Technology of Niobium Oxide Capacitor

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Abstract

Recent developments in tantalum technology have resulted in a new type of solid electrolyte capacitor based upon niobium oxide. Capacitors made from niobium oxide powder exhibit interesting features to the end users such as significantly reduced ignition failure mode, better load resistance, reduced cost, etc. This paper will give an overview of the current “state of the art” on this technology and also identifies key future development directions for the medium and long term.

Introduction

Capacitor development remains a dynamic field, with rapid technology growth during the last few years. While some mature technologies show decreasing average annual growth (AAG), others just emerging face significant challenges for future high volume usage. Leaded tantalums, foil aluminum and some film capacitor types have slowed down their growth below 5% AAG.

Tantalum chip capacitors, on the other hand, are probably at their peak of about 10% AAG while multilayer ceramic capacitors are still in expanding mode with AAG close to 25%. New technologies based on niobium metal (Nb) and niobium oxide (NbO) powders have recently entered the arena targeting the low voltage (around 10/16V max) high capacitance (>100uF) space currently occupied by aluminium, ceramic and tantalum capacitors (see Figure 2).

Niobium Oxide and Niobium Metal Powders

Niobium metal appears next to tantalum in the periodic table and it has similar chemical properties. Niobium ore is more abundant in its raw state and is less expensive. This has given the opportunity for tantalum capacitor manufacturers to evaluate niobium as a potential alternative to tantalum metal; however there were two key barriers to niobium usage that have only been overcome recently. First, the diffusion rate of oxygen from the dielectric (Nb2O5) to niobium metal is higher compared to tantalum, resulting in direct leakage current (DCL) instability. The second barrier was a lack of high purity niobium powders, able to meet the demanding electrical and mechanical specifications necessary for capacitor manufacture. There are two possible ways to reduce oxygen diffusion and improve DCL stability -
either by doping metallic niobium powders with nitrogen or using niobium oxide powder (see Figure 3).

Niobium oxide ( NbO ) is a hard ceramic material characterized by high conductivity, a property usually associated with metals. Niobium oxide powder has a similar morphology to that of tantalum and niobium metals can be processed in the same way. This paper compares features of capacitors made from tantalum, niobium metal (nitrogen doped) and niobium oxide powders. The basic material features are summarized in Figure 4.

Availability - Supply Chain

Niobium and niobium oxide are more abundant in nature than tantalum. These materials are common alloy elements widely used in the production of steel for shipbuilding, pipelines and construction. Usage of niobium for the production of capacitors is dwarfed by these major worldwide industries and thus ensures a long-term stable supply. However, conversion of metallic niobium to capacitor grade niobium ( Nb ) powder requires the same specialized processing as does capacitor grade tantalum powder, and shares the same supply chain. Additionally, production of capacitor grade niobium metal powder has not yet been scaled up to high volume. By contrast niobium oxide ( NbO ) technologies have a much wider material supply base and higher volume availability.

Basic Features of Niobium Oxide Capacitors

An overview of the basic electrical parameters of tantalum, niobium and niobium oxide capacitors is given in Figure 5.

Basic Electrical Features of NbO capacitors

Capacitance: 10 - 470µF
Voltage Range: 4 - 6V
Case Sizes: EIA:A to E case

Temperature Range: -55 to +105°C
(Standard Series)
-55 to +125°C
(Performance Series)
DCL: 0.02CV
Basic Reliability: 0.2% (perf.) and 0.5% (std) /1000hrs

Reliability

The NbO capacitors have very effective self-healing properties that guarantee superior reliability compared to other commercially used capacitor technologies. The reliability specification is as high as 0.2 percent/1,000 hrs., e.g., 500,000 hrs. MTBF, on the Performance Series. The Generic series reliability is 0.5 percent/1,000 hrs., e.g., 200,000 hrs. MTBF. This is superior to most currently available commercial grade capacitors.

Ignition Resistance

Niobium oxide has two orders of magnitude higher ignition energy and twice the specific heat of both tantalum and niobium metals (see Figs. 6 and 7).

This results in a significant reduction (95%) of the ignition failure mode of niobium oxide capacitors compared to conventional tantalum and niobium metal capacitors. Coupled with the lower electrical stress within the dielectric ( Nb_2O_5 dielectric grows thicker per applied volt than Ta_2O_5 and so operates at lower field strength for a given voltage rating), this also enables a higher ripple current load and reduced voltage derating requirements when used in low impedance circuits.

In addition, niobium oxide capacitors behave differently than both conventional counter-electrode (MnO_2) and polymer capacitors in respect to their higher resistance to ignition in typical application. The typical failure mode of niobium oxide capacitors during electrical dielectric breakdown can be divided into two types: The first type is ‘HIGH’ RESISTANCE (typically

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R~30kOhms, characterized by a MIS structure with an “S” shaped V-A (voltage-current) curve), that is different to tantalum and tantalum polymers. The second type is a breakdown after the application of high voltage (U~10v). The high resistance of niobium oxide after electrical breakdown (first type) will limit the current in the circuit below the thermal runaway point so the capacitor shows high resistance to burning.

Application Test

A simple test was developed to compare resistance to ignition for niobium oxide, tantalum and polymer capacitors in a typical circuit following forced failure of the capacitor to a short circuit condition:

1) Forced dielectric breakdown: When a high voltage $U_p$ of approximately (25-30)v (representing ~ 3-4x rated voltage) is applied through a high resistance value $R_h$, the capacitor’s dielectric will be perforated, creating a short circuit condition. The capacitor is effectively a resistor with a non-linear V-A characteristic. The circuit used to generate the short circuit condition is shown in Fig. 8.

2) V-A characteristic measurement: In order to measure the V-A characteristic it is important to have a current source $I_a$ with variable current level settings. The voltage $U_a$ across, and current $I_a$ through the capacitor are recorded. These data are useful for measuring V-A characteristic of the capacitor. By the maximum applied current we can find out the conditions for smoking, burning and destruction limits of this capacitor. The circuit diagram is shown in Fig. 9.

Fig. 8. Capacitor breakdown

Fig. 9. V-A characteristic measurement

are especially important for battery/mobile operated devices where higher leakage current consumes the battery power source and thus reduces life time of the device. DCL specification of niobium oxide capacitors is five times lower than tantalum polymer capacitors.

Typical DCL of 470$\mu$F 4V:
- tantalum polymer capacitor: 190$\mu$A
- niobium oxide capacitor: 38$\mu$A

Typical current through the capacitor in case of dielectric breakdown at operation voltage 3.3V:
- tantalum polymer: 1.7A
- niobium oxide: 97$\mu$A

Based on this comparison, a niobium oxide capacitor after breakdown of its dielectric layer shows lower DCL than a good tantalum polymer capacitor.

Case study

470$\mu$F 4V E case niobium oxide capacitor was used in a TV game device interface (see Fig. 11). A test has been carried to verify operation of this device after breakdown of dielectric.

An oscilloscope device recorded filtering ability with a good NbO capacitor 470$\mu$F 4V in the circuit (see Fig. 12).

The good capacitor was removed from the PCB and subjected to 3x rated volts to initiate breakdown of dielectric as described in paragraph “application test” above. Resistance of the part after dielectric breakdown was 13kOhm (lower resistance distribution value). This part was returned to the TV game device circuit and measured at the same conditions as before breakdown. Ripple output with part after the breakdown (see Fig. 13).

The measurement on the niobium oxide capacitor before and after dielectric breakdown found comparable peak-to-peak ripple voltage output as the most important parameter describing filtering ability. Higher background noise is possible to see on Fig. 13 (part after breakdown) compared to Fig. 12 (before breakdown), however this has no effect to functionality of the TV game device. The TV game device was working without any user noticeable degradation.

Due to the excellent reliability (see Reliability) dielectric breakdown of niobium oxide capacitor will not practically occur in typical application conditions. However if it happens the end device may be still operational.
There are more features of niobium oxide capacitors that can be of significant advantage in some specific applications:

**Lead-free System Ready**

Lead-free assembly systems call for higher reflow temperatures with higher thermo-mechanical stress. Not all capacitor technologies are ready to withstand these rigid conditions. [5]

Aluminum and foil capacitors are most sensitive to thermo-mechanical loads, especially reflow temperature / time soldering profiles that can result in catastrophic electrical failures.

Ceramic capacitors have most resilience to electrical overstress and are thermo-mechanically compatible with Pb-free assembly, but large outline parts can be sensitive to board flexure so manufacturers’ handling guidelines should always be followed. The general ceramic failure mechanism is low insulation resistance or short circuit.

The new niobium oxide capacitors are of special interest, as they also show very good stability under thermo-mechanical stress and higher temperature peak reflow (Pb-free assembly) conditions, similar to ceramic capacitors but without any sensitivity to mechanical weakness.

**No Piezo Effect**

High CV formulations of barium titanate (the base ceramic material for most dielectric systems) exhibit a microphonic effect. For example, if one takes a Y5V capacitor and subjects it to a DC bias with a superimposed signal (e.g. 1kHz sine wave), the capacitor will start to “sing”. This mechanism is also reversible, which means a 1kHz external signal will cause generation of a 1kHz noise to the electrical signal. Niobium Oxide capacitors exhibit no such microphonic effect despite its ceramic material powder. [3]

**Low Weight**

Niobium oxide powder is half the density of tantalum powder. This has an effect on total weight of units. Typical E case niobium oxide capacitor is about 25% lighter than the same capacitor made from tantalum powder. The practical usage is in weight sensitive applications such as mobile devices. Lower weight on the same component footprint will also improve PCB drop test strength as another important parameter for some applications.

**Lower ESR at higher temperatures**

Temperature dependence behaviour of NbO capacitors is identical to tantalum capacitors. ESR drops with temperature due to improvement of MnO2 (second electrode) conductivity. Thus, filtering features at higher temperature are better than compared to the room temperature 25C specification.

**Development Roadmap**

Figure 14 gives an overview of the ongoing development programs for the niobium oxide capacitor to fulfill all of the market’s diverse requirements. These can be sub-divided into four main areas: extension of the maximum temperature rating from 105C to 125C (125C already available in performance series), increased product range, i.e., Range Extension and Voltage Extension to both 2.5V and 10V Rated, and lower DCL (equivalent to Tantalum Capacitors). AVX is also currently working on niobium oxide capacitors utilising our latest generation production technologies to manufacture Low Profile and Microchip capacitors. One of the key requirements of the Power Supply sector is Low ESR. AVX is working on several directions towards lower ESR, as shown below.

Within this Development Program there are key Milestone (see Figure 15). This shows the time scales for the launch of new products over the next 1-2 years. All of these developments stem from the underlying stability and reliability of the current Niobium Oxide Capacitor.

**Conclusion**

Niobium based technology - niobium and niobium oxide capacitors are now entering the high CV capacitor market place. They have a similar capacitance / voltage (CV) range to current tantalum chip and demonstrate ESR characteristics comparable to conventional tantalum ratings. Their parametric stability and less expensive material cost (especially in the case of niobium oxide capacitors), make these technologies promising...
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ing alternatives to low voltage tantalum and ceramic capacitors, and allow downsizing of aluminium foil capacitors. The reduced burning of NbO also makes this a technology of interest.

Both niobium and niobium oxide dielectrics (as well as tantalum) show no piezo effect that could degrade audio clarity if used in critical audio-video applications.

Tantalum and niobium metal capacitors require 50% minimum derating for low impedance unregulated circuits. Niobium oxide capacitors are able to absorb higher load stress and thus the necessary derating can be reduced to 20% minimum.

The new generation of niobium and niobium oxide capacitors share the same robust casing design and industry standard sizes as current tantalum chip capacitors and are suited to low ESR capacitors. However, niobium has the disadvantage of higher cost and relatively higher failure rate.

The key benefits of NbO are long term stable electrical parameters, wide availability of materials, reduced burning and lower cost and capability to withstand high peak temperature reflow (needed for lead-free soldering), which should form the basis for fast design-in cycles in this high growth application area.

References

Figure 14. Niobium Oxide Development Road Map

Figure 15. Niobium Oxide Development Milestones