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Commercial GaN-Based Power Electronic Systems: A Review

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Wide bandgap semiconductor technology is gaining widespread acceptance in the area of high-power and high-temperature power electronics. Gallium nitride (GaN) not only has a wide bandgap of 3.4 eV and all the associated superior electronic properties but also enables the development of high-mobility power devices which is critical in increasing the power density of a power electronics system. Since a commercial GaN power transistor has a lateral structure as opposed to the traditional vertical device structure, commercially available devices are rated below 1000 V breakdown voltage with a maximum value of 900 V and typical value around 650 V. The primary focus of this review will be to introduce readers to the commercially available power electronic systems developed by various manufacturers which employ GaN-based power devices and highlight their remarkable performance which surpasses existing technology. This review also includes a brief introduction on GaN technology followed by current market study showing the roadmap of integration of GaN-based power electronics in the power industry.

Key words: Gallium nitride (GaN), commercial GaN-based systems, power electronics, power semiconductors, wide bandgap

INTRODUCTION

Wide bandgap semiconductors are known for their superior electronic properties as compared to silicon, specifically in the area of harsh environment electronics. These properties include high breakdown electric field, ultra-low intrinsic carrier concentration, and high electron saturation velocity which enables the development of high-power and high-temperature power semiconductor devices.[1–4] Currently, silicon carbide (SiC) and gallium nitride (GaN) are the two main wide bandgap semiconductor materials which have the maximum potential to be adopted in commercial applications as a replacement for silicon.[5–7] From a commercial standpoint, SiC power device technology is relatively mature as compared to GaN. This is due to the following reasons: Firstly, a SiC epitaxial layer can be grown via homoepitaxy with minimum defect density, whereas GaN epitaxial growth requires heteroepitaxy due to high defect density. Since a thick SiC epi-layer can be grown without any defect concerns, it is feasible to develop devices with blocking voltage up to 20 kV using vertical device structure, whereas a GaN-based high electron mobility transistor (HEMT) is a lateral device which places an upper limit on the blocking voltage due to larger chip area, and hence higher cost per die. Secondly, SiC has a high thermal conductivity of 3.9 W/cm^2 K as compared to 1.3 W/cm^2 K for GaN at room temperature which is a major benefit to heat dissipation in power devices.[8–12] Despite the limitations of GaN technology, GaN power devices have a major advantage over their SiC counterpart when it comes to electron mobility and high-speed switching capability. A typical SiC metal oxide semiconductor field effect transistor (MOSFET) has a typical channel electron mobility of 28 cm^2/V s due to surface defects and

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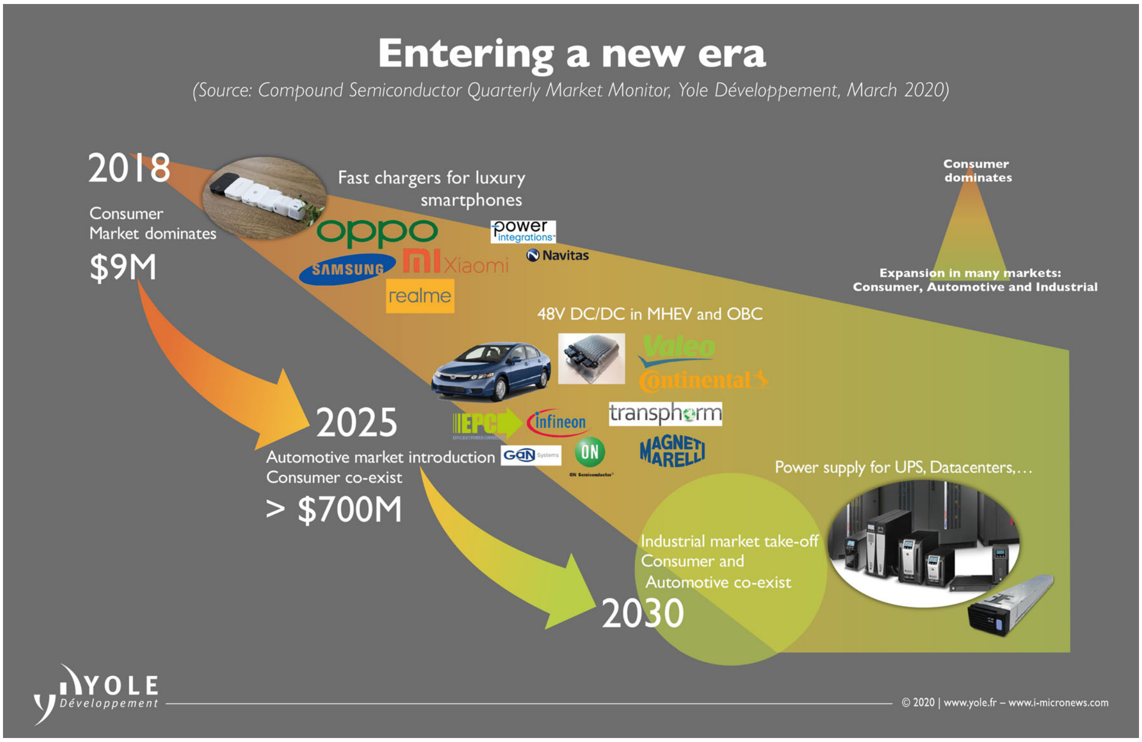
scattering effects, whereas the 2D electron gas (2DEG) formed in a GaN HEMT has a nominal electron mobility of 2000 $\mathrm{cm}^2/\mathrm{V\,s}$.[13–17] This significantly higher mobility in a GaN HEMT (almost 70 × that of a SiC MOSFET) permits high conduction current density through the device for a given active area leading to a much smaller die size. Also, GaN HEMTs have low input and output capacitance which allows the device to be switched at high frequency which is necessary for the design of high power density converters. The typical switching frequency of SiC MOSFETs in a power converter is in the range 200–500 kHz, whereas GaN HEMTs can be switched up to 2 MHz frequency.[18–21] For these reasons, GaN power devices are becoming a popular choice in the low-voltage (< 1000 V) commercial application segment.

GAN POWER ELECTRONICS ROADMAP

In a world where silicon has dominated the power semiconductor industry, it is a huge challenge for wide bandgap semiconductor materials such as SiC and GaN to enter the market and establish a place for themselves; however, in the last 2 years, the scenario has drastically changed for both the materials: SiC power devices made their entry in a Tesla Model 3 in 2018 while GaN found its way in with Oppo, Samsung, Xiaomi, and Realme's fast chargers at the end of 2019 and beginning of 2020. According to the latest Compound Semiconductor Quarterly Market Monitor (Q1/2020) by Yole Développement (shown in Fig. 1), the GaN market is expected to reach beyond US$ 700 million by 2025 due to the expansion of GaN power device technology from the consumer market to the automotive sector and could further skyrocket once GaN power devices find their way into industrial applications.[22]

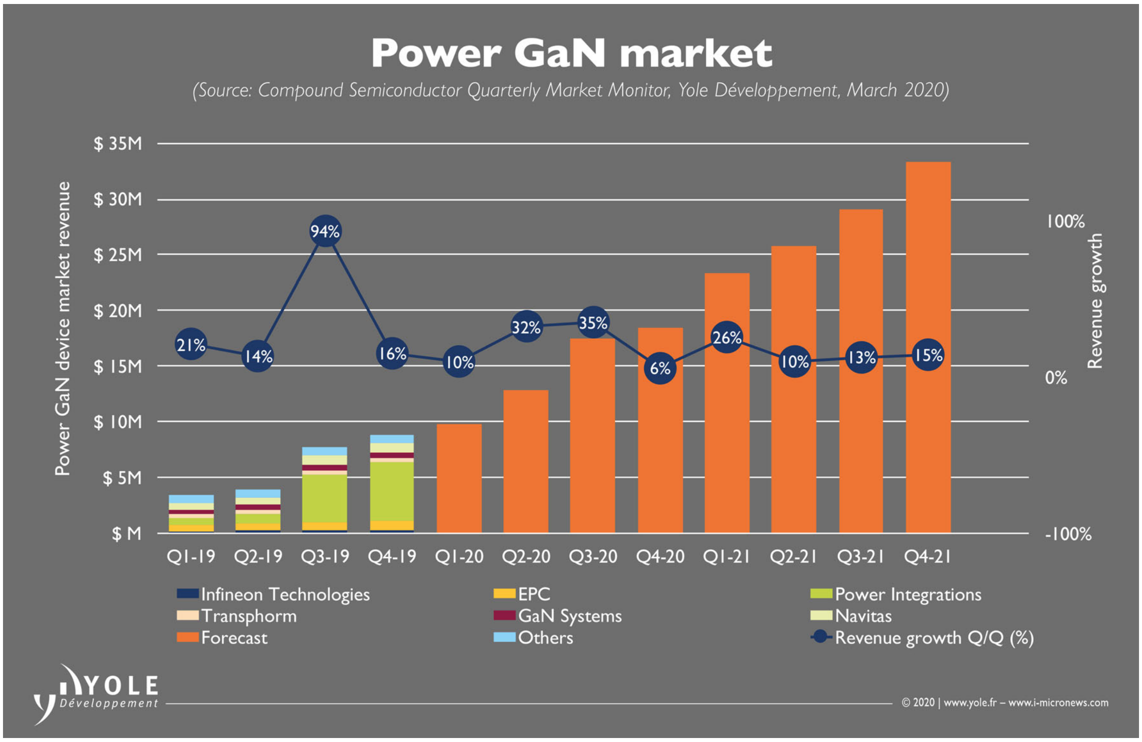
Another set of market research data (shown in Fig. 2) from Yole Développement highlights the GaN power device revenue and growth (existing and future forecast) based on market share held by various discrete semiconductor manufacturers. As per the data in Fig. 2, Power Integrations had the maximum share of revenue from GaN device followed by Transphorm in the last quarter of 2019. The contribution from other manufacturers were more or less unchanged as compared to the previous quarters in 2019.[22]

With respect to commercialization, GaN power semiconductor technology has significant success in the area of consumer fast chargers for smartphones. Many OEMs are developing GaN-based fast chargers to boost the charging time for high-capacity lithium-ion batteries used in their smartphones. These fast chargers are based on USB-C power delivery (PD) and other proprietary charging schemes. The following are some of the smartphone OEMs who are developing GaN-based chargers: Chinese smartphone OEM Oppo released its luxury flagship model; Reno ACE which integrates the Super (voltage open loop multi-step constant-current charging) VOOC 65 W fast charger using GaN technology; Chinese smartphone OEM Xiaomi


Entering a new era

(Source: Compound Semiconductor Quarterly Market Monitor, Yole Développement, March 2020)

Fig. 1. Long-term revenue of GaN power electronics from consumer electronics to various markets © 2020 Yole Développement. Reprinted with permission.


Power GaN market

(Source: Compound Semiconductor Quarterly Market Monitor, Yole Développement, March 2020)

Fig. 2. GaN power device market revenue and growth forecast based on discrete semiconductor manufacturer © 2020 Yole Développement. Reprinted, with permission

announced launching a 65 W rated accessory GaN USB-C fast charger for the Xiaomi Mi 10 Pro series, using GaN-on-silicon devices from Navitas Semiconductor; Chinese smartphone OEM Realme announced launching its X50 Pro 5G phone with GaN chargers using the SuperDart Charger protocol; and in addition to supplying 45 W accessory chargers to Samsung, power management company Power Integrations also scored a design win at the OEM for a 45 W fast charger.[22]

During recent years, GaN devices have been extensively used in the RF industry due to their high-power handling capability at high frequency while maintaining a smaller footprint, an aspect which is critical in RF circuits. As recent market forecast shows (Fig. 3), the overall GaN market is expected to exceed US$ 2 billion by 2024 with telecom and defense sectors being the major contributors. In the telecom sector, GaN is a viable candidate for power amplifiers below 6 GHz frequency in the 5G network.[23]

As discussed in the "Introduction" section, the GaN epitaxial layer is grown via heteroexpitaxy, i.e. an epi-layer is grown on a different material substrate. Silicon, sapphire, and SiC are the common production-grade substrates, whereas diamond is a research-grade substrate used for GaN epitaxial growth. The selection of substrate for GaN epilayer growth is based on the application, cost, and process manufacturability. Despite poor thermal conductivity of Si and a high degree of lattice mismatch between GaN and Si, GaN-on-Si is used due to the availability of low-cost and defect-free large diameter silicon wafers (150 mm and above). Sapphire substrate also suffers from low thermal conductivity and lattice mismatch with GaN; however, due to lower substrate cost and existing industry expertise in material and production, GaN-on-sapphire is used for GaN epilayer growth. The lattice structure of SiC closely matches GaN which means GaN epitaxy can be grown on it with lower dislocation density, thereby reducing leakage and improving reliability. Also, the thermal conductivity of SiC is high which is beneficial for high power density operation. However, the higher cost of low-defect-density SiC substrate and the unavailability of large production-grade wafers (> 150 mm) limits the use of GaN-on-SiC to high performance RF devices. GaN-on-diamond technology is currently in the research phase; however, test data are very promising and prove that this technology can provide very high power density with a smaller footprint.[24–29] Figure 4 shows the development timeline for RF GaN technology classified based on substrate and application. Even though both GaN-on-SiC and GaN-on-Si devices started off almost at the same time, GaN-on-SiC technology matured much faster.

Currently, GaN-on-SiC is widely used in 4G LTE wireless infrastructure and will soon penetrate the 5G network due to high-performance capability of the technology. Even though GaN-on-Si does not provide the same level of performance as GaN-on-SiC, it is still be a potential challenger for GaN-on-SiC due to the possibility of expanding production to

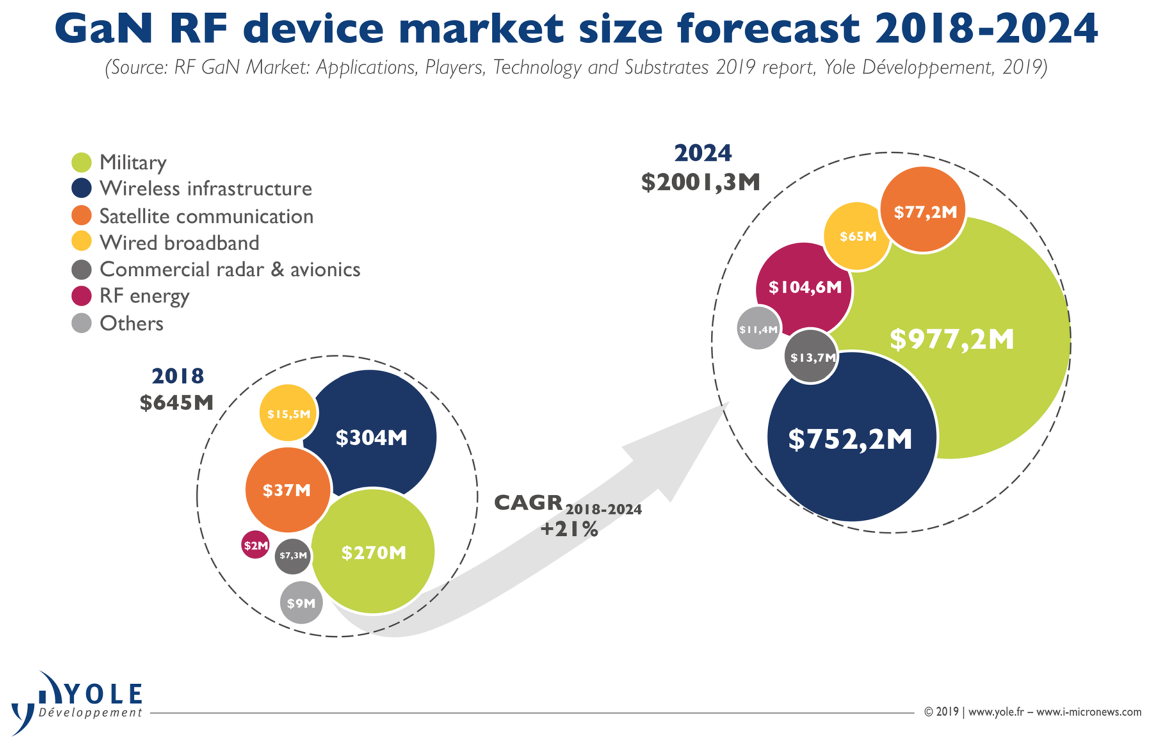


Fig. 3. GaN RF device market forecast 2018 – 2024 © 2020 Yole Développement. Reprinted, with permission

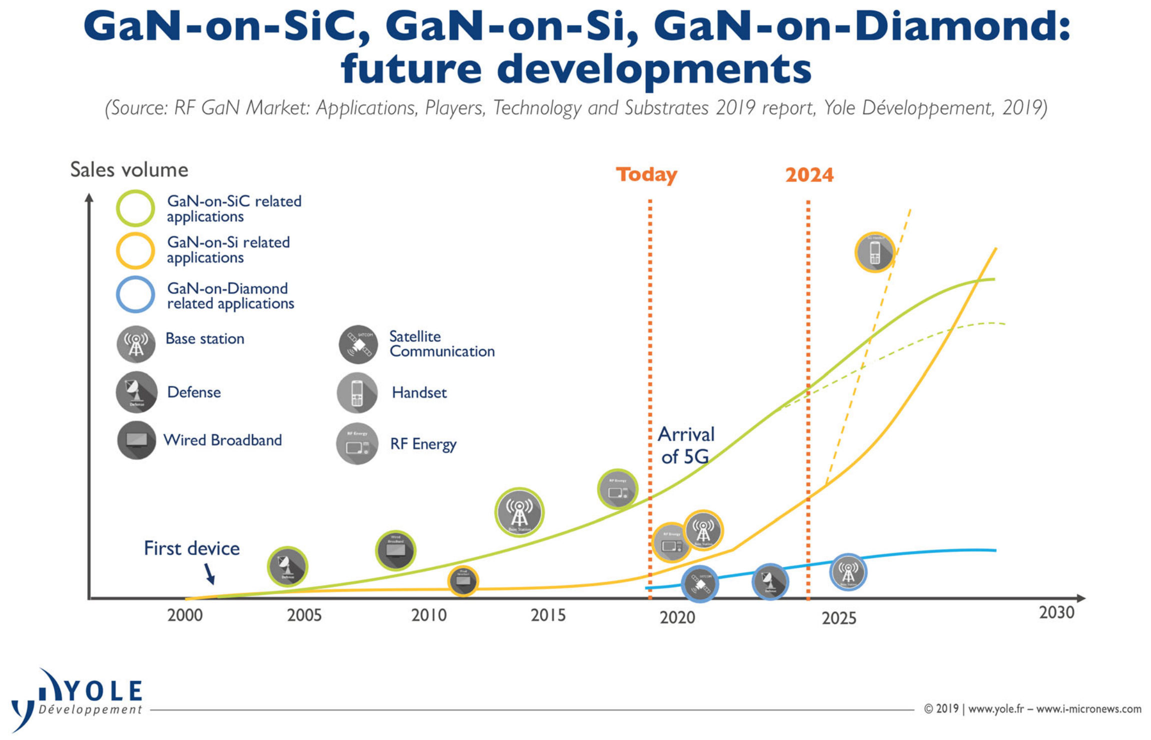


Fig. 4. RF GaN development timeline based on substrate type and application © 2020 Yole Développement. Reprinted with permission

200-mm (8-inch) wafers which provide a cost-effective solution for the commercial market. Because of the limited growth in GaN-on-diamond technology, it will take some time before devices enter production; however, this technology will primarily be applied towards performance-driven defense and telecommunication applications.[23]

GAN DEVICE BASICS

Based on the current status of GaN semiconductor technology, HEMT is the most successful approach for developing semiconductor devices rated up to 650 V for power electronic applications. This section will provide a brief overview of HEMT device structure and working principle. The cross-sectional view of a GaN HEMT is shown in Fig. 5. The device is usually grown on a semi-insulating substrate which has good thermal stability and close lattice-matching with GaN; typical substrates include silicon, sapphire, and SiC. A transition/buffer layer is grown on top of the substrate to isolate the channel from the substrate. It also minimizes any crystal defects arising due to the lattice mismatch between GaN and the substrate. The gate is typically a Schottky contact while the drain and source are ohmic contacts.[10]

The 2DEG formed at the AlGaN/GaN interface enables the flow of current between the drain and source electrodes. Detailed discussion of the mechanism responsible for the formation of 2DEG is beyond the scope of this manuscript. The presence of 2DEG creates a short circuit between the drain and source which is the ON state of the device. In order to turn OFF the device, electrons in the 2DEG must be depleted. This is achieved via the gate electrode which is formed as a Schottky contact on top of the AlGaN. A negative voltage to the Schottky contact will reverse bias the Schottky junction and form a depletion region, thereby turning OFF the device. This is a depletion mode (also known as normally ON) device as negative voltage at the gate electrode is required to keep the HEMT in the OFF state. Since normally-ON devices are not favorable for power electronic applications, cascode configuration (Fig. 6) is used which consists of a series connection of a low voltage (LV) normally OFF silicon MOSFET with a high voltage (HV) normally ON GaN HEMT. In this configuration, the gate of the HEMT is shorted to the source of the MOSFET and the source of the HEMT is shorted to the drain of the MOSFET. The working of a cascode configuration can be summarized as follows: when a positive gate-source bias is applied to the Si MOSFET, effective gate-source voltage of the normally ON HEMT is reduced to zero and the device is turned ON. When the gate-source bias voltage is removed, the applied drain voltage to the cascode configuration creates a negative gate-source voltage across the HEMT which depletes the 2DEG, thereby turning OFF the cascode configuration.[30]

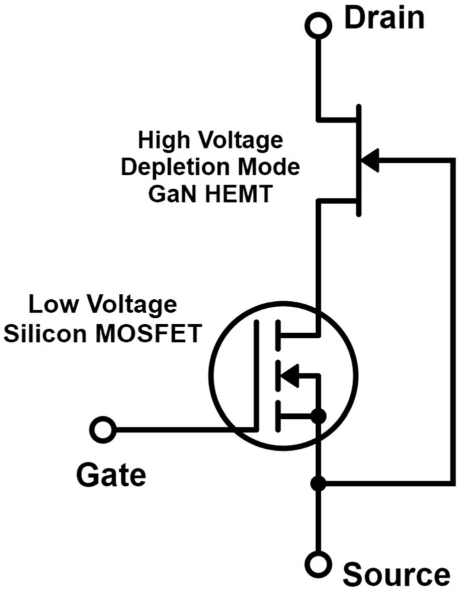


Fig. 6. Cascode configuration using Si MOSFET and depletion mode GaN HEMT

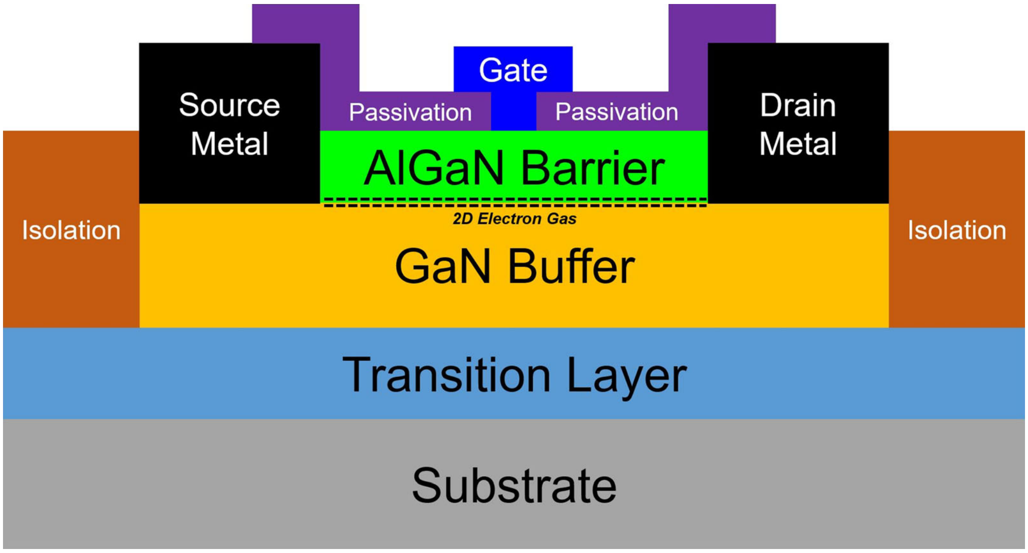


Fig. 5. AlGaN/GaN HEMT cross-section

COMMERCIAL SYSTEMS USING GAN POWER SEMICONDUCTORS

It is quite evident from the references that there is a plethora of research grade GaN-based system prototypes developed at both industry and university levels; however, in order to achieve widespread adoption of GaN technology, it is necessary to have cost-effective commercially available power conversion systems which employ GaN devices.[10,31] The following section will discuss various commercially available GaN-based power electronic systems which highlight the power density and energy efficiency attained by using GaN device. It may be noted that the GaN-based systems discussed in this paper were selected based on the availability of data and permission from information/copyright owner.

1000 W Bidirectional DC–DC Converter Developed by Diamond Electric Mfg. Co.

A 1 kW isolated bidirectional DC–DC converter (shown in Fig. 7) was developed by Diamond Electric Mfg. Co., Japan, using GaN semiconductor technology. The power converter was designed for electric vehicle (EV)- and smart grid-related applications including onboard chargers, grid-connected battery charging and uninterruptible power supply (UPS) systems.

A salient feature of this power converter is that it has the form factor of a business card. This was possible due to the high switching frequency (up to 2 MHz) used in the converter design which greatly reduced the size of magnetic and capacitive energy storage components. Table I summarizes the specification of the power converter.

Fig. 7. GaN-based 1 kW isolated bidirectional DC–DC converter developed by Diamond Electric Mfg. Co. © 2020 Power Electronics World™. Reprinted with permission

500 W AC-DC Power Converter Developed by TDK-Lambda

TDK-Lambda, a group company of TDK, has developed its first 500 W AC-DC power supply (shown in Fig. 8) using GaN semiconductor technology. The power supply was designed for various harsh environment applications including commercial off-the-shelf power supplies, custom fan-less power supplies and traffic signaling.

The AC-DC baseplate cooled power supply module (Model: *PFH500F-28*) uses a bridgeless totem-pole power factor correction topology and was designed using Transphorm's *TPH3206LDG* GaN field effect transistor (FET) which is available in a 8 mm × 8 mm PQFN package (shown in Fig. 9). The ratings of the GaN FET can be summarized as follows: The device is rated for a blocking voltage of 600 V and ON-state current of 12 A (@ $T_C = 100°C$). The maximum ON-state resistance (R_{DSON}) is 180 mΩ and has very low reverse recovery charge (Q_{RR}) of 54 nC which eliminates the need for a free-wheeling diode.[32]

Incorporating GaN technology into the power supply designed increased the power efficiency by 5% and power density by 30% while reducing the size by 28% and heat loss by 38% as compared to the previous product. Table II summarizes the specification of the power converter.[33]

Ultra-High Efficiency AC Power Conversion Modules Developed by Aveox Inc

Aveox Inc., a leading designer and manufacturer of high power density DC motors, controllers and power conversion electronics and a pioneer in unmanned air vehicle (UAV) propulsion systems, collaborated with GaN Systems to develop a compact, light-weight, and ultra-high efficiency 3-phase AC power converter with active power factor correction (APFC) for aerospace and defense applications. The integration of GaN semiconductor technology from GaN Systems into the power conversion system allowed the power modules to be more than 5× smaller than conventional units using silicon technology (form factor comparison shown in Fig. 10). GaN transistors have very low ON-state loss which not only enables high system efficiency of $> 97\%$, but also reduces heat dissipation which is beneficial for limited cooling available in a compact form-factor system.[35]

The GaN-based power converter developed by Aveox is the world's smallest 3-phase APFC module for defense and aerospace applications with a power density of 10 kW/kg which is the highest in the industry. The system is compliant with stringent Radio Technical Commission for Aeronautics (RTCA) DO-160 requirements which pertains to environmental conditions and test procedures for airborne equipment, a set of best practices which has been adopted by all major aerospace and avionics manufacturers.[36] A salient feature of the GaN Systems' HEMT is its proprietary *GaNpx*® package (shown in Fig. 11) which is a 450-μm-thick embedded package with bottom-side cooling. The *GaNpx*® packaging process involves the integration

Table I. Summary of product specifications for GaN-based 1 kW isolated bidirectional DC–DC converter developed by Diamond Electric Mfg. Co. © 2020 PowerPulse.Net. Reprinted with permission

Specification	Rating
Output power	−1000 to +1000 W (bidirectional)
Voltage range	270–330 V
Current range	−3.7 to +3.7 A (bidirectional)
Conversion efficiency	Up to 95%
Switching frequency	Up to 2 MHz
Dimension	93.5 × 60 × 10.5 mm (excluding control circuit and heat sink)

Fig. 8. GaN-based 500 W AC-DC power supply (Model: PFH500F-28) developed by TDK-Lambda © 2020 Business Wire, Inc. Reprinted with permission

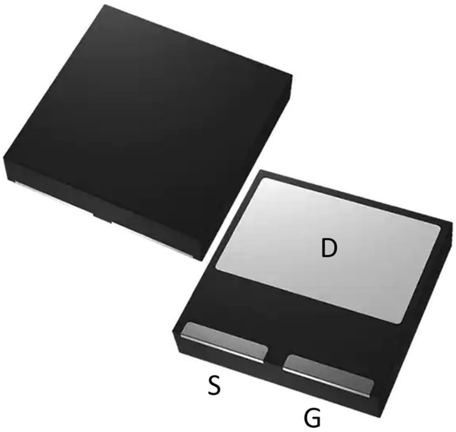


Fig. 9. Top and bottom view of the Transphorm TPH3206LDG GaN FET PQFN package indicating drain (D), gate (G), and source (S) metal pads © 1995-2020 Digi-Key Electronics. Reprinted with permission

of GaN HEMT die into a very thin FR4 matrix. Current flow between the die surface and bottom thick copper foils is facilitated through copper micro vias. The thermal performance is improved by thinning the silicon substrate to 250 μm followed by the deposition of approximately 6 μm of copper on the wafer backside which provides easy connection to the thermal pad on the bottom of the package thereby reducing the junction-to-case thermal resistance ($R_{\theta JC}$). Because of the absence of bond wires, the parasitic inductance of the package is close to that of an unpackaged die. As per manufacturer claim, this unique packaging technology allows faster switching, high power density, better thermal performance, ultra-low inductance, and the smallest footprint for ultra-high density design. More information on this proprietary package scheme is out of the scope of this manuscript and can be found in the references.[37–39]

3000 W AC-DC Power Supply Unit Developed by Bel Power Solutions

Bel Power Solutions, a Bel group and premier global manufacturer of power management devices, has developed a 3000 W titanium efficient AC-DC power-factor-corrected (PFC) DC/DC power supply (Model: *TET3000-12-069RA*) that converts standard AC mains voltage or high-voltage DC bus voltage into an output DC voltage of 12 V for powering intermediate bus architectures (IBA) in high-performance and high-reliability servers, routers and network switches using GaN semiconductor technology. The TET3000 (shown in Fig. 12) is a titanium efficiency DSP-controlled front-end power supply which uses GaN power transistors to achieve a power density of 31.7 W/in^3 in a compact package measuring 2.72 × 1.59 × 21.85 inches. The system employs a resonant soft switching technology and interleaved power trains to reduce component stresses, which lead to increased system reliability and very high efficiency.[40,41]

A salient feature of this power supply is the inclusion of Transphorm's Cascode GaN FET TPH3205WSB into Bel Power's bridgeless totem pole PFC architecture. TPH3205WSB is a normally OFF Cascode GaN FET rated for a blocking voltage of 650 V and ON-state current of 35.2 A (@ T_C = 25°C) with a typical ON-state resistance of 49 mΩ.[42] The high-frequency switching supported by GaN FET reduces crossover losses and increases system efficiency and eliminating the bridge rectifier from the PFC topology decreases losses by 20–30%. Table III summarizes the major specifications of the power supply.

Table II. Summary of product specifications for GaN-based AC-DC power supply model PFH500F-28 developed by TDK-Lambda (Data from Ref. 34)

Specification	Rating
Output power	504 W
Output voltage	28 V
Rated current	18 A
Power efficiency	90–92%
Power density	100 W/inch^3
Dimension	101.6 × 61.0 × 13.3 mm Brick Footprint

Fig. 10. Comparison between Aveox's GaN (compact) and silicon-based (large) power conversion systems highlighting the significant improvement in power density using GaN semiconductors © 2020 GlobeNewswire. Reprinted with permission

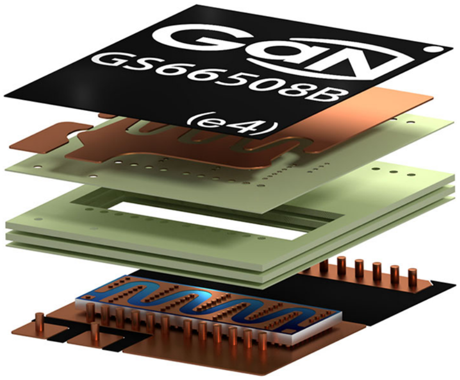


Fig. 11. Exploded view of GaN Systems' GaNpx® package with bottom-side cooling © 2019 Gan Systems Corp. Reprinted with permission

Fig. 12. GaN-based 3000 W AC-DC power supply (Model: TET3000-12-069RA) developed by Bel Power Solutions © 2019 Bel Fuse Inc. Reprinted with permission

Table III. Summary of product specifications for TET3000-12-069RA AC-DC power supply developed by Bel Power Solutions (Data from Ref. 41)

Specification	Rating
Universal input voltage range	90–300 VAC
DC input voltage range	180–410 VDC
Nominal output power*	3000 W
Output DC voltage	12.3 V
Nominal output current*	244 A
Power efficiency$^{\xi}$	94.2%
Power factor	0.96–0.99
Dimension	2.72 × 1.59 × 21.85 inch

*V_{IN} > 180 VAC and V_{OUT} = 12.3 VDC.
$^{\xi}$$V_{IN}$ = 230 VAC, V_{OUT} = 12.3 VDC, I_{OUT} = 244 A, and T_A = 25°C.

3000 W AC-DC Power Rectifier Developed by Eltek

Eltek (a Delta Group company, Norway) collaborated with Infineon Technologies to develop a high-efficiency AC-DC power rectifier module using GaN technology. This super high efficiency (SHE) power rectifier module (Model: *Flatpack2 SHE 48/3000*) shown in Fig. 13 has a peak efficiency up to 98% and achieves a power density of 33 W/inch^3 and was developed for markets and applications where the cost of energy is high, e.g. grid-connected and Telecom (wired and wireless) applications. This high efficiency and power density are achieved using 600 V CoolGaN™ HEMT from Infineon Technologies.[43,44]

The efficiency of a GaN-based power module has been compared to its high efficiency (HE) predecessors in Fig. 14 which clearly shows the reduction in power loss and heat dissipation due to the GaN devices. This not only reduces the energy wastage by 50%, but also the environmental footprint and operating expense (OPEX).

The overall cost saving achieved by incorporating GaN devices in the power electronics design can be seen by the following examples where the existing systems using an earlier version of power supply (Flatpack2 HE with 92% efficiency) were replaced with Flatpack2 SHE power supply: In a single mobile base station implementation in South Italy with a total load of 6 kW, there was an annual energy cost saving of €576 and reduction of CO_2 emission by 2.2 tons. In another scenario, at a central office site in UK with a total load of 250 kW, there was an annual energy cost saving of €18,352 and reduction of CO_2 emission by 97.3 tons. (CO_2 emission data source: the Environmental Protection Agency, EPA, estimated 1 kW-h produces 1.52 lb (0.689 kg) of carbon dioxide excluding line-losses). Table IV summarizes the specification of the Eltek DC–DC power converter.[43]

3000 W Solar Inverter and Battery Charger Developed by Inergy Solar

Inergy Solar collaborated with Transphorm Inc. (the leader in the design and manufacturing of the highest reliability and first JEDEC- and AEC-Q101 qualified GaN semiconductors) and design partner Telcodium Inc. to develop a GaN-based solar inverter comprising a photovoltaic (PV) inverter and battery charger. The inverter unit known as Apex 3 K (shown in Fig. 15) has a storage capacity of 3 kWh and an output power of 3 kW. This inverter was designed to provide reliable off-grid AC power to consumers and professionals in various applications including emergency services, industry, and construction. The inclusion of GaN semiconductor enables high-temperature operation without any internal cooling fan and its rugged

Table IV. Summary of product specifications for GaN-based DC–DC power module Flatpack2 SHE 48/3000 developed by Eltek (Data from Ref. 45)

Specification	Rating
Output power	3000 W
Output voltage	48 V
Rated current	62.5 A
Power efficiency	97.8%
Power density	$33\ \mathrm{W/inch}^3$

Fig. 13. GaN based 3 kW DC–DC power module (Model: Flatpack2 SHE 48/3000) developed by Eltek © 2019 Eltek. Reprinted with permission

Fig. 15. GaN-based 3000 W solar inverter and battery charger (Model: Apex 3 K) developed by Inergy Solar © 2020 Inergy Solar. Reprinted with permission.

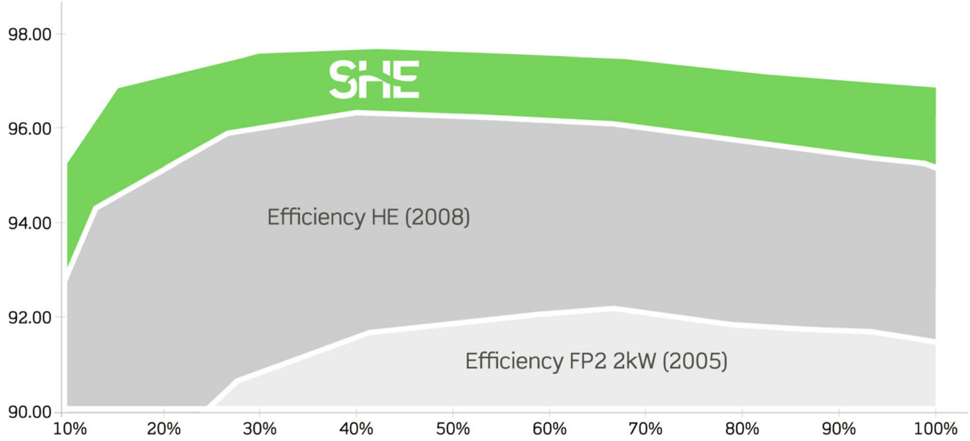


Fig. 14. Efficiency comparison between super high efficiency (SHE) and high efficiency (HE) power modules © 2019 Eltek. Reprinted with permission

construction makes it water-resistant and dustproof.[46,47]

Apex 3 K uses Transphorm's TP65H050WS 50 mΩ TO-247 FET and TPH3206LDGB 150 mΩ PQFN FET for its PV inverter and battery converter power electronics respectively. The characteristics and packaging of the GaN devices made them close replacements for Si-based IGBT and MOSFET which were used in the previous generation inverter model. The main specifications of the GaN devices used in this solar inverter are summarized in the Table V.

The 3rd generation GaN devices are not only capable of increasing the power density by 40% while switching at a much higher frequency than its silicon counterpart, they have a wider range of operating gate voltage ± 20 V which enables robust and reliable operation. With the GaN devices, Apex 3 K achieved 33% higher power output and 4× increase in charging speed while reducing the product weight by 50%.[46,47] The major specifications of Apex 3 K solar inverter are summarized in Table VI.

1600 W Computer Power Supply Unit developed by Corsair

Corsair Components, Inc. has developed the first GaN-based computer power supply unit (PSU) with 80 PLUS Titanium efficiency certification. The AX1600i model (shown in Fig. 16) is a modular PSU rated for 1600 W and is designed for high performance computational platforms, especially for gaming.

A salient feature of this power supply is the inclusion of Transphorm's Cascode GaN FET (TPH3205WS) into Corsair's bridgeless totem-pole PFC architecture. TPH3205WS is a normally OFF Cascode GaN FET rated for a blocking voltage of 600 V and ON-state current of 36 A (@ T_C = 25°C) with a typical ON-state resistance of 52 mΩ.[49,51] Transphorm's GaN device not only increased the PSU's power output by 6.5% as compared to the 1500 W previous generation model AX1500i in an 11% smaller package, but also enabled equivalent 50°C continuous operation with slower fan speed thereby reducing audible noise at full load. Based on independent test results, the power quality of AX1600i is excellent with barely any voltage ripple appearing on any of the voltage rails and under any load, while the voltage regulation is practically ideal. The very high electrical efficiency of the platform not only minimizes energy waste but also allows the PSU to operate very quietly and maintain low internal temperatures even at high load. The high-quality parts used in the system are almost completely unaffected by environmental factors thereby ensuring performance even in harsh conditions.[52] A summary of major product specifications is given in Table VII.

45 W USB Type-C Power Delivery (PD) Charger by RAVPower

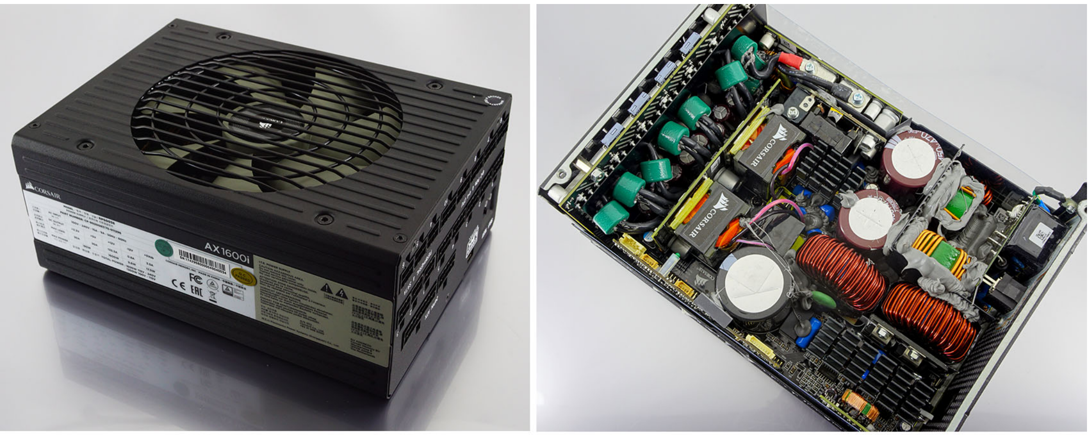
USB Type-C or USB-C is the emerging standard for charging and transferring data and is included in the newest consumer electronic devices such as laptops, smartphones, and tablets and will soon be established as a new standard for power and data exchange. USB-C features a smaller reversible connector and the cable can carry significantly more power and also offer up to double the transfer speed of USB 3.0 at 10 Gbps. The USB PD specification supported by USB Type-C is capable of handling power delivery up to 100 W and is bi-directional in nature, i.e. a device can send or receive power while simultaneously transmitting data across the connection.[54] An ultra-compact 45 W USB Type-C PD charger (Model: RP-PC104) has been developed by RAVPower for portable consumer electronics. The main highlight of this ultra-compact USB-C PD charger (shown in Fig. 17) is the integration of GaN device in the power electronics of this charger which has enabled a power density of 11 W/in^3.

Table VI. Summary of product specifications for Inergy Solar Apex 3 K [Data from Refs. 46 and 47]

Specification	Rating
Output power	3 kW
Output voltage	110/120 VAC
Energy storage capacity	3 kWh
Minimum efficiency	98% (light to full load)
Recharge time	4 h.
Weight	45 lbs

Table V. Summary of GaN Device specifications used in Inergy Solar Apex 3 K solar inverter [Data from Refs. 48–50]

Specification	TP65H050WS	TPH3206LDGB
Blocking voltage (V)	650	650
On-state resistance (mΩ)	50	150
Rated drain current (A) @ T_C = 100°C	25	10
Reverse recovery charge Q_{RR} (nC)	125	52
Operating case temperature (°C)	−55 to +150	−55 to +150
Package	TO-247	PQFN



(a) (b)

Fig. 16. External (a) and internal (b) view of Corsair 1600 W GaN-based computer PSU (Model: AX1600i) © 2020 EnVeritas Group. Reprinted, with permission

Table VII. Summary of product specifications for Corsair's AX1600i [Data from Ref. 53]

Specification	Rating				
Voltage rail	3.3 V	5 V	12 V	5 V_{SB}	−12 V
Rated current	30 A	30 A	133.3 A	3.5 A	0.8 A
Maximum power	180 W		1600 W	17.5 W	9.8 W
Power efficiency	80 PLUS Titanium				
Technology	DSP with GaN-based Totem-pole PFC				
Dimension	150 mm × 86 mm × 200 mm				

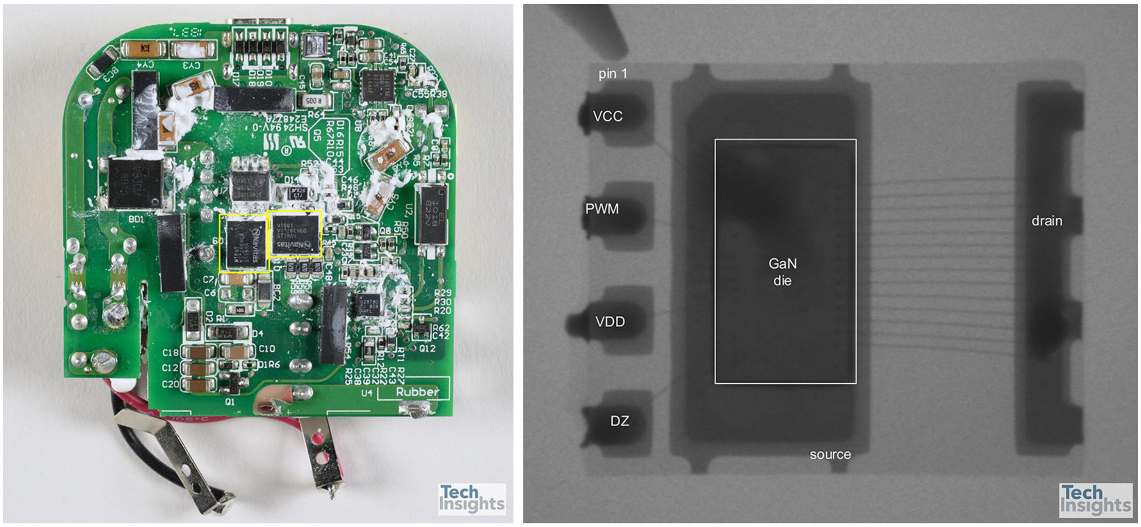
An independent analysis of this charger performed by TechInsights Inc. has revealed the presence of two Navitas NV6115 GaN-based power ICs shown in Fig. 18a. The x-ray top side plan-view of the Navitas NV6115 is shown in Fig. 18b. The source and drain pin connections are wire bonded with multiple wires to the GaN die. The power (VDD), ground (VCC), pulse width modulation (PWM), and VDD setting voltage (DZ) connections are wire bonded to the die with single wires.[55]

The NV6115 is a 650 V GaNFast™ power IC, optimized for high frequency, soft-switching topologies. This power IC consists of monolithically integrated GaN HEMT and gate drive circuitry in a low-profile SMT QFM package. The IC operates at 2 MHz switching frequency and is rated for a continuous drain current of 8 A (@ T_C = 100°C) and has an ON-state resistance of 170 mΩ.[56] The integration of logic, analog and power onto a single GaN IC by Navitas has enabled compact power electronic solutions which is beneficial for consumer electronics. The product specifications of RP-PC104 USB Type-C PD charger are given in Table VIII.

Fig. 17. External view of RP-PC104 charger analyzed at TechInsights Inc. © 2020 TechInsights Inc. Reprinted with permission

Proprietary 65 W GaN-Based Smartphone Charger by OPPO

A 65 W GaN-based smartphone charger (model: VCA7GACH) was designed and developed by Guangdong OPPO Mobile Telecommunications Corp., Ltd (commonly referred to as OPPO) for its Reno Ave smartphone model. Proprietary Super (voltage open loop multi-step constant-current charging) VOOC fast-charging scheme has been used in the charger as opposed to the more common USB-C PD charging scheme. According to OPPO, this charger (shown in Fig. 19) can charge the 4000 mAH dual-cell smartphone battery in 30 min. The



(a) (b)

Fig. 18. Internal view of RP-PC104 charger highlighting the GaN devices in yellow boxes (a) and x-ray view of Navitas GaN power IC NV6115 (b) after product teardown analysis © 2020 TechInsights Inc. Reprinted with permission

Table VIII. Product specifications for RAVPower RP-PC104 USB Type-C PD charger [Data from Ref. 57]

Specification	Rating
Output power	45 W
Input voltage	100 V–240 VAC @ 50/60 Hz
Input current	1.25 A
Output voltage and current	(USB-C PD 3.0) 5 V/3A, 9 V/3A, 12 V/3A, 15 V/3A, 20 V/2.25A
Dimension	3.1 × 2.2 × 0.6 in
Weight	2.72 oz

charger is able to drive 6.5 A at 10 V to deliver a maximum power output of 65 W. The incorporation on GaN technology in the Super VOOC charger has enabled a power density of 11.4 W/in^3 which is comparable to that obtained by the RAVPower RP-PC104 USB-C charger. The Super VOOC charger is also backward compatible with USB DCP and VOOC protocols.[58]

An independent analysis of this charger performed by TechInsights Inc. has revealed the presence of a Power Integrations *PowiGaN* device SC1923 shown in Fig. 20a. Further x-ray analysis of the Power Integrations SC1923 device revealed the presence of four separate dies mounted in a surface mount package shown in Fig. 20b.

These four dies were analyzed to be: DX101C1 and DX121C gate drive ASIC dies, SB190C GaN power FET, and DX120B3 Si MOSFET that is driving the GaN power FET in a cascode configuration. The product specifications of the VCA7GACH charger are given in Table IX.[58]

GaN-Based Software Defined Inverter Developed by Siemens Corporate Technology

TAPAS is a software-defined inverter (SDI) designed and developed by Siemens Corporate Technology in collaboration with Texas Instruments, Efficient Power Conversion (EPC), Würth Elektronik, and Allegro Micro. It is a multipurpose GaN-based development board (shown in Fig. 21) with a TMS320F28x controller onboard. The TAPAS system features a 48 V, 3-phase GaN power stage (with onboard filters) built around (EPC2021) GaN transistors.[59,60]

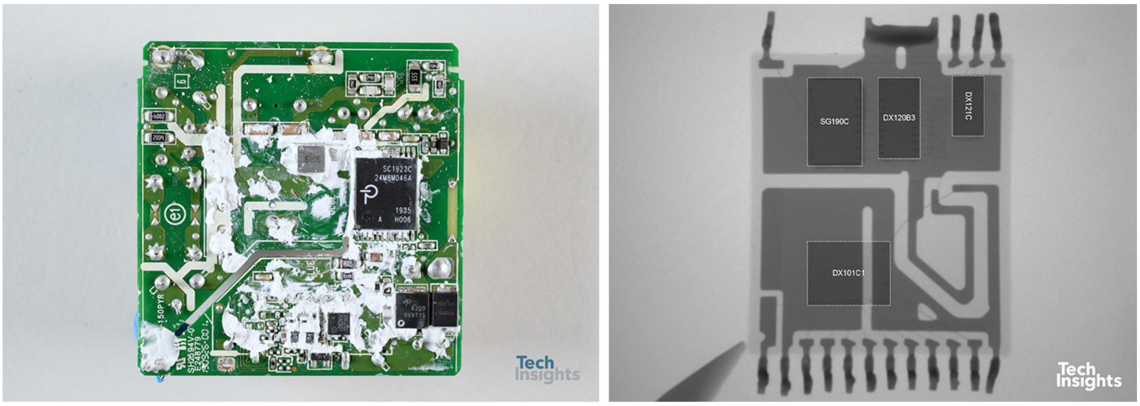
EPC2021 is an enhancement mode power transistor rated for a blocking voltage of 80 V, continuous forward current of 90 A, and an ON-state resistance of 2.5 mΩ. This GaN device is available only in a passivated die form with solder bumps (Fig. 22) and measures 6.05 mm × 2.3 mm.[61]

TAPAS design allows the user to select a high switching frequency/bandwidth (300 kHz and beyond) whilst producing a smooth output waveform. This SDI development board is compatible with Raspberry Pi and can be configured for use in collaboration with other multiple boards, giving rise to multi-phase applications such as quadcopters or multi-axis servo control.[59,62] The specifications of TAPAS SDI have been summarized in Table X.

Fig. 19. External view of VCA7GACH charger analyzed at TechInsights Inc. © 2020 TechInsights Inc. Reprinted with permission

CHALLENGES TO THE ADOPTION OF GAN POWER SEMICONDUCTOR TECHNOLOGY

Even though GaN is a promising WBG semiconductor material for high-temperature, high-speed power electronics application and is already used in commercial products, there are still challenges to its widespread adoption in the power electronics industry. The power electronics industry is currently dominated by silicon-based devices whose performance and reliability are well proven due to several decades of maturity. It is not uncommon for the industry to be reluctant to adopt a new power semiconductor technology such as GaN (or SiC) with limited reliability data when a proven technology such as silicon is available, especially in the automotive sector where reliability is paramount. Another factor that limits the adoption of GaN technology is the cost per amps ($/amps) for a power device which is relatively higher than silicon. Cost reduction can be achieved through a lean high-volume manufacturing process on larger diameter wafers (150 mm or higher) and cost-effective epitaxial process. The blocking voltage capability is also a bottleneck since GaN HEMTs have a lateral structure and higher blocking voltage device, requiring larger lateral spacing thereby increasing the die size and reducing the die per wafer which has financial implications. Even though 900 V GaN



(a) (b)

Fig. 20. OPPO Reno Ace Super VOOC charger main PCB (a) and Power Integration SC1923C package x-ray view (b) after product teardown analysis © 2020 TechInsights Inc. Reprinted with permission

Table IX. OPPO VCA7GACH Super VOOC charger specifications © 2020 TechInsights Inc. Reprinted with permission

Specification	Rating
Output power	65 W
Input voltage	100 V–240 VAC @ 50/60 Hz
Input current	1.6 A
Output voltage and current	(USB) 5 V/2A, (Super VOOC) 10 V/6.5A
Dimension	5.5 × 5.5 × 3.1 cm
Weight	3.98 oz

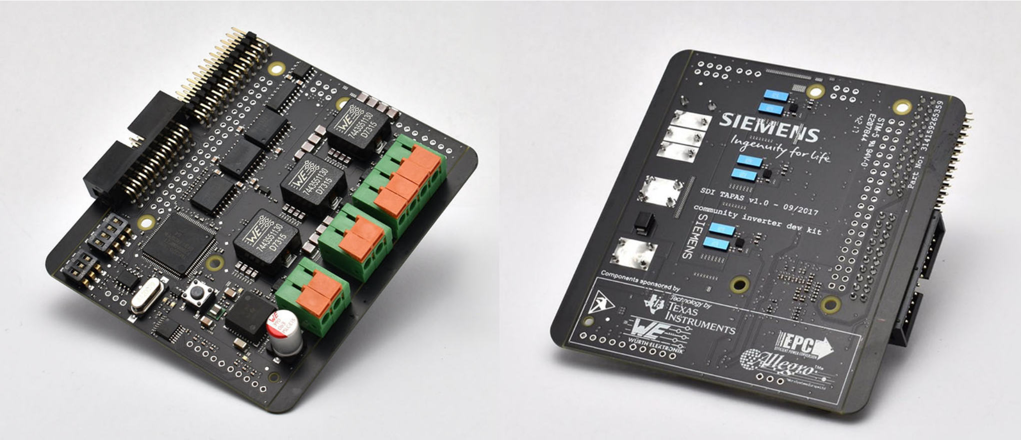


Fig. 21. GaN-based software defined inverter (TAPAS) developed by Siemens Corporate Technology © 2020 PowerPulse. Net. Reprinted with permission

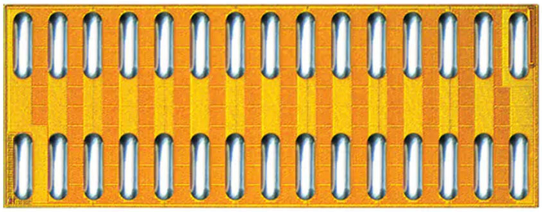


Fig. 22. GaN power transistor EPC2021 in passivated die package © 1995-2020 Digi-Key Electronics. Reprinted with permission

Table X. Summary of product specifications for TAPAS SDI developed by Siemens corporate technology (data from Ref. 62)

Specification	Rating
Input voltage	12–48 VDC
Continuous power	300 W
DC/AC (per phase) current	30 A
Switching frequency	Up to 600 kHz

devices are commercially available, the 600–650 V segment remains the popular choice. Lastly, even though it is possible to design a normally OFF GaN HEMT, it not only requires precise process techniques, but also the resulting device would have a low threshold voltage, thereby resulting in a lower drive voltage requirement which could be a challenge for power electronics designers.[63]

CONCLUSION

Gallium nitride (GaN) as a wide bandgap semiconductor material shows great promise in the area of power electronic devices. In addition to being a wide bandgap semiconductor, the high electron mobility achieved in a GaN HEMT makes it a device of choice for high power density and high-temperature power electronics applications. The ability of a GaN HEMT to operate at high switching frequency can drastically reduce the size of energy storage components in the power circuit thereby scaling down the system form-factor. Based on historical data, market research has predicted astounding growth in the GaN power electronics market. Several companies have developed commercial power conversions systems using GaN devices which have shown tremendous performance improvement as compared to its silicon counterpart. The incorporation of GaN devices in the power converter not only improved the power conversion efficiency, but also reduced the weight and volume of the unit, thereby resulting in a high power density system. Power Integrations, Transphorm Inc., GaN Systems Inc., and Navitas Semiconductor are the major GaN device manufacturers whose devices are used in the commercial power conversion systems discussed in this journal.

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CONFLICT OF INTEREST

The authors declare that they have no conflict of interest.

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