# Strategies for Manufacturing Ultra Low ESR Ta Capacitors

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## Abstract

Leading edge designs for portable electronic devices require capacitors which deliver volumetric efficiency, high reliability, low cost, reduced propensity for ignition, and low Equivalent Series Resistance (ESR). Tantalum capacitors employing a conductive polymer cathode are uniquely capable of providing all of these critical characteristics. Tantalum capacitors have a long track record for unsurpassed volumetric efficiency and reliability. The introduction of conductive polymer cathodes enabled dramatic reductions in ESR and greatly increased resistance to ignition. The lower ESR and enhanced cap retention at high frequency of the conductive polymer construction enabled circuit designers to reduce the number of capacitors required to achieve design solutions, resulting in reduced cost. Although Multiple Anode Tantalum (MAT) designs are capable of achieving the lowest ESR possible with valve metal capacitors (< 6 milliohms), single anode Ta/polymer capacitors with ESR less than 9 milliohms are now. Single anode capacitors with ESR levels less than 7 milliohms are within reach. The ability to achieve ultra low ESR levels with single anode designs provides the lowest cost, high performance solution to many design requirements. This paper describes the strategy used by manufacturers to provide solid state capacitors with ever decreasing ESR levels.

## Introduction

The market demand for low ESR, high capacitance capacitors is driven by industry trends toward reduced circuit voltages operated at increased frequency with higher current demands than in the past. These trends coupled with the need to improve energy efficiency, reduce heat buildup, and increase battery life for portable electronic devices fuel the need for ever lower ESR capacitors. Reed, Marshall, and Prymak[1] provide the mathematical equations which demonstrate the relationship between total capacitance and ESR for an output filter capacitor of a switchmode power supply.

In order to accurately calculate the number of capacitors required for a specific application consideration must be given to the loss of capacitance at high frequency. The loss of capacitance is directly related to the resistance of the solid electrolyte in the pores of the capacitor. Thus to minimize the number of capacitors required low ESR, high capacitance, and good capacitance retention at high frequency are needed. Component manufacturers have made continuous improvements in these areas to provide the electronics industry with components required for today’s design.

## Manufacturing Strategies

In order to manufacture an ultra low ESR capacitor the manufacturer must examine all of the elements used in the construction of the capacitor and seek to reduce the resistance of each element. Tradeoffs between reduced resistance and cost must be understood and taken into consideration in order to provide the lowest cost solution. The general equation for resistance is shown below:

$R=\rho l/A$
Where:
$R$=resistance
$\rho$=resistivity
$l$=path length

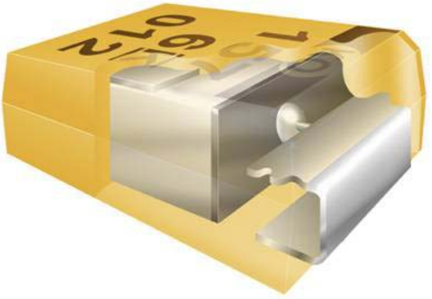
A=cross sectional area available for current flow

The strategy to reduce ESR of the finished capacitor is simple- apply the general equation for resistance to each individual element of the capacitor and relentlessly search for ways to reduce the resistance of each element. Although the strategy is simple, successful implementation is somewhat more difficult. Let us consider how to apply this method to the various elements of the capacitor.

## Lead Frame

The most popular construction for surface mount Ta capacitors is depicted in Figure 1 below.

**Figure 1**. Typical Construction of Surface Mount Tantalum Capacitor



Low ESR capacitors typically utilize lead frame which has a copper core due to the high conductivity and relatively low cost of copper The copper may be plated with tin, lead, nickel, palladium, gold, or other alloys to promote solderability and ESR stability[2], although lead is currently being phased out due to environmental regulations. Small levels of impurities in copper result in substantial changes in conductivity and other characteristics critical to the capacitor manufacturer. Properties of several copper alloys are presented in Table 1.

Capacitor manufacturers often cut ‘windows’ in the lead frame at the egress point to the molded case to reduce the chance for cracking of the molded case. This reduces the cross sectional area available for current to flow, resulting in a small increase in resistance through the lead frame. Although this increase in resistance is very small, manufacturers have developed other methods to insure case integrity without placing windows in the lead frame of ultra low ESR product offerings.

(1): % IACS at 68°F as annealed
(2): BTU per sq. foot per hr. per °F at 68°F
(3): inch/inch °F x $10^6$ from 68°F to 572°F

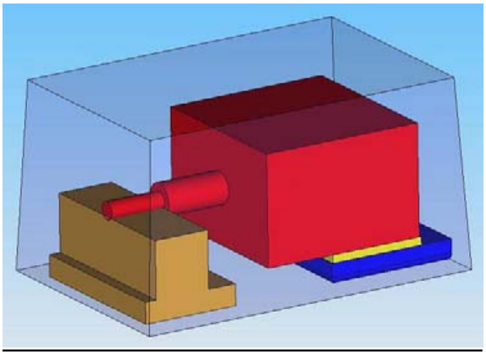
Table 1. Properties of Copper Alloys

| CDA No. | **110** | **197** | **194** | **195** |
|---|---|---|---|---|
| Elec. Conductivity (1) | 101 | 80 | 60 | 45 |
| Thermal Conductivity (2) | 226 | 185 | 150 | 115 |
| CTE (3) | 9.8 | 17.3 | 9.8 | 9.4 |
| % Cu (min) | 99.9 | 98.8 | 97.5 | 97 |

Since the lead frame is the most conductive element of a capacitor, low ESR designs extend the paddle of the lead frame as far up the length of the anode as practical. Tabs which extend the lead frame up one or more sides of the anode offer the possibility of an additional modest decrease in ESR.

Ultimately new constructions which reduce the path length for current flow from the solder pad to the anode will gain popularity as circuit designers continue to push capacitor manufacturers to provide components with ever lower ESR and Equivalent Series Inductance (ESL). One candidate design is depicted in Figure 2.

**Figure 2**. Alternate Design for Solid Electrolytic Capacitor



### Ta Lead Wire

Application of the general equation for resistance to the Ta lead wire is straightforward. Capacitor manufacturers use larger diameter lead wires to increase the cross sectional area available for current flow from the lead frame to the anode body. Reducing the length of the lead stub provides another opportunity for decreasing ESR. The resistance per mm of lead length for various lead wire diameters is provided in Table 2.

Table 2. Resistance per mm of Lead Length (milliohms/mm)

| Lead Wire Diameter (mm) | Resistance (mohm/mm) |
|---|---|
| 0.2 | 4.14 |
| 0.3 | 1.84 |
| 0.4 | 1.03 |
| 0.5 | 0.66 |

Since the values in Table 2 incorporate two terms in the general equation for resistance (resistivity and cross sectional area), the resistance associated with the lead stub is simply the product of the appropriate resistance per mm of lead length found in Table 2 times the length of the lead stub. The decrease in ESR of a capacitor employing a larger lead wire typically exceeds the difference in resistance of the lead stubs alone. This is due to the fact that the lead serves as a conductor inside the body of the anode, providing a lower path of resistance to current flow than is provided through the small necks between tantalum particles in the anode body. Thus the benefits of the larger diameter lead wire extend into the body of the anode. The larger diameter lead wire also provides greater available surface area for current to flow from the lead wire to the tantalum particles of the anode. However, larger diameter leads and reduced lead stub length can result in increased stress on the lead at the egress to the anode. Such stress is commonly associated with an increase in leakage current in the capacitor, and one of the challenges facing capacitor manufacturers is to refine assembly techniques to gain the ESR benefits provided by larger diameter leads and reduced stub lengths without increasing leakage.

### Anode

Resistance inside the body of the anode is primarily due to the small cross sectional area available for current flow through the necks of high CV/g powders used to manufacture capacitors with high volumetric efficiency. Modest improvements in ESR are obtained by using lower CV/g powders. This approach not only reduces volumetric efficiency, but also increases the manufacturing cost as more tantalum is required to achieve a specific capacitance/voltage rating. Higher CV/g powders also allow more flexibility in anode geometries. The reduced resistances associated with the polymer inside the pores of a thin anode pressed from a high CV/g powder often outweigh the marginal reduction in resistance of the anode itself pressed from a lower charge powder. The path length for flow through the anode is reduced by maximizing the insertion depth of the solid lead wire. Table 3 lists the conductivities of several valve metals available to manufacture capacitors. Tantalum is the most conductive valve metal available and hence enjoys a slight ESR advantage over competing materials in this regard.

Table 3. Conductivities of Valve Metals

| Valve Metal | Conductivity (S/cm) |
|---|---|
| Tantalum | $7.7 \times 10^4$ |
| Niobium | $7.7 \times 10^4$ |
| Niobium Oxide | 58 |

### Dielectric

The contribution to ESR from the dielectric decreases linearly with an increase in frequency. For valve metal dielectrics currently utilized to manufacture solid state electrolytic capacitors the contribution of the dielectric to ESR is negligible at frequencies of 100k Hz and greater.

### Primary Cathode Material- Conductive Polymer, TQNC, or $MnO_2$

Capacitor manufacturers employ one of three available materials as the primary cathode material (the material in direct contact with the dielectric) for solid electrolytic capacitors. The traditional primary cathode material is manganese dioxide, created by the pyrolytic conversion of manganese nitrate at temperatures above 220°C. In 1982 capacitors employing a charge transfer salt complex, TCNQ, were introduced into the market. Although significantly more conductive than $MnO_2$, TCNQ found limited acceptance due in large part to the low temperatures required for surface mounting. Most recently intrinsically conductive polymers have been used very successfully as the primary cathode material for capacitors. These materials offer several advantages over $MnO_2$; conductivity up to 100 times that of $MnO_2$, greatly increased resistance to ignitions, and reduced leakage defect sites in the dielectric due to the lower process temperatures. Conductive polymers have a self healing mechanism similar to that found in $MnO_2$. Joule heating at a defect site in the dielectric causes degradation in the conductivity of the polymer, forming a non conductive plug at the defect site in the dielectric. Another advantage of conductive polymers as the primary cathode material for solid electrolytic capacitors is that the temperature at which this degradation occurs is around 200°C, well below the temperature at which additional damage to the dielectric can occur. Manganese dioxide decomposes to manganese sesquioxide ($Mn_2O_3$) at temperatures between 500 and 600°C[4]. At these temperatures significant additional damage to the dielectric can occur during the 'healing' process[5]. This creates latent defects which can ultimately impact device reliability. These factors contribute to the lower derating factors required for polymer capacitors relative to their $MnO_2$, counterparts. The first commercially available capacitors utilizing conductive polymers employed polypyrrole as the primary cathode material (1994). Subsequent introductions to the market have expanded the choice of polymers to include poly [3,4-ethylenedioxythiophene], polyaniline, and combinations of these polymers. Table 4 lists some of the conductivities of these materials commonly used as the primary cathode material in solid electrolytic capacitors.

Table 4. Conductivities of Common Primary Cathode Materials Used in Solid Electrolytic Capacitors

| Cathode Material | Conductivity (S/cm) |
|---|---|
| $MnO_2$ | 0.1-1 |
| TCNQ | 1-10 |
| Polypyrrole, polythiophenes, polyaniline | 5-100 |

The increased conductivity of conductive polymers relative to $MnO_2$ has enabled capacitor manufacturers to dramatically reduce the ESR of solid electrolytic capacitors. Further reductions in ESR are possible by reducing the path length for current to flow from the outside of the anode to the interior of the anode. One approach is to press thin anodes. More recently capacitor manufacturers are reducing the path length for current flow into the anode through the use of so-called fluted anode designs. Although these designs allow for significant further reductions in ESR, they reduce the volumetric efficiency of the anode and increase the complexity of the anode manufacturing process. Improved press designs are required to eliminate powder sticking to the punches of the press and density gradients inside the anode commonly associated with fluted anode designs. Examples of anode cross sections are depicted in Figure 3.

**Figure 3**. Anode Cross Sections

Figure 3A. Conventional Anode

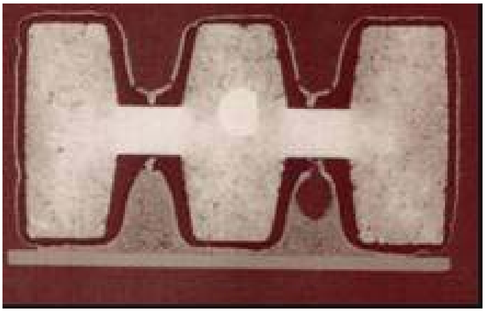
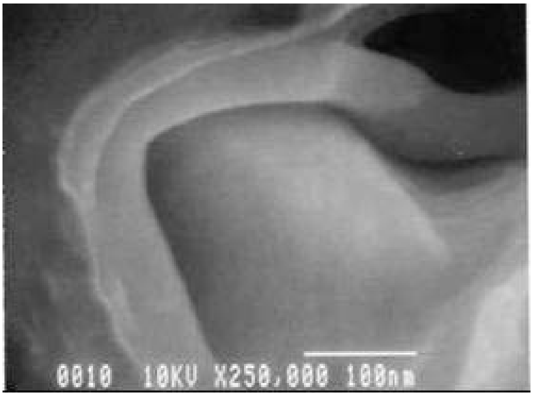


Figure 3B. Fluted Anode

SEM cross sections of anodes employing conductive polymers as primary cathode material indicate that the polymer buildup on the surface of the internal dielectric surfaces is very thin, on the order of a few nanometers (see Figure 4). The cross sectional area available for current flow through the internal polymer is directly related to this polymer buildup. Capacitor manufacturers have introduced ever lower ESR products in part by continuous improvements in the processes used to coat the internal dielectric surfaces of the capacitor. Further reductions in ESR can be expected as capacitor manufacturers find economical methods of increasing the polymer buildup on the internal dielectric surfaces.

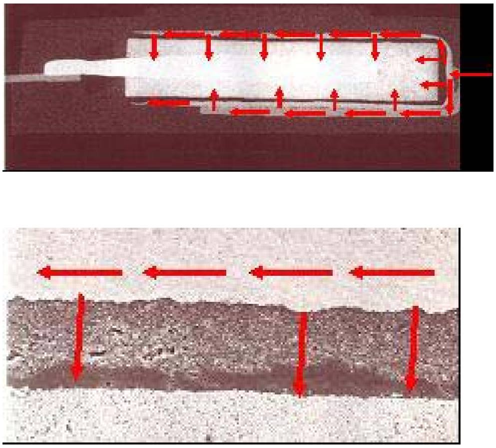
**Figure 4**. High Resolution SEM of Internal Construction of Ta/Conductive Polymer Capacitor



External Primary Cathode Layer

The external surfaces of the anode are also coated with the primary cathode material. The discussions above regarding conductivity apply to this component of resistance in the solid electrolytic capacitor. However, the path length and cross sectional area for current flow are different for the external and internal primary cathode components. For the external cathode layers current is flowing from the highly conductive lead frame or silver coating to the anode as depicted in Figure 5. Thus the path length for current to flow through the external polymer layer is proportional to the external polymer layer thickness. Sufficient thickness must be maintained to insure the carbon and silver layers do not directly contact the dielectric. Any further increase in buildup can lead to an unnecessary increase in ESR.

**Figure 5**. Direction of Current Flow Through The External Layers of a Solid Electrolytic Capacitor

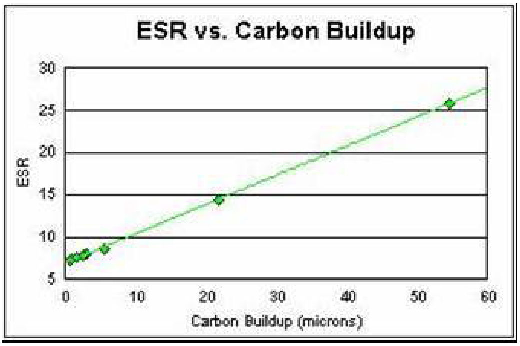


The cross sectional area for current flow through the external polymer layer is essentially equal to the external surface area of the anode. The maximum external surface area and minimum distance for current to flow through the internal polymer is optimized by designing tall, wide, thin anodes. The ability of the capacitor manufacturer to take advantage of this anode shape is limited by other design requirements- the need to fit the anode in the molded case and cap/voltage ratings of specific part types. Fluted anode designs described previously, in addition to reducing the path length through the internal polymer, increase the cross sectional area for current to flow through the external polymer layer. In order to obtain the full potential for ESR reduction offered by the fluted anode design it is necessary to avoid filling the channels of the anode with conductive polymer or carbon.

### Carbon

An analysis of the resistance associated with this external layer closely parallels that of the external polymer layer. The cross sectional area available for current flow is closely tied to the external surface area of the anode. Tall, wide, thin anodes and fluted anodes provide for the greatest cross sectional area for current flow. The path length for current flow through the carbon layer is equal to the thickness of the carbon layer. The relationship between carbon thickness and ESR is convincingly demonstrated in Figure 6. The carbon thickness was varied by changing the viscosity and the number of carbon dips. The slope of the line is related to the conductivity of the carbon formulation. The conductivity of the carbon layer depends on several factors including the particle size of the carbon, the type of carbon used, the resin, and the carbon to resin ratio. When comparing formulations with this technique, differences in the y-intercept reflect differences in interfacial resistance between the polymer/carbon/silver layers.

**Figure 6**. Graph of ESR Versus Carbon Thickness



### Silver

Application of the general equation for resistance to the silver layer is not as straight forward as other elements of the capacitor due to the more complicated pattern for current flow through this layer as illustrated in Figure 4. On the lead frame side of the anode the current flows across the silver layer in the same manner as it flows across the external polymer and carbon layers. The path length for current flow is reduced by decreasing the silver thickness. In order to reach the opposite side of the anode, current first flows through the silver layer, then across it to reach the anode. Thicker silver layers provide greater cross sectional area for current to flow to the sides of the anode not directly connected to the lead frame. Thus the optimum thickness for a silver layer of uniform thickness requires experimentation, and can be different for different anode geometries. As with carbon, the conductivity of the silver layer is related to many factors, including the shape and particle size distribution of the silver particles, the resin used to bind the particles together and to the carbon layer, and the silver to resin ratio.

### Silver Adhesive

Silver adhesive is used to connect the anode to the lead frame. In order to take full advantage of the high conductivity of the lead frame the silver adhesive should provide an electrical contact over the entire surface of the lead frame paddle and between the bottom of the anode and the lead frame pocket (see Figure 5).

### Interfacial Resistances and ESR Stability

Another important factor contributing to the ESR of a solid electrolytic capacitor is the interfacial resistance between the various external cathode layers: polymer-carbon-silver-lead frame. The characteristics of the carbon and silver formulations largely determine the interfacial resistance and the mechanical strength between layers. It is difficult to determine which carbon and silver formulation will result in the lowest ESR in a finished capacitor from the physical properties, including conductivity, of the formulations themselves. For this reason it is important that capacitor manufacturers develop strong relationships with the suppliers of these materials in order to reduce the cycle time for development and implementation of new low ESR formulations.

Weak mechanical bonds between these layers can result in significant increase in interfacial resistances due to thermo-mechanical stresses which occur during the solder reflow process used to mount the capacitors to circuit boards. The ESR increase associated with this increase in interfacial resistance can be significant, especially for ultra low ESR devices where even fractions of a milliohm are important. Capacitor manufacturers seek to minimize the magnitude of these ESR shifts by optimizing the physical characteristics of the carbon, silver, and encapsulating compound employed. Optimization of the molding process can also reduce the ESR shift during board mounting.

## Future Directions

Single anode Ta/polymer capacitors are currently available with ESR levels below 9 milliohms and greater than 90% capacitance retention at 100k Hz. Samples of anodes with ESR levels below 7 milliohms will soon be available. Manufacturers of solid electrolytic capacitors will continue to apply the general equation for resistance to each (element) component of the capacitor in order to continue to drive ESR levels down. As ESR levels have dropped into the single digits, ESL considerations are becoming increasingly important. Capacitor manufacturers will have to modify the lead frame geometry in order to meet the anticipated demand for lower ESL.

## References

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