases in ESR.

The improvement over all other types of tantalum capacitors is substantial. Typical ESRs for these devices are now approaching 10 and 15 milliohms. (Figure 18)

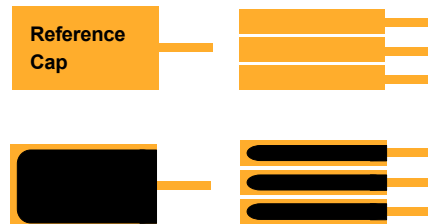
The Pentium Benchmark

The Pentium PowerPro® has a current requirement as it comes out of “sleep” mode that defines the required filter

Figure 17

Multiple Anode Penetration

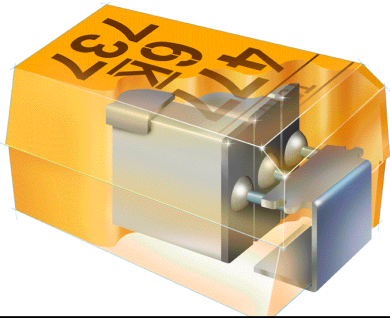
Decreased high frequency loss of volume



Now, 3 narrow anodes lose 1/2 of original, or result in ~ 50% of Reference Cap (instead of 20%).

Figure 18

T510 - Multiple Anode Tantalum Chip



capacitance for the power rails supplying this device. The capacitance is dependent on the (switching) response time of the power supply, the peak current magnitude, allowable change in bus voltage, and the capacitance and ESR of the filter capacitors.

Using the same power supply response capability and the peak current and voltage stability factors as listed in their example, the total capacitance required by this processor calculated to be 4,250 uF — if the capacitor was perfect and had no ESR. If this capacitance was supplied by multiple 470 uF capacitors, then 10 of these capacitors would be required.

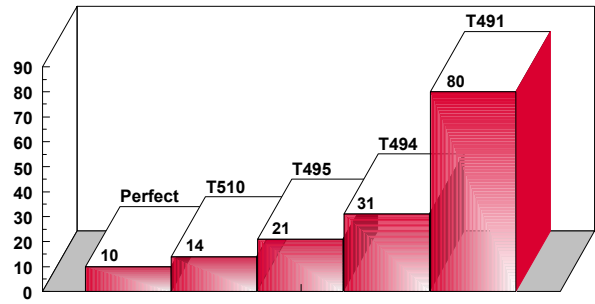
The chart in Figure 20 shows the number of capacitors required across the spectrum of surface mount tantalums we manufacture. The calculations are based on the specified maximum ESRs for each type of device. The perfect capacitor is included as a reference.

These capacitors, utilizing three anodes in place of one are more expensive than the single anode versions, and some might consider this to result in a costlier solution than the older product. The total cost for the capacitors is broken down in Figure 21. The more expensive capacitors offer a cheaper system solution than the older and cheaper capacitors.

Figure 20

Pentium PowerPro® Requirement

Total Capacitance based on ESR Limits
Number of 470 uFd Capacitors



Polymer, the MnO₂ Solution

We have been forced to use the MnO₂ cathode layer because of its self-healing properties. There are many dielectric faults in each tantalum capacitor manufactured. Contaminants may be present somewhere along the enormous surface area of this capacitor even though we hold the material suppliers to very strict levels of identified elements with the tantalum powder. There are also points within the process where contaminants can be introduced that could destroy a capacitor without the self-healing capability.

Since the impregnation process involves a heat cycle, there is also a possibility of inducing a fracture within the dielectric during this process. Regardless, the first electrification of the tantalum capacitor is also called the aging or healing process. Here the capacitors are brought up to voltage through series resistance to limit the current. By limiting the current, the self-healing process can be triggered to remove all the fault sites within the capacitor.

The longer a capacitor has voltage applied to it, the more thorough is the isolation of fault sites. When pieces are

Figure 19

T510 Frequency Response

T510X477M006

Ultra-Low ESR

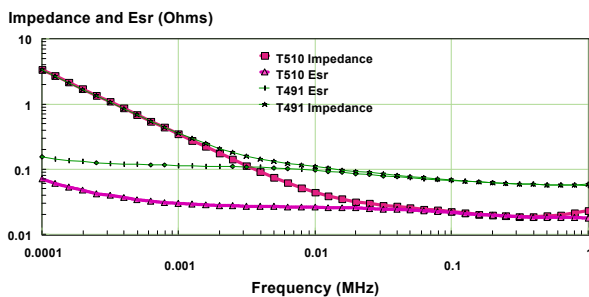


Figure 21

Total cost by type

Voltage Regulation

Number of 470 uF Capacitors

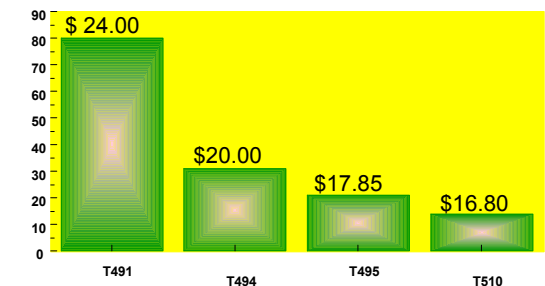
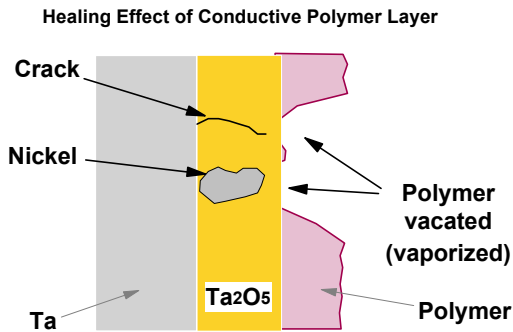


Figure 22

Polymer Self-Healing



put on life test, it is usually the first reading of leakage that appears as the worst, the leakage usually getting better (lower) with time on test.

Up until recently, there was no material that could effectively replace the MnO₂. Conductive polymers are now being used to replace the MnO₂ as the cathode plate layer in the tantalum pellet.

The polymer does not change resistivity, but they have a fairly low thresh-hold for heat. Selecting the proper polymer requires it be capable of withstanding the normal solder heat temperatures, and still has the capability of vaporizing when the current gets too high.

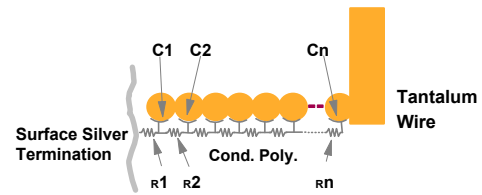
When the current is concentrated into a fault within the Ta₂O₅ dielectric, localized heating will occur within the polymer. That polymer will continue to heat until it reaches its vaporization temperature and vacates the site.

Additional benefits of the polymer include lower resistivity and the lack of oxygen. The benefit of the lower resistivity is apparent in our quest for lower ESR. The RC-Ladder still exists, but the resistive elements are again lowered. Single digit ESR will now become apparent.

The lack of oxygen in the material will impact its failure mode. When a tantalum capacitor has an unlimited current supply, instead of activating the self-healing mechanism, the device may fail catastrophically. This exothermic reaction takes place as the tantalum starts to

Figure 23

Conductive Polymer low O₂ Source



Lack of oxygen cannot sustain exothermic reaction at ignition -- NO Ignitions!

heat and the oxygen is rapidly absorbed from the MnO₂. Eliminating that source of oxygen has eliminated the propensity to fail catastrophically.

The designations for these devices will be T520 for the T495 (low ESR — single anode) version with conductive polymer, and T530, for the T510 (multiple anode) version with conductive polymer

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