

GAN TRANSISTOR IN SPACE EQUIPMENTS: FROM SELECTION TO APPLICATIONS

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ABSTRACT

Two years ago, at ESPC-2014 results of ESA activity on GaN transistor survey has been presented. The main outcome was the existence of an unknown phenomena in silicon MOSFET: the dynamic R_{dson} .

Today we are the time of studying introduction of this technology into products. At least two suppliers (EPC-co & GaN Systems) are proposing stabilized GaN transistors components which are worth spending some time to try to implement in next generation product prototypes.

Space applications aren't very different from terrestrial ones when we speak about benefits of using GaN technology into dc-dc converters: lower losses & more compact designs thanks to higher switching frequencies. Next to reliability analyses proposed by the component vendors to be able to address the automotive markets, there is of course quite a list "space" specific questions that need also to be answered to raise the confidence that GaN will one day be put in orbit: hermetic packaging & assembly on PCBs, radiation harness, reliability impact of radiations, cooling in the absence of air flow, thermal cycling, drivers, deratings to apply...

In this article we present some prototyping results & shares some feedback & concerns about the introduction of GaN into space qualified dc-dc products.

1. CONTEXT

GaN based transistors are promising for power applications because of their higher performances (low losses & high speed) and low size (from transistor size itself up to higher switching frequency ability). Their introduction is progressive on other terrestrial applications, thanks to their progressive cost decrease. But their introduction for space application requests also at least :

- radiation hardness (both total dose and heavy ions)
- robustness & reliability
- thermal draining (no convection)

2. SELECTION

A market survey of commercially available GaN transistors and diodes has been made by mid-2013, under ARTES 5.1 (Advanced Research in Telecommunications Systems) programme element funded by the European Space Agency, and entitled "Demonstration of High Power/High Efficiency Converter Using Commercially Available GaN" (contract 4F.067).

This survey is peculiar to a telecom application being a flight DC/DC converter, fed by the nowadays common 100V satellite bus and with a power level of 600W. Small converters like POL (Point of Load) are clearly out of scope. This led to make a survey on at least 200V rated GaN components with a high current capability.

The contract encompasses the market survey and the procurement of the relevant parts [4], followed by a breadboard manufacturing using the best commercial GaN. The breadboard will be compared in performance with "classical" Si power MOSFET and diode within the selected DC/DC converter: a SMART topology i.e. a buck followed by a push-pull converter (see §5.1) further.

Even for GaN transistors having to work at 100V bus or above, the R_{on} resistance becomes now comparable or better than Si MOSFET for power converters. However one important parameter has appeared in GaN HEMT components datasheets: dynamic R_{dson} . The phenomena seems now understood [6], measurements methods are now available. There is no more bad surprises & we almost don't have to work with data sheets not mentioning dynamic R_{dson} . As a rough order of magnitude, one has to consider a factor x1.6 more conduction losses when using HEMT normally on devices in dc-dc switching conditions. Some experimental devices are even appearing where no dynamic R_{dson} are claimed [5].

Nevertheless, the interest of switching GaN is obvious thanks to their very low capacitances, allowing parallel operation without degrading significantly the switching losses (contrary to Si). When the manufacturers will solve or at least improve the dynamic R_{on} performance,

we will take full benefit of this promising component even at 100V bus.

Another important point also linked to the 100V bus voltage is the fact that the very well-known Figure of Merit (FOM) $RDSon \cdot QG$ is not relevant. For the targeted power converter of 600W, the QG losses represent only 4% of the switching losses against 75% due to Coss. We suggest for high power output and voltage above 50V a $FOM = DynamicRDSon \cdot Coss$.

Finally, we see that within 2.3 years packaging has strongly evolved. All GaN components using the good old TO-xx family of packages have passed over. Indeed high current transients requires low inductance packaging. Furthermore GaN HEMT transistors are now a 4 pin device as its almost mandatory to use Kelvin source to avoid parasitic turn-off.

For diodes, it seems that SiC devices have better performances than GaN in both forward voltage $Vd(I_d)$ and reverse current I_r . The main interest to work with those WBG diodes is their dv/dt capability. Indeed, it is widely known that Si Schottky diodes have a limitation at 10V/ns whereas GaN and SiC have no such rating. Although SiC diodes are available their fail radiation testing. GaN diodes are still lagging behind in terms of performance. So if GaN transistors are to be used in classical buck or boost configurations, it is mandatory to resort to proceed to synchronous rectification.

For dc-dc applications, besides some specific operating conditions [7] dc-dc converters are hard to build using normally-on devices. For terrestrial applications, several component suppliers are moving forward in the cascade direction. For space applications this makes much less sense since a radiation hardened silicon MOSFET is needed to create the normally off feature on top of the GaN device which is used to manage high voltage.

The selection was done with the following criteria :

- Normally Off
- No leaded parts

When prospection was initiated mid 2013 were several parts coming from different manufacturers: EPC-co, Microsemi, GaN Systems, RFMD, Avogy, Transphorm, Panasonic, Fujitsu semiconductor, IR, MicroGaN, ... The world is changing extremely fast. There is no 3 months quarters happening without a new player coming in, some other disappearing & other strategic alliances. The survey turned-out to be a permanent task to be stay up to date.

ESA itself has launched the development (project ESA A/O1-7688/13/NL/RA) of radhard components: "GaN devices for space based DCDC power conversion application» contract between ESA and OnSemi. Thales

Alenia Space is of involved in the project as end-user of these components.

While waiting for true radhard space qualified components, in order to proceed with investigations on GaN applicability into products, a pre-selection has to be made and Efficient Power Conversion Corp. & Gan System Inc. are the candidates retained for current investigations in prototypes within Thales Alenia Space.

3. EXPERIMENTAL RESULTS

After component tests at parts level, implementation exercises started on several low, medium & high applications.

3.1 Multi-purpose low power dc-dc

As part of the roadmap for product evolutions of the low power dc-dc, GaN transistors have been tested. In this type of low power applications, the use of GaN transistor could be viewed as completely overkill: current levels are significantly below the real capabilities of the transistors. Furthermore using advanced technology as GaN (which is still far away for being completely trusted) in a very low power allow to use it with considerable derating hence leading to a higher confidence in the reliability of the devices used in the context of this application. Such low power application also allow designers to get familiar with controlling, driving and electrically interconnecting GaN HEMT devices without having to take care on power dissipation aspects yet!

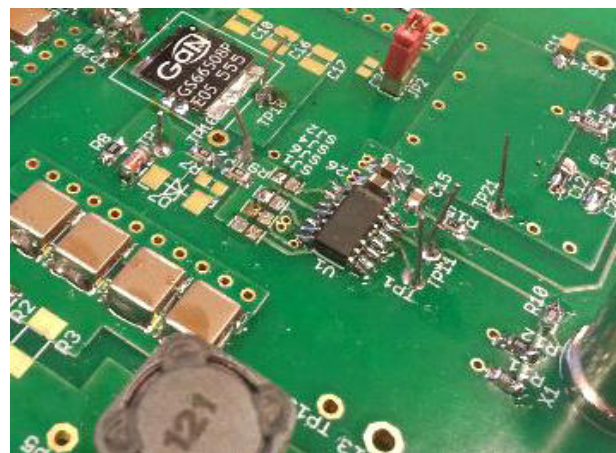


Figure 1. GaN-Systems devices under test

The interest of using GaN transistors in such low power equipment (20...40W) mainly lies in the availability of high voltage transistors capable of managing high input voltage ranges: one hand unregulated bus (22V to 37V) and on the other hand telecommunication satellite power bus at 100V. Today managing this large range requires two different hardware variants: one for high voltage with "high voltage" MOSFET transistors and another hardware variant for equipped with "low

voltage” MOSFET. Using GaN allow to handle both voltages without compromising dc-dc efficiency. Next to that, as expected, size & weight of the converter can be improved by using higher switching frequencies.

3.2 EPC (Electrical Power Converter) for TWTA

Electrical Power Conditioning unit for high voltage Travelling Wave Tube Amplifier is classified as a mid-range power product with powers in the order of 200 to 600Watts. They are present in satellite with rather high quantities: with 20 to 70 tubes per satellites. A recent trend in this product family in the assembly of so-called “dual EPC” where one module deliver high voltages for 2 TWTA resulting in a significant size, weight & cost reduction at satellite level. For an equipment design perspective delivering twice more power from a unit is not that a simple tasks.

In the context of an ARTES 5.1 activity (see §2), GaN normally-on HEMT components have been tested as replacement parts for the usual silicon MOSFET transistors in the primary side of the dc-dc converter.

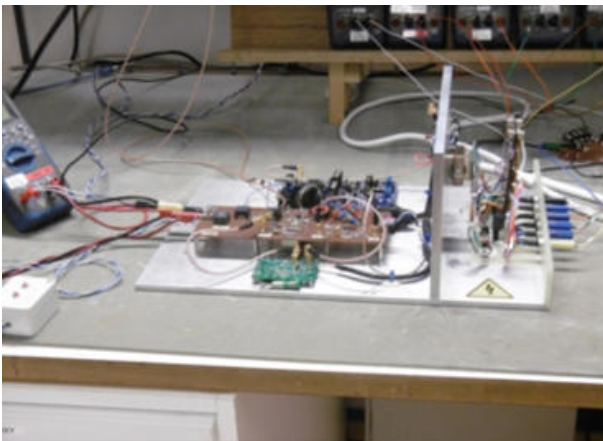


Figure 2. electrical prototype of GaN dc-dc EPC (Electrical Power Converter) for TWTA

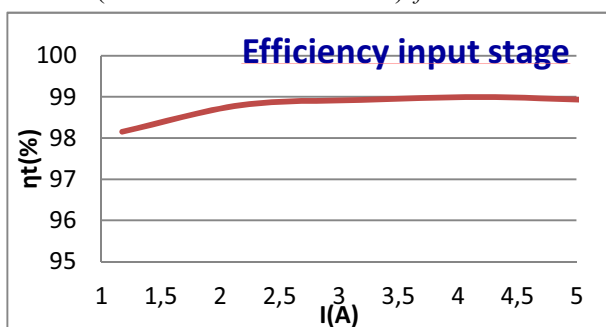


Figure 3. measured efficiency for 100V input bus.

Efficiency of 99.0% at 250KHz achieved for the input stage. After several PCB layout iterations perfect turn-on, turn-off waveform were achieved. The interest of using GaN lies (as usual) in the frequency increase:

practically it means it is possible to transfer power level of dual EPC in a HV transformer of a single EPC at same efficiency.

Lessons learned from these prototypes are that thermal management of GaN is much more complex than with classical silicon MOSFET & hence to be considered as a drawback of the GaN technology. Although GaN devices are dissipating much less than silicon MOSFET, there physical side being significantly lower makes the heat dissipation more complex. Not surprisingly also, the speed of this transistors request careful PCB layout to prevent oscillations, spikes & gate overstress.

3.3 PPU

Power supply system for electrical propulsion is the family of product where real high power are being considered with a target of 5kW per module. Clearly in these type of products we are coming close to component ratings & thermal challenges are very complex to manage. The introduction of GaN devices with their new packaging options (flip chip for Efficient Power Corp. & the innovative packaging of GaNSystems) into high power space product will require significant efforts to create new mechanical structure & assembly process to be able to evacuate high power dissipation without air flow while still managing high currents i.e. keeping low inductances everywhere.

3.4 Low power RF units

As described in [2], telecommunication receivers are widely used in geostationary satellites. On this low power application, the power supply delivers around 10W through several output voltages, with strong requirements on output conducted ripple. The switching frequency has been set at 1MHz and the switching speed of the device was up to 30V/ns. The prototype was 50% smaller but owing an additional tool, it was integrated in a RF unit. The RF output clearly “saw” the new switching frequency and additional simple LC filter suppress it. The prototype worked 1000 hours at 25°C without failure.

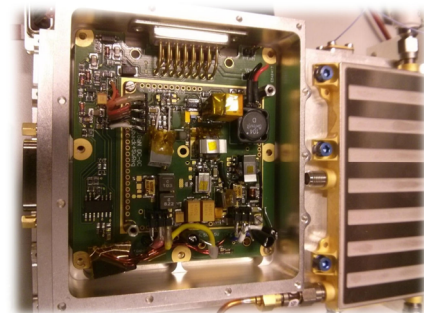


Figure 4. Low power DCDC in RF unit

3.5 EPC (Electrical Power Converter) for SSPA

Then the application on solid state power amplifier was investigated. Usually such power applications uses bridge legs and a specific work has been done on the optimization of legs commutation [1] : through phase opposition method measurements and dedicated software, a prototype has been built and its characteristics was checked in different configurations. Finally, the efficiency was now driven by the losses in the magnetics devices.

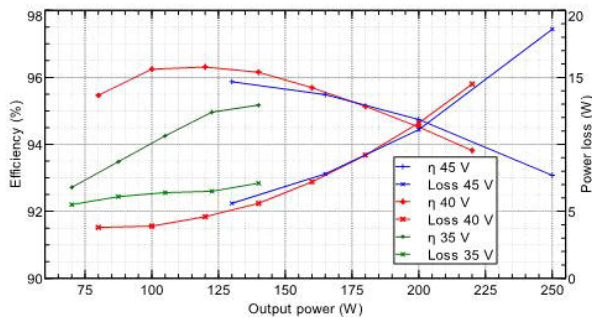


Figure 5. EPC (Electrical Power Converter) for SSPA core efficiency

3.6 Low voltage application

GaN transistors were also evaluated to supply digital application needing low voltage (<3V) high current (>10A) applications. Despite their very low R_{on} , the conduction losses are still “ I^2 ” dependant and parallelisation of several devices has been done owing to intrinsic properties of GaN device (positive temperature coefficient, ...).

4. FEEDBACK & WAY-FORWARD

All the above mentioned prototypes allow to get better confidence on the electrical & thermal aspects of implementing GaN devices in dc-dc converters. On top the central reliability question, there is of course quite a list “space” specific questions that need also to be answered prior to an introduction of GaN transistors into usual space units.

Hermetic packaging is still needed for most space missions. Hence as specific hermetic packaging needs to be developed for space applications. Currently solutions are converging to SMD05 packages with 4 accesses. The design of this package is a complex exercise to get the heat out of a very small die while minimizing the added parasitic: too high inductance of the connections would completely kill the possibility to increase the switching frequency & hence kill one of the main interest of using GaN devices. Furthermore this specific process of encapsulating die following standardized ECSS processes will significantly increase the recurrent cost of the component. Today the main factor for selecting a component remains part cost!

Reliability & Robustness: using components in Space applications requires a complete understanding of the physics of failures. Indeed this allow to design circuits with enough margins (but not too much also) to reach high reliability figures. Over the experiments conducted within Thales several component failures have been observed for a variety of reasons. First one is the high sensitivity of the gate of the GaN. Optimal & safe gate drive of GaN is an art on itself.

This raise the question of margins & deratings to be applied: the low threshold is very low & can easily be crossed during transients. The performance of the GaN is only achieved for high gate drive. While doing this the gate voltage come close the max ratings. And there is not a lot of headroom for margins. Crossing the max rating lead to component destruction or highly accelerated aging.

Thales experiments also showed unexpected increases of the gate current. While gate current is negligible on fresh components, silent increase of the leakage current of the gate has been observed both during accelerated aging tests and also during irradiation tests. Of course this change of behavior creates some worries & we aren’t yet able to declare if this would have any impact on the long reliability of the component. These observations all converge to same point: put a lot of attention on the design of gate drivers!

Radiation tests have been conducted also. As published in NASA reports [8], GaN devices are very robust to total ionizing dose. Threshold drift is can almost be considered negligible for most of standard space missions. The breakdown voltage of requires of course requires to define a safe operating area for each transistor when exposed to heavy ions. Finally gate current leakage has been observed and the phenomena is still not yet explained.

5. CONCLUSION

Today we are the time of pre-introduction of GaN HEMT into products. This introduction in products is going its way & at least isn’t completely blocked. Whereas for example SiC components are still reported to dramatically fail at heavy ion testing.

Promises of higher density thanks to increased switching frequencies are met. Product introduction means also investigating all aspects such as procurement, long term reliability, cooling, radiation robustness. Of course questions & worries are raising & they are not fully answered yet, but perspectives are very attractive.

Thales thanks ESA & CNES teams for their support & advises during these GaN investigation projects.

6. ABBREVIATIONS AND ACRONYMS

PPU : Power Propulsion Unit

EPC : Electronic Power Conditioner

EPC-co : Efficient Power Conversion Corp.

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