Tantalum in Power Supply Applications
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Tantalum Capacitors in Power Supply Applications

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Abstract

The capacitance range for tantalum capacitors spans from singular microfarads (uFd) through a thousand microfarads. It is an electrolytic type of capacitor that can utilize either a liquid type of electrolyte or a solid state material as the cathode connection.

The anode construction utilizes the high porosity of the pressed tantalum material to create an enormous amount of surface area to produce the highest volumetric efficiency of any of the commercial capacitors available. In the solid state devices, these can be readily packaged in a molded plastic package that yields a mechanically consistent surface mount package for high speed automated board processes.

Circuitry that utilizes some of the newer switch mode power supply designs (SMPS), requires capacitance values for their filter circuits that lie well within the capacitance range of tantalum capacitors. With the volumetric efficiency, capacitance range and surface mount packaging, the tantalum capacitor has become a standard device for this application.

Tantalum History in Power Applications

The history of these capacitors in this application is not entirely without failures. Early versions of the surface mount devices were not intended for power supply applications. The "normal" recommendation for these devices included that the circuit offer at least 3 ohms per volt as a series resistance, based on the voltage rating. With the filter circuit requirements in the power supply, this recommendation was either challenged with development efforts of the users and manufacturers, or was totally ignored. This device in the surface mount package was a large enough temptation to result in many early attempts to use the tantalum capacitor in power filter applications, regardless of the recommendations. Most of the results may have been successful, but the failures generated a lot of bad press for this capacitor.

This series resistance requirement was not only a manifestation of the inherent parasitic resistance of the capacitor; but also the inconsistency with internal interconnects. All capacitors are not perfect and this parasitic resistive element is mostly the result of using imperfect conductor materials used in the plate elements of the capacitor.

The manufacturers of the tantalum capacitors have responded to this application need through concerted efforts as well as through a natural refinement of materials, processes, and designs. For the standard commercial product, the three ohms per volt recommendation was soon dropped to one ohm per volt, and the standard line today is 0.1 ohm per volt.

New types of capacitors utilizing design, process and materials specifically to achieve a lower inherent resistance for the power supply application is fairly common among all the manufacturers. With resistance as the target, earlier design changes have dropped the resistive element by 50%. Some of the most recent designs offer another 50%, or even higher degrees of improvement. For these capacitors, there is no suggested series circuit resistance — they don't need any. How these designs differ from the standard design is detailed in this report.

Concentrated Effort on ESR

For the power supply applications, the capacitor must act as an energy source for part of the time. With a pulse modulated switching power supply, the output is fed directly from the input source for only a fraction of the total time. During the period the switch is open and disconnects the input current from the load, the capacitor must act as the energy source. The voltage cannot be exactly the same level, during this period as the capacitor is losing charge and the

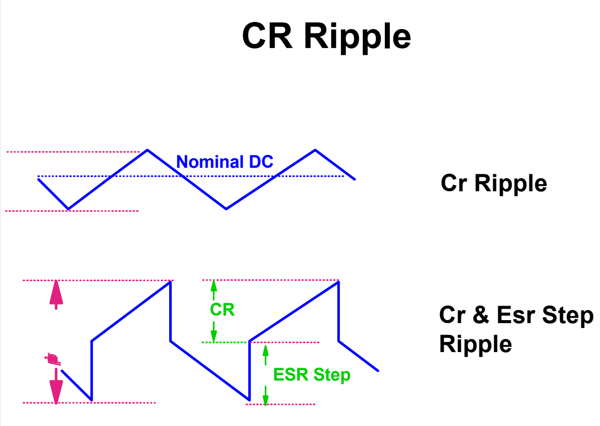

Figure 1. CR ripple factors in SMPS.

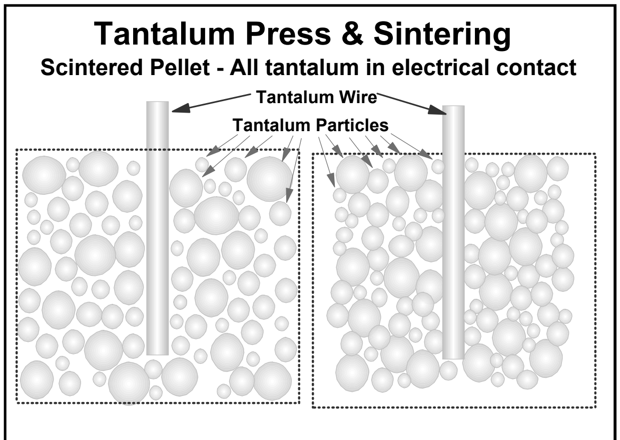

Figure 2. Pressed(l) and scintered(r) anode

voltage is decaying; therefore, an allowable deviation or ripple factor is specified. Based on the rate of charge that the load is demanding (current), and the voltage it is to maintain, the load can be seen as a value of resistance. The first order of calculating the required capacitance is to know how much capacitance is required to maintain the required voltage for a specified period of time. This is usually referred to as the CR ripple factor.

For faster switchers, the periods are shorter, allowing smaller capacitances to be used to maintain the same voltage window as larger capacitances that was required for longer time periods. The voltage wave form for this effect across an ideal capacitor is shown in the top half of Figure 1. The voltage appears as a triangular in shape, decaying while the switch is open and the capacitor is discharging, and increasing while the switch is closed and the input current is supplying charge to both the load and the capacitor.

The main parasitic of a capacitor, the effective series resistance (ESR), creates an additional voltage step in this triangular wave shape. This step voltage, referred to as the “ESR step voltage,” subtracts from the allowable voltage deviation window. If the allowable ripple (window) is specified as 0.10 Vpp, and the step voltage has a magnitude of 0.05 volts, then that allows only 0.05 volts for the CR ripple, and the capacitance must by increased accordingly. The lower the ESR, the closer to the ideal ripple wave form the filter behaves.

Tantalum Construction

The tantalum capacitor utilizes an oxidized layer of the tantalum metal as the dielectric. Construction first involves the formation of an anode pellet structure. Tantalum particles are pressed in a die cavity with a tantalum wire protruding out of the pellet (Figure 2). At this point, the tantalum particles are in chance, point contact with one another and the tantalum wire. The surface areas of the interconnects are small.

A sintering process is used to achieve multiple benefits: it reduces some contaminants by drawing them out of the pellet at this point; it allows the removal of organics that may have been introduced as lubricants in the pressing operations; and, it fuses the tantalum particles to one another. After sintering, the particles bond strength and area of contact between particles has grown. This strength and bond area growth increases are also established between the particles and the tantalum wire protruding out of the pellet. All the tantalum particles are now in very good electrical contact to one another, but the voids, pores, or channels throughout the anode remain. This porous structure is very much like a sponge — with an enormous amount of tantalum surface area exposed to the atmosphere.

Tantalum, like aluminum is a valve metal — an oxide layer is easily formed which is insulative and has dielectric properties (Figure 3). The layer is grown in an electrolyte solution with a bias voltage applied. The growth or thickness of this layer of tantalum pentoxide (Ta_2O_5) is largely dependent on the

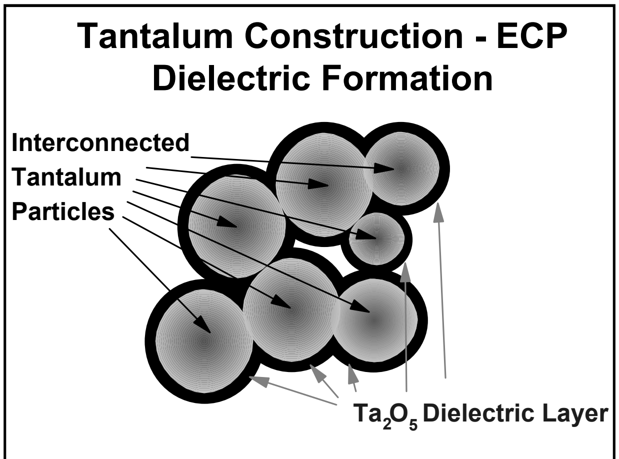

Figure 3. Dielectric formation on exposed surfaces

formation voltage (~170 nm. per volt). The formation voltage is usually a multiple of the final voltage rating to assure reliability.

The fact that the dielectric is an oxide of the base metal establishes the polarization of the device. In application, the interface between the metal and the metal oxide layer are at the same electrical potential as the potential that existed during the formation of the oxide. With a wet or liquid cathode connection, reformation can occur at a weak site if the oxygen can be removed from the electrolyte solution. Water is added to assist this action with the liquid electrolyte. Reverse voltage can allow a reversal of this process to occur where the oxygen is driven out of the oxide region. Depletion of this region creates a thinner dielectric with increases in leakage and subsequent breakdown.

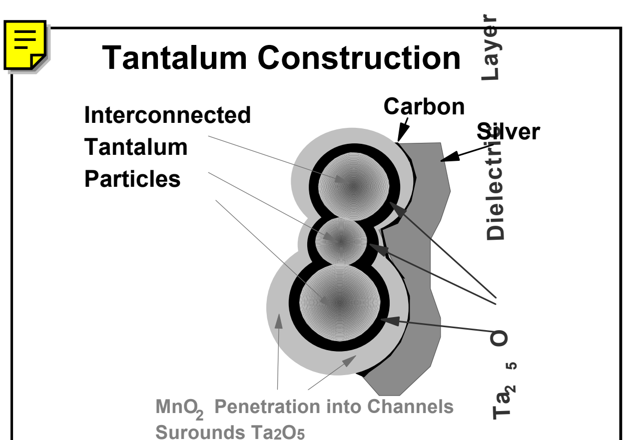

Figure 4. MnO_2 deposition with Carbon & Silver coverage

In the solid state device, the cathode plate is created with a deposited formation of MnO_2 — a semiconductor. This deposition is created through a series of multiple dips into manganous nitrate solutions, with drying cycles in-between. The MnO_2 penetrates into the depth of the anode through the pores, to form a surface coating of the previously exposed Ta_2O_5 dielectric. This surface contact across the dielectric creates the cathode plate within the capacitor.

The pellet is now a capacitor. To facilitate interconnection to the outside world, silver is applied as a paint or epoxy coating on 5 of the 6 faces of the pellet by a dipping and curing process. Because the silver to MnO_2 interface has a high resistivity, a graphite (carbon) pre-coating of the MnO_2 is applied to eliminate this (Figure 4).

As a leaded device, a lead is solder connected to the outside silver coating of the pellet (cathode) and welded to the tantalum riser wire (anode) and then packaged as an axial or radial capacitor. For the surface mount chip, the tantalum wire is welded to one tab of a leadframe while the silver coated pellet is attached to the other leadframe with conductive epoxy. The chip in the leadframe is then molded and the leadframe is cut and formed. The reason for conductive epoxy in place of solder is to eliminate the solder from reflowing if processed through normal surface mount heat exposures.

Self-Healing

Every tantalum capacitor built has tens or hundreds of fault sites in the dielectric layer. The poor conduction (2 to 6 ohm-cm resistivity) of the MnO_2 is overlooked because it has a property that allows conversion from this semi-conductive state to a highly resistive state such as Mn_2O_3. This conversion is activated by localized heating, created in part by the higher current densities in the MnO_2 as it enters the fault site (Figure 5). The localized heating with allowance for a small time period, creates this conversion at the fault site, ideally replacing the conductivity of the MnO_2 with much higher resistivity, thereby isolating the fault. The area removed is lost capacitance, but remember that this capacitor gains its high capacitance density through enormous surface area. The net lost capacitance is totally inconsequential to the gross.

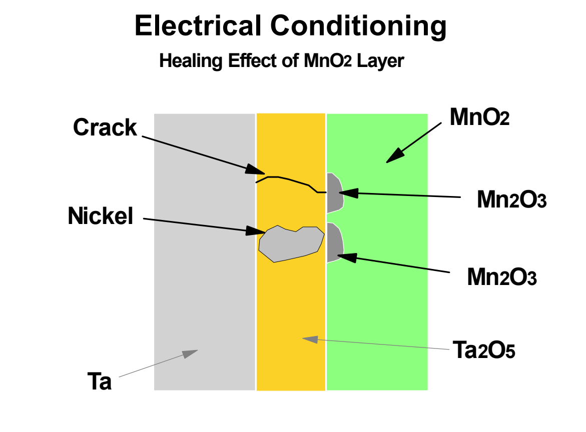

Figure 5. Self-healing mechanism of MnO_2.

All the capacitors are subjected to a controlled current and voltage exposure. This "burn-in" or aging, takes the capacitor up to the rated voltage, or slightly above, through a high resistance. The resistance assures that any fault site uncovered, will not have unlimited current available, which might trigger a total failure. The delayed heating under a lower controlled current assures activation of the healing process, and elimination of the fault site from the capacitor

If the coverage is incomplete, then it is possible that there are necks of high resistivity within the cathode plate connections. High surge currents could cause these necks to get hot, though there was no fault in the dielectric. Finite concentrations of heat in the anode pellet could cause enough of a thermal gradient to develop that will crack a portion of the anode — severing the dielectric, now resulting in dielectric failure and total collapse.

Poor coverage of a fault site might result in the corrective conversion being incomplete, radiusing outward from the fault creating a large enough radius and current dispersion that the device would continue to decay without enough concentrated current to trip the conversion process. Higher surge currents would allow these sites to draw excessive current that concentrates at the fault in the Ta_2O_5, heating the Ta_2O_5 to the point of melting the Ta_2O_5. The fault would grow quickly, soon consuming oxygen from the MnO_2, and resulting in an exothermic reaction.

As a precautionary step, the series resistance was suggested which restricted the amount of available surge current. If there is enough time delay, the conversion process (healing) can dominate the fault discoveries, rather than total failure and ignition. Unlimited current into a fault site allows the tantalum to melt and consume the device, without the conversion process having enough time to activate.

Industry Trends

The development driver for the tantalum capacitors has historically been capacitance per unit volume increases: more and more capacitance in smaller and smaller packages. In order to achieve these higher capacitance densities, finer powders were developed which resulted in more surface area per unit volume. Along with finer powders, the channels in the anode structure that the counter-electrode (MnO_2) had to be deposited into got smaller and smaller, though the number of channels increased (Figure 6). These finer channels should have driven ESRs up, but because these finer channels required changes in the deposition process and materials, the ESR appeared to slightly decrease while capacitance increased.

One byproduct of this refinement of process and materials was more complete coverage of the dielectric with the MnO_2. Without these refinements in the impregnation cycles, the gaps that were previously only problems in high current applications, would have cause tremendous loss of volumetric efficiency.

The first low ESR capacitor (T495 series), took a step back, in that the refined impregnation processes developed for these finer powders, were applied to the

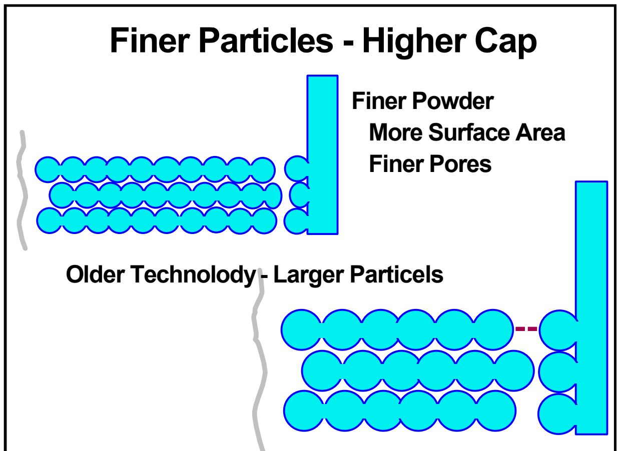

Figure 6. Higher CV - finer Ta powders.

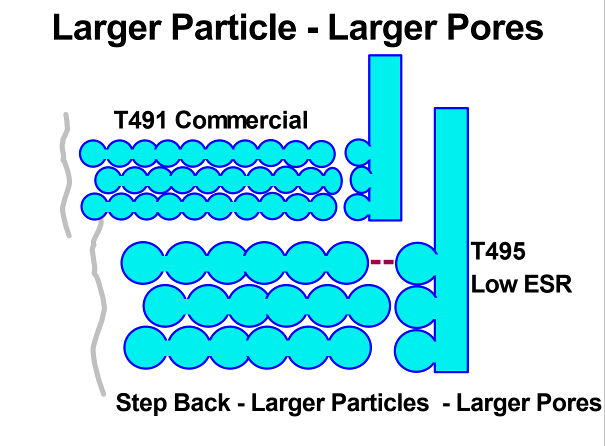

Figure 7. Low ESR through larger Ta particles

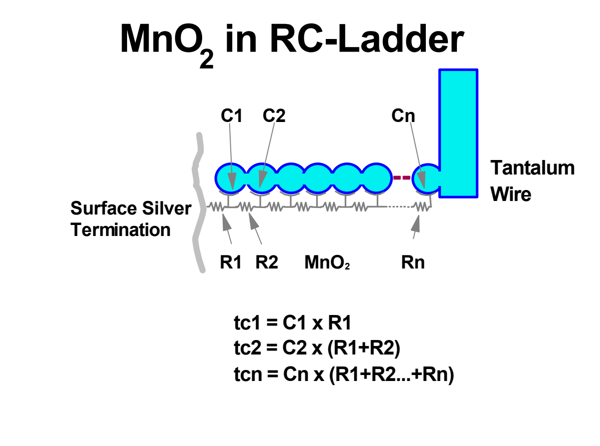

Figure 8. Internal RC-Ladder structure.

older and courser powders (Figure 7). This resulted in a denser, thicker, and more consistent penetration of the MnO_2 in the wider channels. This increased density of MnO_2 was one of the major steps in lowering the ESR. Additional refinements in final coverage of MnO_2, graphite, silver, and the conductive epoxy added to the final low ESR product. The ESR achieved was typically 50% of the commercial product for the same capacitance and voltage rating. The dense and consistent packing of the MnO_2 in the cathode plate, releases these capacitors from any circuit series resistance requirements. There is no series resistance recommendation for this capacitor. These capacitors are 100% surge tested to full rated voltage through a test circuit impedance of ~ 0.4 ohms.

The benefits for higher frequency are realized in both the resistive and capacitve elements. The tantalum capacitor behaves in much the same manner as an RC-Ladder network. The capacitance is composed of multiple, successive capacitance elements separated in each successive step by resistance. The resistance at any frequency is a complex summation of the resistive effects of the total capacitive makeup. At higher frequencies the deepest capacitive elements, with their associated resistance, are effectively "disconnected" from the circuit.

Because this device appears as an RC-Ladder network, there is a measurable loss of capacitance, or cap roll-off with increasing frequency. The period or frequency response is determined by the RC elements. If the capacitive elements are maintained as constant, and the resistive elements are decreased, the circuit has a lower time constant, or can respond to higher frequencies. The improvement realized with lower ESR is that the cap roll-off now occurs at a higher frequency, or the capacitance realized in this region will be higher than before. For filter circuits, this higher capacitance results in lower impedance.

The physical presentation of this RC-Ladder is readily apparent in the tantalum capacitor, if a view of the capacitor elements along the MnO_2 channel is viewed (Figure 8). As the path migrates to the depth of the anode, successive capacitve elements are contacted along the path. The high resistivity of the MnO_2 establishes the ladder and the loss of capacitance in higher frequencies. The resistance of the channel can be reduced by increasing the width of the channel as we have already done with the T495 series to alleviate this effect. The depth of the channel is fixed by the geometry of the anode pellet, and the larger the anode (required for highest capacitance

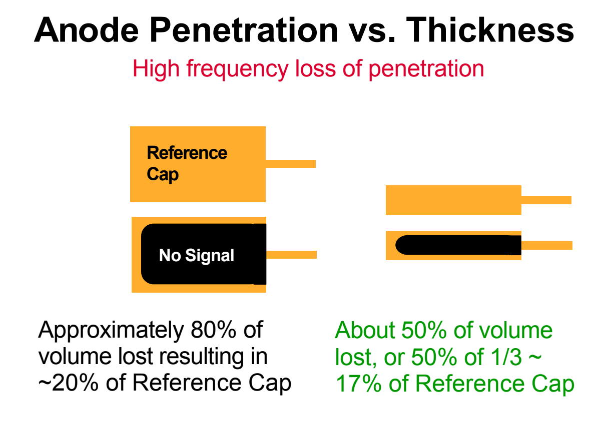

Figure 9. Loss of capacitance and penetration.

values), the greater the effect is noted. The effect is lower ESR, and lower capacitance loss with increasing frequencies.

What we realize in high frequency is that the penetration of the signal into the anode is restricted to a small portion of the overall thickness of the anode slug. As such, we loose the inner geometry of the anode, and its associated capacitance, as if it never existed (Figure 9). The T495 construction reduced this effect, but it still exists. Based on models, the ESR for a 47 uFd capacitor would have to be below 5 milliohms to eliminate the capacitance roll-off, whereas today we are closer to 90 milliohms.

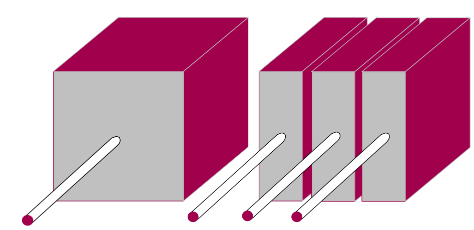

Figure 10. Multiple anode structure.

Multiple Anode Constructions - T510

In process today, we are attempting to reduce the ESR by another 33% to 50% by geometry considerations. These considerations are apparent that by reducing the depth of the channel, we reduce the overall resistance of the path. We make up the loss in volume by utilizing the multiple anode construction. Smaller depth also means more surface area must be created, and the area in immediate contact with the silver overcoat is the capacitance of high frequency.

This construction places three thinner anodes in a set case size (the X or the 7343H-EIA), replacing one wider anode (Figure 10). This also replaces one riser wire with three, dramatically increases the surface area, and decreases maximum depth to center. The ESR of this device is dramatically reduced, especially at higher frequencies. By using three thinner anodes in place of one, the parallel paths (surface area) have increased by a factor close to 100% over the single anode. The same volume is utilized, achieving the same capacitance, but the loss in volume due to depth of penetration is dramatically reduced.

Applications of T510

The driving force for this product came from the computer industry where size, performance and costs demanded new solutions to eliminate existing roadblocks. Specifically, the need is for quieter and smaller energy sources for increased energy demands in logic circuitry. The SMPS used are located as close to the circuitry as possible to eliminate time and noise from interrupting the correct logic flow. The decoupling of the microprocessors is not accomplished by this singular unit, but jointly by this tantalum capacitor as well as different value ceramics. Both standard chip geometries as well as "low-inductance" designs are utilized for the ceramic. This joint effort is intended to accomplish a hand-me-down energy transfer into the microprocessor to the greatest efficiency possible. Extremely low ESR allows fewer components to be used, reduces the overall path length to all the devices, reducing board inductance.

The requirements of the power supply are strictly dictated by the processor manufacturer to eliminate noise from inhibiting performance. The requirements as listed by Intel, for their Pentium® processor were used as a guideline for the ESR goals of this T510 device. For a SMPS with a response time of 30 microseconds, and an allowable change in voltage of 0.15 volts, and a peak current of 8.5 amperes, the total capacitance required would be 4,270 uFd. This calculation is based on the amount of capacitance required to assure that in 30 uS, the capacitor supplies all energy requirements of the processor with a maximum decay in voltage of 0.15 volts, while the power supply gets ready to switch on. While the supply is on, it supplies the energy to the processor, as well as recharges the capacitor to the original voltage. This deviation of voltage between the "on" times of the power supply is because the capacitor is supplying the charge to the circuit, and the loss of charge cause the voltage to drop.

The calculation of 4,270 uFd can be adjusted to subtract the ESR step voltage of the total ripple al-

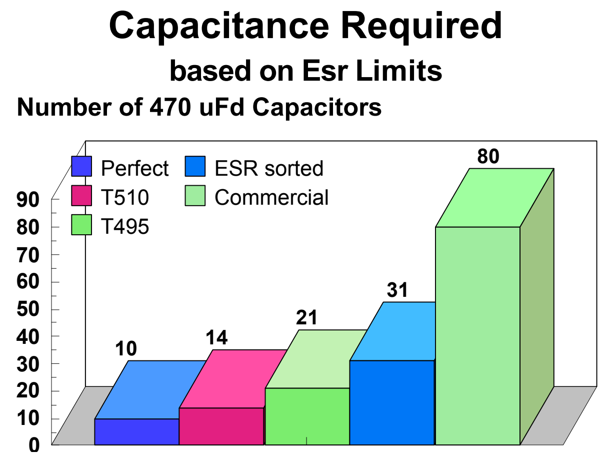

Figure 11. Caps required based on ESR.

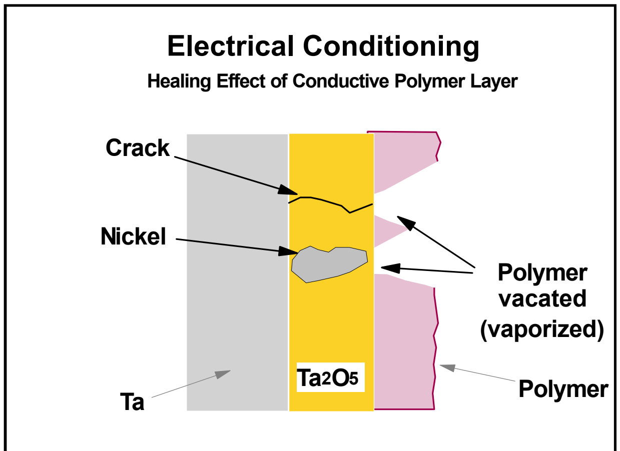

Figure 12. Polymer self-healing.

lowed, to find to total required for real (ESR>0) capacitors. Based on the calculations adjusted for ESR, and using the ESR limits for the various tantalum SMT chips, the number of 470 uFd capacitors, as well as the total capacitance required, increases (Figure 11). The T510 with 14 required is approaching the 10 ideal (0 ohms ESR) capacitors required.

Conductive Polymer Cathode

The requirement of a healing mechanism, eliminates many materials from consideration as the cathode plate. The conversion temperatures are low enough to keep the tantalum metal from reacting, and creates a high enough disparity in conductivity to isolate the fault effectively. Recent work with conductive polymers have shown a great deal of promise. This material has a higher conductivity than the MnO_2, and when heated, evaporate from the material. This creates voids above the fault sites, effectively isolating the defect from the circuit, permanently (Figure 12).

The polymer is polymerized within the anode structure, along the surface of the Ta_2O_5. The process involves a dipping and drying process very similar to the application of the MnO_2. One very important difference is that this polymer material does not have the high amounts of oxygen found in the MnO_2 cathode plate. This lack of oxygen appears to be non supportive of any exothermic reactions involving the melting and ignition sequence of the tantalum in the MnO_2 package. The problem is that it will take time before we effectively deposit the polymer with the same efficiency we do today for the MnO_2.

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