GaN Power Commercialization with Highest Quality-Highest Reliability 650V HEMTs-Requirements, Successes and Challenges

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***Abstract*—**Gallium Nitride (GaN) is now a popular choice for power conversion. High voltage (HV) GaN HEMTs (GaN FETs) in the range of 650-900 volts are emerging as the next standard for power conversion. This paper highlights key successes in efficient and compact converters/inverters ranging from high performance gaming/crypto-mining power supplies, titanium class server power, servo drives, PV inverters, and automotive OBCs, dc-dc converters, pole charges. The reasons for market success including unmatched quality & reliability, high volume GaN on Si manufacturing, robust performance in applications as well as challenges to achieve the full potential of GaN FETs are presented.

I. Introduction

With its proven ability to reduce size (form factor) and save energy (high efficiency) 650V GaN FETs have now been adopted in the mass market. GaN provides cost-competitive, easy-to-embed solutions that reduce energy loss by >50 percent, shrink system sizes by >40 percent, to simplify converter/ inverter design and manufacturing, also contributing to system cost reduction. An un-compromised need for power market is quality and reliability. We have achieved this through appropriate choice of device, package and outgoing quality standards. Next, overall product performance in application including uniformity and repeatability across millions of parts is a must. We tackle this via vertically integrated manufacturing and Si-like production discipline. Third, strong application support and deep understanding of GaN key circuit topologies is required. Last but not least, clear system or circuit level value proposition/cost benefit is essential for adoption.

II. Highest Robustness Normally Off GaN

A. Normally off product configuration

We have designed, qualified and mass produced a 2-chip normally off 650V GaN platform, integrating a low voltage Si FET input/drive stage with a high voltage GaN output stage (Fig. 1). Among the approaches to make a normally-off high voltage GaN switching device, this approach [1] offers strongest gate robustness over the p-GaN alternatives [2] with low safety margins (Table 1) and much lower complexity than the multi-chip direct-drive based designs [3]. It is noteworthy that every Si-MOSFET consists of a normally-off input portion (gate control) with a normally-on output portion (high voltage drift region), that happen to be integrated in one device [4]. We have integrated two separate die in one package in a die-on-die configuration with minimum inductances to achieve best of both worlds- highest gate/input strength of the proven Si LV-MOS (with its ideal Si-SiO_2) dielectric gate and the high-performance high-voltage GaN HEMT to deliver low loss, high voltage switching and reliability. The result is a normally-off power device package with hard to beat combination of reliability, robustness, design margin and performance.

B. Package Choices- Thermal management is key

Along with the device, a robust and easy to use package is key for a power product. The basic concept that heat from any semiconductor die is removed via the package through the system heat sink is many times overlooked. Whether it is surface mount products to benefit from GaN's high frequency capability (reaching 100s of KHz or MHz scale) or the more classic TO packages to get kilo-watt class power that avail of GaN's high efficiency/low loss switching capability; a solid thermal interface without undue system complexity is a must. Industry work-horses such as the TO220 & TO247, their surface mount equivalents as the D^2Pak & D^3Pak or DIP style and top side cooled modules offer robust package environments (Fig. 2). These have been coupled with simple but powerful high frequency/high speed switching design philosophies, to result in GaN parts with stable operation at multi kW at high-speed/multi-100 KHz to MHz and performing better (Fig.3).

III. Quality and Reliability

Suppliers are adopting common standards for reliability needs. While being part of this industry effort, our philosophy is to establish comprehensive reliability testing of products that achieve industry firsts in qualifying 650V GaN products for the marketplace. Instead of academic arguments of JEDEC standards applicability to GaN, the question customers ask is if GaN products are not passing JEDEC tests then what is wrong with those GaN products? Our approach is that JEDEC qualification for GaN (existing standards) is necessary but not sufficient and must be backed up by other comprehensive tests suited for GaN products (Fig. 4)

A. *Qualification and Intrinsic Reliability*

In addition to achieving successful JEDEC and AEC Q101 qualification of the 650V GaN platform [5], intrinsic lifetest along with associated failure modes and acceleration factors was also reported with both voltage and temperature based acceleration factors for the critical high voltage reverse bias failure mode [6], shown in Fig 5. Use plots indicate wear out of the device at 480V does not begin before 1 million hours, at any temperature within the ratings.

B. *Quality levels/FIT rates*

A key consideration is that parts may fail prior to intrinsic lifetime due to defects not screened out in the manufacturing/ test process including infant mortality or random failures during the useful life. Practically, potential fails in the first 10^5 hours for a given mission profile need understanding. The robustness of our 650V GaN FETs to well over 1000 Volts enables testing to failure using voltage acceleration with a 2 dimensional reliability matrix against voltage and temperature. Both FIT (Failure in Time) for constant failure rate (also equivalent to MTBF) and PPM (Parts Per Million) testing was done per the detailed methodology based on JEDEC std. 74A Annex G [7], reported elsewhere [8]. The results (Fig 6) predict FIT of 1.3, along with an annual failure rate of 0.001% (~ 10ppm) at 520V, 100C. This preliminary but comprehensive study gives a strong proof point of quality levels and field performance predictability for GaN devices.

C. *Application centric (Switching) reliability considerations*

We have also subjected our devices to switching stresses including comprehensive HTOL testing under actual power conversion operation at 175C, 300 KHz for 3000 hours (Fig 7) and accelerated switching at 150 KHz, Room Temp-125C at more than 1000 volts. No significant change is observed during as well as before/after HTOL testing. Initial accelerated switching tests indicate switching lifetime $>10^8$ hours (Fig 8).

IV. Manufacturing Scale and Metrics

It is a requirement that for any technology to exhibit the highest levels of quality and reliability, high levels of wafer-fab and product yields with adequate process capabilities and control must be established. Transphorm's commercial JEDEC and AEC qualified GaN HEMT power products are manufactured in an automotive grade 6-inch Si CMOS wafer fab. We have previously reported Silicon like manufacturing, yields (Fig 9) and process capabilities for our HV-GaN manufacturing [9]. Further, complete SPC tracking and control charts for hundreds of manufacturing/test parameters is routine.

V. Application Performance and System Value

The ultimate proof of the accepted reliability and robustness standards comes from use of the high voltage GaN products from various suppliers by a wide customer base. This has already started and many leading companies are now in production with high voltage GaN devices. As examples, Corsair has introduced best in class 1.6kW gaming power supplies with unparalleled performance at par cost based on the Totem Pole architecture enabled by 650V/50mohm GaN in TO247 packages (Fig. 10), Bel Power Systems has introduced these 50mohm TO247 products in their 3kW TET3000 Titanium class Server Power Supplies [10] and Yaskawa Electric has introduced TO220 based products in an innovative integrated servo amplifier-motor drive system [11]. With strong circuit benefits (Fig 11) and ability to reduce size, weight and improve miles per gallon, GaN FETs are being designed in EV & HEV applications such as on & off board chargers and auxiliary power conversion in the 3-10kW range.

VI. Challenges- System Considerations

Challenges for wide adoption lie in the areas of system integration, robust supply, standards and cost improvements.

In systems, GaN offers high value within the AC to DC bridgeless totem-pole PFC, which unlike the well-established analog based classic boost PFC use digital programming. The Totem-pole PFC though using similar control techniques requires ground up development with additional needs such as soft start control and polarity definition with firmware design knowledge. Focused reference design such as the 3.3 kW PFC reference (Fig 12) assist customers get over this digital control hump. Having GaN solutions with sufficient drive margin (gate robustness), preferably with off the shelf standard drivers also aids system design experience.

As another challenge, customers designing with GaN must be assured performance in actual ac operation during power conversion as claimed on the datasheet and not suffer from any dynamic effects. In addition to designing for and 100% monitoring for such dynamic effects control, we ensure that datasheet ratings and maximums include such effects. In other words, what you see should be what you get. The good news for the GaN industry is now that this standard is widely agreed and various manufacturers have embraced it.

A robust supply chain with multiple sources enables user confidence. Transphorm has partnered with Fujitsu to establish 6-inch GaN wafer manufacturing in an automotive certified Si-wafer foundry in Aizu-Japan (now beginning to offer 3rd generation products) while others like GaN Systems, Navitas and EPC avail external foundries in Taiwan. Like Transphorm, companies like Infineon, Panasonic control their manufacturing lines, a distinct advantage in the first 10-15 years of any new semiconductor ramp. Transphorm is also committed to expand partnerships, including establishing credible second sources for its products. Finally, GaN device costs are on course for continuous reduction to approach and in some cases already beat Si Super-junction, especially at the system level.

VII. Summary and Acknowledgements

As GaN FETs launch into an exciting growth phase with multiple suppliers, continuous focus on reliability, supply assurance, value/cost will enable user confidence that will let GaN challenge the existing slots and be a forerunner for new growing power conversion applications like automotive.

The authors sincerely appreciate the contributions of the broader Transphorm team, our vendors, manufacturing partners notably Aizu-Fujitsu foundry, customers and financial partners in making this happen.

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2-chip normally off approach with
LV Si MOS and HV GaN HEMT

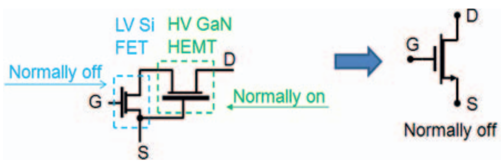


Fig. 1. Robust normally off GaN achieved by integration of LV Si MOSFET and HV GaN

Device	Threshold Voltage (V)	Gate Plateau Voltage(V)	V_{GS} Rating (V)	Gate Safety Margin (V)
Transphorm GaN, Gen-3, 2-chip normally off	4.0	6	20	20 – 6 = 14
1-chip normally off, A	1.7	3	7	7 – 3 = 4
1-chip normally off, B	1.2	2.2	4.5	4.5 – 2.2 = 2.3
1-chip normally off, C	1.4	2.7	6	6 – 2.7 = 3.3

Table 1. Common approaches for normally-off: 2-chip integrated solution provides +4V threshold, high design margin and gate robustness

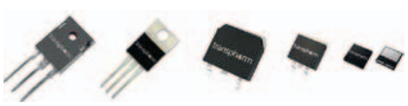


Fig. 2 Array of packaged products both lead based, surface mount that are amenable to meeting stringent qualification standards: TO-247, TO-220, D3PAK, D2PAK (Auto Q101 standards) and PQFN (JEDEC/Industrial standards.)

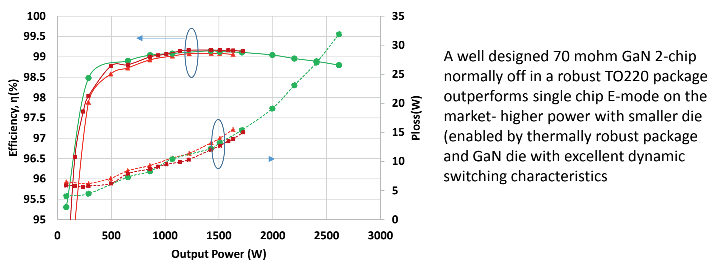
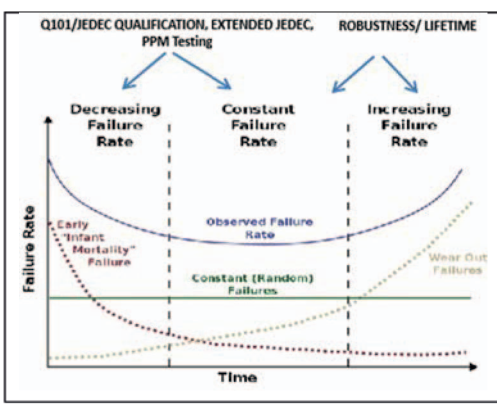


Fig. 3.Superior performance from a robust package GaN 650V product- 99% efficiency, 2kW, 50 KHz, 200V input



	Some of the comprehensive Qualification and Reliability (Q+R) requirements to be met for GaN Products
1.	Std. JEDEC based tests (1000 hours type of tests), 3 lots x 80 devices, pass with 0 fails.
2.	Extended JEDEC Tests like 5000 hour HTRB, multiple devices across lots, 2-3x testing for other tests like Power cycle, Temperature cycle, HAST
3.	HTOL Switching operation at 175C over 3000 hours (in actual power converters)
4.	Automotive Q101 based qualification testing, 3 lots x 80 devices, pass with 0 fail and meet Q101 parametric shift targets
5.	Intrinsic lifetime for various modes of failure for both die and package (high voltage, high temperature, high current for GaN die as well as higher delta-T for power cycle and temperature cycle for packaged parts). GaN lifetime established with 1200V stress testing for 650V rated GaN parts
6.	AC switching lifetime establishing no discrepancy under high voltage switching conditions (lifetime established by over 1000V switching for 650V application)
7.	FIT testing studies to establish FIT and PPM levels

Fig. 4. Complete suite of quality and reliability for 650V GaN in volume production

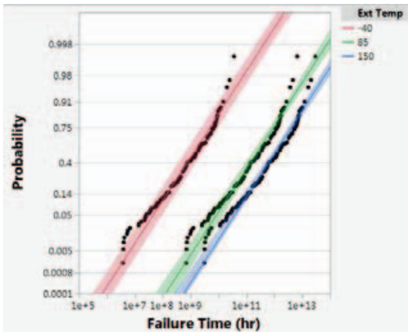


Fig. 5. Use plot from intrinsic life testing based on 1000V+ HVOS accelerated testing: GaN device wear-out does not begin before 1Million hours, MTTF much higher.

Average PPM		Voltage 400	Voltage 480	Voltage 520
Temp	25	16.8	78.6	169.5
	50	8.6	40.3	86.8
	100	3.0	13.8	29.8
	150	1.3	6.1	13.2
Average MTBF		**400**	**480**	**520**
Temp	25	5E+08	1E+08	5E+07
	50	1E+09	2E+08	1E+08
	100	3E+09	6E+08	3E+08
	150	7E+09	1E+09	7E+08
Average Annual Failure Rate		**400**	**480**	**520**
Temp	25	0.001680%	0.007860%	0.016949%
	50	0.000860%	0.004030%	0.008680%
	100	0.000300%	0.001380%	0.002980%
	150	0.000130%	0.000610%	0.001319%

Fig. 6. Average PPM per year, MTBF and Failure rate based on a pessimistic view of test data that includes infant mortality (typically screened out). This conservative view still predicts 480V/100C (use condition assumption) sub 20 PPM, 6E8 years MTBF and 0.0014% average annual failure rate

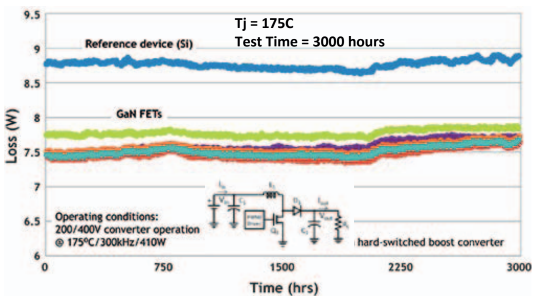


Fig. 7. High temperature operating life under hard switch actual boost converter with accelerated (temperature) conditions- no performance degradation as shown and also minimal change in before-after key datasheet parameters

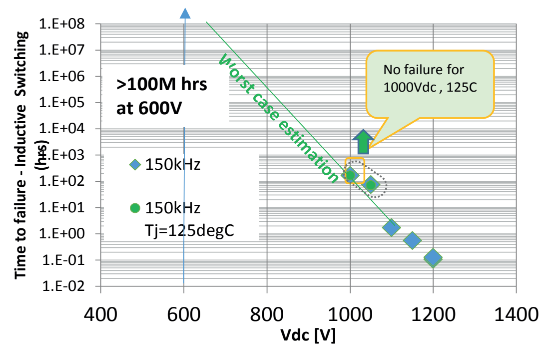
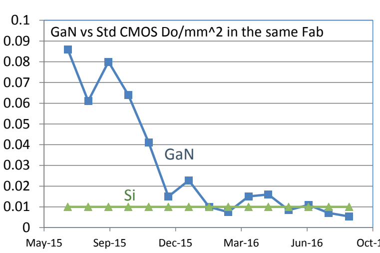


Fig.8. Preliminary AC Switching Accelerated high voltage testing at 1000V+ and 150 KHz: Indicative lifetimes of 1 Billion hours. Key conclusion- No adverse lifetime related phenomena during AC switching of Transphorm GaN FETs.



Fie. 9. Yields (represented by Do/defect density) for GaN have been on par with Si CMOS run side-by-side in our 6-inch Aizu Japan Wafer Foundry

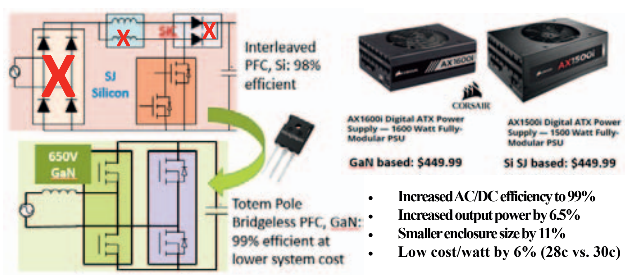


Fig. 10. Key application value, end user product: GaN provides unique benefits in Totem Pole PFCs=>99%+ efficiency, cost effective system by reducing part count. Higher performance power supply product at lower cost per watt are in market

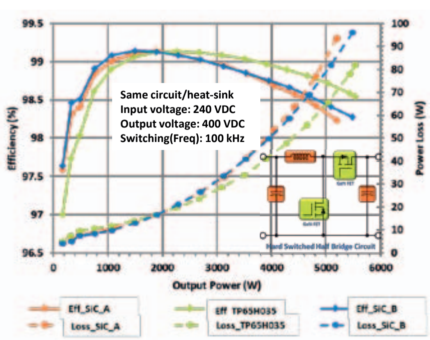


Fig. 11. GaN excels in both hard-switch (shown here) and resonant topologies. E.g. shows TP65H035WS (35 mohm GaN) outperforming 35mohm (A) and 65mohm (B) SiC MOSFETs

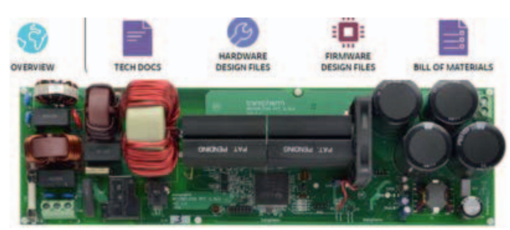


Fig. 12. Easy to adopt reference designs that illustrate breakthrough GaN performance/features like the 3.3kW /50-150 KHz Totem Pole PFC above are essential in increasing market traction