Body of Knowledge (BOK): Gallium Nitride (GaN) Power Electronics for Space Applications

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Abbreviations & Acronyms

Acronym	Definition
2DEG	Two Dimensional Electron Gas
AlGaN	Aluminum Gallium Nitride
ARPA-E	Advanced Research Projects Agency - Energy
BOK	Body of Knowledge
CIRCUITS	Creating Innovative & Reliable Circuits Using Inventive Topologies and Semiconductors
CTE	Coefficient of Thermal Expansion
DOE	Department of Energy
EEE	Electrical, Electronic, and Electromechanical
ESA	European Space Agency
ETW	Electronics Technology Workshop
FET	Field Effect Transistor
GaN	Gallium Nitride
GIGA	GaN Initiative for Grid Applications
GRC	Glenn Research Center
GSFC	Goddard Space Flight Center
HEMT	High Electron Mobility Transistor
IR	Infrared
JPL	Jet Propulsion Laboratory

Acronym	Definition
JSC	Johnson Space Center
LET	Linear Energy Transfer
LBNL	Lawrence Berkeley National Laboratory
MMIC	Monolithic Microwave Integrated Circuit
NASA	National Aeronautics and Space Administration
NEPP	NASA Electronic Parts and Packaging
R_{ON}	On Resistance
SEE	Single Event Effect
Si	Silicon
SiC	Silicon Carbide
SWITCHES	Strategies for Wide Bandgap, Inexpensive Transistors for Controlling High-Efficiency Systems
TAMU	Texas A&M University
TID	Total Ionizing Dose
UAV	Unmanned Aerial Vehicle
UPS	Uninterruptible Power Supply
V_{TH}	Threshold Voltage
WBG	Wide Bandgap

Body of Knowledge Documents

- **Provide a brief guidance to a technology and create a “snapshot” of the current status**
  - **Technology overview**
  - **NASA Applications**
  - **Other current work (government, industry, academia)**
  - **Challenges**
  - **Reliability**
  - **Future direction**
- **SiC BOK was completed in 2017 by members of NEPP Wide Bandgap (WBG) working group; GaN BOK to be released soon**

Why WBG Devices?

- Majority of today's electronics based on Si technology
- Approaching theoretical limit of Si technology
- New operational environments
- Stringent application requirements
- Evolving technology: WBG semiconductors
- SiC and GaN most promising candidates, especially for power electronics

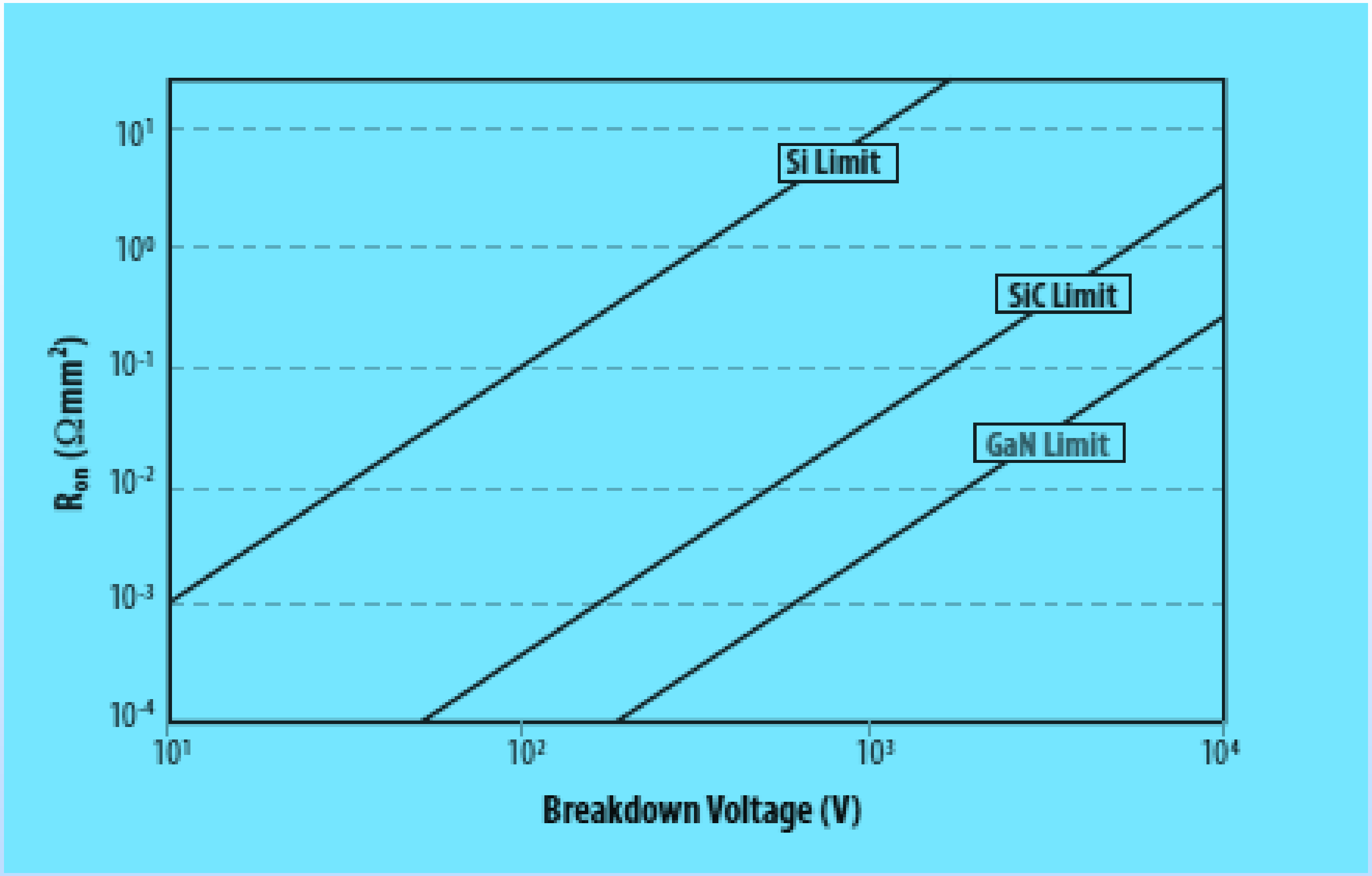
Benefits of GaN

- Higher breakdown voltage
- Higher operating temperature
- Minimal (no) reverse recovery
- Reduced switching losses
- Increased efficiency
- Faster switching speeds
- Reduced thermal management
- Improved system reliability
- Reduced system cost

Relative Comparison of Semiconductors

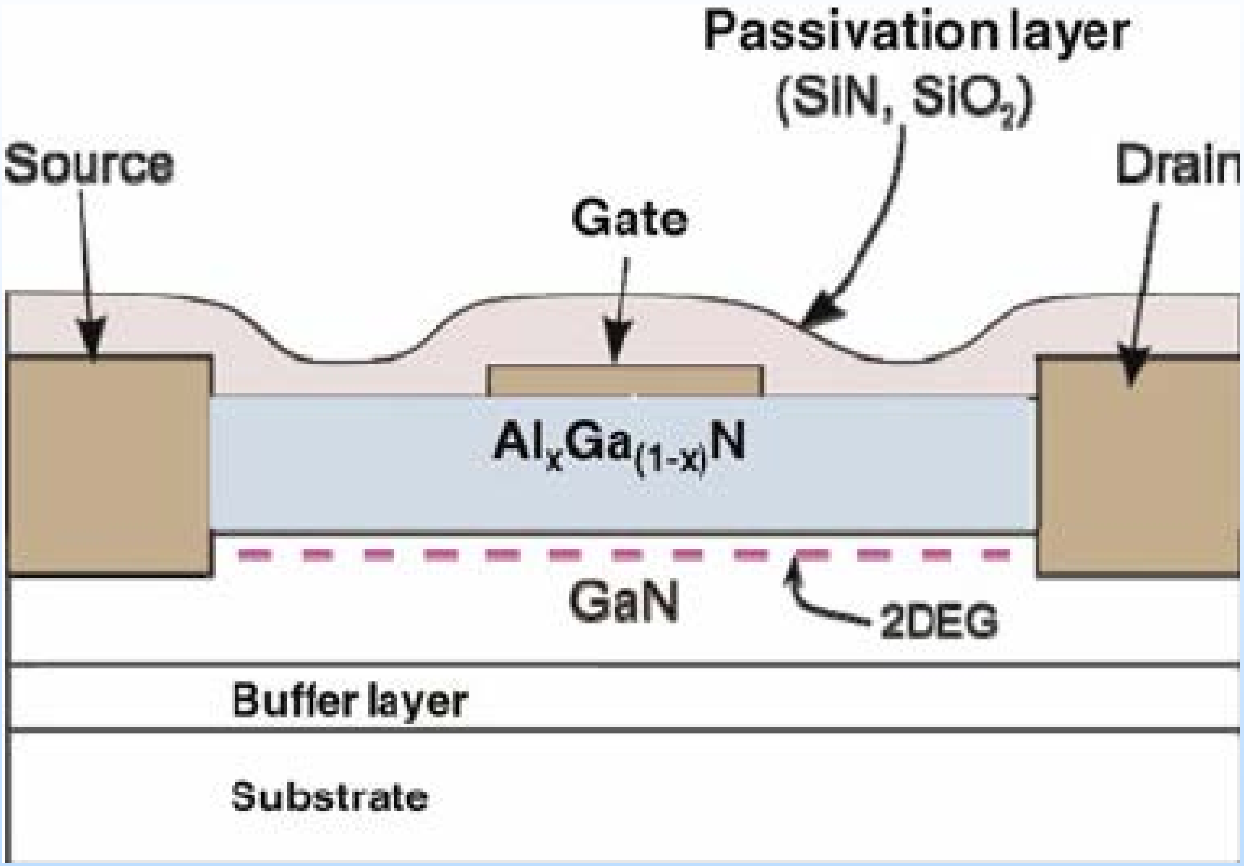
Property (relative to Si)	Si	SiC	GaN
Thermal Conductivity	1	3.1	0.9
Thermal Expansion Coefficient	1	1.6	2.2
Dielectric Constant	1	0.9	0.9
Electron Mobility	1	0.67	0.83
Hole Mobility	1	0.08	0.42
Breakdown Electric Field	1	7.34	6.67
Saturation Velocity	1	2	2.2
Maximum Working temperature	1	5.2	5.34

Theoretical On-Resistance vs Breakdown Voltage



*** J. Strydon et. al "Using Enhancement Mode GaN-on-Silicon Power FETs (eGaN FETs)." Efficient Power Conversion, Application Note: AN003, 2017.**

Typical GaN HEMT Structure



* S. Piotrowicz et. al "Overview of AlGaN/GaN HEMT Technology for L- to Ku-band Applications." Int'l Journal of Microwave and Wireless Technologies, 2010, 2(1), 105-114.

GaN Issues

- **Lower thermal conductivity**
  - **Layout**
  - **Packaging**
- **Higher frequency operation**
  - **Layout**
  - **Parasitics**
- **Gate-source voltage limit**
  - **Gate drive circuit**
  - **Voltage regulation**
- **Enhancement-mode devices**
  - **Cascode structure**
  - **New processes**

NEPP GaN Work

- **NEPP Task: Wide Bandgap Reliability and Applications Guidelines**
- **Task**
  - **NASA Working Group on Wide Bandgap Semiconductors**
- **Objective**
  - **Address reliability of and issue guidelines on GaN & SiC power electronics**
- **Members**
  - **GRC, GSFC, JPL, JSC**
- **Activities**
  - **Collaboration on test activities**
  - **Parts performance and reliability determination under radiation and extreme temperature exposure**
  - **Disseminate information and publish on NEPP website**

Radiation and Thermal Cycling Effects

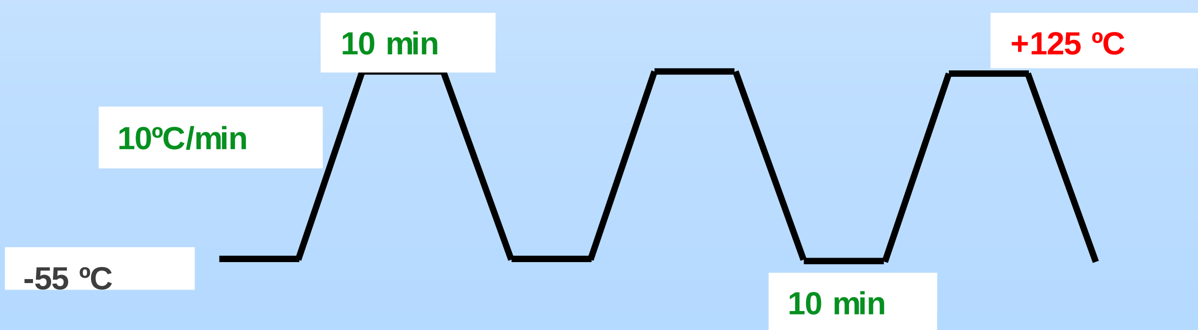
Manufacturer	Part #	Parameters	# Samples (control/Irradiated)	Radiation	Cycling
EPC	2012	200V, 3A, 100mΩ	15/26	✓	✓
GaN Systems	GS61008P	100V, 90A, 7.4mΩ	11/10	✓	✓
	GS66508P	650V, 30A, 52mΩ	4/0	Planned	✓

Radiation Exposure						
Device	Ion	Energy (MeV)	LET ($MeV.cm^2/mg$)	Range (µm)	Incidence Angle	Facility
EPC	Xe	3197	41	286	Normal	TAMU*
GaN Systems	Ag	2651	42 - 48	90	Normal	TAMU*/LBNL*
	Au	2594	87	118	Normal	TAMU*/LBNL*

* TAMU: Texas A&M University; LBNL: Lawrence Berkley National Lab

Thermal Cycling:

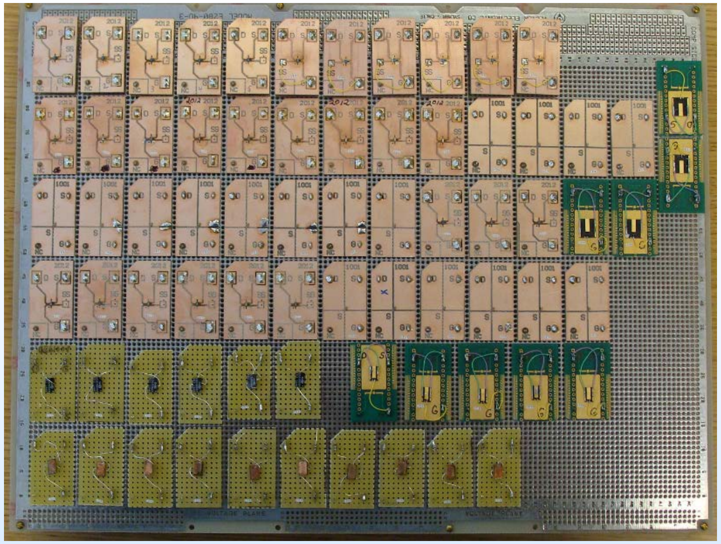
- 1000 cycles
- Rate: 10 °C/min
- Range: -55 °C to +125 °C
- Soak time: 10 min

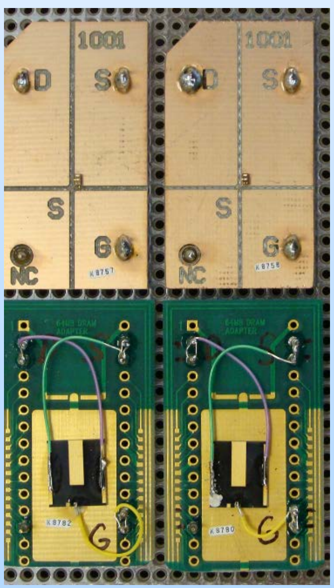


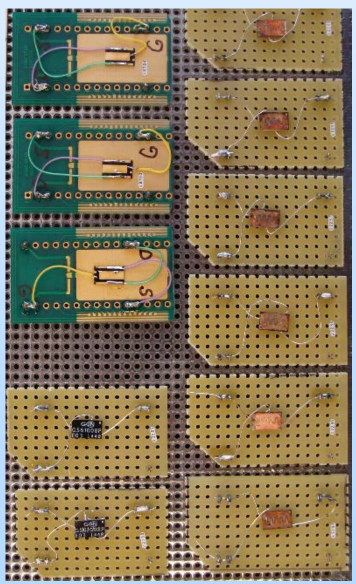
Parameters and Setup

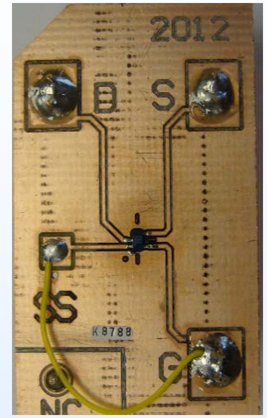
- I-V output characteristics
- Gate threshold voltage, V_{TH}
- Gate leakage forward current, I_{GLF}
- Gate leakage reverse current, I_{GLR}
- Drain leakage current, I_{DL}

Device-Mounted Boards

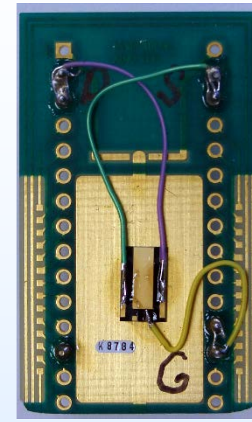




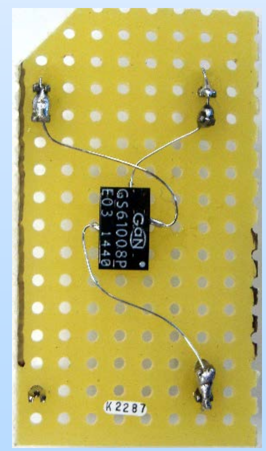




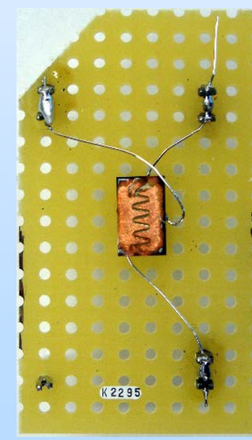
EPC 2012



GaN GS66508P



GaN GS61008P



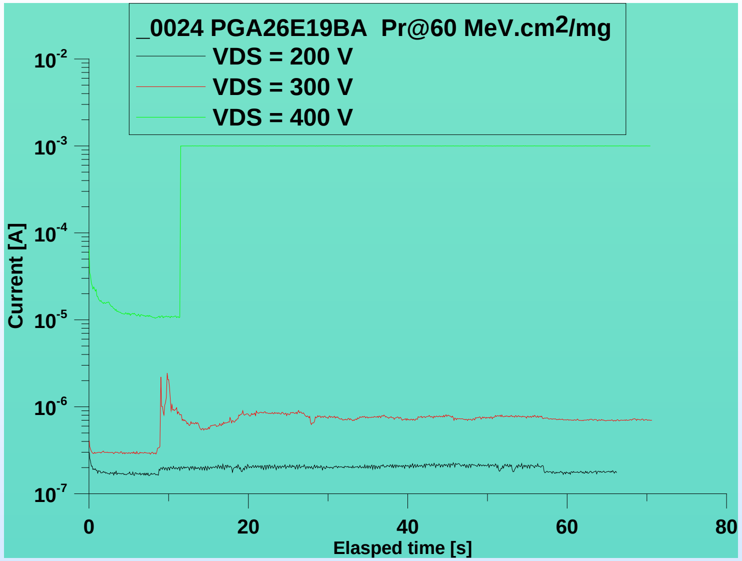
GaN GS61008P

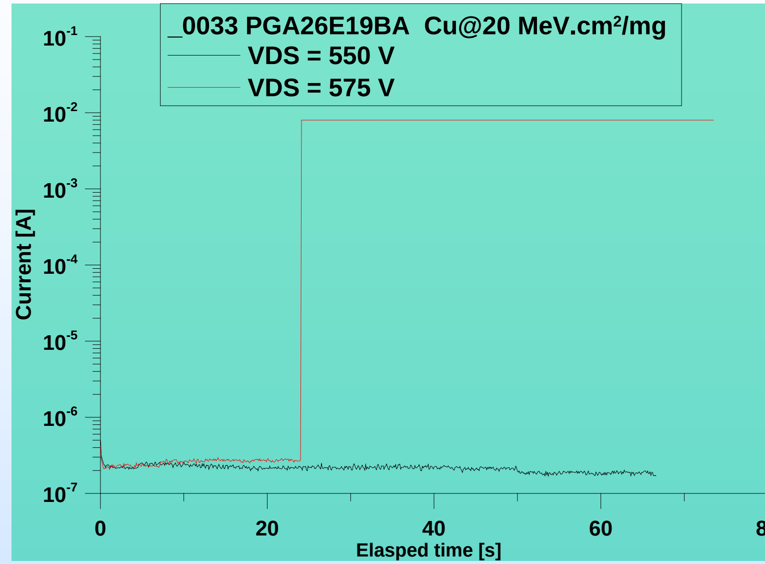
(Un-capped/irradiated)

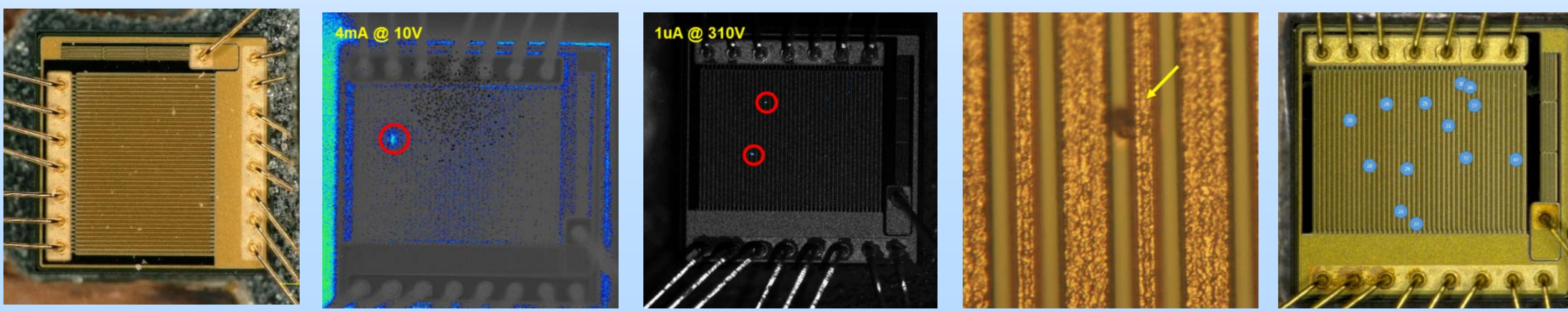
Testing Results Summary

- SEE susceptibility has been a concern in devices tested
- Radiation exposure caused changes to several parameters, most notably drain leakage current
- Significant part-to-part variation in failure levels
- Both control & irradiated parts remained functional after exposure to thermal cycling
- Part-to-part variation in output characteristics
- Negligible effects of cycling on measured properties
- No alteration in device packaging or terminations due to cycling

GaN HEMT Devices (Courtesy of JPL)







Post SEE failure analysis: IR, photoemission & optical images of bare die & failure sites

Potential NASA GaN Applications

NASA Technology Roadmap

Technology Area	Capability Needed	Challenges	Mission	Launch Date
Communications, Navigation, and Orbital Debris Tracking and Characterization Systems	Advancing power efficiency, higher frequency communication, and reduced system mass by utilizing GaN HEMT and MMIC	Small form factor, reliability, radiation hardness, and other extreme space environment	Earth Systematic Missions: Precision and All-Weather Temperature and Humidity (PATH) Climate Absolute Radiance and Refractivity Observatory (CLARREO) Hyperspectral Infrared Imager (HyspIRI)	2024 2021 2023
Science Instruments, Observatories, and Sensor Systems	Highly integrated instrument electronics capable of operation over a wide temperature range and cycling	Reliable, wide-temperature electronics and electronics packaging capable of operating between -230° C and 480° C.	Earth Systematic Missions Strategic Missions Discovery New Frontiers	-- -- -- --
Aeronautics	Alternative propulsion system (hybrid/electric)	High power, high density motors, and wide temperature range electronics and controllers	Ultra-efficient, environment-friendly vehicles	--

Commercial Applications

- Motor drives
- Uninterruptible power supplies (UPS)
- Photovoltaic inverters
- Power utilities, energy conversion, power distribution
- Automotive industry (hybrid/electric vehicle)
- Industrial equipment
- Consumer electronics, data & communication networks
- Down-hole drilling
- Cellular base stations

Military Applications

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

Aerospace Applications

- **High altitude aircraft**
- **Low earth orbit aircraft**
- **Sensors & imaging systems onboard satellites**
- **Data communication & networking**

Major Providers of GaN Parts

Manufacturer	Part/Product
EPC	eFET, half-bridge modules, development boards
GaN Systems	HEMT, half-bridge boards, buck converter
Transphorm	FET cascode, half-bridge
Infineon	FET HEMT, cascode
Panasonic	Transistor, evaluation boards, chopper with driver
VisIC Tech	Power switch, evaluation boards
Freebird	Rad-hard eFETs
Sanken Electric	HEMT with integrated driver
Exagan	FETs
Dialogue Semiconductor	Integrated FET, half-bridge with driver
Navitas	Integrated FET, half-bridge with driver

Major Providers of GaN Parts

Manufacturer	Part/Product
MicroGaN	FET cascode
Texas Instruments	Power stage, half-bridge with driver
Wolfspeed	HEMT
Toshiba	HEMT
Oorvo	HEMT
Macom	HEMT
Mitsubishi Electric	HEMT
Microsemi	HEMT
NXP Semiconductor	HEMT, GaN on SiC
Sumitomo Electric	HEMT
United Monolithic	HEMT

Ongoing GaN R&D Programs

- **U.S. DOE joint academia/industry/government SWITCHES program (Strategies for Wide-Bandgap, Inexpensive Transistors for Controlling High-Efficiency Systems)**
- **U.S. ARPA-E CIRCUITS program (Creating Innovative & Reliable Circuits using Inventive Topologies & Semiconductors)**
- **U.S. Naval, Army, & Air Force Research Labs projects on materials processes, device structure and power systems development**
- **U.S. Department of Energy/PowerAmerica, (a partnership of academia and industry to develop WBG advanced manufacturing methods)**
- **NASA development of cryogenically-cooled megawatt inverter**
- **U.S. DoE GIGA project (GaN Initiative for Grid Applications)**
- **ESA, JAXA pursuing similar programs (diodes and power transistors for space)**
- **Industry-led programs (higher generation, high voltage, vertical structure)**

GaN Technology Limitations

- **Lattice Mismatch**
  - **High strain due to lattice & CTE mismatch between GaN & Si results in high-density dislocations**
- **Cost**
  - **Cost-effective growth of high-quality nucleation layers needed**
- **Packaging**
  - **New material & packaging methods needed to accommodate robust high power, high temperature applications**
- **Layout**
  - **High frequency operation requires careful design**
- **Supporting Electronics**
  - **Fast switching requires optimized gate driver to prevent gate overstress, shoot through, & switching transients**
- **Vertical Devices**
  - **Vertical design yields reduced die size & cost, higher voltage & power rating, & improved reliability**

Acknowledgements

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