eurocomp
The newsletter of the Space Components Steering Board

# Introduction

Welcome to the eighth issue of Eurocomp, the newsletter of the Space Components Steering Board (SCSB).

The Components Technology Board (CTB) is one of the primary organisational bodies in the SCSB. Its major objective is to formulate strategic programmes and work plans for technology research and development. In previous issues we have highlighted the technology dossiers defined by the CTB. In this issue we spotlight the internal workings of the CTB.

In order to identify and anticipate the needs of the community, the CTB sponsors 'round table meetings' to improve research coordination. Two such round tables were held this year, co-sponsored by the European Space Agency (ESA) at the European Space Research and Technology Centre (ESTEC) in Noordwijk, The Netherlands. The round tables on wide band gap technologies and DC-DC converters helped to consolidate the needs of academia, industry, government and satellite operators. The outcome of these round tables is briefly detailed in two accompanying articles. In the next volume of Eurocomp, we hope to bring you results of another round table directed at micro/nano technologies for space applications.

Also in this issue, Paul Collins from ESA's Component Technology Section at ESTEC asks "*…with all the reported reliability concerns associated with this technology, particularly in low impedance circuits, why would designers want to use solid tantalum capacitors in ESA flight applications at all?*"

Indeed, solid tantalum capacitors have been viewed with some wariness for many years in the power supply community, particularly in their filtering applications. Our feature article presents a synopsis of a risk mitigation investigation involving surface mount solid tantalum capacitors. And yes, that is a remnant of an exploded solid tantalum capacitor captured on film, above.

A regular feature of Eurocomp is the European Space Information Exchange System, or ESCIES, which can be reached at http://escies.org/. Its goal is to serve as a central point for collaboration and data exchange within the Space Components community. In addition to providing standard and legacy information that greatly improves our concurrent engineering efforts, it provides a portal for the collaborative workings of the ESCC groups at https://spacecomponents.org/. The diverse groups can rely on ESCIES for informed interaction leading to formulation of policies and technology programmes, as well as the administration of all ESCC specifications. A brief overview is presented here, giving us a picture of a busy site dedicated to meeting its goal.

Finally, the 7th issue of the European Preferred Parts List (EPPL) is now available online at https://escies.org/public/eppl/. We reported in the very first issue of Eurocomp that the EPPL is a result of collaborative efforts involving and on behalf of all partners of the ESCC. It is a standardisation tool for designers to apply type reduction and thereby achieve cost effective and efficient component procurement. The commitment of the Technical Authority to maintaining this list for our users is appreciated. ●

## In this issue...

# Tantalum capacitors

## 1. Introduction

Since its first appearance in the mid 1950s, the solid tantalum capacitor has enjoyed increasing popularity with circuit designers, mainly due to the huge advantages the SMD styles offer in volumetric efficiency over other capacitor types available. This popularity has not always been shared in the space sector, leading to some restrictions in its application, notably in power supply filtering circuits, where high current-handling capability and low impedance are prerequisite. These concerns were largely due to the fact that the tantalum capacitor industry itself had set an application requirement for a minimum of 3 Ohms/Volt to be present in series with each capacitor in circuit. ESA PSS-01-301 'Derating requirements applicable to EEE components for ESA space systems' (last issue circa 1992) formalised the capacitor industry's concerns and banned the use of solid tantalum capacitors in power supply filters completely. This directive has not been rigidly adhered to in recent years, but appeared more than justified after the occurrence of several high profile failures in flight equipment. The ensuing investigation, performed with the support of AVX Tantalum Division, the ESA-qualified source for this technology, revealed some critical process improvements, which led to a relaxation of the PSS-01-301 directive. Thus the use of SMD solid tantalum capacitors in power supply filter applications is now allowed, provided that certain risk management activities are carried out. This article gives an insight into the manufacturing processes used, the reasoning behind the relaxation in application rules, and the risk mitigation activities.

## 2. Capacitance and the Dielectric Constant – Volumetric Efficiency

*"…with all the reported reliability concerns associated with this technology, particularly in low impedance circuits, why would designers want to use solid tantalum capacitors in ESA flight applications at all?"*

First some important volumetric considerations.

The effects of capacitance were first discovered circa 1746, during Muschenbroeck's Leyden Jar experiments. The fundamental principle investigated was that electrodes separated by a non-conductive dielectric material will store a charge when a potential difference is applied. Capacitance is defined as the charge stored per unit potential difference, i.e.

[1] $$C = \frac{Q}{V}$$

where: $C$ = capacitance in Farads
$Q$ = charge in Coulombs
$V$ = potential difference in Volts

Dielectric materials are graded relative to the dielectric properties of free space, which is said to have a relative dielectric constant of 1 and a permittivity of 8.85 x $10^{-12}$ F/m. The total capacity of a sample of dielectric material is a function of the dielectric constant, is proportional to the total surface area of the electrodes or plates, and is inversely proportional to the distance between the plates or the dielectric thickness. i.e.

[2] $$C = (\varepsilon_o \varepsilon_r A) / d$$

where: $\varepsilon_o$ = The dielectric constant for free space, 8.85 x $10^{-12}$ F/m
$\varepsilon_r$ = Relative dielectric constant (also referred to as K)
$A$ = Area of the electrode plates (dielectric area)
$d$ = Dielectric thickness

From [2] it is clear that in order to design a capacitor with a relatively high value, in excess of say 1µF, whilst at the same time keeping the physical dimensions within practical limits for electronic assemblies, i.e. minimising the dielectric area and thus increasing volumetric efficiency, it is necessary to choose a dielectric whose properties are such that it can exist in a thickness of less than 1 µm whilst supporting a realistic working voltage of, say, 5 to 50 V. Within the solid tantalum capacitor, electrochemically formed tantalum pentoxide ($Ta_2O_5$) dielectric provides one such solution. $Ta_2O_5$ dielectric formed to a thickness of approximately 200nm will support a working voltage of at least 50 V. However, the dielectric constant of $Ta_2O_5$ is just 27, which, from equation [2] above, dictates that a relatively large electrode surface area is required in order to provide a capacity that is attractive for the designer to use.

The required electrode surface area is derived from the formation voltage (and hence the formation ratio of the dielectric material) as follows:

[3] $V_F = R_F \times V_W$

where: $V_F$ = formation voltage
$R_F$ = formation ratio
$V_W$ = working voltage

[4] $d = V_F \times$ dielectric growth rate

where: $d$ = dielectric thickness

Hence substituting in equation [2] gives:

[5] Dielectric surface area $A = C\, d \,/\, (\varepsilon_o\, \varepsilon_r)$

Example

For a 22 µF, 35 V capacitor, this becomes

$V_F = 3 \times 35\ \text{V} = 105\ \text{V}$

$d = 1.7 \times 10^{-9}\ \text{m/V} = 105 \times 1.7 \times 10^{-9}\ \text{m} = 178.5 \times 10^{-9}\ \text{m}$

$A = (22 \times 10^{-6} \times 178.5 \times 10^{-9}) / (8.85 \times 10^{-12} \times 27) = 0.0164\ \text{m}^2$

The dimensions of an ESA-qualified TAJ-type 22 µF, 35 V capacitor from AVX are 4.3 x 4.5 x 7.5 mm. This equates to an overall volume of 0.145 $cm^3$. However, the capacitive element (slug) only occupies about one third of the overall case volume, 0.048 $cm^3$. So, incredibly, the required 164 $cm^2$ of dielectric surface area is formed in a pellet with a volume of approximately 0.048 $cm^3$. This clearly illustrates the advantages of using this technology in applications where mass and volume budgets are a major consideration.

## 3. Construction and the Manufacturing Process

*"...but exactly how is this dielectric surface area requirement achieved within such a small volume?"*

The manufacture of a solid tantalum capacitor is a surprisingly complex process and contains many stages. These stages can loosely be grouped as:

1. Tantalum powder formation
2. Anode construction
3. Dielectric formation
4. Cathode formation
5. Interconnection
6. Packaging and test

These are described in more detail in the following sections.

### 3.1 Tantalum Powder Formation

Solid tantalum capacitors are manufactured from high-purity tantalum powders obtained from mined raw tantalum using a hydrofluoric acid extraction process. Particle sizes are normally processed and shaped to range from 2 to 10 µm, the exact size used being dependent upon the working voltage and capacitance requirements of the finished product (CV value). Typical powders are shown in Figure 1 below, with their capacitance voltage per product gram (CV/g) values.

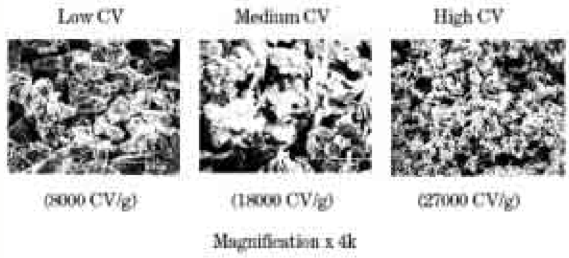
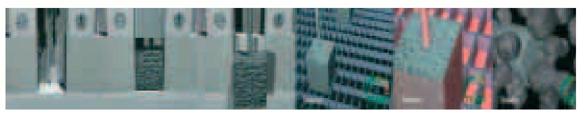



*Figure 1 – Typical Tantalum Powders (Courtesy of AVX)*

### 3.2 Anode Construction



Anode manufacture involves tantalum powder being mixed with a binder and pressed at high pressure around a tantalum wire, known as a riser, forming an anode pellet. The binder also acts as a lubricant to ensure an even flow into the press tool. After removal from the press, the green anode assembly is sintered under vacuum at a temperature of between 1500° and 2000°C. This process also burns off the binder, along with many other impurities, and fuses the pressed tantalum anode pellet into a sponge-like structure. The pellet at this stage has very good mechanical properties. Normally a sample of sintered anode pellets is taken at this time and anodised (see the following section), and a wet capacitance check is then made, allowing verification of the expected capacitance value.

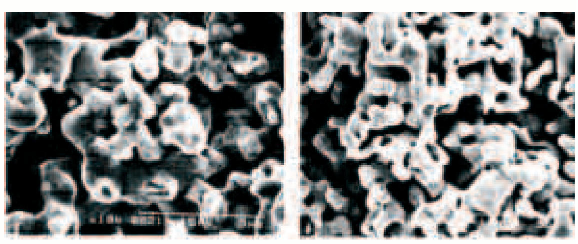


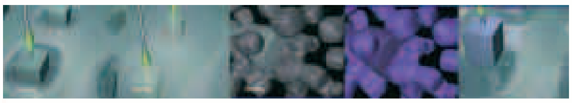
*Figure 2 – SEM Image of Tantalum Anode Pellet, Pre-Sinter left, Post-Sinter right (Courtesy of AVX)*

In addition to the verification of the wet capacitance value, an SEM image is used to verify sintering. In addition a density check is also performed. Figure 2 shows the difference in SEM images between sintered and unsintered green pellets.

It is the density in combination with the high porosity that results in the very large surface area required to form the dielectric. It should be noted that the surface area for dielectric formation is the whole of the pellet, from the outer shell right through to the central anode riser wire.

A Teflon washer is added to the anode riser wire to prevent possible short circuits after formation of the manganese dioxide cathode contact.

### 3.3 Dielectric Formation



The dielectric, tantalum pentoxide ($Ta_2O_5$), is formed on the exposed tantalum surfaces within the pellet, using electrochemical anodisation. The pellet is dipped in a weak acidic solution, normally phosphoric acid, and a forming voltage applied to the anode riser wire.

The oxide forms with about two thirds growing on the surface and one third growing into the tantalum by approximately 1.7 nm/V. The choice of formation voltage is dependent upon the working voltage requirement of the finished capacitor. A higher working voltage obviously requires the formation of a thicker dielectric, which in turn requires a higher voltage for formation. However, it should be noted that thicker dielectrics mean lower capacitance, larger anodes, and hence lower volumetric efficiency. The formation voltage is usually set at between 3 and 4 times that of the required working voltage, and it is applied from a power supply initially in constant current mode. As dielectric starts to form, the voltage rises and current decays as the forming dielectric offers more resistance. This process continues until the pre-set formation voltage value is reached and the current becomes limited to that of dielectric leakage only. At this point the power supply is switched from current to voltage mode until formation is complete. Figure 3 shows a section of the formed dielectric, using SEM imagery.

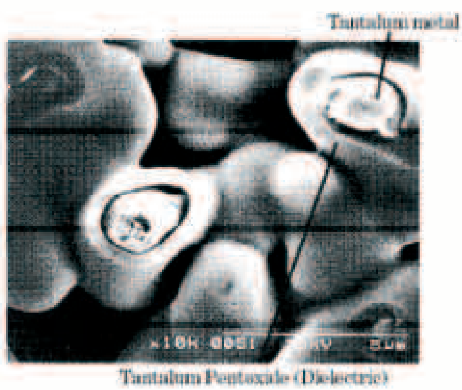



*Figure 3 – SEM Image of Tantalum Pentoxide Dielectric Layer (Courtesy of AVX)*

During formation, unwanted semiconducting tantalum oxide forms between the tantalum metal and the tantalum pentoxide dielectric. It is this phenomenon that polarises tantalum capacitors. The tantalum oxide is kept to a minimum by interrupting the formation process and removing the anode from the formation bath when 90% of the formation voltage is reached, followed by a bake-out at approximately 400°C.

The importance of selecting the correct powder size, sinter temperature and formation voltage for the required CV characteristic of the finished product now becomes very clear. The dielectric contains a low PPM count of evenly-distributed impurity sites, which are responsible for the leakage current characteristic. It is possible to partially isolate these sites by increasing the forming voltage. However, this is limited by the required thickness and hence the capacitance of the dielectric.

### 3.4 Cathode Formation

The cathode is formed using Manganese Dioxide ($MnO_2$) in a process called manganising, and this is achieved by the pyrolysis of manganese nitrate. The slug is submerged in a nitrate slurry and then baked at approximately 250°C to produce a dioxide coat. This

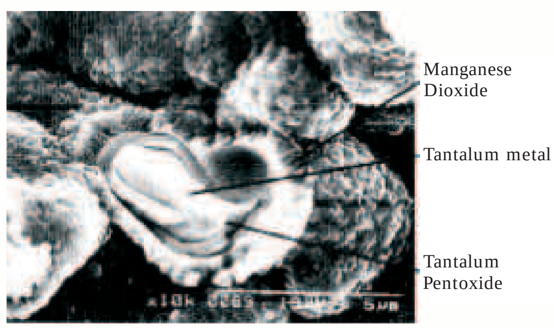
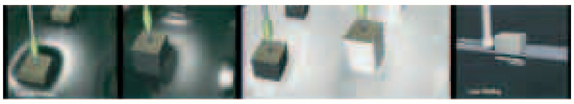



*Figure 4 – SEM Image of Manganese Dioxide Cathode Contact Layer (Courtesy of AVX)*

process has been continually improved and now consists of several stages with differing concentrations of nitrate slurry, allowing maximum penetration into the anode structure. This in turn gives greater dielectric contact and results in a reduction in the all-important series resistance characteristic.

All tantalum capacitors have many fault sites in the dielectric layer, resulting in high leakage current paths. In order to remove these sites during production, the assembly is dipped into an acetic acid bath with a voltage applied of approximately half the forming voltage. This process removes manganese from the fault sites and forms a dielectric which literally plugs the gap. This process is known as 'reform'.

### 3.5 Interconnection



The next stage is to make the cathode and anode connections to the lead frame. The slug is dipped into a graphite solution, transferred to an oven and baked to assure adhesion. This process is then repeated with a silver solution which forms the final layer for connection of the cathode. The graphite layer is required in order to separate the manganese dioxide from the silver. Any contact between these two materials would result in a chemical reaction leading to the silver becoming oxidised and forming high-resistance silver oxide. Additionally, the manganese dioxide would be reduced to a higher-resistance manganese oxide.

The cathode connection is made to the lead frame with silver epoxy whilst the tantalum anode riser wire is laser-welded into position.

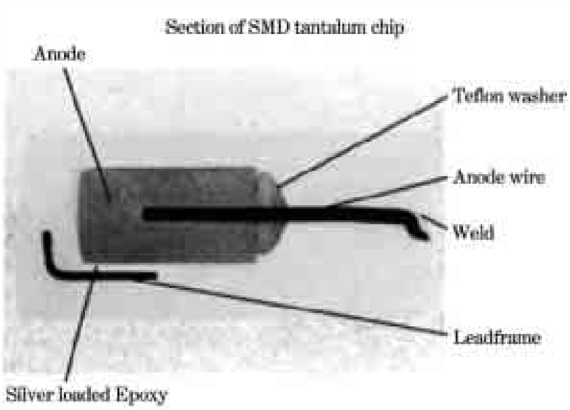
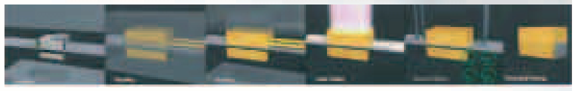



*Figure 5 – Section Through a Completed SMD Tantalum Capacitor (Courtesy of AVX)*

### 3.6 Packaging and Test



The slug and lead frame assembly is moulded into an epoxy resin case which is laser marked with the manufacturer's identification, value, polarity and date code. In-line electrical testing is performed, normally consisting of capacitance, ESR, tan delta and leakage current tests. Additional tests and screening can be performed as per customer requirements. Finally the capacitor assembly is packaged ready for delivery.

## 4. Failure Modes and Self Healing

*"…OK, but what of the known failure modes and reliability issues?"*

The images shown in this section header illustrate exactly what can happen when a tantalum capacitor fails. The explosive nature of the failure, which usually results in a short circuit condition, has understandably been the cause of much concern in the space industry. There have been many articles and papers written by the tantalum capacitor industry, giving in-depth explanations of failure mechanisms and preventative application restrictions. The fact that so many documents exist, written over many years, must be an indication of the magnitude of the problem, and acts as a historical record of the problems encountered by users of these devices in certain applications.

The fundamental problem, which has been well documented over the years, is that of irregularities or weaknesses in the delicate constituent layers, resulting in high-leakage current paths introduced during either the manufacturing process, the mounting or application. Irregularities can be formed by impurity sites that are not totally eradicated during reform,

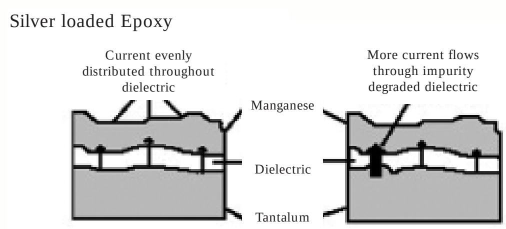



*Figure 6 – High Leakage Current Through Fault Site*

dielectric cracks, delaminations, thinning of either the dielectric or manganese dioxide layers, voltage breakdown, or popcorning of the manganese dioxide (caused by moisture ingression during storage, boiling off during solder reflow). This list is by no means exhaustive.

High leakage current paths result in localised heating, which will cause the following chemical reaction to occur in the Manganese Dioxide layer if the temperature rise exceeds approximately 450°C:

$$2MnO_2 + \text{Energy} \rightarrow Mn_2O_3 + {}^1/_2\, O_2$$

$MnO_2$ has relatively poor conduction characteristics (2 to 6 Ohms/cm), but this is generally overlooked due to a more valuable property that allows conversion from the semi-conductive state ($MnO_2$) to the highly resistive state ($Mn_2O_3$) *with the appropriate energy available*. The $Mn_2O_3$ formed literally plugs the high leakage path, a process which is referred to as 'self healing'. Without this ability to 'self heal', the solid tantalum capacitor would not be a viable proposition, due to severely degraded reliability and yield.

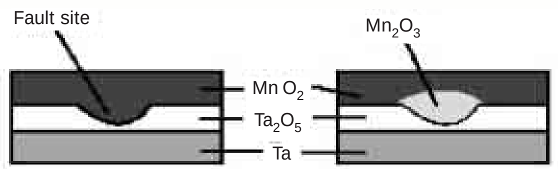



*Figure 7 – Self Healing*

From the above it would be easy to assume that the self healing reaction is a 'cure all' and that there should be no further need for discussion. However, note the use of the term 'with the appropriate energy available'. There are two further scenarios wherein the capacitor's ability to self heal will not necessarily prevent failure:

- Insufficient Energy

  If a solid tantalum capacitor is used in a circuit with a high series resistance, it may be the case that insufficient energy (current) is available for a self healing reaction to take place. Hence any fault site will remain 'leaky', and the capacitor could exhibit a high leakage current failure mode. This is particularly problematic and noticeable in timing circuit failures.

- Excessive Energy

  The self-healing process described generates oxygen and $Mn_2O_3$. As with all reactions, a finite amount of time is required for this to occur. Should excessive energy be available, the production of oxygen will occur faster than it can recombine, causing combustion and a thermal runaway condition with explosive results. This is the type of failure associated with low impedance power supply filter applications. This type of failure is unpredictable and could occur either after many hours of operation or after the application of a high transient current surge at switch-on or -off.

In all of these scenarios, energy levels are not predictable, hence the need for the tantalum industry's historical 3 /V series resistance recommendation, later reduced to 1 /V followed by 0.1 /V and below for some products, as process improvements were made.

## 5. Process improvements made since the PSS-01-301 directive circa 1992

*"…so what exactly has the tantalum capacitor industry done to improve the overall performance of their product since the 1992 issue of the ESA derating directive, and why are certain types now being considered as acceptable for use in power supply filter applications?"*

With the most dramatic developments driven by the telecomms boom of the 1990s, a general policy of continual improvement in raw material processing, chemical formation, packaging and parametric testing has led to a greatly enhanced product with vast improvements in electrical characteristics, reliability and volumetric efficiency.

In discussions with the tantalum capacitor industry, it was made clear that supply chain development became an essential element in their quest for range extension, miniaturisation and improved reliability. Powder formation and shaping is one of the key areas in solid tantalum capacitor construction and has been improved steadily over the past ten to fifteen years. Powders are now available with CV/g values approaching an order of magnitude higher and impurity levels an order of magnitude lower than was possible at the beginning of the 1990s. The overall effect has been to assure the production of a more homogeneous anode with far fewer high-leakage fault sites.

Much development effort has been concentrated on the reduction of ESR (Effective Series Resistance), a key parameter in power supply filter applications. ESR is of great importance because, primarily in order for the filter to function efficiently, the capacitive element should offer very little resistance (ESR) to ground at switching frequency. Low ESR will not only enhance the filter's electrical characteristics, but will also reduce joule heating and hence increase the capacitor's long term reliability. In all capacitors, ESR is a combination of the real series resistance of all the interconnects (DC component) and the hysteresis losses in the dielectric (AC component). In order to reduce ESR, manufacturers have increased the $MnO_2$ cathode contact area in a number of ways, including angular shaping of the anode pellet, multi-anode construction, and optimisation of the cathode manganising process as previously discussed. In addition, laser welding has been introduced at the interconnect of the anode riser wire to the lead frame, which significantly reduces the DC resistance component. The results can clearly be seen by reviewing current data sheets. Certain types now such as the AVX TPS III and TPM product exhibit ESRs of only a few mOhms, some orders of magnitude better than types available in the early 90s. These products have been specifically designed for power supply filter applications, and equivalents are available from all major manufacturers including Kemet and Firadec.

With the reduction in ESR and subsequent use in lower impedance circuits, came an increase in the probability of high transient surge current failure. The risks associated with surge currents meant that process improvements were necessary to increase the capacitors' reliability under surge conditions. For low ESR types, dielectric formation was optimised and made thicker at the outer anode region. Considering that capacitance drops with frequency, an effect largely caused by current density migration to the outer region of the anode, it follows that a high frequency event such as surge causes very high current density in this outer region. Hence the outer dielectric region was thickened, which resulted in a much better surge handling capability.

Several other improvements have been made which have had a very positive effect on reliability, including the addition of a moisture barrier layer, in-line transient surge current screening, and in-line solder reflow screening. The industry's addition of solder reflow screening highlights a major concern, and the importance of remaining within recommended solder profiles during mounting.

## 6. Risk Mitigation and Additional Activities

To complement the in-depth investigation into the development activities outlined above, ESA has undertaken a series of evaluation test campaigns specifically targeted at the use of solid tantalum capacitors in power supply filter applications. The testing has included both single and parallel bank configurations in real power supply filter circuits. Results of these tests have been very positive, and a paper has been written outlining the test conditions used and results obtained. The paper, "Investigation on Tantalum Capacitors in Parallel Configuration", written jointly by Paul Collins, Olivier Mourra, John Hopkins and Ferdinando Tonicello, was presented at Cartes Europe in October 2005.

In the future, a study into the criticality of applied solder profiles is planned, but at the time of writing no start date has been fixed.

The relevant section of the new derating document, ECSS Q30-11, reflects the findings of the investigation and evaluation testing to date with a series of application and procurement directives.

For further information please contact:
*Ferdinando.Tonicello@esa.int*

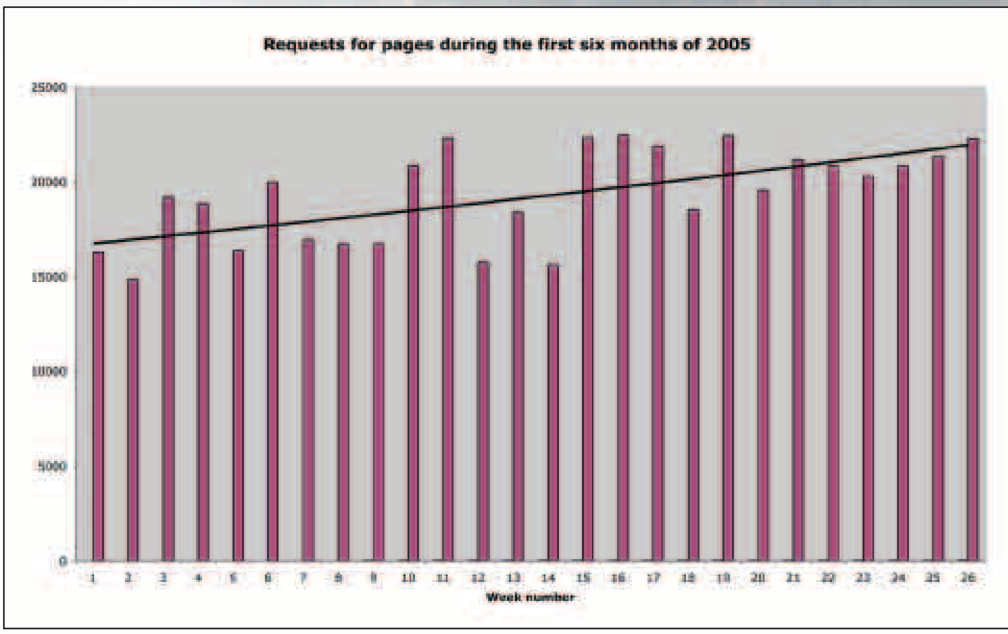
## References


[1] "Basic Tantalum Capacitor Technology", John Gill, AVX Ltd.
[2] "Tantalum and Niobiam Technology Roadmap", T. Zednicek, B.Vrana, AVX Czech Republic.
[3] "Tantalum in Power Supply Applications", John Prymark, Kemet


# ESCIES: ESCC and ESCIES websites

ESCIES, the European Space Components Information Exchange System website, is a system by and for the space components community; it has been hosted and facilitated by ESA for the last five years. The system has run successfully with approximately 99.9% availability over this time. Any unavoidable planned 'downtime' is always announced in advance on the website.

In the past period, data contribution from registered organisations was actively encouraged. Presentations to parts of the ESA Science Directorate have led to





valuable feedback. The preparation of a data providers' kit is in its final stages: the kit should be available by the time you read this article.

As we have seen the usage of and contribution to ESCIES increase steadily over the last five years, it is safe to say that ESCIES is meeting its goal of serving as a central point for collaboration and data exchange within the Space Components community. You will find a more detailed description of the growth below.

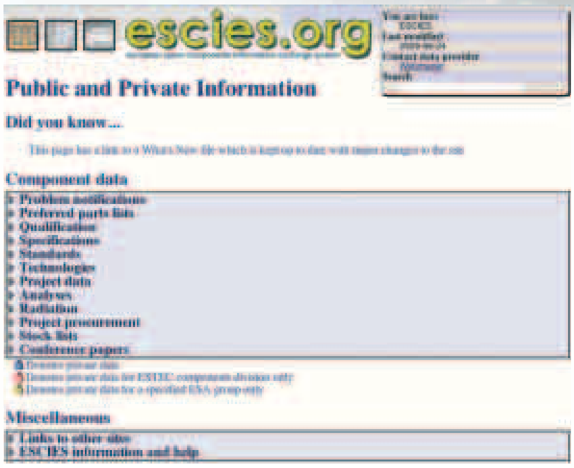

The parent of ESCIES, spacecomponents.org, is the ESA ESCC website. ESCIES is defined as an ESCC product; what is produced on the ESCC website will be published in ESCIES. The ESCC site provides a means for working groups to collaborate in private, prior to publishing papers.

Both sites hold a large amount of information (several gigabytes). They have fine-grained access control: a user has to belong to a 'group' to see a link to a document on either website, e.g. the ESCIES private area or MEMS. If a user does not belong to a group and happens to know the link to a page, then a second layer of security prevents the user from accessing the page. There are further levels of security at lower layers, beyond the scope of this article.

## Growth of ESCIES

June 2005 was the busiest month ever for ESCIES. Initially, several years ago, the increase in traffic was close to exponential; now it is close to linear but still increasing. That may just be a sign of a slowdown in rate of increase in Internet connections, which no longer follows Moore's Law.

| | |
|---|---|
| WEEK ONE, JUNE 2000 | 4000 hits |
| WEEK 144, YEAR 2003 | The first week with more than 30000 hits. |
| YEAR 2005 | The trend continues with 1.5 million requests so far this year, 6000 per day (excluding search engines). |




In other words, ESCIES now receives approximately as many requests per day as it did per week during its first year of operation.

### Growth of ESCC

The ESCC website, spacecomponents.org, has grown rapidly with the addition of new data and applications. When you log in, you will see only a small fraction of what is available, depending on your working group membership. This site is developing into an on-line application for workflow management, rather than the traditional website envisaged at its conception. ●

# ESCC-Sponsored Technology 'Round Tables'

## ESA-CTB Round Table Consultation on Wide Band Gap Technologies for Microwave Application

Wide band gap semiconductor materials have fundamental properties which make them highly suitable for a variety of RF and microwave applications. These electrical properties are summarised in Table 1 and include a band gap that is much higher than Si or GaAs (e.g. 3.4eV for GaN compared with 1.4eV for GaAs), a large breakdown field, and a high saturated electron velocity [1]. The high electron mobility of the AlGaN/GaN material system, along with the ability to grow device heterostructures such as high electron mobility transistors (HEMTs), means that it is the preferred choice for frequency operation above 8GHz [2].

| | Si | GaAs | 4H-SiC | GaN |
|---|---|---|---|---|
| Bandgap (eV) | 1.12 | 1.43 | 3.26 | 3.4 |
| Breakdown field (V/µm) | 30 | 30 | 250 | 250 |
| Thermal conductivity (W/cmK) | 1.5 | 0.5 | 4 | 1.5 |
| Sat. velocity (cm/s) | 1E7 | 1E7 | 2E7 | 1.5-2.7E7 |
| Elec. mobility ($cm^2$/Vs) @2E17$cm^{-3}$ | 600 | 4000 | 400 | 1000-2000 |

*Table 1: Comparison of material electrical properties*

GaN devices offer significant potential for realising microwave components with an order of magnitude improvement in output power capability compared to GaAs or Si, with frequency of operation up to at least 100GHz [3]. The wide band gap means that the material is radiation hard and that there is the potential to operate devices at temperatures of 200°C or higher, with significant reduction in the size, mass and complexity of cooling systems.

These performance benefits are of significant interest for realising next-generation space-based payloads.

ESA has been undertaking research into wide band gap semiconductors for several years. Ongoing research activities are listed in Table 2. In addition, national defence agencies have been undertaking research into wide band gap technologies across Europe, which has culminated in the recent launch of KORRIGAN (a multi-nation European R&D project aimed at developing wide band gap technology for defence applications).

To help improve research coordination across Europe, ESA held a round table meeting to promote and facilitate information exchange on wide band gap technologies for microwave applications. The event took place on 17/18 March at ESTEC in Noordwijk, The Netherlands. Over 60 people attended the round table, from academia, industry and government research establishments (including members of the KORRIGAN consortium). 23 presentations were given over the two-day period, covering aspects such as device physics, material growth, transistor electrical performance and disruptive applications of GaN technology.

| ESA research contract | Objectives | Industrial partner |
|---|---|---|
| Microwave frequency capability of wide band gap semiconductors | Investigation of the microwave and mm-wave frequency potential of GaN HEMTs. Device demonstration at 30GHz, 60GHz and 94GHz. | TNO (NL) and IAF (D) |
| Athena | Development of high quality epitaxial growth techniques. | IMEC (B) |
| Noise assessment of wide band gap semiconductors (two consortia, work recently completed) | Assessment of the low frequency and RF noise performance of wide band gap devices, including receiver overdrive measurements, transmit/receive module simulation, oscillator phase noise evaluation. | (1) Thales (F), IEMN(F), TNO (NL)<br>(2) QinetiQ (UK), Astrium (UK), phConsult (UK), IXL (F) |
| X-band TT+C SSPA | Development of a hermetically packaged transistor family for realisation of a 30W, X-band power amplifier. | TESAT (D) and FBH (D) |
| Thermal management and packaging | Investigation and demonstration of novel thermal management techniques. | Inasmet (S),CNM (S), UPM (S), AMS (I) |

*Table 2: ESA Research Programmes on Wide Band Gap Semiconductors*

Highlights of the workshop included results presented by IMEC on novel interlayer growth techniques that can allow high quality, low dislocation density growth of GaN/AlGaN layers on host substrates. This is important since GaN is not currently available in single crystal boule form. Accordingly, GaN and its alloys have traditionally been grown epitaxially on dissimilar substrates, in particular sapphire, SiC and more recently Si. There is a large lattice mismatch of ~3% on SiC and ~12% on sapphire, so a very high density of dislocations in the structures is required to accommodate the mismatch (typically $10^8 – 10^{10}$ cm$^{-2}$ of threading dislocations compared with $10^3$ cm$^{-2}$ on GaAs). IMEC have shown that they are able to grow high quality GaN/AlGaN device layers using AlN interlayers that reduce formation of threading dislocations, as illustrated in Figure 1.

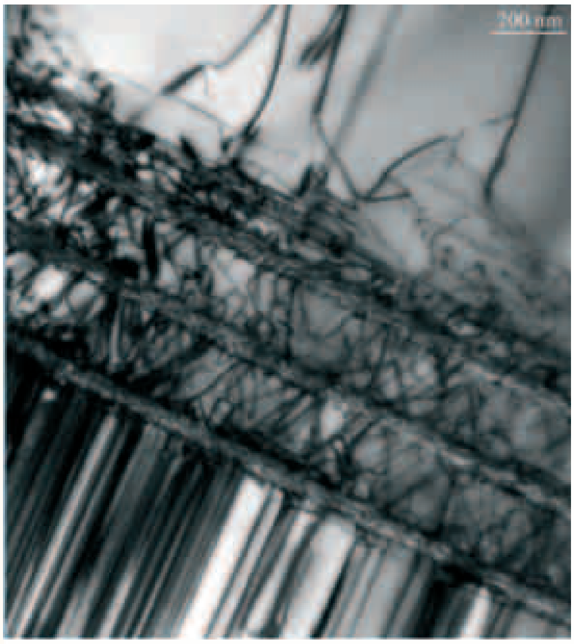



*Figure 1 : Reduction of threading dislocations at the AlGaN/GaN interface (Courtesy of IMEC)*

Impressive results were also presented by TNO and IAF for the first ever reported European Ka-band GaN MMIC power amplifier ($P_{sat}$ 2W at 27GHz). A photograph of this state of the art MMIC is shown in Figure 2.

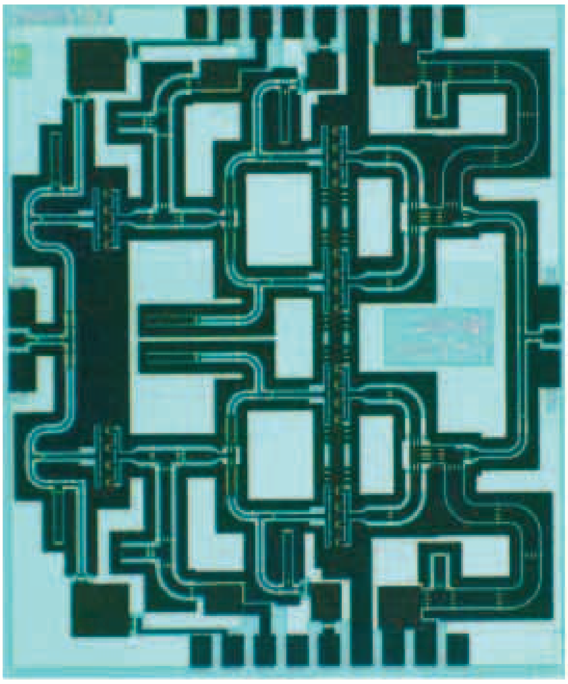


*Figure 2: First 2W Ka-band GaN power MMIC in Europe (Courtesy of TNO)*

Impressive noise figure and overdrive measurement results were also presented by two research groups (QinetiQ and Thales), illustrating that there is excellent potential for realising highly robust receiver front-ends using GaN HEMTs, but without the need for expensive and bulky limiters.

Overall the round table event was well received and showed that excellent headline performance results are now being obtained in Europe.

The key conclusions were as follows:

- Good RF output power performance and high power densities are being achieved by several companies (e.g. 7W/mm at 2GHz, 6W/mm at 10GHz, 3-4 W/mm at 30GHz)
- NORSTEL AB announced it is setting up a new commercial facility for manufacture of SiC wafers. This will allow Europe to establish an independent supply route without having to rely solely on US suppliers such as Cree.
- United Monolithic Semiconductors (UMS) announced it has included GaN on its development roadmap, with MMIC production planned for 2009-2010.
- More work is required on fully understanding the system drivers and implementation benefits of using GaN. In addition a wider range of device functions (e.g. switches, mixers, multipliers, diodes and oscillators) should also be considered.
- Component reliability is felt to be the number one problem to resolve, with device output power typically fading after only a few hundred hours of operation. As a result, significant research and development effort is still needed within Europe to ensure this problem is overcome and that GaN technology is available for use in space-based systems by 2009-2010.

ESA is currently using the key findings from the round table to better focus its future research programmes on wide band gap technologies. One of the outcomes will be to ensure that there is coordination and information exchange between the ESA and KORRIGAN research activities, to avoid duplication and ensure rapid transition of the technology from research to manufacturing industry.

For more information on ESA wide band gap research activities contact: *andrew.barnes@esa.int*

### References

[1] R J Trew et al, “Microwave AlGaN/HFETs”, IEEE Microwave Magazine, March 2005

[2] S McGrath and T Rodle, “Moving past the hype: real opportunities for wide band gap compound semiconductors in RF power markets”, GaAs Mantech digest”, 2005

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# ESA-CTB DC-DC Converter Round Table Consultation

DC-DC converter technology is essential to the space user: it appears on every spacecraft and the interface between the power system and the analogue or digital equipment. The types of DC-DC converter topologies and the voltage supplied for European missions vary significantly, and even though converters are used consistently and extensively, they are generally considered by systems people as an afterthought to the equipment. The types of converters used to date in European missions include custom-designed PCB based units, 3D modules, and off-the-shelf hybrids.

The driving factor for the procurement of a DC-DC converter is usually the efficiency, which is typically between 65% and 85%, and for EPC applications it is »85%. Other factors include power rating, output signal quality, synchronisation to allow multiple converters to be coupled, and a design mitigation that ensures that the spacecraft power bus is not compromised if there is a short circuit condition.

ESA has long recognised that DC-DC converter technology is very complex and that for European missions it is one of the last items considered, resulting in a custom design solution. Consequently, European DC-DC converters often carry long lead times, high non-recurring engineering costs and large unit costs. In addition, the technology often chosen in the converter is subject to the application of ITAR restrictions or export license, or procured through a controlled supply chain; in particular the power MOSFET, the driver and the pulse width modulator (PWM).

The US market is of interest to European users with the hybrid DC-DC converter solutions reportedly offered to Mil38534 QML system. However, these off-the-shelf items often do not have the assurance levels required for the space user, or they are subject to export restriction. Additionally, the European user has no visibility of the design, the testing or the heritage of the product, all of which is an unsuitable state of affairs for the high-reliability space manufacturer. ESA therefore hosted a round table meeting at ESTEC on 13 April 2005, held in conjunction with the Component Technology Board and the ESCC, to understand the space users' needs and determine European industry's level of interest in developing a series of off-the-shelf, reliable converters that are short lead time and low cost.

The meeting consisted of DC-DC converter manufacturers, space users and other interested parties, and suggested that while some DC-DC converter manufacturers are indeed producing radiation-tolerant devices, they are, as predicted, high cost and long lead time. However, what is of interest is that when European 'components' are compared with their U.S. equivalent converters, the pricing is of the same order and yet the performance and quality assurance provisions are as good as or in some cases better than the US products. The meeting also discussed off-the-shelf converter products, which are provided by several European manufacturers as prototype DC/DC converter items with a tailored up-screening process that also assures the off-the-shelf constituent parts being used in the design. In addition, the range of these products consists of those with alternative packaging methods, for example the types announced by the company 3D-Plus. The price of these 'commercial' units is cited as very low, however they are not yet qualified and the risks to date are unquantified.

The ESA round table meeting provoked many discussions. The presentations of the attendees are listed in the ESCIES conferences section on https://escies.org/, while the conclusions of the meeting may be summarised as follows:

- Innovative topological solutions are not evident, therefore the use of commercial components may have to be evaluated.
- The price of Hi-Rel components can account for 60 or even 70% of the recurring price
- At present, Hi-Rel MFET drivers and PWM controllers are only available from US manufacturers, and these may be subject to ITAR restrictions in the near future.
- It seems urgent and appropriate to develop basic European components to be used in DC-DC converters (e.g. Hi-Rel, possibly radiation-hard MFET drivers and PWM controllers).
- The availability of the basic power conversion building blocks must be guaranteed before the development of the hosting equipment.
- Existing European DC/DC converter products and solutions are not always known to external potential users (PIs, etc)
- It is necessary to advertise what EU industry can offer!
- A handbook or datasheet file of available offerings may be one way of doing this.

The DC-DC converter user's (payload developer's) point of view needs to be further investigated.

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