Low Impedance Ta Capacitors to Serve the Needs of the Electronics Industry

Randy Hahn, and Jonathan Paulsen
KEMET Electronics Corp
PO Box 5928
Greenville, SC 29606
Tel: +1 864-963-6300
Fax: +1 864-228-4333
randyhahn@kemet.com

Abstract

Trends in circuit design for miniature consumer electronics are driving the need for very low impedance capacitors. Increasingly complex IC's requiring higher current and operating at higher frequencies have led to a need to reduce operating voltages to minimize heat buildup. All of these factors contribute to the need for low impedance decoupling capacitors. In order to meet the challenges posed by the changes in circuit design passive component manufacturers have increased capacitance density and reduced ESR and ESL. This paper reviews enabling technologies currently being used, as well as those being developed, by tantalum component manufacturers to continue to provide low cost solutions to fulfill the needs of the electronics industry.

Low Impedance Applications

Capacitors are used in electronic circuits to store and manage energy. Their functions include filtering, tuning, energy storage, decoupling, etc. Tantalum capacitors have been the components of choice for years in applications requiring high volumetric efficiency and reliability. In applications such as output voltage filtering or decoupling, low impedance, excellent surge performance, and high ripple current capability are critical.

Impedance is a measure of the sum of elements in a capacitor that resist the flow of AC current. Within a capacitor, three quantities comprise the impedance:

<u>Equation for Impedance</u>

$$Z = \sqrt{R^2 + \left(X_C - X_L\right)^2} \qquad (1)$$

R = Equivalent Series Resistance (ESR)
X_C = Capacitive reactance= $1/(2\pi fC)$
X_L = Inductive reactance= $2\pi fL$
f = frequency
C = capacitance
L = Equivalent Series Inductance (ESL)

ESR for tantalum capacitors is measured at a test frequency of 100k Hz. Due to the porous internal structure of tantalum capacitors, their performance at higher operating frequencies is inferior to ceramic capacitors, but generally better than aluminum electrolytic capacitors. Tantalums have traditionally excelled at low frequency applications (at or below 120Hz). However, improvements in the performance characteristics of modern tantalum capacitors (such as lower ESR and reduced capacitance roll-off) have enabled their use in more demanding, high frequency applications. Once parts with ESR below 10mΩ became commercially available, inductance within the devices became a significant portion of the overall impedance and a target for reduction.

Voltage Regulation for Switch Mode Power Supplies

The primary function of a filtering capacitor in switching power supply is ripple voltage suppression. Ripple voltage, an undesirable remnant of rectification and switching, is a function of frequency, current, capacitance, and ESR. Reed, Marshall, and Prymak have described the mathematical relationship between these factors (1). Reed et al. use a representation of a typical voltage waveform from a capacitor in a circuit with alternating charging and discharging current cycles to illustrate these relationships. The current waveform applied to the capacitor is considered to be a square wave with the direction of the current alternating between charge and discharge cycles. The steep increase in voltage is a result of the ESR of the capacitor and follows Ohm's law: V=I*ESR. The second component of the ripple voltage is the voltage change which occurs due to the charging and discharging of the capacitor. This component of the ripple voltage is equal to I*t/C where t is the length of time of the constant current portion of charge or discharge cycle.

In this idealized illustration, the impact of inductance on the shape of the waveform has been disregarded and the magnitude of the ripple voltage is determined solely by ESR and capacitance.

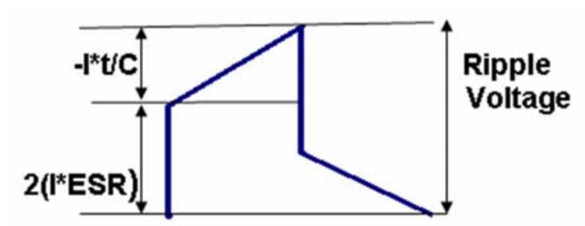

Figure 1. Drawing depicting relationship between ripple voltage and current (I), ESR, and capacitance

Decoupling Capacitors

Typically, microprocessors operate at speeds much greater than that of the power supplies which provide power to the IC. The purpose of a decoupling capacitor is to provide power to the microprocessor during the time it takes the power supply to catch up. Larry Mosley provided a more detailed description of the use of capacitors in voltage decoupling applications in which several stages of capacitance are employed (2). Closest to the IC are capacitors with relatively low capacitance and low inductance. Subsequent stages employ higher capacitance ratings, typically with correspondingly higher ESR and inductance levels. The capacitors used in the final stage serve not only to decouple the capacitor from the power supply, they also serve to filter the output voltage of the power supply. Tantalum capacitors are often used in this final stage. Driving the need for low impedance capacitors in this application is the trend toward microprocessors which require higher power and higher current and operate at lower voltage and higher speed. In order to meet the market needs in these low impedance applications component suppliers need to develop products with higher volumetric efficiency of capacitance, lower ESR, and lower inductance.

Enabling Technologies to Reduce Impedance

Enabling Technologies to Increase Volumetric Efficiency of Capacitance

Modern capacitors must have high volumetric efficiency to provide decoupling and filtering in advanced applications. The volumetric efficiency of a capacitor can be expressed as:

$$C/cc_{cap} = \frac{\left(CV/g \times g/cc \times \prod CF_{1-3} \right)}{V_f} \tag{2}$$

Where:
C/cc_{cap} = capacitance per unit volume of the finished component
CV/g = charge of the Ta powder used to press the anode (measured at the formation voltage)
g/cc = density of the sintered anode
$CF_{1\text{-}3}$ = correction factors to account for:
CF_1 = ratio of solid cap to wet cap
CF_2 = ratio of volume of sintered anode to anode after application of cathode (conductive polymer or MnO_2), carbon, and silver
CF_3 = ratio of volume after application of cathode to volume of finished capacitor package
V_f= formation voltage

In order to improve volumetric efficiency, capacitor manufacturers are addressing every aspect of equation (2). Historically, improvements in tantalum capacitors were achieved largely through improvements in the CV/g of available capacitor grade tantalum powders. Figure 2 provides a perspective of the gains achieved as a result of the first term of equation (2).

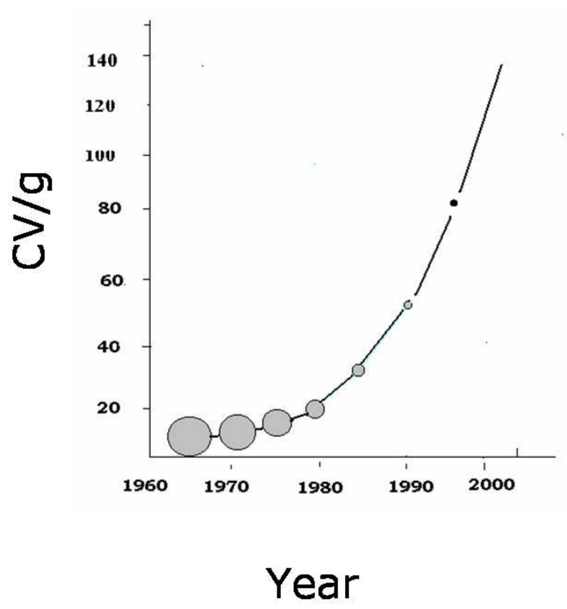

Figure 2. Historical perspective of the CV/g of tantalum powders used to manufacture solid electrolytic tantalum capacitors.

As the CV/g of the tantalum powder increases, pore size throughout the sponge-like structure of the anode decreases. Smaller pore size is more challenging to fully impregnate with the solid cathode, although this tends to be less of an issue for capacitors employing conductive polymer as the cathode. Moreover, the size of the tantalum particles and the necks between them also decreases as CV/g gets larger. This increases the resistance to current flow in the anode, worsening ESR. Further, anodes pressed from high charge powders are less robust to thermo-mechanical stress due to the smaller necks. This problem of fragility gets worse as anode size increases. Current state-of-the-art, 7343-19 case-size, low impedance tantalum capacitors employ CV/g powders in the range of 40,000-60,000 CV/g. Since tantalum powders with CV/g values as high as 200 CV/g are currently available, cap/cc of the finished capacitors can be increased by a factor of nearly 4 fold within the foreseeable future.

The next term in equation (2) is the sintered density of the anode. As the density of the sintered anode increases, the theoretical volumetric efficiency of the finished device increases. Pore size decreases as sintered density gets larger. The practical range of tantalum anodes used today is 4.5-6.5 g/cc.

The next series of terms in equation (2) represent correction factors used to convert the theoretical efficiency of the sintered anode to the actual volumetric efficiency of a finished device. The first correction factor results in a reduction in the overall volumetric efficiency of the device due to differences in the capacitance of the finished component compared to the capacitance available in the anode after formation. This factor is often referred to as capacitance recovery. For tantalum capacitors employing MnO_2 as the solid cathode, capacitance recovery decreases for the higher CV/g tantalum powders, higher sintered density anodes, and larger anodes. For tantalum capacitors manufactured with an intrinsically conductive polymer (ICP) as the cathode, however, the dominant effect on capacitance recovery is the relationship between capacitance recovery and formation voltage as demonstrated in Figure 3.

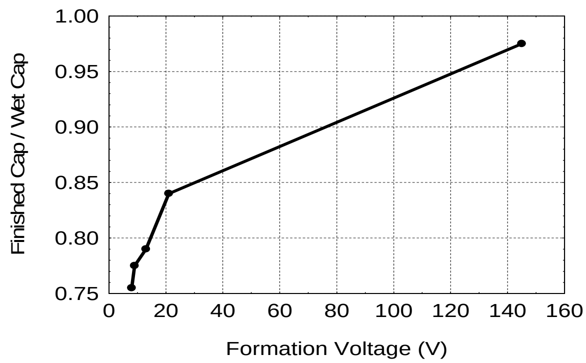

Figure 3. CF_1 plotted versus formation voltage for tantalum capacitors employing an intrinsically conductive polymer as the cathode.

The second correction factor in equation (2), CF_2, corrects for the increase in volume of the solid electrolytic capacitor due to the buildup of the external cathode layers: the conductive polymer (MnO_2), the carbon, and the silver. Typically the buildup of the conductive polymer is 10-20 microns per side. The external MnO_2 buildup varies widely: values from 50 to 200 microns per side are typical. Carbon buildup for low impedance capacitors is thin, generally less than 10 microns per side. Silver buildup also varies widely. Since ESR tends to decrease with additional silver buildup, the thickness of the silver layer can exceed 50 microns per side. Efforts to decrease the buildup of conductive polymer, carbon, or silver can degrade the electrical performance of the finished device (leakage reliability, ESR, etc.) Efforts to reduce external MnO_2 buildup provide some opportunity to increase CF_2.

The final correction factor in equation 2 is CF_3. This factor corrects for volumetric inefficiencies in packaging design resulting from space taken up by anode and cathode connections and the molded case. A traditional surface mount tantalum capacitor is depicted in Figure 4 to illustrate this loss in volumetric efficiency. For example, in order to prevent thin areas in the case and anode show-throughs, minimum epoxy wall clearance must be maintained.

The result is a corresponding decrease in the width and thickness of the anode. The anode length is further limited by the need to attach positive and negative terminations to the capacitor. CF_3 is a function of both the package design and the process capabilities of the manufacturer. Design tolerances for epoxy wall clearance and termination specifications must allow for the variation in the process. Since these tolerances are essentially the same for small case size product as large case size product, CF_3 decreases with smaller case sizes as indicated by the changes in total volumetric efficiency in Figure 5.

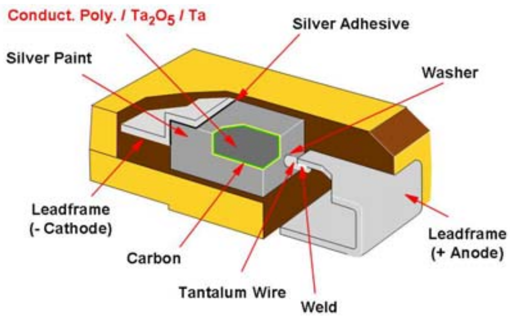

Figure 4. Traditional surface mount capacitor.

One approach to increase CF_3 is to reduce the distance between the positive lead frame and the top of the anode. Improved materials and processes to control buildup of cathode material on the tantalum lead wire and laser welding technology allows this distance to be reduced up to 0.5 mm.

In order to improve the packaging efficiency some component manufacturers have developed conformal coated product lines. Face down products which have recently been released to the market improve the packaging volumetric efficiency significantly, especially for small case size products (see Figure 5). In order to continue to improve volumetric efficiency of capacitance, new packaging designs must be developed to increase CF_3.

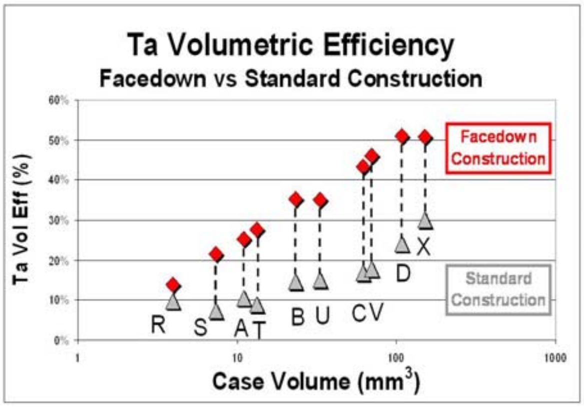

Figure 5. Plot of volumetric efficiency vs. case size for standard surface mount construction and face down construction.

The final term in equation 2 is the formation voltage. Dielectric thickness increases with formation voltage resulting in the drop in capacitance efficiency. Product reliability is also related to the dielectric thickness. The ratio of formation voltage to rated voltage typically was about 4:1 when surface mount products were first introduced to the market, but process and material improvements resulting in improved quality of the dielectric have allowed component manufacturers to decrease this ratio to 2.5:1 for low voltage capacitors typically used for decoupling or filtering. Manufacturers continue to develop technologies to allow for incremental reductions in formation voltage without sacrificing product reliability.

Enabling Technologies to Decrease ESR

Dramatic reductions in ESR have been achieved during the last 15 years. Figure 6 documents changes in ESR for 7343-19 capacitors available in the market place. The dates correspond to product release dates by KEMET Electronics Corporation; release dates for other manufacturers may be different. The 6 mΩ ESR available in this case size represents leading edge technology for single anode designs. ESR levels below 4 mΩ are available in multiple anode 7343-43 case size designs.

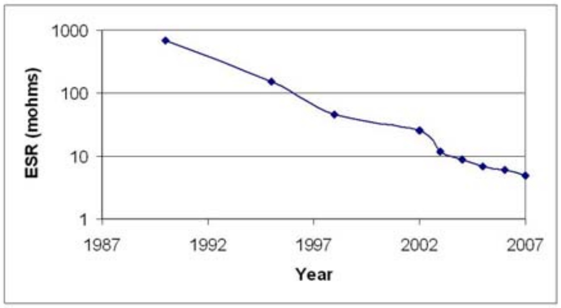

Figure 6. Decrease in ESR for 7343-19 case size since 1990.

The strategies used by component manufacturers to reduce ESR revolve around the conceptual application of the general equation for resistance to the various elements of the capacitor (3).

$$R = {\rho L}/{A} \tag{3}$$

Where:
R = resistance
ρ = resistivity
L = path length
A = cross sectional area available for current to flow

One of the key enabling technologies utilized to drive ESR down has been the emergence of intrinsically conductive polymer materials used as the cathode. Intrinsically conductive polymers are two orders of magnitude more conductive than MnO_2. The actual reduction in ESR achieved with these materials does not match the difference in conductivity, due in part to the tendency of conductive polymers to form very thin films inside the pores of the anode. Further reductions in ESR may come from technology which enables the component manufacturer to apply thicker films of conductive polymer inside the pores of an anode at a reasonable cost. Efforts to further optimize the conductivity of the films are on-going.

Equally important has been the use of multiple anode and fluted anode designs to take advantage of the reductions in path length and increase in cross sectional area available for current to flow that these designs offer. These designs reduce contributions to ESR from the cathode, carbon, and silver layers in the capacitor.

Since the anode is constructed of tantalum metal (conductivity=7.7 x 10^4 S/cm) the contribution to device ESR from the anode might be overlooked. However, the small cross sectional area available for current flow through the necks within the sponge-like morphology of a tantalum anode causes the anode resistance to be significant, especially for devices with single digit ESR levels. This resistance is decreased through the use of higher press densities, lower charge powders, and larger lead wires. Each of these approaches present difficulties the component manufacturer must overcome. The smaller pores resulting from higher press densities are more difficult to impregnate with the cathode, while lower charge powders reduce capacitance. Larger diameter lead wires are more difficult to cut and weld. Recently KEMET Electronics Corporation has introduced product manufactured with multiple lead wires to minimize the anodes contribution to ESR (see Figure 7). In the years ahead, tantalum anode designs will continue to evolve to allow for further ESR reductions. Thinner, longer anodes, deeper flutes, anodes with flutes and flat wire will be developed to meet the market demands for low impedance capacitors.

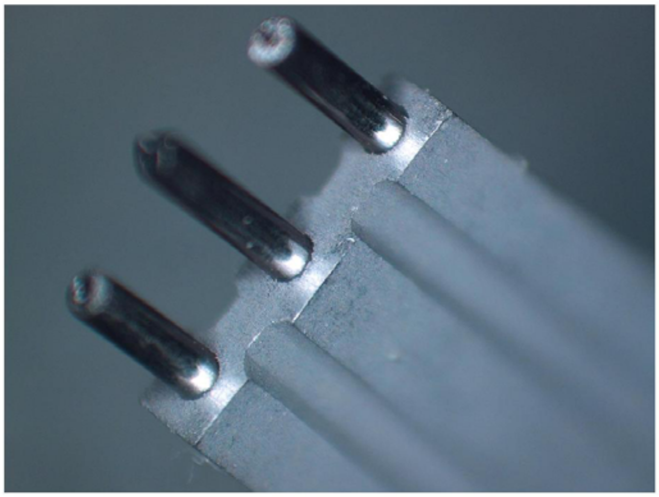

Figure 7. Fluted anode with multiple lead wires.

Process and material improvements in the carbon and silver coatings have also played a role in the ESR reductions achieved in recent years. The carbon layer is required due to the chemical incompatibility between the silver layer and solid cathode. Naturally, this layer contributes to the ESR of the tantalum capacitor. One strategy to reduce the contribution to ESR of this layer is to minimize the layer thickness, thus reducing the path length for current flow (Figure 8).

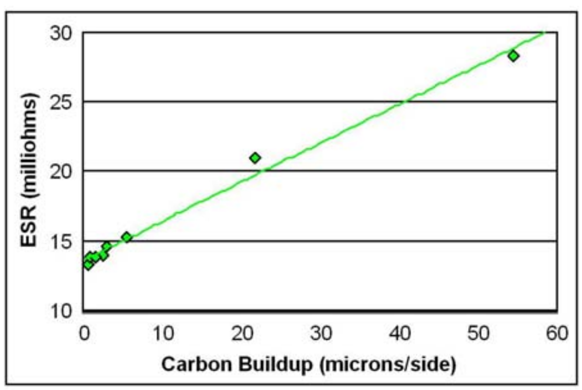

Figure 8. ESR versus carbon buildup.

Electric current essentially flows across the carbon layer, but through the silver layer. Thus the relationship between ESR and layer thickness are different for the carbon and silver layers. As demonstrated in Figure 9, ESR tends to decrease with additional silver buildup. It is relatively easy to manipulate carbon and silver buildup by modifying the viscosity and percent solids of the materials used. However, in order to minimize ESR the material sets must be optimized to reduce interfacial resistances between the solid cathode, carbon, and silver layers. Thermo-mechanical stresses of the board mount process result in an increase in resistance at these interfaces. The elimination of lead from solders in order to comply with RoHS legislation has resulted in an increase in surface mount temperature profiles. This places an even greater importance on the use of optimized carbon and silver materials to prevent shifts in ESR during the board mount process. This remains an area of active development in the industry.

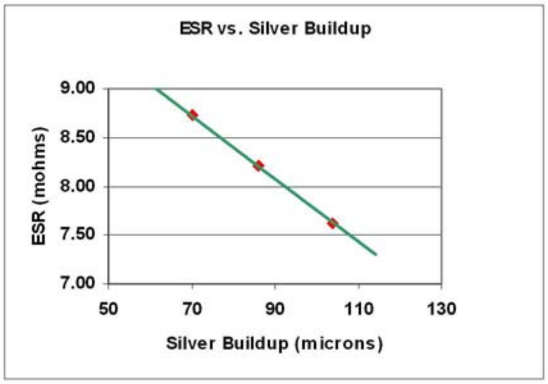

Figure 9. Relationship between ESR and silver buildup.

As indicated by the general equation for resistance, geometric considerations play an important role in determining the resistance of each of the elements that comprise a capacitor. Although single digit ESR levels have been achieved by taking advantage of geometry to reduce resistance, manufacturing smaller footprint capacitors with ultra low ESR will require new innovations and material sets.

Enabling Technologies to Decrease Inductance

The general equation for inductance in a coil is given by equation (4).

$$L = \mu_f \times N^2 \times A \times L \tag{4}$$

Where:
L = inductance
μ_f = permeability factor
N = number of turns per unit length
A = area of loop
L = length

The Equivalent Series Inductance (ESL) of a capacitor is determined primarily by the area of the current loop which depends on the geometric construction of the component. The loop area is reduced for smaller form factors and lower profile designs. Typical ESL values for C, V, D, and X case tantalum parts can range from 1.2 nH to 3.0 nH. Smaller case sizes, such as A and B, can have ESL as low as 1.0 nH.

Although ESL is lower for smaller case sizes, impedance is higher due to reduced capacitance and increased ESR. Facedown designs offer another approach to reduce ESL while improving packaging efficiency (4). The improved packaging efficiency allows for the use of a larger anode with a higher capacitance value. For small case size anodes facedown designs allow for a nearly two fold increase in anode size.

For larger case sizes the relative impact on anode size is less, but the impact on ESL is significant. The ESL of a traditional 7343-19 tantalum capacitor is approximately 1.4 nH. The ESL is reduced to about 0.5 nH with a facedown construction (see Figure 10).

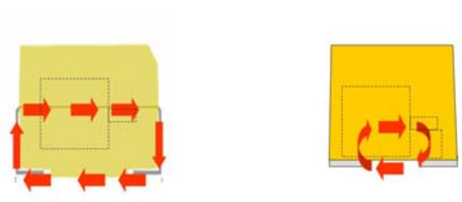

Figure 10. The decrease in current loop area with face down design compared to traditional surface mount device reduces ESL of the facedown configuration.

In addition to optimizing anode and case designs in tantalum capacitors, superior impedance can be achieved by combining the performance of tantalum and ceramic capacitors within a single package as described by Reed in KEMET patent 5,973,907[5]. Decoupling capacitors for use with high-speed microprocessors and advanced power conversion circuitry need low impedance and excellent high-frequency characteristics. Previously, electronics manufacturers have used combinations of metal oxide dielectric and ceramic capacitors that are mounted in parallel on the circuit board. Although this arrangement provides acceptable high frequency response and charge storage, it takes up a considerable amount of circuit board space. Additionally, the interconnecting circuitry often worsens ESL. To reduce the footprint of the decoupling device while preserving the advantages of the parallel metal oxide dielectric-ceramic arrangement, the two components are combined within a single package. Frequency response of such a device is shown in Figure 11.

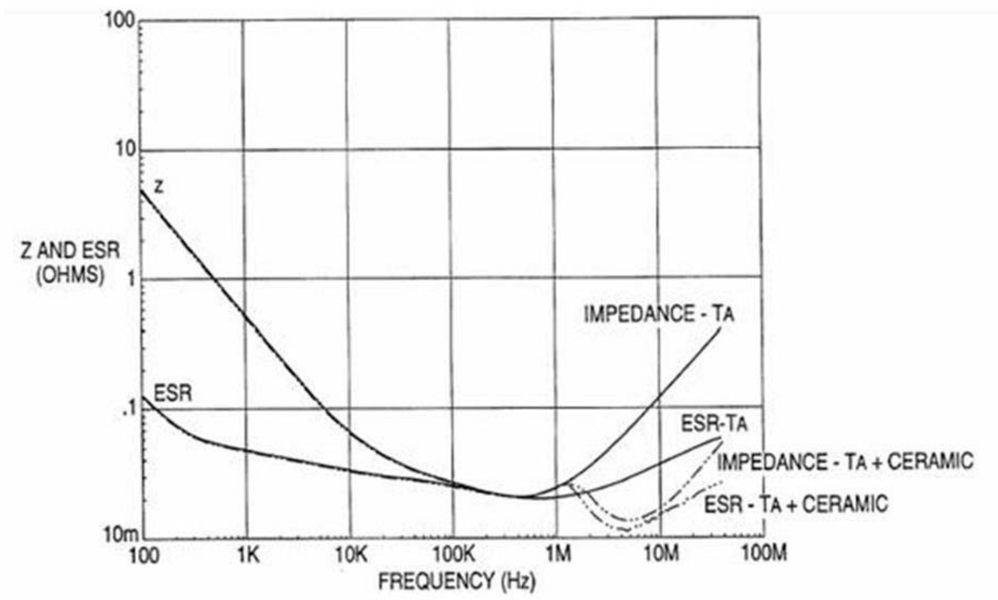

Figure 11. Frequency response of device utilizing a tantalum-ceramic parallel arrangement

Conclusions

Tantalum capacitor manufacturers continue to develop new technologies to meet the needs of the electronics industry. Low impedance capacitors used as decoupling capacitors require high capacitance density, low ESR, and low ESL. Improvements in capacitance density come largely from the use of higher CV/g tantalum powders and improvements in packaging design. ESR reductions are driven primarily by improved conductivity of the cathode materials and anode geometry modifications. Manufacturers have recently released facedown product lines to reduce ESL. Component manufacturers are currently working to apply the technologies which drove ESR into the single digits, multiple anodes, fluted anodes, multiple lead wires, to the low ESL facedown construction to provide very low impedance products for the electronics industry.

References

1. E. K. Reed, J. C. Marshall, and John Prymak, "Lowest ESR Tantalum Chip Capacitor," Proceedings of the 18th Capacitor and Resistor Technology Symposium, p. 22 (1998)
2. L. Mosley, "Capacitor Impedance Needs for Future Microprocessors," Proceedings of the 26th Capacitor and Resistor Technology Symposium, p. 193 (2006)
3. R. Hahn and K. Pritchard, "Strategies for Manufacturing Ultra Low ESR Ta Capacitors," Proceedings of the 18th European Capacitor and Resistor Technology Symposium, p. 166 (2004)
4. P. Blais, B. Long, J. Prymak, M. Prevallet, "Facedown Terminations for Higher CVand Lower ESL," Proceedings of the 26th Capacitor and Resistor Technology Symposium, p. 333 (2006)
5. E. K. Reed, "Multiple Element Capacitor", US Patent No. 5,973,907, 1999.