



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

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## **Acknowledgment:**

This work was sponsored by:

NASA Office of Safety & Mission Assurance



# 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 <sub>ON</sub>	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 <sub>TH</sub>	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



# 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

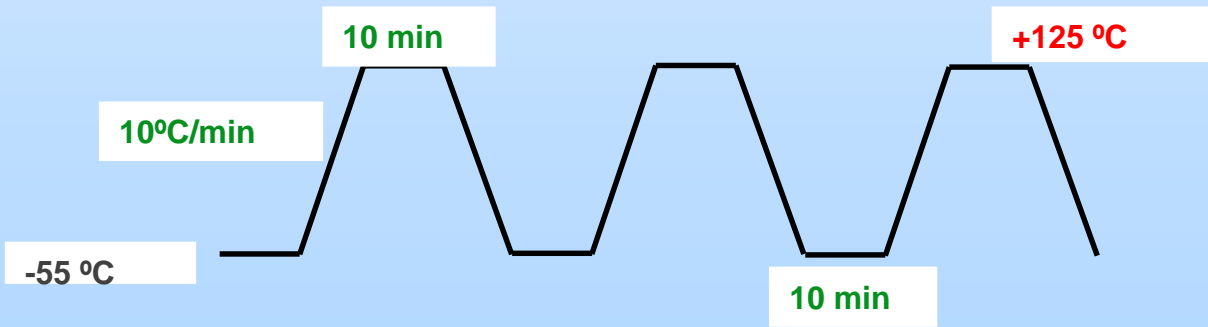
Manufacturer	Part #	Parameters	# Samples (control/Irradiated)	Radiation	Cycling
EPC	2012	200V, 3A, 100mΩ	15/26	✓	✓
GaN Systems	GS61008P	100V, 90A, 7.4mΩ	11/10	✓	✓
	GS66508P	650V, 30A, 52mΩ	4/0	Planned	✓

Radiation Exposure						
Device	Ion	Energy (MeV)	LET (MeV.cm <sup>2</sup> /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





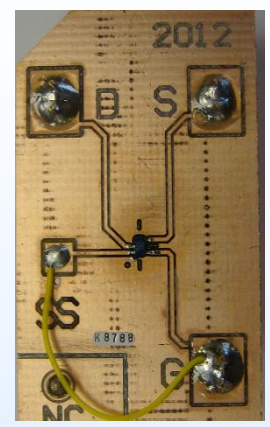
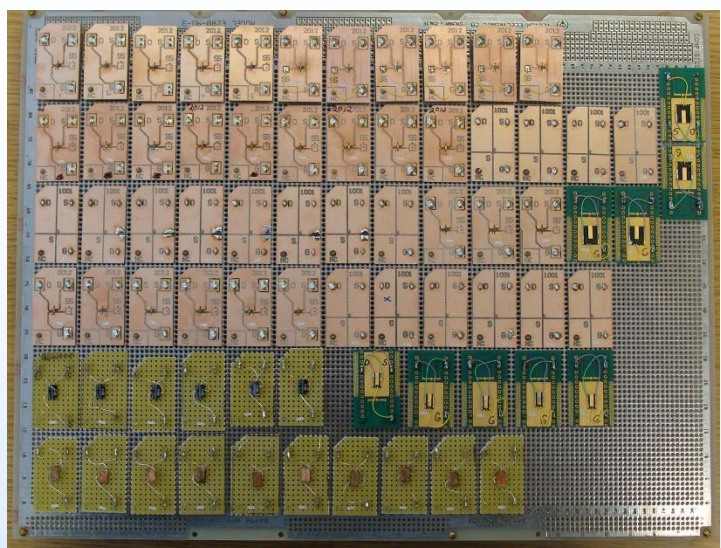
# Parameters and Setup

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

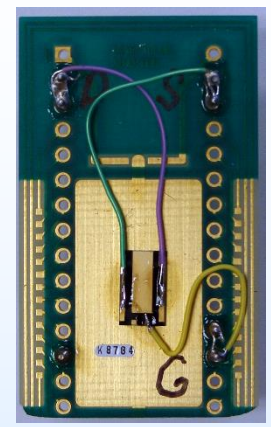




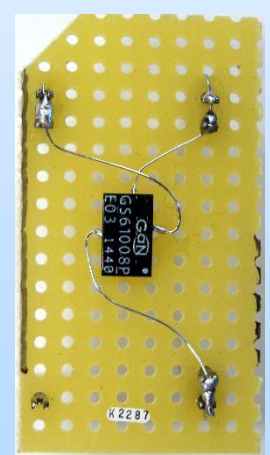
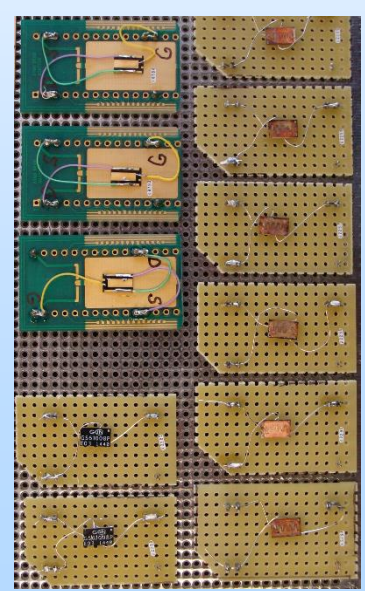
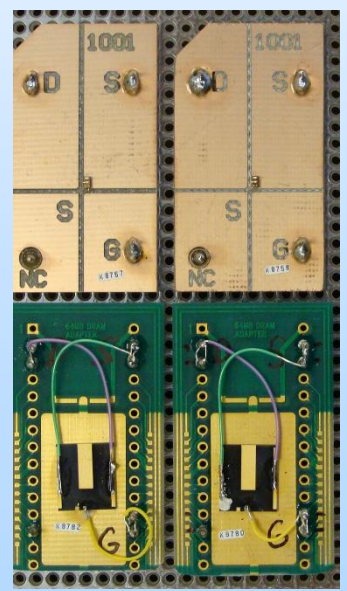
# Device-Mounted Boards



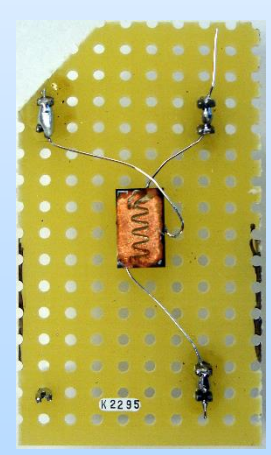
**EPC 2012**



**GaN GS66508P**



**GaN GS61008P**



**GaN GS61008P  
(Un-capped/irradiated)**

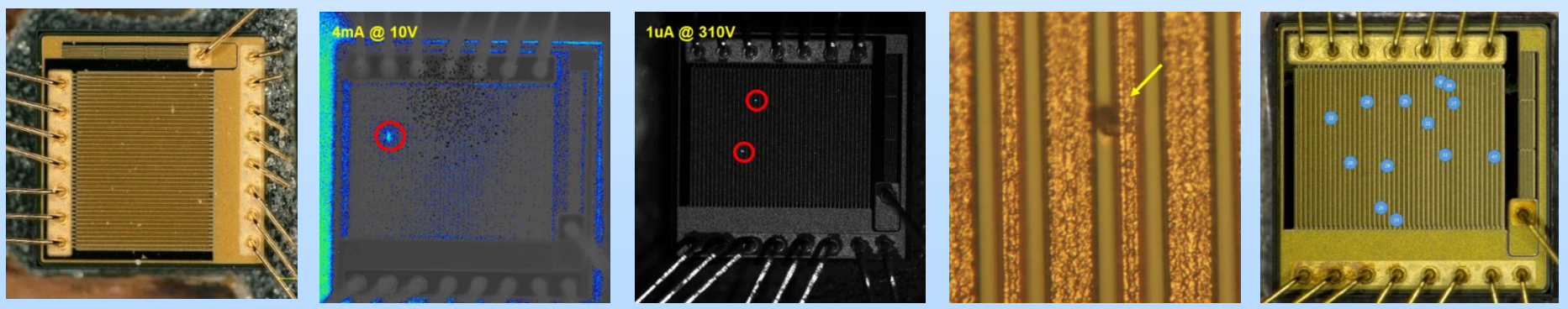
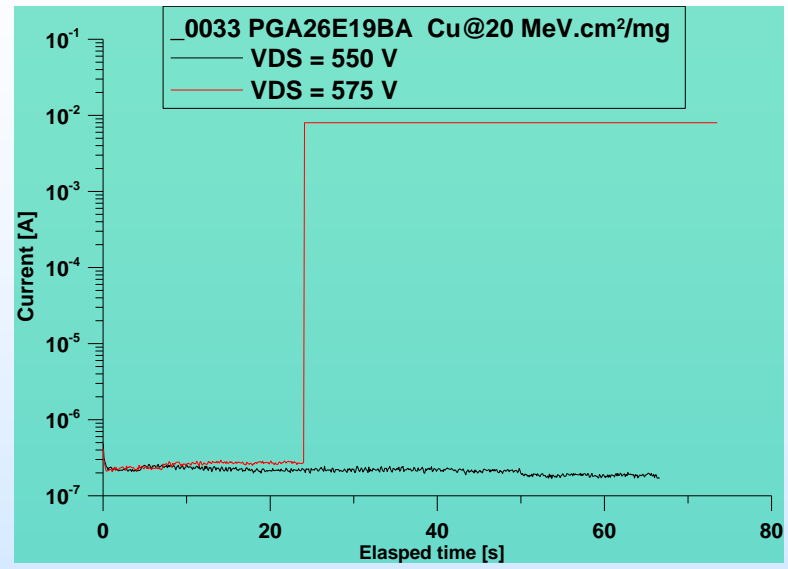
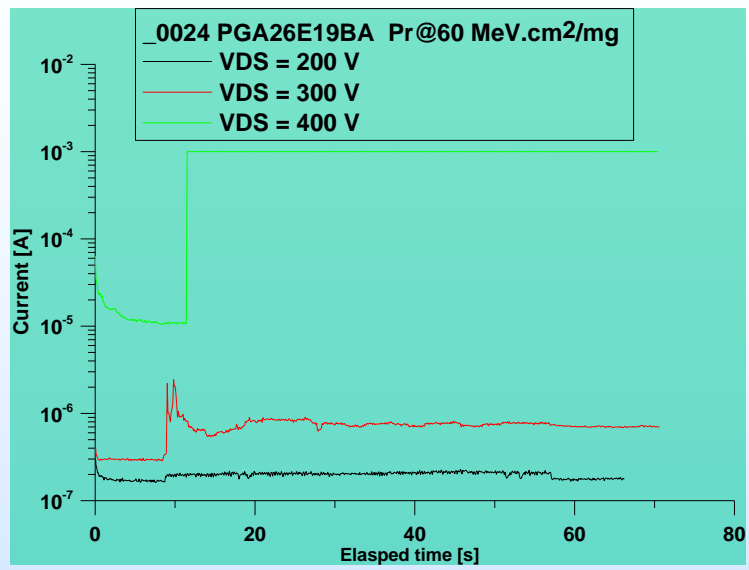


# Testing Results Summary

- **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)	2024
			Climate Absolute Radiance and Refractivity Observatory (CLARREO)	2021
			Hyperspectral Infrared Imager (HyspIRI)	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

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



# Major Providers of GaN Parts

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



# 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

- **This work was performed in support of the NASA Electronic Parts and Packaging (NEPP) Program. Part of this effort was performed at the NASA Glenn Research Center under GESS-3 Contract Number NNC12BA01B.**