

## **Challenge: Highest Capacitance Tantalum Powders**

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### **Introduction**

To meet the challenge of the electronic industry to further miniaturise electronic devices, especially for portable applications, capacitors have to provide higher and higher volumetric efficiencies.

There is also competition of capacitor types over the  $\mu\text{F}$  range. MLCC's and Al capacitors are competing with Ta capacitors in their traditional range of application (figure 1<sup>1</sup>). In the past, volumetric efficiencies of MLCCs and Al capacitors were not competitive when compared to the tantalum capacitors. However, this has changed in recent years. Especially MLCC's have improved by reducing dielectric thickness and increasing the number of layers. Currently they can reach capacitance levels comparable to those of tantalum capacitors in similar case sizes<sup>2</sup>. This paper describes some of the capabilities that powder manufacturers have to support the tantalum capacitor makers

need to increase the volumetric efficiency and bring tantalum capacitors back to the lead position.

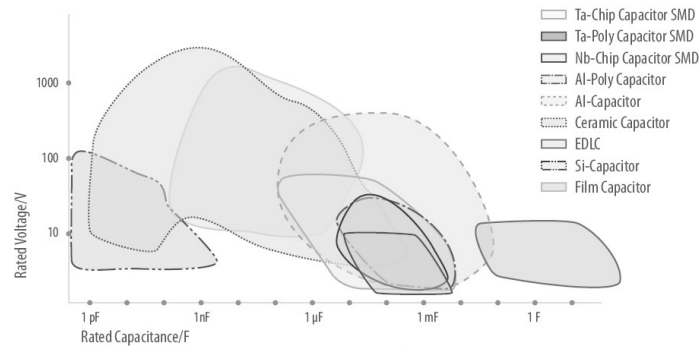


figure 1<sup>1</sup>

The traditional way to reach even higher capacitance in a given volume was to develop powders with higher and higher surface areas. Today tantalum powders with specific surface areas of up to 4.5m<sup>2</sup>/g are available in the market. By using these tantalum powders, energy densities of 1,000,000 μFV/cm<sup>3</sup> can be reached. However, the traditional production processes for making tantalum powders with such high surface areas have reached their limits, either from the viewpoint of quality or economics. During the last years, the Mg vapour reduction process of tantalum oxides<sup>3-10</sup> has been developed and continuously advanced by H.C. Starck to overcome these limits. Today this process can provide tantalum powders with surface areas of >10 m<sup>2</sup>/g that are designed for the next generation of tantalum capacitors.

However, increasing surface area is only one part of the story. All other powder properties have to be adjusted to meet the demands of anode miniaturization. In particular, particle stability, shape and size distribution as well as porosity and impurity levels have to be optimized. Some of these topics will be discussed in this paper and possible solutions will be introduced.

Recently, the Mg vapour reduction process has been investigated in greater detail to get a better understanding of reaction mechanism. We will report on these investigations, showing the possibility to create nano sized tantalum particles that can provide extremely high surface areas for the next generation of tantalum capacitors.

We will also discuss the challenges we observed during the electrical evaluation of these very high capacitance, very high surface area tantalum powders. Both the powder and capacitor makers will need to modify their processes to successfully transition these new powders into the next generation of extremely high surface area tantalum powders for commercial use.

### Highest Capacitance Tantalum Powders – Needs and Possibilities

Capacitance per volume of a tantalum capacitor anode is directly correlated to the surface area of the anode. To increase the capacitance, the surface area of the tantalum powder is the major parameter that can be influenced by powder manufacturers. In addition to surface area, there are other important powder parameters such as powder morphology, particle stability, sinter activity etc. that are also being given more attention.

#### Increased Surface Area

With the existing powder production processes in use, surface areas up to 4.5 m<sup>2</sup>/g can be reached. The conventional process of reducing K<sub>2</sub>TaF<sub>7</sub> with sodium reaches its limitations. The reduction has to be done with higher and higher amount of diluents salts and sinter retardants to create and keep the high surface area. Utilizing this process it is difficult to economically produce high quality tantalum powders with surface areas > 4.5 m<sup>2</sup>/g. It is fair to say, that the sodium reduction process has reached its limits and new technologies are necessary to produce ultra high surface area powders.

H.C. Starck has already developed such a technology in the magnesium vapour reduction process. By continuous improvement, this process can now produce tantalum powders with surface areas of > 10 m<sup>2</sup>/g. Recent lab trials (see below) show that this process has the potential to allow production of tantalum powders with surface areas exceeding even 20 m<sup>2</sup>/g. To what extent these powders are feasible for commercial capacitor manufacturing, only the future will show. Looking back to theoretical calculations made in 2004<sup>11</sup> (figure 2), those high surface area values are not necessary for the short and mid-term demands of tantalum capacitor makers. Powders with surface areas of 5 – 6 m<sup>2</sup>/g, which are necessary to achieve 250,000 - 300,000 μFV/g, are already accessible with the current magnesium reduction process.

	<b>STA 150 KA</b>	<b>STA 200 KA</b>	<b>STA 250 KA</b>	<b>STA 300 KA</b>
<b>BET</b> sintered Anode	~ 2,0 m <sup>2</sup> /g	~ 2,7 m <sup>2</sup> /g	~ 3,4 m <sup>2</sup> /g	~ 4,0 m <sup>2</sup> /g
<b>BET</b> powder	~ 3,0 m <sup>2</sup> /g	~ 4,0 m <sup>2</sup> /g	~ 4,9 m <sup>2</sup> /g	~ 5,9 m <sup>2</sup> /g
<b>O content</b> powder	~ 9000 ppm	~ 12000 ppm	~ 14700 ppm	~ 17700 ppm
<b>average sinter</b> <b>neck size</b>	~ 106 nm	~ 85 nm	~ 70 nm	~ 60 nm
<b>average</b> <b>pore size</b>	~ 208 nm	~ 160 nm	~ 130 nm	~ 110 nm

**figure 2** prediction of future high capacitance tantalum powders

#### Sinter Activity

To maintain the surface area as high as possible during sintering of the tantalum anodes, the sinter temperatures need to be reduced more and more. But there is a natural limit for decreasing the sinter temperature. The temperature has to be high enough to allow sintering in-between the powder particles and the powder to the anode contact (i.e. wire). The sinter activity of tantalum powders is influenced by addition of sinter retardants like boron, nitrogen and phosphorous. To keep high surface areas of powders during their production process, these retardants have to be added. However, excessive use of these dopants also results in decreased sinter activity during anode sintering. At some point anode strength and wire bonding will be too low to be useable for capacitor anodes.

During the sodium reduction process, nitrogen is introduced to keep temperatures high enough to produce stable agglomerates and to keep high surface area, but on the other hand sinter activity is decreased in comparison to powders with lower nitrogen content. Phosphorous is also added during the production process and is even more effective than nitrogen. Phosphorous is usually added up to 250 ppm, whereas nitrogen content of actual tantalum powders can exceed 2000 ppm. If the nitrogen content is above 3000 ppm, crystal nitrides will be formed that can reduce the capacitance and reliability of the dielectric film.

There are two different ways to dope the nitrogen into the tantalum powder. First, doping into the bulk of the tantalum grains reduces the sinter activity of the powder. Second, doping the surface of the grains only reduces the total oxygen content of the tantalum powder and is normally the last step in powder production. During anode sintering the surface nitrogen will diffuse into the bulk of the tantalum grains. But, if there is already a high content of nitrogen in the bulk of the tantalum grains, this diffusion can be hindered and crystalline nitrides can be created on the surface.

Commercially available magnesium reduced powders also contain nitrogen and phosphorous as sinter retardants, but on a lower level compared to traditional sodium reduced materials (figure 3). Recently, powders with even lower phosphorous content have been developed which allow anode sintering at even lower temperatures.

Another parameter that influences the sinter activity of powder is the highest temperature that the powder has seen during its production process. If this highest temperature is close to the sinter temperature of the anodes, shrinkage during anode sintering will be not sufficient. The traditional sodium reduction process requires high temperatures to get sufficient agglomeration between primary powder grains and to remove volatile impurities like i.e. fluorine and nickel. The magnesium vapour reduction process does not need those high temperatures, because morphology and stability of powder agglomerates are already defined by the precursor material and is retained during the following process steps<sup>12</sup>. Additionally, due to the higher purity of the precursor materials, primary powders do not need any heat treatment to remove impurities. To maintain high surface area during powder production, new downstream processes have been developed to avoid excessive shrinkage of the powder.

**Chemistry**

	Mg ppm	O ppm	H ppm	N ppm	C ppm	Fe ppm	Cr ppm	Ni ppm	Na ppm	K ppm
STA 150 KA	18	7469	352	1500	12	<3	<2	<2	<0.5	<0.5
STA 200 KA	31	11400	434	2018	15	3	<2	<2	<0.5	<0.5

	Nb ppm	Ti ppm	Mo ppm	Si ppm	Ca ppm	Cu ppm	Mn ppm	P ppm	W ppm	Q (Q/BET)
STA 150 KA	4	<2	<2	<3	<3	<1	<1	105	<5	2612
STA 200 KA	<1	<2	<2	<3	<3	<1	<1	158	<5	2689

**Physics**

	BET m <sup>2</sup> /g	BD g/cm <sup>3</sup>	BD g/inch <sup>3</sup>	Master Sizer without US [µm]			Master Sizer with US [µm]			d50/d50
				10%	50%	90%	10%	50%	90%	
STA 150 KA	2.86	1.88	30.8	18.6	34.3	63.5	12.7	29.7	44.2	1.15
STA 200 KA	4.24	2.09	34.2	17.8	35.0	71.2	3.6	28.1	41.8	1.24

	FSSS µm	Hall FL ±25g	+300 µm	+212 µm	+150 µm	+106 µm	+63 µm	+38 µm	-38 µm
STA 150 KA	2.13	24.0	0.0	0.0	0.0	1.3	3.1	11.8	83.8
STA 200 KA	2.00	23.5	0.0	0.0	0.0	3.6	4.4	14.4	77.6

**figure 3** typical chemical and physical properties of actual high cap magnesium reduced tantalum powders

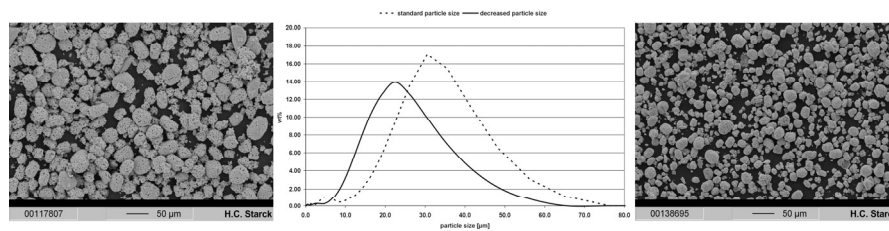
### Particle Shape and Size distribution

Another advantage of the magnesium vapour reduction process, compared to the conventional tantalum production processes, is the possibility to control the morphology of the powder agglomerates. This can be done by variation of the starting oxide precursor, whose morphology is then retained during the production process<sup>12</sup>.

H.C. Starck has chosen to produce tantalum powders with small spherical agglomerates. This special morphology of the magnesium reduced tantalum powders shows a very tight particle size distribution with very small average particle size. More than 75 % of the particles typically are below 38  $\mu\text{m}$  in size, but still exhibit excellent flow characteristics (figure 3). Pressing of these powders results in anodes with a very homogenous press density distribution and high homogeneity. In addition, the variation in weight of these anodes even for very small capacitors is distinctly lower as compared to those prepared from typical tantalum powders with a broader particle size distribution and irregular shaped particles.

As the case sizes get smaller and thinner, even with the standard particle size distribution of the spherical tantalum powders only a few particles are lying in one dimension of the die between each other. To increase the filling density the particle diameter must be reduced further. First trials have been made with particle diameters  $d_{50} < 20 \mu\text{m}$  with still acceptable powder flow (figure 4).

The fact that the macroscopic morphology is only defined by the precursor material and is retained during powder manufacturing, leads to the conclusion that the change for the anode manufacturer switching from one powder to the next one will be less difficult. As soon as the manufacturer has learned to handle one powder grade from spherical magnesium reduced powders, it will be easier to switch to the next grade.



**figure 4** Mg reduced tantalum powder with standard (left) and reduced particle size (right)

### Particle Stability

As anodes get smaller and thinner, the strength of the anode in the green and sintered stages becomes more important. To achieve this, anode manufacturers are pressing the anode to comparably high press densities. Currently press densities of 6  $\text{g}/\text{cm}^3$  and above are normal for tiny and flat anodes. During hard pressing of the powder, soft particles are crushed to fines and the sinter necks of the formerly well-formed powder agglomerates are destroyed. The connection between these powder fragments have to be reconnected in the later sintering step of anode. Due to the lower sinter temperatures and decreased sinter activity caused by use of sinter retardants, this re-connection becomes difficult. In

addition, high amounts of hydrogen and nitrogen lead to a more ceramic behaviour of the particles resulting in more of a crushing than deforming of particles.

Due to the very small particle size and shape of the spherical particles from Mg reduction, the filling density of the dies is already higher in comparison to standard powders and therefore it is not so much compressed and destroyed during pressing.

Powder particle stability can be measured by comparing particle size measurement data with laser scattering before and after ultrasonic treatment of the powders. The d50 value before the treatment divided by the same value after ultrasonic treatment is normally quite close to 1 (d50/50, figure 3), which equates to the minimum destruction of particles. Traditional powders normally show values well above 2 and even higher for high surface area materials. The stability of the magnesium reduced powders is defined first by the special morphology, but also by the lower levels of nitrogen, which can keep the particles more ductile. They can be better deformed, before they break. The internal sinter necks can be kept intact and do not have to be reconnected during sintering.

### Porosity

The spherical powders produced by H.C. Starck result in anodes, that show a bimodal pore size distribution, that can also be seen on SEM pictures of both the powders and the anodes. The bigger pores are contributed from the precursor material, the smaller ones are produced during the reduction and give the largest contribution to surface area.

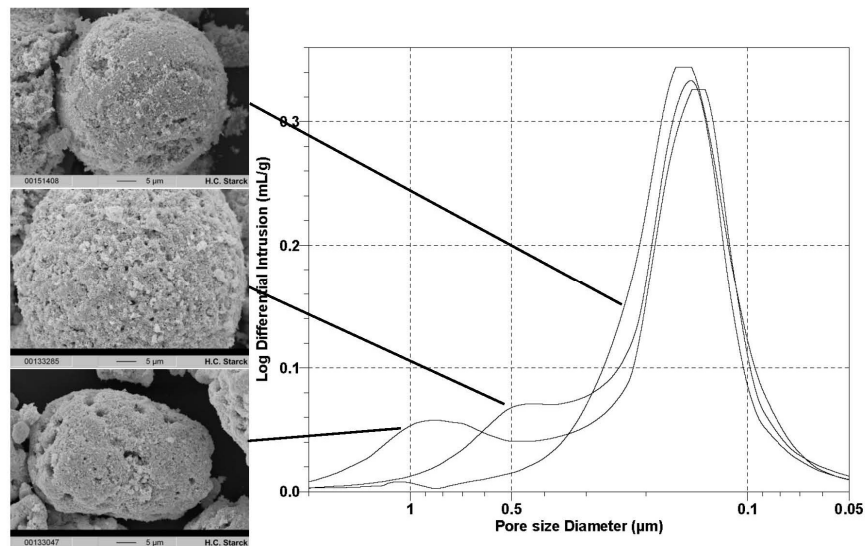


figure 5 Mg reduced tantalum powder particles with different porosity

The big pores can act as highways to the inner part of each powder particle during anode impregnation. But, on the other hand these big pores are wasted volume. If they would be filled with tantalum metal with same small pores, the surface area per volume could be increased by even a few percent. Recently spherical powders have been made with only one maximum in the porosity data (figure 5).

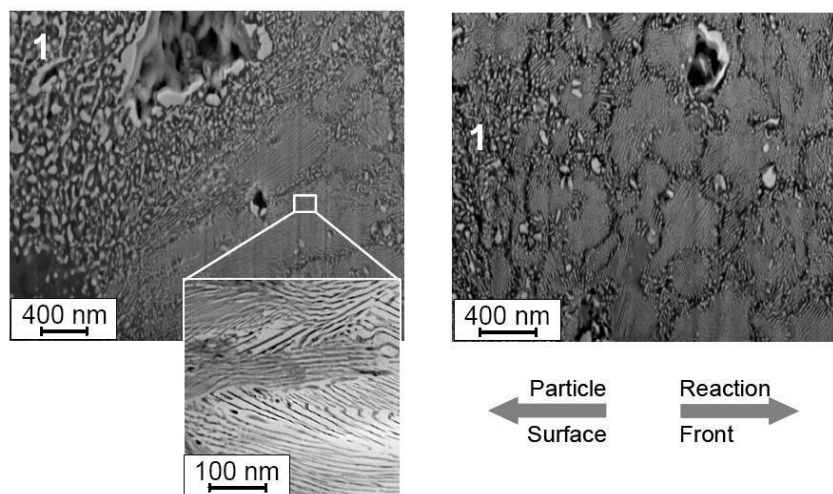
### Impurity Level

In case of magnesium reduction of tantalum oxide, the purity level of the finished tantalum powders is strongly influenced by the purity level of the raw material oxide. These oxides can be made at H. C. Starck with the highest purity, with impurity levels below 1 ppm for alkali metals and fluorine (figure 3). In addition, no corrosive molten halide salts have to be used in the new process, unlike in the conventional sodium reduction process, and therefore the halide content and metallic impurities like Fe, Cr and Ni of the produced tantalum powders are usually below detection limit. It is well known that all of these elements are deleterious to the anodic oxide film and that low levels of these elements are necessary for manufacturing of good electrolytic capacitors.

### **Fundamental Research on the Mg Reduction Process**

As shown, it is possible to produce tantalum powders with the Mg vapour reduction process that have surface areas  $> 10 \text{ m}^2/\text{g}$ . To understand, if even higher surface areas are possible, we started collaboration with the Technical University in Dresden<sup>13</sup>. The samples that have been investigated were made with an interrupted reduction process. We wanted to determine, if there are any intermediate phases during the reduction. The powder has been embedded into a resin with following polishing of this sample. A FIB (Focused Ion Beam) lamella has been prepared from a non- completely reduced powder particle that has been investigated further on with FESEM and HRSTEM/HAADF.

During the Mg vapour reduction of tantalum oxides, micro pores and cracks are created due to shrinkage. In these pores and cracks immediately at the reaction front solid magnesium oxide crystallizes and prevents further shrinkage. On the contrary, the higher effective molecular volume of the Ta/MgO composite generates internal stresses: pressure in the reaction products Ta and MgO behind end tension in the Ta<sub>2</sub>O<sub>5</sub> before the reaction front. This local internal stresses at the reaction front accelerates the reduction process<sup>13,14</sup>. The history of the creation and the mechanisms of this structure building can be investigated with FESEM and HRSTEM/HAADF of FIB samples, from non-completely reduced particles. Directly behind the reaction front inside the powder particle, lamellar and tubular structures are formed in nano sized scale. Inside a region of 0.5 to 1  $\mu\text{m}$ , correlating to the former tantalum oxide primary crystallites, very regularly ordered layers (10 – 20) can be found, which consist of alternate Ta and MgO with layer thicknesses of 10 to 13 nm and 30 to 40 nm respectively. The orientation of the stacked layers correlates with the former lattice orientation of the reduced tantalum oxide primary crystallite.



**figure 6** FESEM- (big pictures, bright color corresponds to Ta) and HRSTEM (small picture, dark color corresponds to Ta) micrograph of partly reduced tantalum oxides

Area 1 in figure 6 is situated in direction to the particle surface and relatively far from the reaction front. Therefore the layer shaped structure has already transformed into coarser, globular shaped structures. By increasing reaction time, transformation of lamellar structure continues and results in strong coarsening by a factor of 5 – 10 and changes in its morphology. This leads to final micro structuring of the particles, as known for finished tantalum powders.

During the reaction, the Mg atoms can first penetrate the oxide through the open porosity and through the oxide grain boundaries from the particle surface and also reach the inner part of the particle. The reaction speed is defined by the following diffusion into the 0.5 to 1  $\mu\text{m}$  sized tantalum oxide primary particles. This diffusion takes place at first via favoured lattice planes and after a certain depth via the Ta- MgO grain boundaries, which are laying parallel to lattice planes und perpendicular to the reaction front. Because of the high numbers of boundary surfaces, these layered structures are unfavourable energetically. Only the strong exothermic nature of the reduction reaction installs these boundary surfaces as straight highways for the Mg diffusion, to bring this system as fast as possible to a thermodynamic condition of equilibrium.

If this equilibrium is reached, the lamellar transport structure starts to move by reducing the energy of the boundary planes. This leads to coarsening and change in morphology to a favourable energy level where a further and final minimization of surface energy is hindered by the MgO that is located between the metal areas. But finally, after some hours of high temperature treatment the typical interpenetrated and connected Ta-MgO composites are formed, resulting in highly porous sponge like Ta powders after leaching out the magnesium oxide<sup>13-15</sup>.

The actual furnace technology that is used for the Mg vapour reduction currently produces powders with surface areas of up to 15  $\text{m}^2/\text{g}$ . Even higher surface areas up to

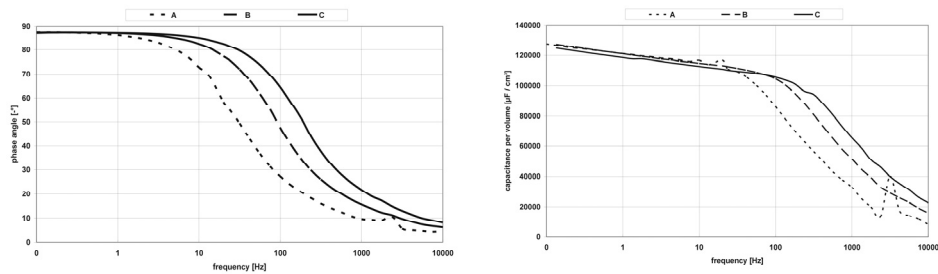
100 m<sup>2</sup>/g should be possible by changing the temperature time profile during the reduction, that allows achieving a complete reduction, but avoiding too much coarsening.

### New testing parameters for wet electrical testing

For the wet electrical testing of tantalum anodes, the last testing step at powder manufacturers and the first at powder customers, the process parameters have been fixed in the early 1960<sup>th</sup> and have not been changed dramatically since then. Already S. E. Hluchan<sup>16</sup> stated, that for powders designed for highest capacitance (at this time < 10,000 μFV/g) these conventional testing procedures are not suitable. He stated that “the different time constants for accessing the centre of the anode and the surface may effectively preclude utilizing the centre. The measured capacitance will be less than that predicted from the absolute surface area in the sintered anode. The effect increases with the complexity of the structure, frequency....”.

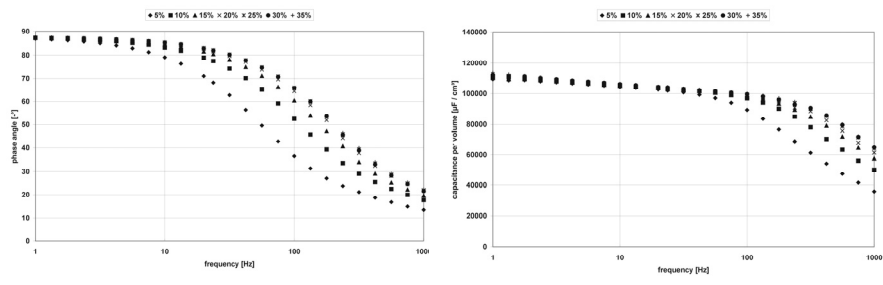
Due to the very tiny pores of anodes made of high capacitance powders and because of relatively low conductivity of the measurement electrolyte (18 wt% sulphuric acid ~ 0.7 mS cm<sup>-1</sup>), the resistance in the pores is so high, that not all of the available surface area can be addressed during capacitance measurement at high frequencies. The capacitance level measured with conventional parameters results in low capacitance level values not expected for very high surface areas detected in the sintered and anodized pellet. This fact has delayed the development and introduction of even higher capacitance powders.

To investigate the influence of anode size, conductivity of electrolyte and measurement frequency, we prepared three different anode sizes from a 200 K material (STA 200 KA). They have been sintered at the same temperature and formed at 10 V. All anodes have been tested with a potentiostat to measure an impedance spectrogram. Out of this spectrogram capacitances and corresponding phase angles can be extracted. Only if the phase angle is above 85°, the corresponding calculated capacitance is deemed reliable.



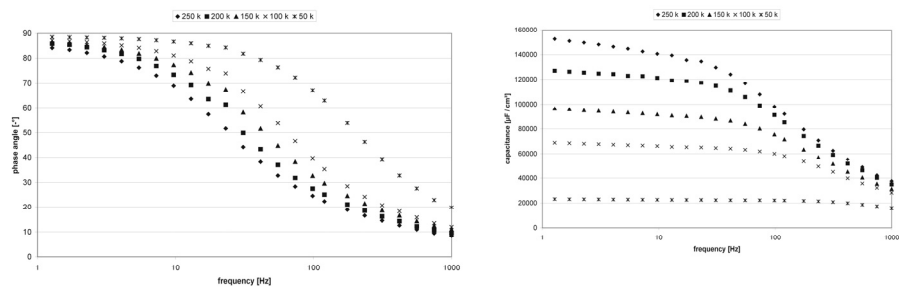
**figure 7** phase angle and capacitance of 200 k anodes measured in 18 wt% sulphuric acid with different sizes in correlation to measurement frequency  
 A: cylindrical (diameter 3 mm)    B: cylindrical (diameter 2 mm)    C: cuboid (1.1 x 2.2 x 1.15 mm)

The smallest anode reaches phase angles above  $85^\circ$  earlier than the bigger anodes (figure 7). This observation corresponds very well with the statements of S. E. Hluchan. The smaller the anode is, the easier is the access to the center. The conductivity of sulphuric acid reaches its maximum between 25 – 30 wt%. An increase of concentration of the electrolyte from 10 to 35 % results in increased phase angles (figure 8), corresponding to the higher conductivity. This influence is a few magnitudes lower than that of decreasing the measurement frequency. Therefore changing the measurement frequency is more effective.



**figure 8** influence of concentration of measurement electrolyte (sulphuric acid) in correlation to measurement frequency

In figure 9 anodes of different powder types are compared. All of them have been made with same press density, size, sintered to densities of  $\sim 6 \text{ g/cm}^3$  and formed to 10 V. The lowest capacitance material reaches an angle of  $85^\circ$  at highest measurement frequency when compared to the other anodes. This corresponds to the lower resistance of the electrolyte in the bigger pores. In addition the relative decrease in capacitance with increasing measurement frequency is not so pronounced in comparison with higher cap materials.



**figure 9** phase angle and capacitance of different powder types in correlation to measurement frequency

Review of all the diagrams results in the determination that the measurement frequency has to be lowered to detect the real capacitance of the anodes made from very high surface area powders. A decrease down to 1 Hz is more efficient than the options of decreasing the anode size or increasing the conductivity of measurement electrolyte.

How far the capacitances in wet electrical test measured with low frequency correlates with impregnated and finished anodes, has to be proven by the powder manufacturers. With this new test, only the potential of powders can be shown, if anodes would be impregnated perfectly.

### Conclusion

The magnesium vapour reduction process already shows the capability to produce tantalum powders for the next and future tantalum capacitor generations. The powders combine

- Highest surface area
- High sinter activity
- High particle stability
- Well to adjust powder particle shape and size distribution
- Low impurity level

designed for the tantalum capacitors of the future with highest volumetric efficiency. The newest magnesium reduced tantalum powders show capacitances exceeding 1,000,000  $\mu\text{FV}/\text{cm}^3$  and first samples with more than 1,400,000  $\mu\text{FV}/\text{cm}^3$  (corresponding to  $> 250,000 \mu\text{C} / \text{g}$ ) and surface areas  $\sim 5.5 \text{ m}^2/\text{g}$  have been already developed on lab scale. Even higher surface area tantalum powders have been prepared in lab scale. They already show similar macroscopic behaviour to the powders in the market from magnesium reduction.

Investigations of the nanoscale structure development during Mg-vapour reduction of Ta-oxides show that it will be possible to still significantly enhance the specific surface area of the Ta-capacitor powders.

For electrical evaluation of anodes with very high surface area in wet stage, measurement frequency has to be lowered. New standard test parameters have to be decided between powder and anode manufacturers to have a better correlation between wet and solid capacitance.

### Bibliography

- <sup>1</sup> Leading in Electronic and Optics, Electronic and Optics Products, H.C. Starck, 2007.
- <sup>2</sup> R. Hahn, M. Randall, J. Paulsen, Proc. 28th Passive Components Conference – CARTS USA, 2002.
- <sup>3</sup> L. Shekhter et al., U.S. Patent No. 6,171,363.
- <sup>4</sup> L. Shekhter et al., International Published Application No. WO00/67936.
- <sup>5</sup> A. Michaelis, C. Schnitter, K.-H. Reichert, R. Wolf, U. Merker, Proc. 16th Passive Components Conference- CARTS-Europe, 2002, 209-212.
- <sup>6</sup> H. Haas, Proc. 18th Passive Components Conference- CARTS-Europe, 2002, 5-8.
- <sup>7</sup> H. Haas, C. Schnitter, Proc. EMC 2005, 903-910.
- <sup>8</sup> H. Haas, C. Schnitter, Journal of Passive Components Industry (PCI), Jan. 2007, 10-12.
- <sup>9</sup> H. Haas et al., International Published Application No. WO 05/105346
- <sup>10</sup> H. Haas et al., International Published Application No. WO 06/039999
- <sup>11</sup> H. Haas, Proc. 18th Passive Components Conference- CARTS-Europe, 2002, 5-8.

<sup>12</sup> J. Loeffelholz et al., DE 10307716 A1

<sup>13</sup> R. Müller, M. Bobeth, H. Brumm, G. Gille, W. Pompe, J. Thomas, Int. J. of Materials Research 98 (2007) 11, 1138- 1145.

<sup>14</sup> G. Gille, to be published in: Proceedings of Advanced Processing for Novel Functional Materials Conference (APNFM), Dresden, January 24<sup>th</sup> and 25<sup>th</sup>, 2008.

<sup>15</sup> G. Gille, Pulvermetallurgie in Wissenschaft und Praxis, Hagener Symposium 2007, 23, 83-117.

<sup>16</sup> Stephen E. Hluchan, IEEE Transactions on Parts, Hybrids and Packaging, Vol. PHP-9, No. 3, September 1973, pp. 148-155.