National Aeronautics and Space Administration

BODY OF KNOWLEDGE FOR GALLIUM NITRIDE POWER ELECTRONICS

NASA Electronic Parts and Packaging (NEPP) Program
Office of Safety and Mission Assurance

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Executive Summary

Gallium nitride (GaN), a wide bandgap (WBG) semiconductor, has emerged as a very promising material for electronic components due to the tremendous advantages it offers compared to silicon (Si), such as power capability, extreme temperature tolerance, and high frequency operation. This report serves as a body of knowledge (BOK) in reference to the development and current status of GaN technology obtained via literature and industry surveys. It provides a listing of the major manufacturers and their capabilities, as well as government, industry, and academic parties interested in the technology. The document also discusses GaN's applications in the area of power electronics, in particular those geared for space missions. Finally, issues relevant to the reliability of GaN-based electronic parts are addressed and limitations affecting the full utilization of this technology are identified. This BOK focuses mainly on power applications for GaN, but will also briefly mention radio frequency (RF) applications for completeness.

Acronyms

2DEG	Two-Dimensional Electron Gas
AlGaN	Aluminum Gallium Nitride
AlN	Aluminum Nitride
ARPA-E	Advanced Research Projects Agency-Energy
ASIC	Application Specific Integrated Circuits
BJT	Bipolar Junction Transistor
BOK	Body of Knowledge
CAVET	Current Aperture Vertical Transistor
CTE	Coefficient of Thermal Expansion
DC	Direct Current
DOE	Department of Energy
EMI	Electromagnetic Interference
ESTD	Electronics Science and Technology Division
FET	Field Effect Transistor
FOM	Figure of Merit
GaN	Gallium Nitride
GIGA	GaN Initiative for Grid Applications
g_m	Transconductance
HEMT	High Electron Mobility Transistor
I_{DSS}	Drain Current Leakage
LET	Linear Energy Threshold
MMIC	Monolithic Microwave Integrated Circuit
MOSFET	Metal-Oxide-Semiconductor Field-Effect Transistor
NASA	National Aeronautics and Space Agency
NEPP	NASA Electronic Parts and Packaging
PEIC	Power Electronics Industry Collaborative
PIDS	Post-Irradiation Drain Stress

PIGS	Post-Irradiation Gate Stress
POL	Point of Load
PV	Photovoltaic
$R_{DS(ON)}$	On-State Drain-Source Resistance
RF	Radio Frequency
SBIR	Small Business Innovation Research
SEB	Single-Event Burnout
SEE	Single-Event Effect
SEGR	Single-Event Gate Rupture
Si	Silicon
SiC	Silicon Carbide
STTR	Small Business Technology Transfer
TCAD	Technology Computer Aided Design
TID	Total Ionization Dose
TX	Technology Taxonomy
UAV	Unmanned Aerial Vehicle
UPS	Uninterruptible Power Supply
V_{DS}	Drain-Source Voltage
V_{TH}	Threshold Voltage
VFET	Vertical Field Effect Transistor
WBG	Wide Bandgap

Background

Integrated circuits and power devices utilized by the semiconductor industry for the production of advanced computers, consumer electronics, communication networks, and industrial and military systems have been almost exclusively based on silicon technology. The requirements of future electronics place a great emphasis on achieving new devices with greater power density and energy efficiency, especially in the power electronics arena. This emphasis poses an increasing challenge to come up with new design protocols, innovative packaging, and even new semiconductor materials, as it is widely believed that silicon technology has finally reached its fundamental physical limits. In addition to the devices' electrical requirements such as voltage and power ratings, the operational environments of power systems might encompass challenging conditions that include radiation, extreme temperature exposure, and wide-range thermal cycling, where conventional silicon-based systems are incapable of survival or efficient operation.

Wide Bandgap Technology

Power semiconductor devices are critical to the development of lightweight, highly efficient electronic systems needed for a wide variety of applications such as planetary exploration, deep space missions, terrestrial power grids, industrial machinery, and geothermal energy extraction. The next generation of power electronics necessitates different types of semiconductor materials as today's dominant power semiconductor device material, silicon, is limited in terms of performance and efficiency at higher power levels and higher temperatures. WBG semiconductor devices, such as those based on GaN or silicon carbide (SiC), have emerged in the commercial market and have shown great potential to replace traditional silicon parts gradually in the high power arena. The benefits that GaN semiconductor devices offer over their silicon counterparts in power applications include greater efficiency at higher voltage, higher temperature operation, and higher frequency switching [1]. Compared to 1.1 eV for Si, the bandgap of GaN is 3.4 eV. A wider bandgap results in a higher critical electric field, which, together with a lower dielectric constant, translates to a lower on-state resistance for a given blocking voltage. The wider bandgap also enables higher-temperature operation before the device "goes intrinsic," that is, before the intrinsic carrier density exceeds the donor impurity density [2]. GaN, like SiC, exhibits a phenomenon called polytypism where the differing atomic radii of gallium and nitrogen result in different semiconductor parameters depending on the stacking sequence of the layers. GaN is often grown in a Wurtzite hexagonal crystal structure, but can also be grown in a cubic structure known as zinc-blende. While the band gap of the zinc-blende is about 3.2 eV, Wurtzite crystal is closely related to the structure of hexagonal diamond and has a larger energy band gap of 3.4 eV. The Wurtzite structure, which is thermodynamically stable under ambient conditions, is the one commonly used in electronics [3].

One area where GaN is less advantageous than Si is its slightly lower thermal conductivity, which necessitates careful design in circuit layout and packaging techniques to efficiently dissipate the heat generated internal to the device. Some material properties of Si, GaN, and SiC are compared in Table I [4].

Table I. Comparison of Si, GaN, and SiC Semiconductors [4]

Property	Si	GaN	3C-SiC
Bandgap, E_g (eV at 300K)	1.12	3.4	2.4
Critical electric field, ε_c (V/cm)	2.5×10^5	3×10^6	2×10^6
Thermal conductivity, (W/cm.K at 300K)	1.5	1.3	3-4
Saturated electron drift velocity, V_{sat} (cm/s)	1×10^7	2.5×10^7	2.5×10^7
Electron mobility, μ_e (cm^2/Vs)	1350	1000	1000
Hole mobility, μ_h (cm^2/Vs)	480	30	40
Dielectric constant	11.9	9.5	9.7

The benefits of GaN over Si or SiC technologies extend from small signal to high power applications. Power Metal-Oxide-Semiconductor Field-Effect Transistors (MOSFETs) have a figure of merit (FOM) called the RQ product, which is defined as a device's on-resistance multiplied by the total charged required by the gate to switch a device at a given voltage and current. GaN and SiC have a markedly improved RQ product over Si [5]. A lower FOM leads to higher efficiency in high-frequency DC-DC converters [6]. Figure 1 shows the FOM for the three aforementioned technologies [4].

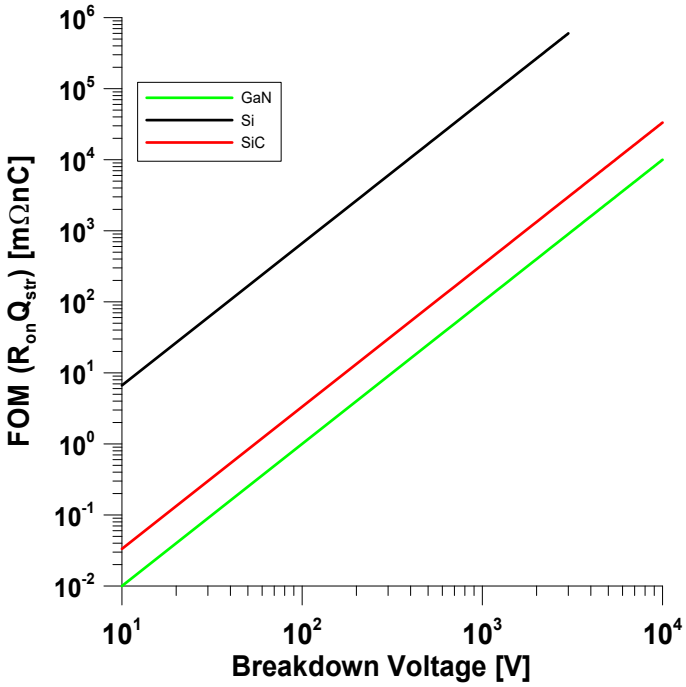

Figure 1. FOM comparison for Si, SiC, and GaN technologies [4]. Lower FOM is better.

Gallium Nitride Devices

GaN devices were first developed for use in RF applications as they offer the best combination of power and gain at a given frequency, operation at higher voltages, and maximized efficiency. The high power density allows the construction of small devices with wide bandwidth leading to lower materials costs as well as reduced capacitance and losses, thereby rendering the devices attractive for use in high RF applications such as satellite communications, radars, and military warfare [7]. Improvement in materials processing and device fabrication over the last decade has allowed power-level GaN devices to become a potential replacement for Si-based power MOSFETs [5]. The majority of these GaN power devices are referred to as high electron mobility transistors (HEMT), and they are becoming widely used in power and high-frequency switching applications. Starting with a silicon wafer, a typical enhancement-mode HEMT is formed by initially growing a thin layer of aluminum nitride (AlN) on the silicon substrate followed by deposition of gallium nitride. Afterwards, a thin layer of aluminum gallium nitride (AlGaN) is grown on top of the GaN, creating a strained interface between the GaN and AlGaN crystal layers [8]. Due to GaN's piezoelectric properties, the resultant interface generates high-conductivity, high-velocity electrons confined in a small region, forming a layer known as the two-dimensional electron gas (2DEG), which has a much higher mobility than a semiconductor crystal [9]. HEMTs built in this fashion are naturally depletion-mode (normally on) devices, with the source and drain terminals making ohmic contact with the 2DEG, and the gate placed on top of the AlGaN layer.

While the original GaN devices used Si as the base substrate material due to larger wafer size and lower processing cost of the well-established Si technology, the growth of high quality GaN material was challenging due to the mismatch in the coefficient of thermal expansion (CTE) and the lattice constant [10]. Other semiconductor substrates that have been used in the manufacture of GaN devices include sapphire and SiC. Due to the poor thermal conductivity of sapphire, GaN on sapphire was deemed unsuitable for use in high power applications but is used in GaN light emitting diodes [10]. SiC, on the other hand, has the least variation in lattice mismatch and CTE as compared to GaN and recently has become the substrate of choice for high power and RF applications. Although GaN-on-SiC devices have been reported to be the most reliable and have excellent electrical properties, some issues still exist pertaining to direct growth of GaN on the SiC substrate due to wettability [11].

Early GaN HEMTs offered were comprised solely of depletion-mode (normally on) devices that were, and continue to be, used in the RF and communication sectors. The basic depletion-mode GaN transistor structure consists of having the source and drain contacts perforate through the top AlGaN layer to form an ohmic contact with the underlying 2DEG. By doing so, a short circuit is created between the source and the drain until the electrons in the 2DEG layer are depleted, and the semi-insulating GaN crystal can block the flow of current. Depletion of the 2DEG electrons occur when a negative voltage relative to both drain and source electrodes is applied to the gate [12]. Enhancement-mode (normally off) devices, which are more advantageous for power applications, require the application of a positive voltage to the gate to turn the device on. A common way to achieve a normally-off device is by tuning the AlGaN/GaN polarization to modulate the 2DEG by changing the doping or thickness of the AlGaN layer [13]. The 2DEG is

populated only enough for conduction when a sufficient bias is presented to the gate. The AlGaN barrier thickness is minimized to increase transconductance and switching speed. However, this minimization results in higher gate leakage currents and makes devices vulnerable to failure from overstress on the gate, especially for high drain-to-source biases. Figure 2 [14] shows the band diagram of a normally-off GaN HEMT.

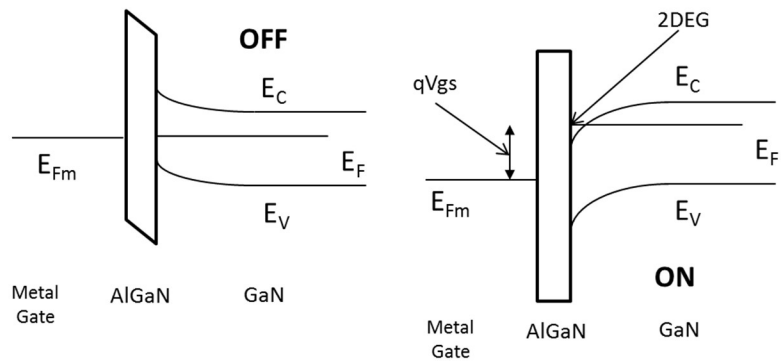

Figure 2. GaN HEMT band diagram [14].

Another common device structure is to create an enhancement mode transistor using a cascode structure with a normally on GaN device and a normally off Si MOSFET [12], [15]. A typical cascade enhancement-mode structure is shown in Figure 3 [12]. The effects of the on-resistance of the Si MOSFET dominate at lower voltages, so building devices in this configuration is only advantageous for applications with voltages greater than 200V. However, one advantage of the cascode topology is that it allows the gate voltage to be higher. Typical enhancement mode devices have very small gate voltages that are easily exceeded if the designer is not careful. To date, only lateral-type GaN power devices are available on the market, with voltage ratings limited to a maximum of 650V, though development of higher-voltage devices utilizing vertical-structure topology GaN devices is ongoing [15]-[17].

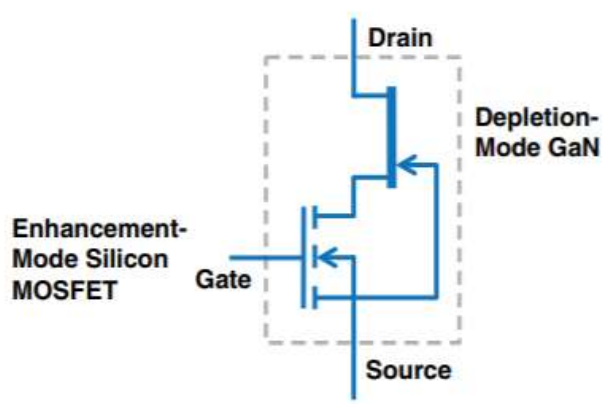

Figure 3. Cascode hybrid enhancement-mode structure [12].

The advantages of GaN over Si for power devices include lower losses leading to higher overall system efficiency, and higher breakdown voltages. The large bandgap of GaN allows the devices to operate at higher switching speeds and at higher temperatures. Inherently, GaN does not exhibit reverse recovery characteristics common to Si and SiC, due to the absence of a body diode and minority carriers. These properties lead to reduced switching losses and to lower electromagnetic interference (EMI), thereby eliminating or reducing the need for snubbers [18]. Because of the low switching losses, GaN devices can operate at higher frequencies resulting in smaller capacitive and inductive components, which, in turn, reduce size, weight, and cost of power systems.

Various projections anticipate that GaN devices will become a much larger share of the power electronics market in the upcoming years. According to Inkwood Research, market share of GaN power devices was estimated around US $515 million in 2018 and is expected to undergo more growth in the near future [19]. This tremendous growth in the global market for GaN power devices is projected to reach a level of US $1.89 billion in 2022 as reported by MarketsAndMarkets, a custom research service [20], and to exceed US $ 2.1 billion in 2027 by Inkwood Research [19]. Due to the evolving 5G network and the increasing demand for more efficient devices, the GaN market sector is also envisioned to undergo significant growth [21]. The recent advances in GaN semiconductor technology have opened up tremendous opportunities in various power electronics industries according to the Power Electronics Industry Collaborative (PEIC), which is a national, industry-focused, member-based consortium consisting of industry, academic and government entities in power electronics. In its latest power technology roadmap, which was funded by the National Institute of Standards and Technology, PEIC addresses issues pertaining to the manufacturing of GaN substrates, development of GaN-on-Si and bulk GaN power devices, and WBG packaging for the development of a robust domestic power electronics industry [22].

NASA Technology Taxonomy

An updated version of the NASA Technology Roadmaps was created in 2020, called the 2020 NASA Technology Taxonomy [23]. Development of new technologies, spanning from structural materials and propulsion to electronics and health monitoring, will be required to achieve deep space missions. Therefore, innovative research and design is needed to overcome the numerous technical challenges anticipated to render these endeavors successful. Emerging GaN technology is considered a prime candidate for addressing and meeting requirements pertaining to electronics and power management. Power devices based on GaN offer many benefits and are in some ways well-suited for application in the harsh environment of space where traditional electronics fail to survive, or require special control or enclosures that result in weight and cost penalties and affect reliability. Some of the space and aeronautics missions where GaN power electronics could potentially be applied are shown in the NASA Technology Roadmap, listed as TX (Technology Taxonomy) Table II [23].

Table II. Partial Listing of NASA Technology Taxonomy [23]

Technology Area	Capability Needed	Challenges	Anticipated Mission
TX01: Propulsion Systems	1.2: Electric Space Propulsion 1.3 Aero Propulsion	High efficiency, high power electronics for electrostatic, electromagnetic, and electrothermal systems High power, high density motors, and wide temperature range electronics and controllers	• Gateway in Lunar Orbit • Moon Lander • Mars 1 • Advanced Exploration Landers • New Frontiers • Exoplanet Finder • Saturn/Titan Robotic • NEO (Near Earth Orbit) • Precision and All-Weather Temperature and Humidity (PATH) • Climate Absolute Radiance and Refractivity Observatory (CLARREO) • Hyperspectral Infrared Imager (HyspIRI) • Ultra-efficient, Environment-friendly Vehicles
TX02: Avionics Computing and Avionics	2.1: Avionics Component Technologies, 2.2: Avionics Systems, and Subsystems	Rad hard extreme environment components, Point-of-load converters	
TX03: Aerospace Power and Energy Storage	3.3: Power Management and Distribution	Advanced electronic parts, low loss, high voltage power modules for power conversion and control, distribution, and transmission	
TX05: Communications, Navigation, and Orbital Debris Tracking and Characterization Systems	5.2 Radio Frequency	Small form factor, reliability, radiation hardness, and other extreme space environment	
TX08: Sensors and Instruments	8.1 Remote Sensing Instruments/Sensors 8.3 In-Situ Instruments/Sensors	Reliable, wide-temperature electronics and electronics packaging capable of operating between -230° C and 480° C.	

In addition to supporting NASA missions, as stated earlier, GaN technology may be beneficial in supporting exploration and science missions being pursued by other government agencies, commercial sectors, and the communication and aerospace industries. The following is a listing of some specific markets where GaN power devices might be good candidates for utilization [24]:

- ***Commercial***
  - Servers and uninterruptible power supplies (UPS)
  - Hybrid and electric vehicles
  - Industrial motor drives
  - Photovoltaic inverters

- Power distribution systems and wind turbines
- Traction
- Cellular base stations
- Medical imaging
- Down-hole drilling

➢ ***Military***

- High-energy laser and advanced armament
- All-electric planes and boats
- Unmanned aerial vehicles (UAV)
- Next generation warships
- Armored robotic vehicles
- Communication and strategic satellites

➢ ***Aerospace***

- High altitude aircraft
- Sensors and imaging systems onboard satellites
- Data communication and networking

GaN Technology Status

GaN semiconductor devices are available today from various manufacturers as well as small start-up business firms. While some supply discrete parts such as HEMTs, others offer customized application specific integrated circuits (ASICs) and power modules. Some of these companies also offer these GaN parts in bare die form or in the form of evaluation boards. A listing of some of the major manufacturers/providers of GaN parts is shown in Table III. Although this information was obtained via thorough industry and literature search, it does not include all organizations involved in the production of GaN parts due to issues relating to proprietary information, lack of public reporting, still-under-development status, etc. Manufacturers are listed in alphabetical order. For completeness, both power-level and RF devices are listed. The product description includes language used by the manufacturers. It should be noted that where manufacturers describe their products as "FETs" they are still HEMT devices. In addition, this technology is advancing at a rapid pace, both in terms of the development of new innovative processing techniques and new material and the introduction of new players into the market through acquisitions and start-up entities.

Table III. Major Providers of GaN Power and RF Electronic Parts.

Manu-facturer	Part/ Product	Capability/ Specification	Product Status	Relevant Information	Reference
Power Devices					
EPC	FET	15-300V, 0.5-90A, 2.5-550mΩ, BGA, LGA package	Available	Data sheets, application notes, design files, device models, reliability reports http://epc-co.com/epc/DesignSupport/eGaNFETReliability.aspx	http://epc-co.com
	FET (dual)	120V, 3.4A, 60mΩ, BGA	Available		
	FET (with gate diode)	100V, 0.5A, 3300mΩ, BGA	Available		
	Module (half-bridge)	30V, 9.5-38A, 2-8mΩ, BGA	Available		
		60V, 23A, 4.4mΩ, BGA	Available		
		80V, 23A, 5.5mΩ, BGA	Available		
		100V, 1.7A, 70mΩ, BGA	Available		
		100V, 30A, 6.3mΩ, BGA	Available		
		60V, 0.5-1.7A, 150-190mΩ, BGA	Available		
		100V, 0.5-1.7A, 320-3300mΩ, BGA	Available		
	Module (half-bridge with bootstrap)	30-200V, 1.6-2.7A	Available		
	Development Board half-bridge with driver	30-350V, 1-40A	Available		
	Power Stage	60-100V, 15-20A	Available		
EPC.Space	FET	40-300V, 4-30A, 6-404mΩ, rad hard	Available	Data sheets, application notes, reliability reports	https://epc.space/products/drivers-and-power-stages/
	Multi-function Driver	50V, rad hard	Available		
	Power Module	50V, 10A, rad hard	Available		
Exagan	FET, Half-bridge, Module	650V, 10-75A, 30-190mΩ	In production	Data, simulation, and reliability information upon request http://www.semiconductor-today.com/news_items/2017/may/exagan_090517.shtml	http://www.exagan.com/en/products/g-fet/

Table III (cont'd). Major Providers of GaN Power and RF Electronic Parts

Manu-facturer	Part/ Product	Capability/ Specification	Product Status	Relevant Information	Reference
GaN Systems	HEMT Evaluation Board	100V & 650V, 7.5-150A, 7-450mΩ, GaN PX™ package 650V, 750-2.5kW, half bridge 100V, 240W, Buck converter	Available Available Available	Data sheets, application notes, spice models, reliability report	http://www.gansystems.com/transistors.php
Infineon	FET Half-bridge, Evaluation Boards	400 & 600V, 10-31A, 70-190mΩ, DSO & HSOF package 450-650V, 2.5kW	Available Available	Data sheets, application notes, qualification report https://www.infineon.com/cms/en/product/power/wide-band-gap-semiconductors-sic-gan/gallium-nitride-gan/	http://www.infineon.com/cms/en/product/promopages/gallium-nitride/
Navitas	FET GaNFast Power IC	650V, 120-300mΩ, 5-12A , QFN package	Available	Data sheets, application notes, reliability report upon request https://media.digikey.com/pdf/Data%20Sheets/Navitas%20Semi%20PDFs/NV6113%20Datasheet%20(FINAL)%208-28-18.pdf http://www.prweb.com/releases/2017/02/prweb14082523.htm	http://www.navitassemi.com/
Panasonic	Transistor Evaluation Board	600V, 9.4-31A, 56-270mΩ, SMD/SMT 600V, 70mΩ, 400-800W, half-bridge with driver 600V, 70mΩ, chopper with driver	Available Available Available	Data sheets, application notes, design & simulation tools, reliability report https://www.mouser.com/catalog/additional/Panasonic_productstandards.pdf	https://industrial.panasonic.com/ww/products/semiconductors/powerics/ganpower/gan-power-devices?reset=1 http://www.mouser.com/Panasonic/Semiconductors/Discrete-Semiconductors/_/N-awhngZ1yzvjj0?Keyword=GaN
Renesas	FET Gate Driver	40-200V, 7.5-60A, rad hard Low side, rad hard	Prototype Prototype	Data sheets, application notes, reliability reports https://www.renesas.com/us/en/products/space-harsh-environment/rad-hard-power/rh-gan-drivers.html	https://www.renesas.com/us/en/products/space-harsh-environment/rad-hard-power/rh-gan-fets.html
Sanken Electric	HEMT (with integrated driver)	600V, 10-20A, 50-100mΩ, QFN package	In development	Technical data upon request	http://www.semicon.sanken-ele.co.jp/en/guide/GaNSiC.html
Texas Instruments	Power Stage Power Stage	600V, 6-12A, 50-150 mΩ, single channel FET with driver, QFN package 80V, 10A, 15 mΩ, half-bridge with driver, QFM package	Available Available	Data sheets, application notes, Spice models, reliability report http://www.ti.com/lit/wp/slyy070/slyy070.pdf http://www.ti.com/power-management/gallium-nitride/Products.html	http://www.ti.com/lsds/ti/power-management/ganfet-products.page

Table III (cont'd). Major Providers of GaN Power and RF Electronic Parts

Manu-facturer	Part/ Product	Capability/ Specification	Product Status	Relevant Information	Reference
Trans-phorm	FET cascode FET cascode Half-bridge Module	600-900V, 6.5-47A, 35-240mΩ, TO-220, TO-247, PQFN88 650V, 35-50mΩ, 35-47A, TO-247, automotive-qualified 650V, 30mΩ, 70A	Available Available Lead time	Data sheets, application notes, design guides, simulation models, reliability reports http://www.transphormusa.com/?s=reliability	http://www.transphormusa.com/
VisIC Tech	All-Switch Evaluation Board	System-in-package power switch (FET), 650V, 100A, 18-22mΩ, SMT & SMD package 650V, 50A half bridge with gate driver	Lead time Lead time	Data sheets, application notes, spice models, reliability report upon request	http://visic-tech.com/index.php/products/
RF Devices					
MACOM	HEMT	28-50V, 1.3-14A, 5-300W RF power, die, QFN, SOIC, TO272, & flange package	Available/ Inquire	Data sheets, application notes, model data, reliability report upon request https://cdn.macom.com/datasheets/NPT2018.pdf	https://www.macom.com/products/rf-power-products/rf-power-amplifier---gan-on-si/rf-power-amplifier---gan-on-si-
Microsemi	HEMT	50-54V, 12-1000W RF power, GaN on SiC, QFN, QP, QQP, KR, & pallet package	Available/ Quote	Data sheets, product brief, reliability report upon request	https://www.microsemi.com/product-directory/power-transistor-products-si-bjt-mosfet-gan/3309-transistors-gallium-nitride#resources
Mitsubishi Electric	HEMT	24-50V, 1.2-2.4A, 5-100W RF power, GF & flangeless package	In production	Data sheets, application notes, reliability report upon request http://www.mitsubishielectric.com/semiconductors/content/product/highfrequency/gan/internally/mgfk50g3745.pdf	http://www.mitsubishielectric.com/semiconductors/php/oSearch.php?FOLDER=/product/highfrequency/gan

Table III (cont'd). Major Providers of GaN Power and RF Electronic Parts

Manu-facturer	Part/ Product	Capability/ Specification	Product Status	Relevant Information	Reference
NXP Semiconductor	HEMT	48-50V, 14-300W RF power GaN, NI package	Available/ Lead time	Data sheets, product brief, reliability report https://www.nxp.com/docs/en/data-sheet/A2G35S160-01S.pdf	http://www.nxp.com/products/rf/rf-power-transistors/rf-power-gan-portfolio:RF-POWER-GAN-PORT?fsrch=1&sr=2&pageNum=1
Qorvo	HEMT	12-50V, 0.3-15A, 5-500W RF power, GaN on Si and GaN on SiC, QFN & flange package	Available/ Lead time	Data sheets, application notes, reference design, life cycle report https://www.qorvo.com/products/p/QPD1017	http://www.qorvo.com/products/discrete-transistors/gan-hemts
Sumitomo Electric	HEMT	24 & 50V, 0.15-5.3A, 125-600W RF power, IV,MK,Z2D, & I2F package	Inquire	Data sheets, application notes	https://www.sedi.co.jp/products/wireless/GaNHEMTsforRadarList.html?version=en
Toshiba	HEMT	24-40V, 2.5-18A, 70-280W RF power, GF & flangeless package	Available/ Lead time	Data sheets, application notes, reliability report upon request	https://www.toshiba.co.jp/infrastructure/en/defense/solution_product/microwave-semiconductor/gan-hemt/index.htm
United Monolithic Semiconductors	HEMT	30-50V, 7-130W RF power, GaN on SiC, QFN, DFN, SMD, die, & flange package	Available/ Lead time	Data sheets, models, reliability report upon request	https://www.ums-gaas.com/products/product-support/brochures/
Wolfspeed	HEMT	28-50V, 0.75-24A, 2-800W RF power, SMT, QFN, bare die, MMIC, & flange/pill package	Available	Data sheets, application notes, design files, reliability report "Wolfspeed GaN RF Devices Demonstrate Reliability to Perform in Harsh Space Environments" http://www.wolfspeed.com/news/space-qual	http://www.wolfspeed.com/rf/products/table

The research, development, and application of GaN technology and devices are pursued not only by commercial entities but also by a broad spectrum of organizations. These include non-profit institutions (academia), clean-environment advocacy groups, civilian space agencies, and national defense departments. For instance, a public-private manufacturing innovation institute was established under an initiative by the White House in 2014 [25] aimed at enabling the next generation of energy-efficient, cost-competitive, high power WBG-based devices, and for strengthening US manufacturing. This initiative led to the establishment of the US Department of Energy's (DOE) PowerAmerica Institute, a consortium of companies, universities, and US federal government laboratories engaged in various WBG semiconductor activities. Tasks focusing on GaN technology include [26]:

- Manufacturing and demonstration of vertical GaN devices on bulk GaN wafers for high-power applications
- Development of an open-source transformer-less, grid-tied 3kW photovoltaic (PV) inverter
- Establishing reliability of GaN power devices
- Establishing efficiency of GaN-based chargers
- Insertion of GaN technology in college curriculums

From 2009-2014, the DOE Office of Electricity Delivery and Energy Reliability (OE) funded the GaN Initiative for Grid Applications (GIGA) project, which focused on the development of power electronics devices based on gallium nitride on silicon (GaN-on-Si) technology. While this initiative was geared to enhance the capabilities of today's aging electric grid to adequately control, absorb, and reroute power, this project helped to catalyze and develop an industrial base for high-powered GaN-on-Si power electronics devices that can be utilized across multiple sectors of the U.S. economy [27].

Currently, the DOE is also funding various GaN semiconductor technology programs through the Advanced Research Projects Agency-Energy (ARPA-E). Among these programs is Strategies for Wide-Bandgap, Inexpensive Transistors for Controlling High-Efficiency Systems (SWITCHES), a program with various projects, involving universities, national laboratories, and private companies, funded through ARPA-E's Small Business Innovation Research (SBIR) and Small Business Technology Transfer (STTR) programs. The aim of SWITCHES is to develop next-generation power switching devices that could dramatically improve energy efficiency in a wide range of applications and to find innovative GaN device fabrication processes and device architectures at substantially lower cost relative to today's solutions [28]. The Power Nitride Doping Innovation Offers Devices Enabling SWITCHES (PNDIODES) program is an extension of the SWITCHES program and specifically focuses on improving the doping process in GaN, a critical need to advance vertical GaN technology [29]. Another research program is Creating Innovative and Reliable Circuits Using Inventive Topologies and Semiconductors (CIRCUITS), which has the objective of accelerating the development and deployment of a new class of efficient, lightweight, and reliable power converters, based on WBG semiconductors, including GaN. These efforts are anticipated to have a big impact in a wide range of applications including the electric grid, industrial motor controllers, solar and wind power systems, automotive electrification, datacenters, aerospace control surfaces, and wireless power transfer [30].

Other US Government Agencies supporting the development of GaN power devices include NASA and the Naval Research Laboratory. For example, NASA has supported SBIR proposals on radiation and high temperature tolerant GaN power electronics, a GaN-based high-power, high-frequency resonant converter, GaN power amplifiers, and bulk GaN Schottky diodes [31]. NASA also supports development programs such as the construction of a cryogenically-cooled megawatt inverter, being developed jointly by Boeing and the University of Tennessee at Knoxville, which will potentially use GaN power transistors [32]. The NASA Electronic Parts and Packaging (NEPP) Program also addresses issues pertaining to reliability, in particular radiation effects, of WBG power devices. The NEPP Program provides guidance for the selection and application of technologies for space use through performance evaluation, qualification guidelines development, risk determination, and reliability assessment [33]. One of the program-supported tasks addresses the effect of radiation, including heavy-ion exposure, on GaN-based electronics. Similarly, the Naval Research Laboratory Electronics Science and Technology Division (ESTD) has numerous research activities on wide bandgap materials and power devices. The research spans several areas, including development of epitaxial growth to eliminate defects and improve yield, establishment of novel device structures and advancement of passivation and termination processes, and development of unique tools to identify degradation/failure mechanisms for device optimization and reliability improvement. ESTD anticipates that GaN power electronics would enable utilization of advanced power converters, with approximately 10x higher switching frequency, 5x lower volume, and a 60-80% reduction in energy loss, in platforms and missions such as new weapon systems, new radars, combat vehicles, and more-electric aircraft [34].

Examples of industry-led work include newer generations of GaN power devices with emphases on smaller footprints and lower capacitance, resulting in lower gate-drive losses and lower device-switching losses at higher frequencies for the same on-resistance and voltage rating [35]. Other efforts comprise pushing the voltage ratings to 650V or more, as well as the expansion into the Ka-band on the RF side of this technology [35]-[36].

<u>Technology Limitations</u>

Although GaN devices offer tremendous benefits when compared to their silicon counterparts, research and development efforts are continuing to mature this technology in order to fully exploit these advantages. Some of the challenges that are hampering the progress of the technology include:

Lattice Mismatch:

Several substrate materials were considered during the early development of GaN HEMT devices to address both lattice and CTE mismatches. These materials included sapphire, SiC, and Si, but the substrate material properties have a major impact on device performance and reliability [37]. For instance, lattice and CTE mismatches between GaN and Si are very large, leading to high-density dislocations formed during the initial growth and cooling process [38]-[39]. Similarly, both sapphire and SiC have different lattice mismatches with GaN, resulting in layers grown with varying degrees of dislocation densities [40]; however, SiC's crystal structure is the closest match and thus is the preferred choice for now, if cost is not an issue. Additionally, SiC's high thermal conductivity, which translates into minimum self-heating and increased power handling capability,

also makes it the substrate material of choice, particularly for high power and RF GaN devices [40].

Cost:

The majority of present GaN power devices are grown on the relatively low-cost 6" & 8" Si substrates, and in the long term, cost may not be of great concern. However, cost-effective growth of high-quality nucleation layers for GaN crystal growth is not yet readily available to make GaN parts cost-competitive to those of Si. Formation of the nucleation layer, typically AlN, is usually difficult because a pre-reaction between the gases at high pressures is required prior to deposition of the nucleation layer, which leads to a trade-off between growth rate and quality [41]. While SiC substrates offer great promise in delivering numerous benefits in the development of next-generation power electronics over the conventional GaN-on-Si substrate technology, controlling defect density and the availability of large-diameter SiC wafers, albeit progressing, is still an issue of concern. For example, while nearly-defect-free, affordable 150-300 mm diameter Si wafers are readily available, today's work on SiC wafers is centered on 76 and 100 mm diameter sizes [42]. However, some ongoing progress is being reported on acceptable-quality, larger-size (150-200 mm diameter) SiC wafers [43]. Good-yield, large-size SiC wafers not only would bring the cost down but also would lead to increased power density and reduced device/system size due to the superior material characteristics of SiC.

Device Packaging:

To utilize the benefits of the higher temperature capabilities (target $T_J > 175\text{-}200^{o}C$) of GaN power devices, new packaging materials and techniques are required that do not sacrifice device footprint size or volumetric efficiency. In addition, higher power and temperature operation will necessitate strong attachments and bonding mechanisms, with minimal parasitics, that can withstand repeated power and wide-range thermal cycling [44].

Layout:

Operation at high switching frequencies, a major benefit of GaN devices, may introduce a concern at both the power module and circuit board levels as parasitic impedances can result in significant power losses and enhance the risk level of gate/device damage at these frequencies. It is, therefore, imperative to optimize the layout so that parasitic elements, mainly inductive and capacitive, are efficiently eliminated or minimized to significantly decrease voltage and current overshoots, reduce EMI, and prevent cross-talk or other circuit noise interference [45]-[46]. Such optimized techniques are usually addressed internally at the device level, as shown in Figure 4 [47], as well as in the design and layout of the printed circuit board, as depicted in Figure 5 [48].

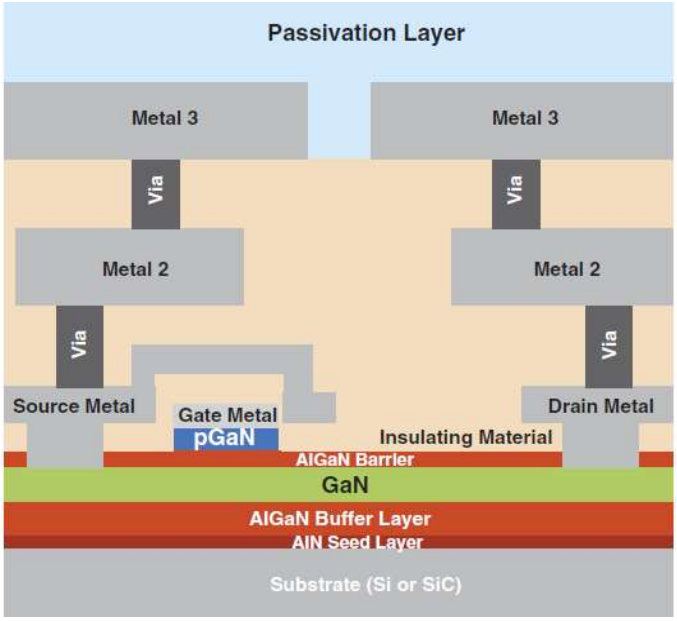

Figure 4. Optimized internal structure of a GaN FET [47].

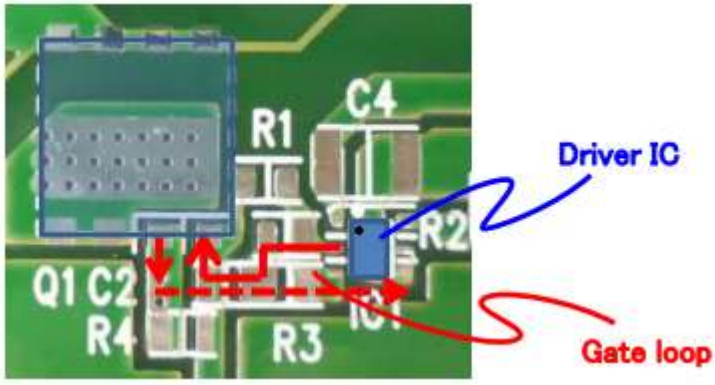

Figure 5. Recommended circuit board layout for a GaN device [48].

Supporting Electronics:

GaN FETs switch much faster than Si-based MOSFETs, which allows for a dramatic reduction in the size and weight of power supplies and other electronic modules. These high-performance GaN transistors, however, need an optimized gate driver to reach their performance potential. The driver must charge and discharge gate capacitance as quickly as possible, must have low propagation delay to allow fast signals, and must avoid "shoot through" by preventing turn-on of high-side and low-side FETs at the same time [49]. When AlGaN/GaN HEMTs are subjected to a forward gate bias overstress, a time-dependent degradation process, with an exponential dependence on the gate bias, is encountered preceding device failure [50]. Thus, GaN HEMTs exhibit tight tolerance on gate voltage as the application of large positive gate bias degrades the Schottky contact due to large current or high temperature [51]. In addition, switching transients

and hard-switching stresses were found to greatly diminish the robustness and reliability of GaN-based devices [52].

Vertical Devices:

The majority of present day GaN power transistors are based on lateral device structure relying on the high electron mobility in the 2DEG. These lateral HEMTs, however, are known to be susceptible to surface breakdown and are not easily scalable to higher voltages and higher currents; hence, lateral GaN power transistors are expected to find applications limited to a maximum of 650V, as listed in Table III. With lateral geometry, both the transistor area and the device cost are proportional to the breakdown voltage. In addition, exposure of the numerous material interfaces to high electric fields affects overall reliability. Finally, for high-current applications, the lateral-device size has to increase dramatically [53]. To overcome these limitations and to fully compete with their SiC counterparts, GaN devices with bulk avalanche breakdown, i.e. vertical-structure transistors, likely need to be developed [54]. The vertical design would allow for reduced die size and improved reliability by diverting the high electric fields away from the surface [53]. Vertical GaN devices are very limited today due to the lack of homogeneous GaN substrates at reasonable cost. Research efforts are currently underway to develop vertical devices using various topologies. Researchers have demonstrated vertical GaN-based trench MOSFETs on a free-standing GaN substrate with a blocking voltage of 1.6 kV [55], and of 1.9 kV by removing local substrate material around the drain to impede electron accumulation around the site, thereby improving the device's breakdown voltage [56]. Other proposed structures include the current aperture vertical transistor (CAVET), in which the source region is separated from the drain region by an insulating layer with a narrow conducting aperture [57], and a novel device structure that does not require the use of a p-GaN layer, known as vertical fin field-effect transistor (VFET) structure. In the latter construction, which consists of a MOS gate-stack on the sidewalls, the current is forced to flow vertically through submicrometer channels [58]-[60]. The use of multiple channels operating in parallel allows a significant increase in current density of this type of device structure; however, a shift in the threshold voltage of the devices occurs [61].

Reliability:

Unlike Si-based electronics technology which is well-established and has been thoroughly investigated, the reliability of GaN devices is not fully understood, although recently there have been several efforts to close the knowledge gap [62]-[65]. This gap exists mainly due to the relatively recent emergence of GaN power devices and to the distinct architectures in the construction of devices between Si and GaN counterparts, in particular HEMTs. Thus, traditional qualification methods used to determine product-level quality and reliability of conventional Si components may or may not fulfill the same purposes for GaN parts. Typical qualification assessments, including highly accelerated stress test (HAST), high temperature reverse bias test (HTRB), high temperature operating life (HTOL), and accelerated life test (ALT), for example, may need to be expanded or complemented with new characterization protocols. For instance, GaN devices do not have native substrates; giving rise to mismatch defects, and because of the piezoelectric nature of the material, operating the device under high electric field creates high mechanical stresses [62]. Such excessive mechanical stresses were reported to induce defects concentrated at the gate edge as well as on top of the lattice mismatch between the GaN and the

AlGaN barrier layer. These electrically active defects tend to cause a decrease in the drain current capability, an increase in the dynamic $R_{DS(ON)}$, and to create a conductive path for leaky gate current. Such failure mechanisms occurring particularly under high voltage in GaN HEMTs are referred to as an inverse piezoelectric effect that is responsible for the introduction of the mechanical stresses in the AlGaN barrier layer [63]. Other factors leading to increase in the $R_{DS(ON)}$ are attributed to the time-dependent, high off-state stress-induced electron injection from the substrate, or from the gate, if poorly passivated [64]-[65]. These failure modes and other mechanisms, such as hot electron trapping, detrimentally affect the reliability of the devices, as they cause decreased device performance and alter key parameters, such as current capability, threshold voltage stability, static and dynamic resistance, and breakdown. Common failure modes are listed below and the sites of these mechanisms in a typical GaN HEMT are shown in Figure 6 [66].

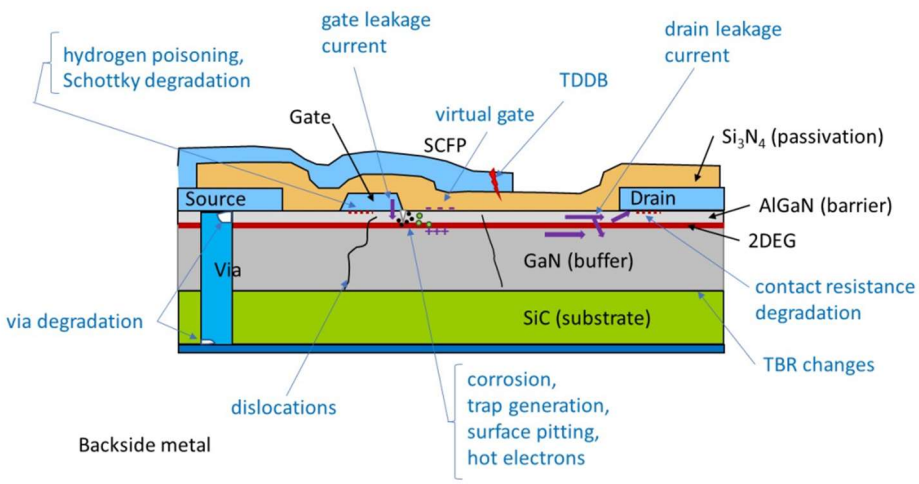

Figure 6. Cross section of a typical HEMT identifying some failure mechanisms and sites [66].

- Increase in drain and/or gate leakage currents
- Time-dependent dielectric breakdown
- Moisture-induced corrosion and surface pitting at gate-drain edge due to piezoelectric strain
- Trap generation due to hot electron effects
- Schottky gate contact and via degradation
- Dislocation or interfacial degradation between substrate and GaN layer
- Shift in threshold voltage and increase in on-resistance due to trapping and dislocations

For space applications, the effect of radiation on the survivability and performance of GaN power devices is a major factor in determining their suitability and reliability under such environments. Some information pertinent to the operation under the influence of radiation on GaN HEMTs is presented in the following section.

Radiation Effects

Radiation deposits energy in matter and may remove an electron from an atom or displace atoms from their position in the material. If the electron, or lack of electron, called a hole, finds an energetically favorable site in the material, then the charge will present an influencing electronic potential to the surrounding material. This effect is called total ionizing dose (TID) damage and typically manifests in silicon dioxide where it may influence a semiconductor device. For MOSFET transistors, this oxide-trapped change will affect threshold voltage (V_{TH}), transconductance (g_m), and subthreshold leakage current (I_{DSS}). When atoms are removed from the initial site, the damage is called displacement damage and mainly affects minority carrier devices like bipolar junction transistors (BJTs). When the radiation is made up of ions, the charge liberated is dense enough to interact with local electric fields and cause device malfunction or failure. These effects are called single-event effects (SEEs). In MOSFETs, this manifests as single-event gate rupture (SEGR), where an ion destroys the gate oxide, or single event burnout (SEB), where a coincidental BJT activates and burns a path from the drain to the source.

The radiation effects testing for GaN HEMTs has concentrated on SEEs. Since HEMTs have no gate oxide, TID effects are minimal. A GaN HEMT is a majority carrier device and the polarization fields are relatively insensitive to defects in the GaN, so displacement damage is also expected not to be a large risk. The effect of ion interaction in or near the gate for SEE is the larger risk since stress from charge collection or ion damage to the gate directly leads to the known failure mechanisms of damaged GaN HEMT gates.

Destructive SEEs have been seen in GaN HEMTs since 2009 [67]. Different RF HEMTs were studied that showed little damage from heavy ion irradiation [68]. Studies have been reported on charge collection and damage from heavy ions and destructive SEE in RF devices [69]-[71]. Other types of GaN HEMTs have been studied for SEE such as in [71], where the response of an insulated gate HEMT was presented. Some of these devices have been investigated for radiation effects [67]-[68]; however, these were HEMT devices tailored for RF applications. Damage in GaN HEMTs from heavy ions has been seen in DC [69]-[70] and RF [71] testing. The results of [69]-[70] are particularly surprising since the pinch-off and on-condition of the GaN HEMT are more susceptible conditions for SEEs. This has a critical implication for point-of-load (POL) and bootstrapped buck converters since these applications require n-channel devices that are on for a considerable portion of the duty cycle. An argument for the mechanism to be SEB in the gate structure was presented in [14].

Illustrative Results

To date, SEE testing of GaN HEMTs has been performed mostly in the same manner as power MOSFET SEE testing – in static mode in the off condition. The test procedure has generally followed MIL-STD-750 Test Method 1080, as shown in Figure 7 [72].

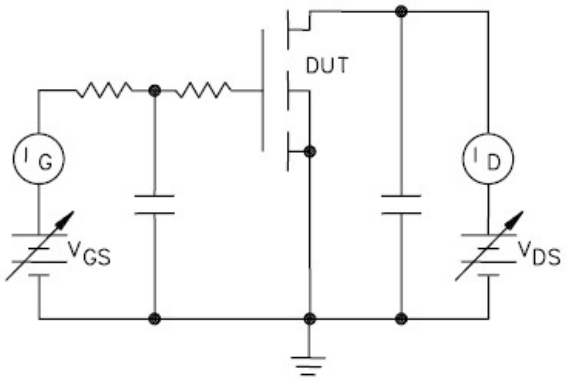

Figure 7. Standard test circuit in MIL-STD-750 used in most testing [72].

Multiple vendors' GaN HEMT devices have been investigated under the NASA NEPP Program and were found to exhibit the same failure mechanism of increasing drain current under ion radiation; however, the nature of the event varies among manufactures. To illustrate this variance, Figures 8-11 [14], [73] show a typical failure behavior for the four manufacturers. It should be noted that, in all cases, significant lot-to-lot variance has been seen so the results shown here should not be considered final. Since all of these manufactures are on commercial fabrication lines, there is considerable variance in architecture and manufacturing. This would account for the lot-to-lot variance.

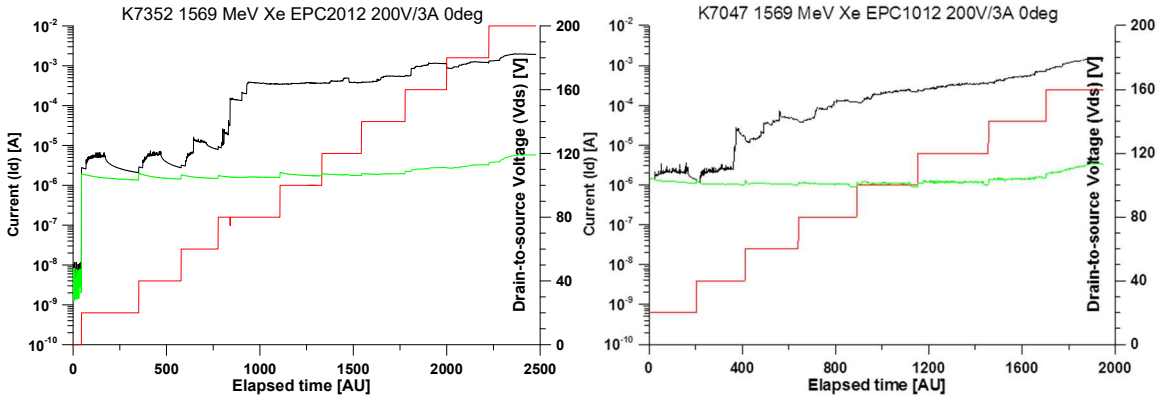

Figure 8. Typical SEE behavior of EPC GaN HEMTs. The device experience SEE, but in most cases the drain leakage never exceeds a few mA [14], [73].

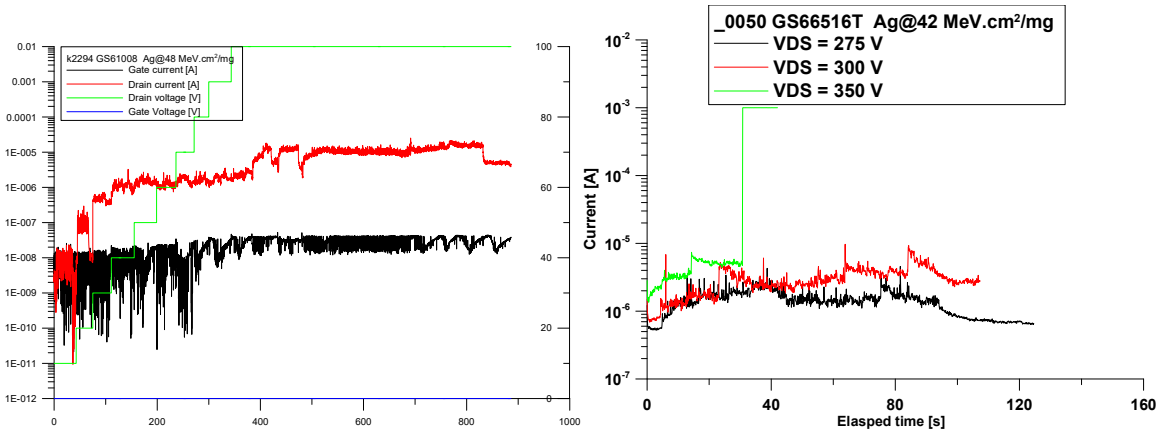

Figure 9. Typical SEE response for GaN system parts. SEE usually occur in small breaks that do not result in a full short, but exceptions have been seen like on the right [14], [73].

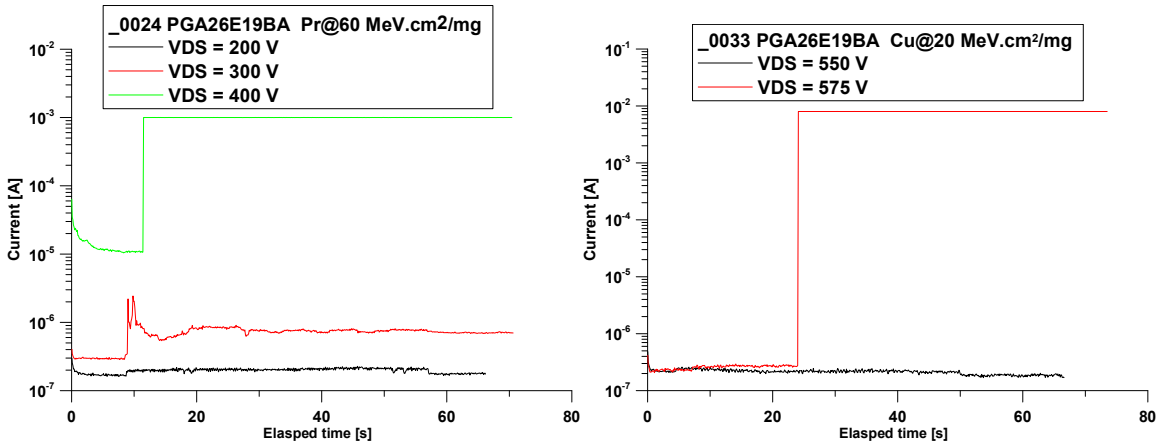

Figure 10. Typical SEE in Panasonic devices. The SEE always results in a full short in the device [14], [73].

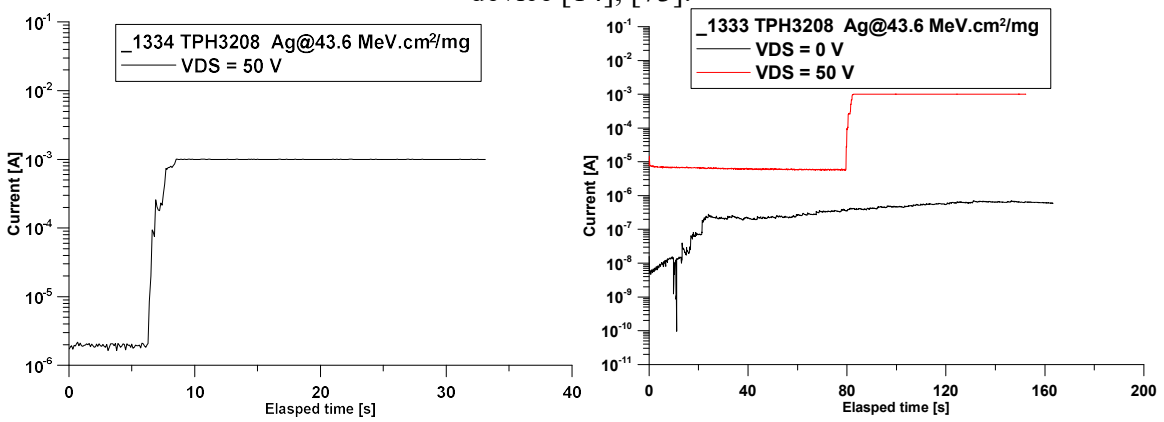

Figure 11. Typical SEE of the Transphorm device. The devices are very soft and incur damage even unbiased, an indication that the ion displacement damage may have a role [14], [73].

The survival voltages of these various parts that were SEE-tested under the NASA NEPP program are shown in Table IV.

TABLE IV. LOWEST V_{SEE} AT ZERO GATE BIAS

Part number	V_{DS} [V]	Ion	Gen 1 V_{SEE} [V]
EPC1014	40	Xe	>40
EPC1001	100	Xe	40
EPC1012	200	Xe	40
EPC1014	40	Kr	>40
EPC1001	100	Kr	100
EPC1012	200	Kr	200
EPC1014	40	Au	>40
EPC1001	100	Au	40
EPC1012	200	Au	40
EPC2014	40	Xe	40
EPC2001	100	Xe	60
EPC2012	200	Xe	40
EPC2014	40	Kr	NA
EPC2001	100	Kr	NA
EPC2012	200	Kr	NA
EPC2014	40	Au	40
EPC2001	100	Au	NA
EPC2012	200	Au	40
GS61008	100	Xe	40
GS66516T	600	Xe	30
PGA26E19BA	650	Xe	300
TPH3208	650	Xe	10
TPH3202	600	Xe	10

Note that the EPC 40 V devices experience no SEE at any gate and drain voltage combination.

While there is diversity in the SEE response of various vendors, there are trends that can be extracted. Results of a destructive SEE demonstrate an increase in drain leakage that increases in magnitude with increasing drain-to-source voltage (V_{DS}). Larger linear energy transfer (LET) ions result in a lower voltage at which SEE occurs. The SEE cross-section of the tested device is approximately equal to the area of the drain edge of the gate. There are also some trends that are not uniform over the various vendors, such as angular response to SEE. Some devices demonstrated device failure after a post irradiation gate stress (PIGS) and post irradiation drain stress (PIDS) stress while others did not.

Circuit test set up might influence the sensitivity of the results, to a certain degree. For example, in [73], the effect of increased capacitance on the drain of the device with respect to ground, as depicted earlier in Figure 7, led to a decrease in V_{SEE}. This trend is important since circuit capacitance may affect survivability of the device. In [73]-[75], the effects of gate-to-source

voltage on the survival of the devices from two manufacturers were observed, and the results are very different, possibly due to the observed lot-to-lot variability.

Proton irradiation has also been performed on devices, and seemed to induce a very slight change in the threshold voltage due to displacement-type of damage, but the effects of heavy ions are more profound [14]. Results have indicated that increasing the ion LET lowers the V_{SEE} due to the deeper ion penetration. Such behavior implies that the GaN substrate participates in the charge collection phenomenon [14], [74]-[75].

De-lidded bare dies of parts have been subjected to post-SEE failure analysis. Failed devices exhibited heavy leakage at the damage sites [74]. These sites were then scanned visually to verify the damage, which was seen to occur on the drain edge of the gate structure [74]. Locations of the damage are attributed to the fact that the drain edge of the gate experiences the largest electric field and, with such a stress, becomes prone to breakdown. In general, when a heavy ion hits the drain edge of the gate to cause an avalanche failure, it produces a transient on the gate and is dependent on the LET and applied voltage of the device. Longer-range ions would engage more of the substrate and increase charge collection and device damage. A simulated vertical electric field distribution of a HEMT device in the off-mode is shown in Figure 12, and the corresponding calculated magnitude of the electric field for various depths under the drain edge of the gate is plotted in Figure 13 [74]. It is noted that device failure due to voltage overstress is very similar in residual damage and time evolution as the SEE failures [74]. Both drain-to-source DC bias and transient over-stress on the gate have been seen to induce SEE failure modes [73]. Recent technology computer aided design (TCAD) study [76] results shown in Figure 14 show the most sensitive region for the ion response is the drain edge of the gate, which agrees with the contention above.

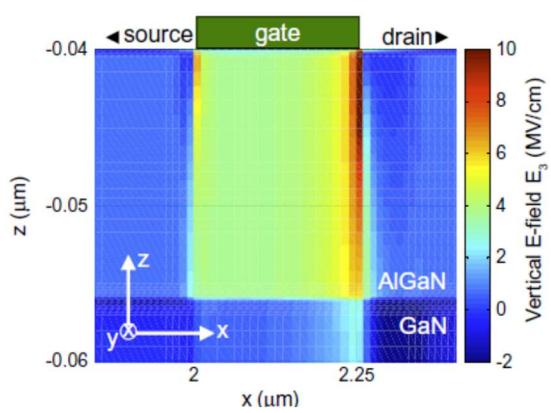

Fig. 12. E-field distribution of an off HEMT.

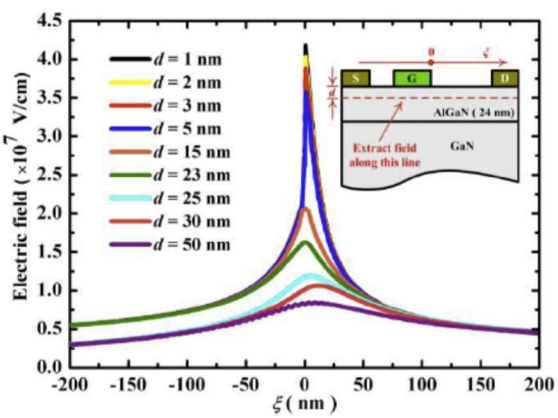

Fig. 13. E-field distribution under an off HEMT.

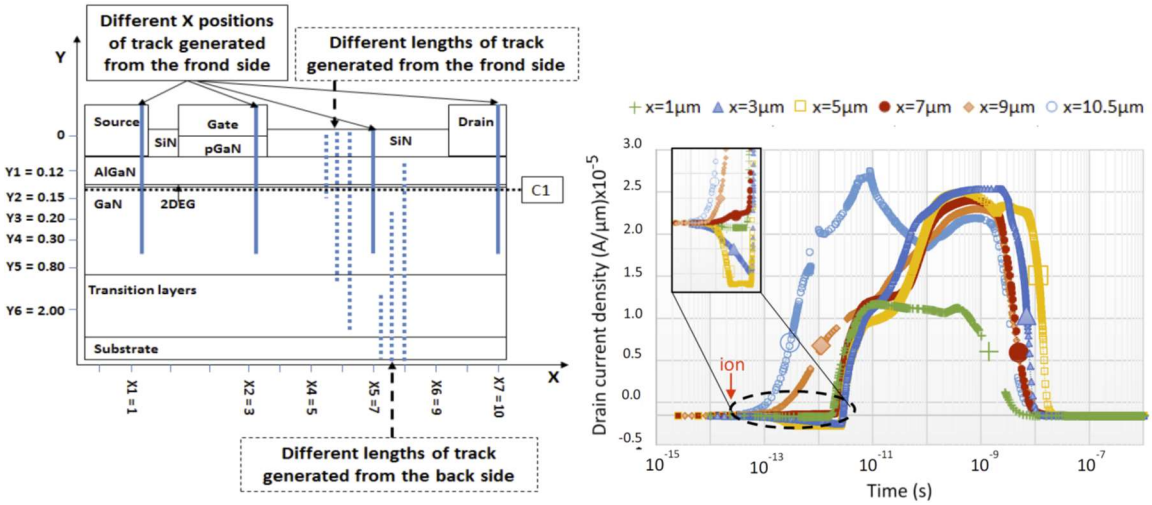

Figure 14. Simulation of ion strikes on a GaN HEMT. An ion strike on the drain edge of the gate causes the most effect [76].

Understanding the effect of radiation and determining failure mechanisms have a profound impact on the reliability of GaN-based devices. Understanding these mechanisms is crucial to the future use of GaN power devices in NASA missions. The database of radiation results is small but growing; however, many questions remain. The following are the most pressing:

1. What temperature is worst case for SEE testing?
2. What are the latent damage effects of ion testing?
3. What is the best approach for PIGS and PIDS testing?
4. What is the effect of burn-in on the testing?
5. Is there a synergistic effect between dose and SEE?
6. What is the worst-case ion condition for SEE testing?
7. Does gate stress exacerbate dose or ion effects?
8. What is worst case: static or dynamic?
9. What is the effect of dynamic $R_{DS(on)}$ on dose or SEE effects?
10. Are there any device specifications that could indicate radiation effects?

Conclusion

Recent advances in GaN material technology have opened up new opportunities for innovation in power electronics due to this semiconductor's tremendous advantages, as compared to silicon, offered in terms of power capability, fast switching, extreme temperature tolerance, and high frequency operation. Such attributes offer the potential for smaller, more efficient and robust, high power and low-cost devices. This report documents some issues pertaining to GaN technology and its application in the area of power electronics. It also serves as a body of knowledge in reference to the development and status of this technology obtained via literature and industry survey as well as providing a listing of the major manufacturers and their capabilities. Finally, limitations affecting the full utilization of this technology are identified, and reliability issues pertaining to commercial GaN-based electronic parts are addressed.

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