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# *Evaluating Tantalum Electrolytics As Replacements For MLCCs In High-Capacitance Applications*

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Over the years, ceramic capacitors have been used interchangeably with tantalum in many applications, class II ceramics being the one electrostatic technology that can achieve the high capacitance values typically associated with electrolytic capacitors. But because of MLCC shortages, we are currently at a point where designers are reconsidering electrolytic capacitors for applications that had switched to class II ceramic in recent years.

However, migrating circuit designs from MLCCs to tantalum electrolytics requires an understanding of multiple issues that impact how these different styles of capacitors will perform in the intended application. This article discusses the key parameters that differentiate these two capacitor categories in the various roles they play in power supply applications (bypassing, filtering, decoupling, bulk hold up and pulse power). It not only describes the range of parametric values, characteristics and options associated with MLCCs and tantalum electrolytics, but also the underlying differences in device construction and material properties that account for the differences in device performance and capabilities.

The discussion on electrolytics covers both tantalum and niobium oxide types and differences in these two material systems are explained. In addition to explanations of device physics and chemistry, details are provided here on capacitor packaging formats and capacitor modeling. All of this information is intended to help designers assess the viability of electrolytic capacitors as replacements for MLCCs in power supply and other high-capacitance applications.

But before deliving into the finer points distinguishing MLCCs and electroytics, we look at the most basic distinction between them—how electrostatic and electrolytic capacitor technologies differ.

## *Electrostatic Versus Electrolytic*

At its most basic, a capacitor is a disconnect in a circuit—when dc is applied, the current cannot flow (ideally an open circuit). But the disconnect will have an electric field across it allowing positive and negative charge to build up on either side. The amount of charge that can build up—the capacitance—depends on three factors.

The first two relate to the strength of the E field: the size of the gap (the smaller the gap, the greater the E field), and any material in the gap to enhance the E field (the dielectric). The third factor is the total surface area available for the charge to build up on. The surface area is not much in the case of a cut wire, more in the case of a pair of parallel plates (single-layer capacitor), and increasing with multilayer construction (MLCC) to nanoscale porosity (electrolytic capacitors).

This brings us to the issue of electrostatic versus electrolytic capacitors. What distinguishes electrostatic capacitors from electrolytics is how the dielectric is made or formed. For electrostatics, the starting place is the dielectric (a thin layer of insulating material such as ceramic, mica, plastic film etc.) to which a conductive metallized coating (nickel, copper, palladium silver etc.) is applied to the top and lower surfaces. This gives a symmetric, bipolar design.

For electrolytics, the starting place is a metal plate, which then undergoes electrolysis. For most metals, when configured as an anode in an electrolytic bath, they will plate out their material onto the cathode. For a certain group of metals, they instead grow a protective oxide which shuts the process down—the more current and voltage applied, the thicker the oxide growth.

These metals include tantalum, niobium and aluminum, and their oxides have excellent dielectric properties. A counter electrode is applied to complete the capacitor element—making these non-symmetric and, unlike electrostatic capacitors, having polarity. As a result, they can only be operated when biased in the direction in which the dielectric was formed (Fig. 1).

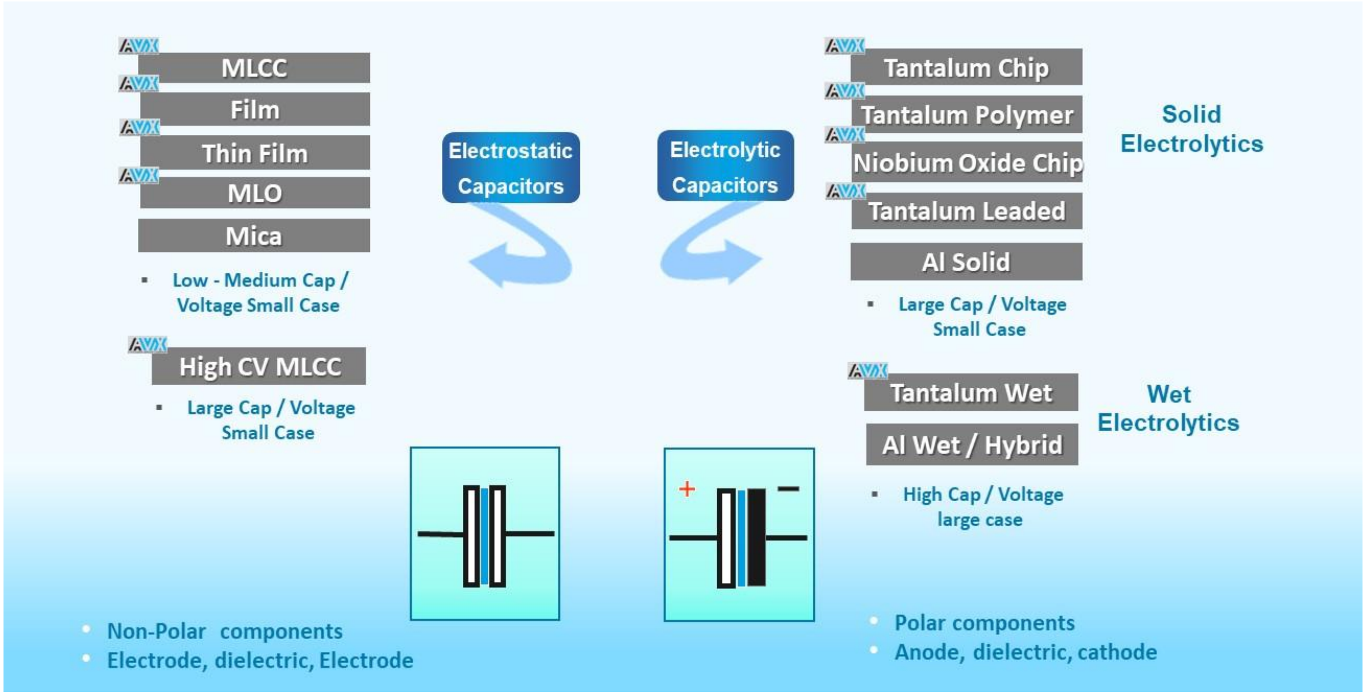



*Fig. 1. Electrostatic and electrolytic capacitor families.*

These differences give rise to the parametric characteristics that delineate these capacitor technologies, which need to be taken into account in certain applications.

## *Comparing Key Parameters*

Historically, electrolytic capacitors were the technology of choice for high, dc bulk capacitance applications in high-density circuit assemblies. In recent years, class II MLCCs have been developed with thinner dielectrics and greater layer counts to achieve high capacitance in the 10-µF to 100-µF range (and lower voltage ratings) that cross over with electrolytic technology. Simultaneously, advances in tantalum and niobium electrolytic technology have enabled downsizing of electrolytics.

While most applications are amenable to such tantalum electrolytic and MLCC interchangeability, some parametric factors can arise due to the differences in their technologies, which need to be taken into consideration.

To put the level of their interchangeability into perspective, a simplistic approach to their application overlap in general usage is shown in the Venn diagram in Fig. 2. It's no surprise that the vast majority of applications that account for the greatest volume of usage are bulk capacitance and general decoupling or bypass, where the key parameters are capacitance value and voltage rating and the technologies are fully interchangeble. Indeed, as the industry has gone through supply cycles in the past, many MLCC manufacturers have promoted their high-capacitance MLCCs as tantalum/niobium alternatives when tantalum electrolytic lead times were long.

However, the overlap is not 100%, and the diagram shows areas where issues may arise if designers switch from one to the other without checking the application. The lower half of the diagram shows some of the more common issues arising when switching from tantalum to MLCC, while the top of the diagram shows areas that need consideration when switching from MLCC to tantalum. Currently, the supply cycle is such that there is a short-term focus on reverting to, or evaluating, tantalum or niobium electrolytics in all these applications.

When considering tantalum or niobium electrolytics as alternatives to high-capacitance MLCCs, the areas in the lower half of the diagram show the major advantages of electrolytic technology. Capacitance loss due to voltage coefficient and piezo effects do not occur with electrolytics, while temperature coefficient effects are reduced.

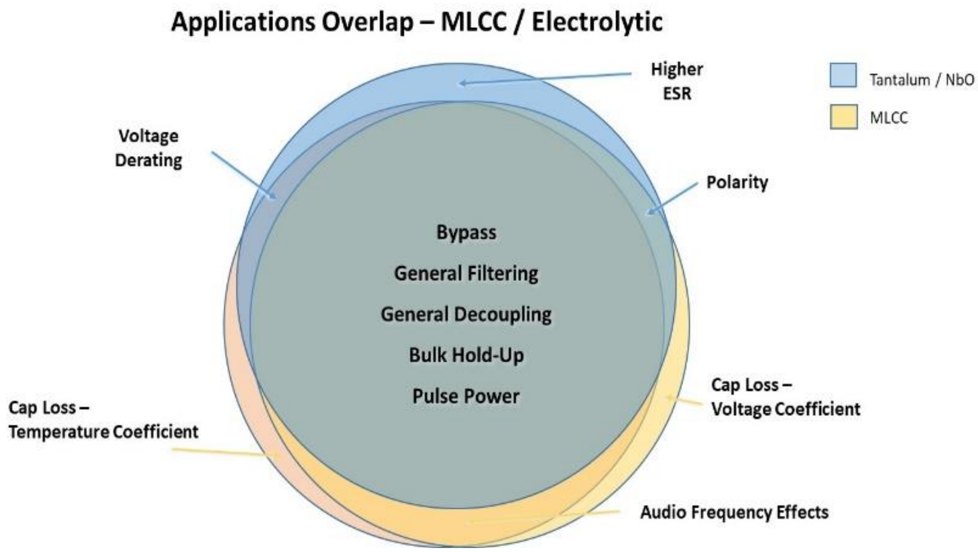



*Fig 2. Application interchangability: small-size MLCC and SMD electrolytic capacitors.*

As discussed above, capacitance is a function of the surface area of a capacitor's plates, their distance apart and the dielectric constant of the insulating material in between. Electrolytic technologies are characterized by high surface area and thin dielectric layers with good dielectric constant. In contrast, MLCCs have a layered construction with less surface area and a deposition process yielding thicker dielectrics (Fig. 3). Where the high capacitance MLCCs gain ground is by having a far higher dielectric constant, but this in turn gives rise to some unwanted effects.

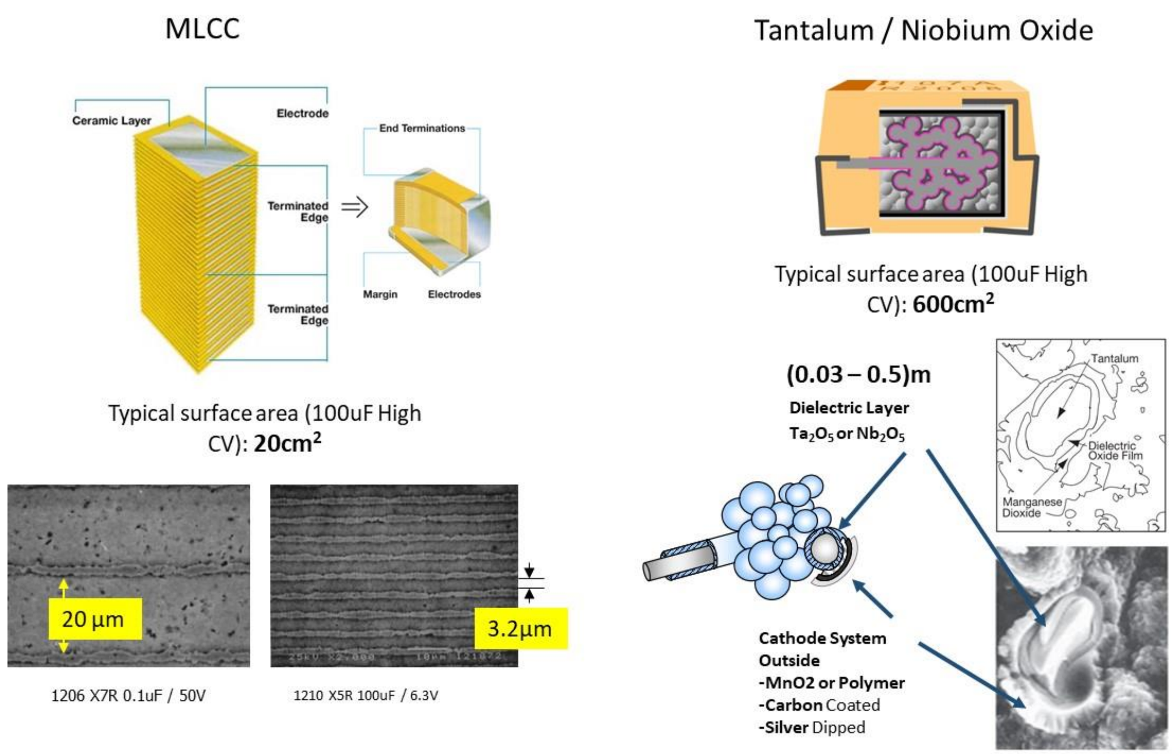



*Fig 3. Comparing typical electrode surface area and dielectric thicknesses of MLCCs versus SMD electrolytic capacitors.*

The relative dielectric constant value is a function of how well the material can polarize in an electric field and add to the field strength. For most capacitor technologies, this is achieved by the electrons in the material aligning with the field when a voltage is applied across the material. If an ac power or signal voltage is applied to the plates, then the electrons will oscillate with the field.

Typically, materials which allow the least bulk charge oscillation will have the lowest dielectric constant and hence very low capacitance values. However, they will be able to keep pace with the incoming signal and operate at higher frequencies. Materials such as Class I ceramics and silicon dioxide yield low capacitance, high frequency response characteristics, while metal oxides such as tantalum pentoxide and niobium pentoxide give high capacitance but a lower frequency-response range.

The Class II MLCC dielectrics are different; while the electrons within the material polarize, this effect is dwarfed by an additional contribution from elements of the dipoles associated with crystal lattice itself. The lattice can physically distort and align at the domain level, to give a much higher contribution to the E-field. This gives rise to certain characteristics of Class II MLCCs:

- When an ac signal at an audio frequency is applied, the constriction and relaxation of the crystal domains will cause an audible noise (microphonics) and contributes to signal voltage distortion.
- Conversely, if the part undergoes a physical shock causing a similar constriction and relaxation, the capacitor can generate a spurious voltage.
- If the part has a dc bias applied, then there will be a constant physical offset within the domains that limits further movement of the dipoles to contribute to the field strength, and the effective capacitance is reduced (voltage coefficient).
- The high dielectric constant of high-capacitance MLCCs is dependent on polarization at a domain level and so is more sensitive to material temperature changes, losing more capacitance at high and low temperatures compared to other dielectric types.

Using tantalum or niobium electrolytics in these types of applications will avoid these effects.

### *ESR, Voltage Derating And Polarity*

The top portion of the chart in Fig. 2 highlights the main differences between tantalum or niobium electrolytics and MLCCs that will require checking when attempting replacements of one type with another. Parametrically, the main difference is the higher equivalent series resistance (ESR) of the electrolytics. And from a design standpoint, in some applications, the electrolytics may require more voltage derating and, of course, correct polarity must be maintained. Let’s consider each of these factors in more detail.

In general, the ESR of tantalum or niobium electrolytics is higher than that of MLCCs near their self-resonant frequencies (SRFs). The SRF is the point at which a capacitor’s impedance is at a minimum. There is a marked difference in the impedance curves of MLCCs versus those of tantalum or niobium electrolytics.

The construction diagram in Fig. 3 shows that the MLCC has a regular geometric layered construction. This provides a short mean free path for an ac signal to pass through the device, yielding a “tuned,” notch-like impedance curve as illustrated in Fig. 4. The effect on ESR is to minimize it close to self-resonance, but at lower frequencies away from the SRF impedance does increase.

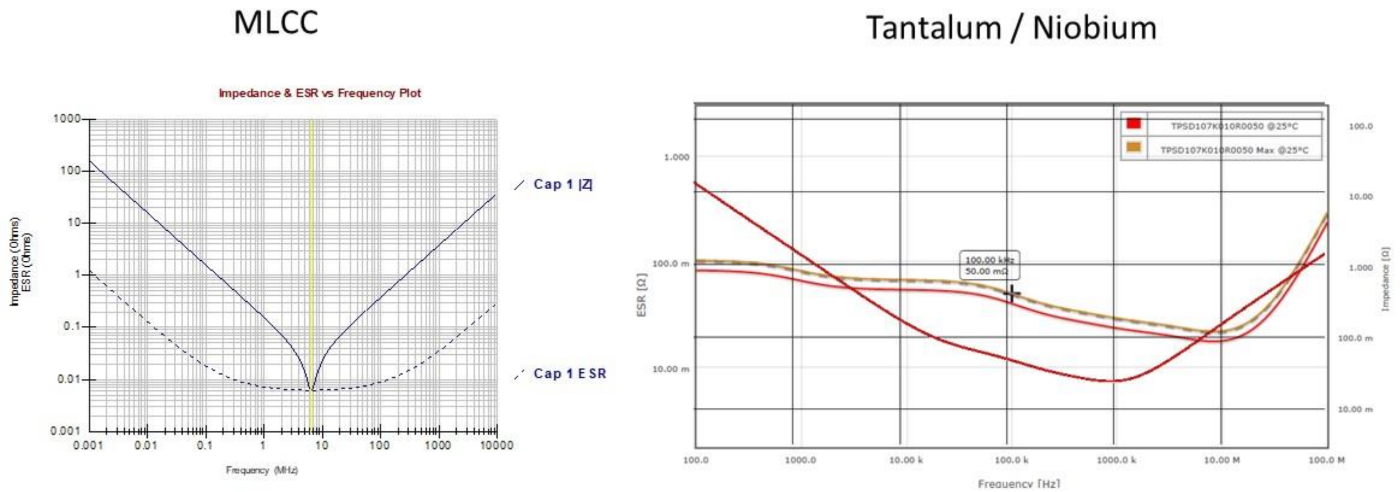



*Fig 4. Typical impedance and ESR characteristics for MLCCs versus SMD electrolytic capacitors.*

The construction of tantalum or niobium electrolytics, with their porous anode structure, is much more convoluted than the regular layers of an MLCC and gives a longer mean free path for a signal. As a result, the impedance cure has a much more broadband appearance than a tuned MLCC as also seen in Fig. 4. While this form of curve is ideal for decoupling, the disadvantage is that there is no low point to take the ESR down to the level of an MLCC at high frequencies. Although, at lower frequencies there is more similarity with the MLCCs.

Polarity is important if the capacitor is in a circuit at zero bias with an ac component added. For high-capacitance, low-voltage devices, this seldom arises as most applications are for power management in digital and low-voltage analog systems, all requiring a positive dc line. For any application where a negative bias may be present, an often-overlooked solution is to connect a pair of electrolytic capacitors in series back-to-back (typically common negative). For two identical capacitors, this series configuration will have half the capacitance of a single capacitor with the same voltage rating, but will now be bidirectional (non-polar) (Fig. 5).

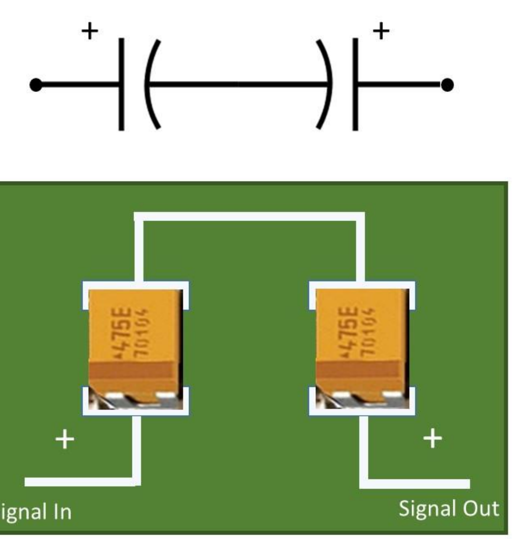



*Fig. 5. Non-polar configuration for electrolytic capacitors in series.*

Voltage derating is often a design consideration. The reliability of both MLCCs and tantalum or niobium electrolytics in a circuit is calculated using the voltage and temperature acceleration factors for any given application. For MLCCs, temperature has a greater acceleration effect than voltage, and vice versa for tantalum or niobium electrolytics. Because of this, voltage derating is often used as a standard design feature for these capacitors, with a 50% voltage derating yielding approximately two decades improvement in application reliability.

There is a third reliability factor for tantalum and niobium electrolytics—the application's series impedance. If there is close to zero external resistance, then voltage derating should be considered. But where there is high circuit impedance, it becomes less necessary.

## *Temperature Characteristics*

Having reviewed the basic parametric details for MLCC, tantalum and niobium electrolytic capacitors, the next step is to look at the various types that are available. For purely commercial, high-capacitance applications, the most popular MLCC is the X5R temperature characteristic. This is the standard high CV (capacitance x voltage), low ESR type and it has a maximum operating temperature of 85°C. An X5R capacitor is characterized by a high layer count, thin dielectric (for lower voltage ranges) and thin body margins to maximize the volumetric efficiency of the active element. The construction of an X5R MLCC is shown in the lower left quadrant of Fig. 6.

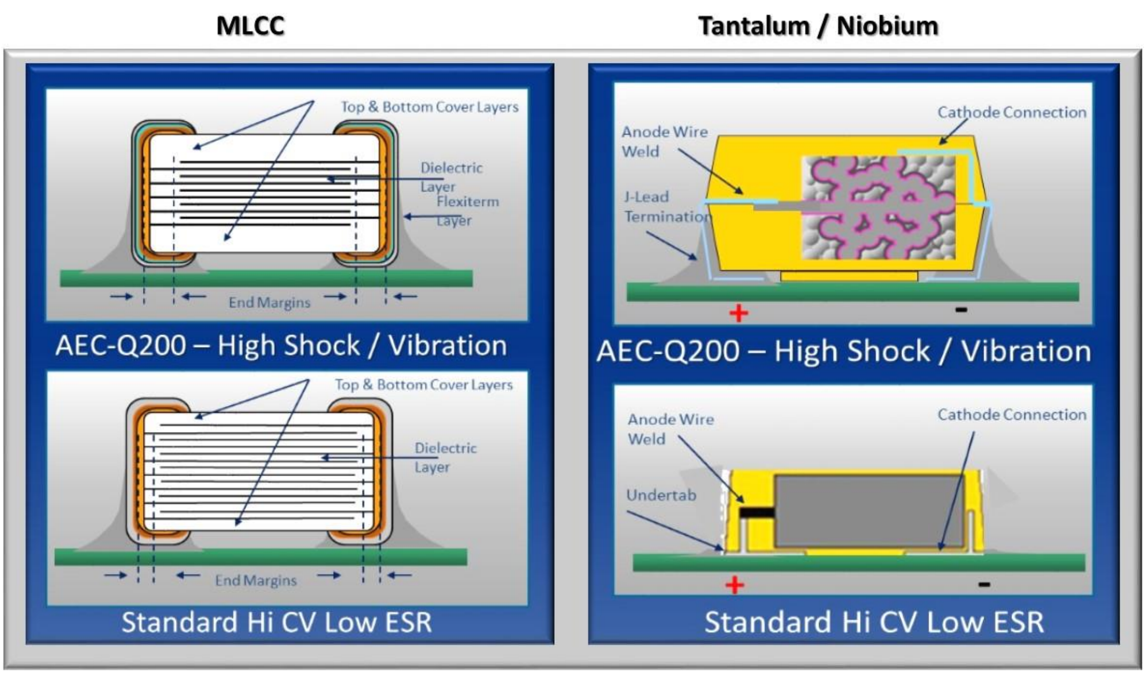



*Fig. 6. Construction styles for MLCCs, and tantalum and niobium electrolytics.*

For more demanding applications, the X7R temperature characteristic comes into play (high shock and vibration design shown in the top left quadrant of Fig. 6). This type has a maximum operating temperature of 125°C and can be used as the basis for more critical applications, such as automotive (to AEC-Q200), where, in addition to the higher temperature capability, it can also be supplied with flexible terminations for greater mechanical robustness.

The downside of this improved mechanical capability is that the maximum capacitance available in any given case size and voltage is less than that of an X5R equivalent. As an example, for a 1210 size 10-V dc rating, the X5R will yield 100 µF, while an AEC-Q200 X7R with flexible termination will only accommodate 10 µF.

In contrast, the standard construction method for tantalum and niobium electrolytics is a molded body with J-lead terminations, as shown in the top right quadrant of Fig. 6. In a 1210 equivalent size, this style has 100 µF available at 10 V matching the X5R MLCC, but with the added advantage of having the same mechanical capability and 125°C maximum operating temperature as the automotive X7R design, with 33 µF available at full AEC-Q200 specification.

### *Alternative Construction Methods*

There is an alternate molded construction for tantalum electrolytics shown in the lower right quadrant of Fig. 6. This is the "face down" style, with termination on the underside of the capacitor only. This enables greater volumetric efficiency for commercial high-capacitance/high-energy applications, such as solid-state drives.

One construction method not shown for tantalum and niobium electrolytic capacitors is the multi-anode. As the current discussion is regarding the overlap between these SMD electrolytics and standard MLCC chip sizes, the larger case sizes (C, D, E, etc.) are not included as there are no equivalent IPC SMD footprints that correspond to these. Although, some stacked ceramic capacitor series are available in similar sizes.

The multi-anodes are designed for more critical filtering applications. Given that the ESR of an electrolytic is limited by the signal mean-free path through the device, having an array of three low-profile anodes connected internally in parallel, where each has a much shorter path between the anode wire and external cathode connection, yields much lower ESR (Fig. 7). The external appearance is identical to the high shock and vibration design in the top right quadrant of Fig. 6.

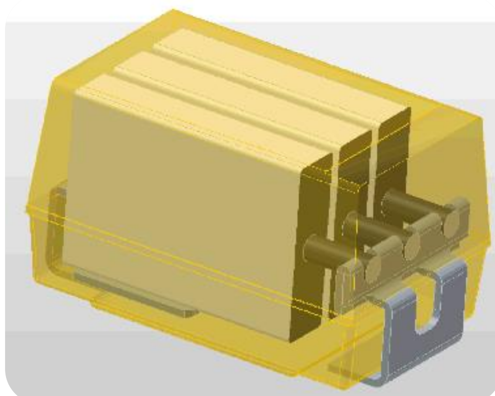


*Fig 7. Multi-anode construction for tantalum and niobium electrolytics.*

### *Tantalum Versus Niobium Electrolytics*

Moving to a tantalum or niobium electrolytic design brings a number of options for fine-tuning an application. A standard tantalum capacitor has tantalum as the anode and tantalum pentoxide with manganese dioxide as the electrolytic counter electrode. This counter electrode material provides good self-healing for long-term reliability. It also has low resistivity, which gives rise to the typical room temperature ESR characteristics shown in Fig. 4, although ESR does increase a little at low temperatures.

Polymer tantalum capacitors share the same anode and dielectric construction as a traditional tantalum, but a conductive organic polymer material replaces the inorganic manganese dioxide counter electrode. This has lower resistivity than manganese dioxide and produces lower-ESR capacitors. The ESR also remains low at low temperatures, similar to the characteristics of an MLCC. Being an organic material, the polymer counter electrode has a level of time dependency that is not seen with inorganic manganese dioxide; the result is that capacitance can decrease, and ESR increase, over time when operated close to maximum operating temperature and voltage.

The acceleration factors for this effect are such that, when operated in benign environments typical of most consumer applications, there would be no measurable changes for many years. However, if they are required to operate continuously close to their maximum specification limits, then manufacturers' data should be consulted for possible parametric change over the application's design lifetime.

Niobium oxide electrolytic capacitors have niobium oxide, a conductive ceramic-like material, as anode, with a niobium pentoxide dielectric and a manganese dioxide counter electrode. Niobium oxide electrolytic capacitors are unique among both electrostatic and electrolytic capacitors in that they have no metallic content within the capacitor element itself.

Niobium is in the same periodic group as tantalum and niobium- and tantalum-pentoxide have similar dielectric properties, One key difference is that niobium is less dense than tantalum, so when the dielectric is formed, it grows thicker for any given voltage rating than its tantalum equivalent. Because this increases the distance between the anode and counter-electrode, it would normally limit the available capacitance, but this is offset by niobium pentoxide having a higher dielectric constant. This results in both niobium and tantalum electrolytic capacitors having equivalent capacitance and voltage ratings available for similar case sizes.

Where the lower density of niobium does have an effect is in limiting the maximum voltage ratings available for niobium capacitors. Because tantalum and niobium oxide anodes have similar particle size and porosity characteristics they share similar limits to maximum dielectric thickness. In tantalum capacitors, this thickness represents ~ 50-V equivalent of dielectric, in niobium, due to its lower density, the same amount of growth is achieved at only ~ 10 V, so niobium capacitors are limited to lower-voltage applications. This is not in itself a disadvantage as this is a perfect fit for the majority of digital decoupling applications that require capacitance to be maximized at ever-lower voltages.

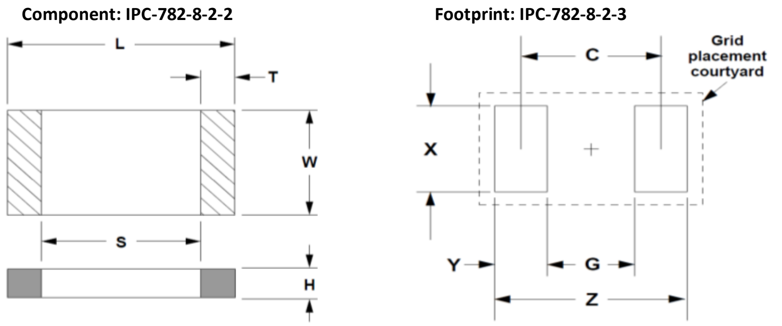
Niobium oxide electrolytic capacitors have distinct advantages over their tantalum equivalents in terms of reliability and failure mode. The fact that the niobium pentoxide dielectric is thicker for equivalent ratings means that the capacitor operates with less electric field stress resulting in higher intrinsic reliability than an equivalent tantalum capacitor. Because the anode is oxide based, in the event of a dielectric overvoltage failure, a resistive path is formed resulting in fail-safe operation compared to the hard short failure mode of MLCC, tantalum or tantalum polymer capacitors.

### *Package Types And Compatability*

The final thing to discuss is physical interchangeability on the PCB. The original reference for SMD footprints was IPC 782A. At the time that standard was issued, the smallest tantalum chip available was A case (3216 metric), which was designed to fit a 1206 MLCC footprint. These share a common footprint within IPC 782A. This standard is often supplanted by an OEMs' own internal PCB layout standards, but remains a good reference for case size comparisons.

Since the publication of IPC 782A, new, smaller tantalum chip case sizes have been developed, all designed to match the smaller MLCC sizes—0805, 0603 and 0402, and all designed to share a common footprint with MLCCs. Going up in dimension to the tantalum B case, although similar in size to an MLCC 1210, it was actually designed to fit the maximum cavity size that could be accommodated on 8-mm tape and reel and so has slightly larger dimensions (see Fig. 8).

**1210 MLCC vs Ta / NbO Series Case Sizes**




**Component Outline:**

| All dims mm | | L | | S | | W | | T | | H |
|---|---|---|---|---|---|---|---|---|---|---|
| Metric | EIA | min | max | min | max | min | max | min | max | max |
| 3225 | [1210] | 3 | 3.4 | 1.5 | 2.31 | 2.3 | 2.7 | 0.25 | 0.75 | 1.35 |

**Footprint:**

| Metric | EIA | Z (mm) | G (mm) | X (mm) | Y (mm) ref | C (mm) ref | RLP |
|---|---|---|---|---|---|---|---|
| 3225 | [1210] | 4.4 | 1.2 | 2.7 | 1.6 | 2.8 | 135A |

*Fig. 8. IPC-782-8-2-2 1210 footprint.*

In metric terminology, the 1210 MLCC corresponds to a 3225, while the tantalum B case is a 3528. The 3-mm difference in nominal component length has not been an issue in practical terms; the maximum termination length of the B case is 4 mm within the IPC envelope, while the metallized termination of the B case is actually narrower than a 1210 MLCC end termination.

The table below shows the maximum capacitance currently available in the various electrolytic technologies corresponding to each MLCC case size.

Table. Maximum capacitance available by MLCC case size for tantalum and niobium electrolytics.

| **Maximum Available Capacitance by Case Size (6.3v):** | | | | | |
|---|---|---|---|---|---|
| **uF** | 0402 | 0603 | 0805 | 1206 | 1210 |
| Tantalum | 22 | 100 | 100 | 220 | 220 |
| Polymer | 4.7 | 47 | 100 | 100 | 330 |
| NbO | | | 22 | 47 | 100 |

## *Capacitor Models*

In conclusion, it can be seen that in the majority of standard applications, small case size MLCCs and tantalum or niobium electrolytics can be used interchangeably on the PCB. For applications that may be more critical in terms of ESR, polarity or voltage and temperature characteristics, most technologies have full modelling available that enable parametric comparisons, or SPICE/s2p files to be downloaded and simulated (Fig. 9).


*Fig. 9. Example of tantalum polymer ESR simulation.*

This modeling capability will become of increasing importance as the design challenges associated with capacitor selection grow. As digital processing applications have been progressively demanding higher current supply at lower voltage in smaller PCB area, MLCC, tantalum and niobium electrolytics have evolved higher capacitance, lower voltage solutions and have maintained their positions as key enabling technologies. This trend is set to continue for the foreseeable future, and flexibility of design choice will remain an important factor for an increasing number of applications.

## About The Author

Chris Reynolds is a technical manager at AVX, based in Fountain Inn, SC, with over 30 years' experience across many passive component technologies in both R & D and applications. Recently, he has been involved in automotive designs from ECU to interior that employ the latest SMD, through-Hole and bolt-in capacitor technologies. Chris holds a BSc in physics from Birmingham University, UK.

*For more information on capacitor issues in power design, see How2Power's Design Guide, locate the Component category and Capacitors.*