Wide-Bandgap Semiconductors in Space: Appreciating the Benefits but Understanding the Risks

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<td>2-D</td>
<td>Two Dimensional</td>
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<td>AlGaN/AlN</td>
<td>Aluminum Gallium Nitride/Aluminum Nitride</td>
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<td>BV_{DSS}</td>
<td>Drain-Source Breakdown Voltage</td>
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<td>C</td>
<td>Carbon</td>
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<td>DDD</td>
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<td>Fermi Level Energy</td>
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<td>E_{gap}</td>
<td>Bandgap Energy</td>
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<td>ESA</td>
<td>European Space Agency</td>
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<td>E_{V}</td>
<td>Valance Band Energy</td>
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<td>FIT</td>
<td>Failures In Time</td>
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<td>FOM</td>
<td>Figure of Merit</td>
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<td>FY</td>
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<td>GaAs</td>
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<td>GaN</td>
<td>Gallium Nitride</td>
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<td>Ga_{2}O_{3}</td>
<td>Gallium Oxide</td>
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<td>GCR</td>
<td>Galactic Cosmic Ray</td>
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<td>GEO</td>
<td>Geostationary Earth Orbit</td>
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<tr>
<td>HEMT</td>
<td>High Electron Mobility Transistor</td>
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<tr>
<td>I_{D}</td>
<td>Drain Current</td>
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<tr>
<td>I_{DSS}</td>
<td>Drain-Source Leakage Current</td>
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<tr>
<td>I_{G}</td>
<td>Gate Current</td>
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<tr>
<td>I_{GSS}</td>
<td>Gate-Source Leakage Current</td>
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<td>InP</td>
<td>Indium Phosphide</td>
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<td>I_{R}</td>
<td>Reverse Current</td>
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<td>ISS</td>
<td>International Space Station</td>
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<tr>
<td>JBS</td>
<td>Junction Barrier Schottky diode</td>
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<td>JFET</td>
<td>Junction Field Effect Transistor</td>
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<td>LEO</td>
<td>Low Earth Orbit</td>
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<td>LET</td>
<td>Linear Energy Transfer</td>
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<td>MESFET</td>
<td>Metal-Semiconductor Field Effect Transistor</td>
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<td>MOSFET</td>
<td>Metal Oxide Semiconductor Field Effect Transistor</td>
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<tr>
<td>NO</td>
<td>Nitric Oxide</td>
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<td>PIGS</td>
<td>Post-Irradiation Gate Stress</td>
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<td>R&amp;D</td>
<td>Research and Development</td>
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<tr>
<td>R_{DS,ON}</td>
<td>On-State Drain-Source Resistance</td>
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<tr>
<td>RF</td>
<td>Radio Frequency</td>
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<td>RHA</td>
<td>Radiation Hardness Assurance</td>
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<td>RHBP</td>
<td>Radiation Hardened By Process</td>
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<tr>
<td>SBD</td>
<td>Schottky Barrier Diode</td>
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<td>SBIR</td>
<td>Small Business Innovative Research</td>
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<tr>
<td>SEB/GR</td>
<td>Single-Event Burnout/Gate Rupture</td>
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<tr>
<td>SEE</td>
<td>Single-Event Effect</td>
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<tr>
<td>Si</td>
<td>Silicon</td>
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<tr>
<td>SiC</td>
<td>Silicon Carbide</td>
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<tr>
<td>Sn</td>
<td>Tin</td>
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<tr>
<td>SOA</td>
<td>State Of The Art; Safe Operating Area</td>
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<tr>
<td>STMD</td>
<td>Space Technology Mission Directorate</td>
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<tr>
<td>SWAP</td>
<td>Size, Weight, And Power</td>
</tr>
<tr>
<td>TAMU</td>
<td>Texas A&amp;M University cyclotron facility</td>
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<tr>
<td>TID</td>
<td>Total Ionizing Dose</td>
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<tr>
<td>UWBG</td>
<td>Ultra-Wide Bandgap</td>
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<tr>
<td>VDMOS</td>
<td>Vertical Double-diffused MOSFET</td>
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<tr>
<td>V_{DS}</td>
<td>Drain-Source Voltage</td>
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<td>V_{GS}</td>
<td>Gate-Source Voltage</td>
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<td>V_{R}</td>
<td>Reverse-bias Voltage</td>
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<td>V_{TH}</td>
<td>Gate Threshold Voltage</td>
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<td>WBG</td>
<td>Wide Bandgap</td>
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<tr>
<td>Xe</td>
<td>Xenon</td>
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To be presented by J.-M. Lauenstein at the Radiation Effects on Components and Systems (RADECS) Topical Day, Gothenburg, Sweden, September 16, 2018
Outline

• Overview
  – Bandgaps: the simple explanation
  – Wide-bandgap (WBG) technology advantages & applications
  – Space environment hazards
• Radiation Hardness Assurance (RHA) of Commercially-Mature WBG Semiconductors
  – SiC discrete power devices
  – GaN high electron mobility transistors (HEMTs):
    • RF
    • Enhancement-mode
• A Glimpse into the WBG Semiconductor Horizon
  – Qualification standardization & technology maturation
  – The future of SiC and GaN
  – Ultra-Wide Bandgap (UWBG) semiconductors
    • Diamond
    • Ga$_2$O$_3$
As atoms come together to form a crystal, their electron shells form bands:

- the highest-energy band containing electrons at 0 K = Valence Band
- the next highest energy band = Conduction Band
  
- Electrons in the conduction band (and subsequent holes in the valence band) are able to move freely about the lattice and thus conduct current

In order to become conducting, an electron must have enough energy to jump the gap
- this jump can be assisted by traps, or energy states, located in the band gap

Wide bandgap materials have different electrical properties than conventional bandgap materials (e.g., Si) due to their different band structure and band gap
Wide-Bandgap Technology Overview: Properties Associated with the Bandgap

- **WBG semiconductors** can:
  - Operate at higher temperatures without “going intrinsic”
  - Block higher voltages for a given thickness of material (breakdown voltage $\propto (E_{\text{gap}})^4$)
  - Switch at higher speeds due in part to higher saturation velocities
  - … and other WBG-material specific advantages
SiC out-performs Si on 5 different parameters, lending itself to high-power, high-temperature, and fast-switching applications
To date, GaN’s upper limit on voltage rating is dictated primarily by device degradation/reliability issues.
RF power amplifiers are critical for radar and communications systems. Choice of semiconductor material will depend in part on power and frequency needs. Plot on left is intended only to provide a general idea of the capabilities of each material.

Future RF amplifiers may combine different semiconductor technologies for system optimization.
Wide-Bandgap Technology Overview: Translation of Properties into Performance

**Higher Blocking Voltage:**
- Reduced current for the same power
  - Smaller-gauge harnesses/cabling
- Decreased design complexity
  - Reduced need for device stacking

**Faster Switching Speeds & Lower Losses:**
- Smaller, lighter passive circuit elements
- Smaller, lighter cooling elements

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**High Power Density:**
- 5x – 10x smaller footprint for RF power GaN vs. GaAs
- Easier impedance matching
  - lower circuit losses

![Image of power module](Image modified from: Kong, K. et al., IEEE CSICS, 2014)

**Toyota estimates 80% volume reduction of Prius power control unit using SiC vs. Si**
https://newsroom.toyota.co.jp/en/detail/2656842 (Image used with permission)

**Ka-band power amplifier:**
72% area reduction & 4x power increase using GaN vs. GaAs

Source: Mercer, AIAA 2011-7252; Image: NASA
Wide-Bandgap Technology Overview: The Space Radiation Environment

- **Trapped radiation belts**
  - High & variable flux of protons and electrons
  - Concerns include:
    - Total ionizing dose (TID)
    - Displacement damage dose (DDD)
    - Proton-induced single-event effects (SEE)

- **Solar Particle Events (SPE)**
  - Intermittent high flux of moderate-energy protons, electrons, and ions with atomic number $Z = 1$ to $\sim 26$
  - Concerns include TID, DDD, and SEE

- **Galactic Cosmic Rays (GCR)**
  - Low flux of very high energy ions of all $Z$
  - Primary concern = SEE

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Image modified from:
Wide-Bandgap Technology Overview:
“But I Heard that WBG Semiconductors are Rad-Hard!”

• “Inherent” radiation hardness of WBG semiconductors typically refers to their tolerance of total dose:
  – Both the ionization energy and threshold energy for defect formation (atomic bond strength) exceed that for Si
    • Must also consider the material density (interaction cross section)
  – Early WBG devices did not have gate oxides
  – For the same working voltage range, SiC and other doped WBG materials can have a higher doping concentration to decrease sensitivity to carrier removal
  – Operation of WBG devices at high temperature results in greater mobility of defects, reducing formation of defect complexes
SILICON CARBIDE POWER DEVICE RADIATION EFFECTS
SiC Outline

• **Effects of radiation:**
  - Displacement damage dose
    • Diodes, JFETs
  - Total ionizing dose
    • MOSFETs
  - Single-event effects
    • Diodes, MOSFETs

• **Radiation hardness assurance (RHA) guidance for risk-tolerant applications**

• **RHA considerations: looking forward**
Silicon Carbide: Displacement Damage Dose Effects

- SiC Schottky diodes are DDD-robust
  - Most mission DDD(Si) levels are $<< 10^{10}$ MeV/g
  - Europa Clipper is one exception at $1.7 \cdot 10^{10}$ MeV/g
    - (Green dashed vertical line on plot)

*Europa Clipper DDD(Si) behind 100 mil Al
From: JPL D-80302, Aug 18, 2016.

Modified from: Harris, IEEE REDW, 2007
Silicon Carbide: Displacement Damage Dose Effects

- SiC Schottky diodes are DDD-robust
- Schottky barrier diodes (SBD) may be more tolerant than junction barrier diodes (JBS)
  - Most commercial SiC Schottky’s are JBS
    - Protects the Schottky barrier from the high field achievable with WBG materials
Silicon Carbide:
Displacement Damage Dose Effects

- SiC Schottky diodes are DDD-robust
- Schottky barrier diodes (SBD) may be harder than junction barrier diodes (JBS)
- Direct comparison with Si is difficult
  - Harris, 2007 showed carrier removal rate in SiC Schottky diodes was higher than in Si Schottkys, suggesting Si more DDD tolerant
  - Comparison was of 4H-SiC JBS vs. Si SBD
    - Si PiN diodes were least DDD tolerant as expected (minority-carrier device)
  - Higher-voltage rated devices were less tolerant
  - At higher temperature, SiC removal rate may be reduced (see Lebedev, Semiconductors, 2002)

Are Si Schottky's more DDD tolerant than SiC or is the difference due to device structure and voltage rating differences?

Modified from: Harris, IEEE REDW, 2007
Silicon Carbide: Displacement Damage Dose Effects

- **Impact of DDD is temperature dependent:**
  - DDD effects in SiC reduced when measured at 300°C
  - In agreement with Lebedev’s 2002 work suggesting reduced carrier removal rate at higher temperature
  - Primary effect is donor compensation
    - Impacts transconductance, pinch-off voltage, and on-state resistance

JFET Performance with Dose at 25 °C and 300 °C:

![Graph showing JFET performance with dose at 25 °C and 300 °C](Image)

Modified from: McGarrity, IEEE TNS, 1992

**SiC DDD tolerance increases with temperature, and SiC can operate at these high temperatures**
Silicon Carbide: Displacement Damage Dose Effects

- SiC DDD tolerance depends on polytype
  - Comparison of 4H- and 6H-SiC JFETs from Popelka (2014) and McGarrity (1992), respectively, suggests 6H-SiC more tolerant
  - Lebedev, JAP 2000, shows that defect behavior differs between 4H- and 6H-SiC:
    - Uncompensated donors increase with radiation in 6H-SiC but decrease with 4H-SiC
    - McGarrity (1992) calculated a carrier removal rate ~3x lower than Si, suggesting 6H-SiC more DDD tolerant than Si
  - Apparent discrepancy with Harris (2007) findings regarding SiC vs. Si may be due to polytype

For most missions, DDD in SiC will not be a concern. Actual DDD performance depends on device structure, polytype, and application temperature.
Silicon Carbide: Total Ionizing Dose Effects in MOSFETs

Despite thick oxides, SiC MOSFETs can be TID-robust:

- **Cree Gens 1 & 2 in spec up to 100 krad(Si)**
  - Above 300 krad(Si), significant gate-drain capacitance changes can strongly impact switching performance

- **Expect variability between manufacturers and processes**
  - Hole trapping depends strongly on NO anneal time and temperature
  - Interface state formation with radiation can vary
  - Substantial fundamental differences between radiation responses of Si and SiC MOSFETs found via electrically detected magnetic resonance (EDMR)

**TID hardness is coincidental and may change**
Silicon Carbide Schottky Diodes: Single-Event Effects

- SEEs in SiC Schottky diodes include:
  - Transient charge collection
  - Permanent increased leakage current
  - Catastrophic single-event burnout (SEB)
Silicon Carbide Schottky Diodes: Single-Event Effects – Thresholds

- Onsets for ion-induced leakage current and single-event burnout saturate quickly with linear energy transfer (LET)
  - Saturation occurs before the high-flux iron knee of the GCR spectrum

Typical risk-avoidant mission LET requirements for SEB are > 40 MeV-cm²/mg
Silicon Carbide Schottky Diodes: Single-Event Effects – SEB

- Prior degradation can impact SEB susceptibility, interfering with identification of “SEB safe operating area (SOA)”
  - At a given reverse-bias voltage ($V_R$), ion-induced leakage current ($I_R$) can impact SEB susceptibility if SEB does not occur early in the beam exposure
    - Can’t obtain “highest passing $V_R$” and “lowest $V_R$ for SEB” within the same device

Adequate heavy-ion test fluence levels are difficult to obtain

Thresholds for SEB have uncertainty:
- at $V_R = 485$ V, after $<10^4$ Xe/cm$^2$, $I_R = 10$ mA with non-linearity of $\Delta I_R$ before that. Is this fluence adequate to rule out SEB? (No)

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Silicon Carbide Schottky Diodes: 
Single-Event Effects – Leakage current

Ion-induced leakage current ($\Delta I_R$) findings:
- Linearly increases with fluence (independent of flux)
- $\Delta I_R$ depends on
  - Applied bias voltage
  - Ion energy deposition (linear energy transfer (LET))
  - Ion angle of incidence

RHA in SiC is challenging: 1) Safe Operating Area to avoid SEB is difficult to identify;
2) Non-catastrophic degradation effects on lifetime reliability are unknown
SiC MOSFETs exhibit complex effects from heavy ions

- Catastrophic failure or degradation shown in drain and gate currents ($I_D$, $I_G$) during 10 MeV/u Xe irradiation
  - Results shown are for a 1200-V device
- At all biases above $V_{DS} = 50$ V, part fails post-irradiation gate stress (PIGS) test
  - At low $V_{DS}$, PIGS outcome is dependent on ion fluence
SiC MOSFET Effects as a Function of $V_{DS}$ at $V_{GS} = 0$ V:
Latent Gate Damage

Grey = no ion effects;
Green = $V_{DS}$ range for which only latent damage occurs

Voltage range of no effects (grey) or only latent damage (change in PIGS test: green) is a function of ion/LET, device voltage rating, and manufacturer/generation

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SiC MOSFET Effects as a Function of $V_{DS}$ at $V_{GS} = 0$ V: Latent Gate Damage

Measurement Results

Grey = no ion effects;
Green = $V_{DS}$ range for which only latent damage occurs

No latent damage to gate from low LET/light ions
SiC MOSFET Effects as a Function of $V_{DS}$ at $V_{GS} = 0$ V: Latent Gate Damage

Measurement Results

- **Q Collection**: Drain-Source Voltage

  - **$I_{GS}$**
    - **Onset is independent of MOSFET voltage rating and manufacturer/generation at higher LETs**

Green = $V_{DS}$ range for which only latent damage occurs

Grey = no ion effects;

**No Measurable Effect**

During Irradiation

Post Run

**Latent Gate Damage**

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MOSFET Effects as a Function of $V_{DS}$ at $V_{GS} = 0$ V:
Degradation During Beam Run

Measurement Results

Yellow = $V_{DS}$ range for $\Delta I_D = \Delta I_G$ degradation
Green = $V_{DS}$ range for which only latent damage occurs

Not all MOSFETs exhibit drain-gate leakage current degradation:
Design techniques may eliminate this vulnerability

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**MOSFET Effects as a Function of $V_{DS}$ at $V_{GS} = 0$ V:** Degradation During Beam Run

**Drain-Source Voltage**

*Q Collection*  
*During Irradiation*  
*Post Run*  

**Measurement Results**

$I_{DS}$ degradation least influenced by electric field and ion LET: linked to material properties??

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MOSFET Effects as a Function of $V_{DS}$ at $V_{GS} = 0$ V: SEB/GR

**SEB/GR vulnerability at LET(Si) < 1 MeV-cm$^2$/mg**

*Vulnerability saturates before the GCR flux “iron knee”*

Red = $V_{DS}$ range for SEB/GR
Blue = $V_{DS}$ range for $\Delta I_D >> \Delta I_G$ degradation
Yellow = $V_{DS}$ range for $\Delta I_D = \Delta I_G$ degradation

Color gradients span between known $V_{DS}$ for given response types

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**Measurement Results**

**Drain-Source Voltage**
**Q Collection**
**During Irradiation**
**Post Run**

- Sudden high-$I$ event: $I_{DG}, I_{DS}$, $\Delta I_D >> \Delta I_G$
- Catastrophic Failure: $B V_{DSS} < 2$ V, $I_{DSS} \uparrow$; or Failed $I_{GSS}$
- $I_{GSS}, I_{DSS} \uparrow$; Failed $I_{GSS}$
- $I_{GSS} \uparrow$; No Measurable Effect

**Device:**
- Latent Gate Degradation: $I_d=I_g$ or $I_d>I_g$
- SEE

**Ion/LET:**
- B 0.9
- Ar 8.9
- Cu 23
- Ag 47
- Xe 63

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SiC Radiation Hardness by Process: 1200 V MOSFET

- Reduced SEB/GR susceptibility
  - Thicker epilayer

Just as with silicon MOSFETs, epilayer optimization must be done to balance SEE tolerance with on-state resistance ($R_{DS\_ON}$) performance

After Zhu, X., et al., 2017 ICSCRM
SiC Radiation Hardness by Process: 1200 V MOSFET

- Reduced SEB/GR susceptibility
  - Thicker epilayer
- Degradation of $I_{DG}$ eliminated
  - Drain neck width reduction

Elimination of drain-gate leakage current degradation mode is possible through established silicon MOSFET hardening techniques

After Zhu, X., et al., 2017 ICSCRM
SiC Radiation Hardness by Process: 1200 V MOSFET

- Reduced SEB/GR susceptibility
  - Thicker epilayer
- Degradation of $I_{DG}$ eliminated
  - Drain neck width reduction
- Minimal change in onset of other degradation effects:
  - $\Delta l_D >> \Delta l_G$
  - latent gate damage
- Rate of degradation at a given voltage is reduced

Continued research and development efforts are necessary to understand residual degradation mechanisms!

Color gradients span between known $V_{DS}$ for given response types

After Zhu, X., et al., 2017 ICSCRM

To be presented by J.-M. Lauenstein at the Radiation Effects on Components and Systems (RADECS) Topical Day, Gothenburg, Sweden, September 16, 2018
Normalized Onset Voltage for Immediate SEB/GR: Comparison of Device Types

Measurable onset for SEB/GR similar across device types:
~40% to 50% of rated $V_{DS}$
Must derate below this level to account for SEB/GR SOA uncertainty

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Comparison of SEB/GR Susceptibility Across SiC Power Devices: Neutron Data

Terrestrial neutron failures-in-time (FIT) data normalized to the active die area, as a function of bias voltage normalized to measured avalanche voltage.

The data strongly suggest that for SEB/GR, the electric field strength is driving the susceptibility; there is no indication of a different mechanism involved for the different device types.
RHA Guidance

• SEB/GR safe operating area (SOA) is difficult to reliably define
  – Susceptibility quickly saturates before the high-flux iron knee of the GCR spectrum

• (Unvalidated) failure rate prediction methods developed for Si power devices may provide an upper bound
  – Degradation of gate/drain leakage currents hides onset bias for SEB/GR at all but lowest LETs
    • For risk-tolerant applications, margin and unpowered redundancy is advised

• Non-catastrophic damage has unknown longer-term effects
  – Extent of damage is part-to-part variable
  – Consider application temperature and functional lifetime requirements
    • For risk-tolerant applications, margin and unpowered redundancy is advised
  – Life tests of damaged parts may reveal higher-likelihood failure modes - sample size will limit discovery of rarer modes

• Remember to consider other non-RHA concerns:
  – There are no space qualification standards specific for WBG technologies
SiC RHA Considerations

• There are limited efforts underway to develop radiation-hardened SiC power devices
  – Some degradation mechanisms may persist despite RHBD efforts
  – Impact on device long-term reliability must be established

• Radiation hardening comes with a cost
  – As with Si power MOSFETs, electrical performance will suffer from hardening techniques

• Testing with lighter ions/lower LETs will reveal nuances between designs and aid on-orbit degradation predictions
  – Responses are saturated at LETs dictated by typical mission destructive-SEE radiation requirements
  – LET should be specified in terms of LET(Si) but penetration range must be for SiC

• Characterization data should include identification of voltage conditions at which different effects occur
  – Richer dataset will include how susceptibility to these effects changes with ion species/LET/angle/temperature
GALLIUM NITRIDE HIGH ELECTRON MOBILITY TRANSISTOR (HEMT) RADIATION EFFECTS
GaN HEMT Outline

- Introduction to GaN high electron mobility transistors (HEMTs)
- Effects of radiation:
  - Displacement damage dose
  - Total ionizing dose
  - Single-event effects
    - RF GaN HEMTs
    - Enhancement-mode HEMTs
- Radiation hardness assurance guidance

SEE failure sites (ex/ right photo) superimposed onto optical image (left) suggest random distribution

Images: NASA JPL, courtesy of L. Scheick
GaN HEMT Introduction: Device Structure

- Two primary flavors of GaN HEMTs:
  - Depletion mode (normally on)
  - Enhancement mode (normally off)

- Normally-off GaN is achieved in several ways:
  - Cascode with a low-voltage normally-off silicon MOSFET
    - Penalty to $R_{DS\_ON}$ lessens with higher voltage-rated GaN HEMTs
  - p-doped GaN gate
    - Used in first commercial eGaN devices
    - Gate built-in voltage exceeds piezoelectric field
  - Recessed Schottky gate
    - Thinned AlGaN barrier beneath gate to reduce piezoelectric voltage below Schottky built-in voltage
  - Flourine-implanted AlGaN barrier
    - Traps negative charge in the layer

Many gate designs: How will these differences affect space qualification standards development for GaN?

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GaN HEMT Introduction: Applications

• RF GaN HEMTs
  – Initially, RF applications dominated due in part to depletion-mode operation
  – Designed to work well in linear region for max gain, min distortion
    • Characterization includes incident and reflected wave power measurements as well

• Enhancement mode GaN HEMTs as switches
  – Development of normally-off HEMTs provided in-road to power management applications
    • Start-up does not require an initial gate bias to be applied to avoid short-circuit damage
  – Designed to work well in on-state/transition states to minimize losses
    • Low $R_{DS\,ON}$ and off-state drain leakage current ($I_{DSS}$)

Can a single set of radiation test method standards be developed for both RF GaN and enhancement-mode GaN HEMTs?
GaN HEMTs:
Displacement Damage Dose Effects

- Parametric degradation in GaN HEMTs occurs at DDD levels far above those for space applications
  - Weaver, et al., 2015 show order-of-magnitude better performance of GaN vs. GaAs HEMTs
  - Possibly due to re-injection of scattered carriers

- GaN HEMT DDD effects include
  - Decreased drain current
  - Threshold voltage shift (typically positive)
  - Decreased mobility and transconductance
  - Decreased power gain

For extreme DDD environments, use of a feedback system to maintain quiescent $I_D$ will improve radiation tolerance
GaN HEMTs: Displacement Damage Dose Effects

Concentrations of existing defects increase with radiation exposure

- DDD susceptibility is greater when:
  - parts are biased during irradiation
  - parts have had prior hot-carrier stress
  - see Chen, et al., IEEE TNS 2015
- Radiation increases the concentration of existing defects

GaN HEMT DDD effects:
1) Bias matters during irradiation
2) Prior hot-carrier stress can enhance radiation effects
3) There is significant variability of response to radiation
Many gate designs:

- **RF GaN HEMTs (Schottky gate)**
  - Aktas, 2004 demonstrated 0.1 V threshold shift after 6 Mrad(Si) $\gamma$ irradiation
  - Harris, 2011 demonstrated no significant shift after 15 Mrad(Si) proton irradiation

- **p-GaN gate**
  - 500 krad(Si) $\gamma$ irradiation: < 18% Vth shift (Lidow, 2011)

- **MOS gate**
  - No data
  - This design is most likely to be sensitive to TID effects

**GaN HEMT TID effects:**
Robust in absence of gate oxide; To be determined for those with oxides
• **Catastrophic SEE:**
  - In some parts, SEB occurs only at $V_{DS}$ levels above those reached during RF operation
    - Rostewitz, 2013 and Osawa, 2017 tested in both DC and RF modes: Calibrated measurements of max transient $V_{DS}$ during RF operation showed no excursions above SEB failure threshold $V_{DS}$ found in DC mode tests
      - Osawa, 2017 noted the failure threshold in DC mode was over 3X $V_{DS}$ bias level for RF mode; no failures in RF mode
      - Armstrong, 2015 showed no failures in RF mode
  - However, some unpublished data suggest some parts/lots may be susceptible to SEB in RF mode
    - Lot-lot variability found

*Although generally SEB-robust, some unpublished SEB failures have occurred at biases relevant to RF operation*
RF GaN HEMTs: Single-Event Effects

- Increased leakage currents
  - Armstrong, 2015 study of 5 different HEMTs from 4 manufacturers revealed manufacturer and part-part variability in susceptibility to increasing gate leakage current due to heavy-ion induced damage
  - Kuboyama, 2011 study reveals two different degradation modes
    - At lower DC VDS bias, $I_{DG}$ degradation
    - At higher DC VDS bias, $I_{DS}$ degradation

All heavy-ion studies of RF GaN HEMTs report increased leakage current

$I_D$ and $I_G$ as a function of 3.5 MeV/u Kr fluence and $V_{DS}$ reveals 2 damage pathways
Enhancement-Mode GaN HEMTs:
Single-Event Effects

- Catastrophic SEE:
  - Susceptibility is very wafer-lot specific
    - Likely accounts for some data discrepancies in the literature
    - Lot-specific testing is critical
  - Susceptibility can depend on test circuit design (Scheick, 2014, 2015, and 2018)
    - When gate is tied to the source at the part level, threshold for SEE improves
      - Gate transients upon ion strikes are unrealistically dampened
    - Gate off-state bias level has minimal effect
  - Angle effects are variable
    - Variability between lots of same part (Scheick, 2018)
    - Compounds difficulty of estimating an on-orbit failure rate
- Increased leakage currents:
  - Drain-source leakage current affected

Lot-specific testing is critical
RHA Guidance

• Lot-specific heavy-ion testing is necessary
  – Several suppliers now offer “space qualified” enhancement-mode GaN HEMTs, providing wafer lot level screening for SEE
    • Radiation test methods for GaN are not standardized

• Unlike for SiC, GaN SEE safe operating areas (SOAs) can be identified
  – Valid for the tested lot only
  – Part-part variability reduces confidence
    • Derate, derate, derate
  – Ensure that all transient voltages fall within the SOA

• More data are needed on angle effects to understand worst-case test conditions
  – SEB SOAs to date are established with data taken at normal incidence only
    • Until effects are understood, additional margin (derating) may reduce risk

• Effect of leakage current degradation on device reliability/lifetime is unknown

• Remember to consider other non-RHA reliability concerns
  – Hot carrier damage
  – Current collapse
  – Dynamic $R_{DS\_on}$
  – And others
A GLIMPSE INTO THE FUTURE
• Supplier qualification data are based on standards for silicon
  – Methods vary between vendors
• JEDEC has established a new committee to address this need
  – JC-70 Wide Bandgap Power Electronic Conversion Semiconductors
    • Sub-committees for SiC and GaN
  – Focused initially on non-radiation reliability
• Aerospace Corporation Guideline document for GaN now available
• NASA Electronic Parts and Packaging Program RHA guidelines to be developed
  – Work to begin FY2019
• Funded efforts to mature WBG technologies for space application are underway
  – ESA Materials and Components Technology Section (TEC-QTC) programs
  – NASA and Dept. of Defense Small Business Innovative Research (SBIR) awards and other grant mechanisms
  – Other international government and industry programs
The Future of SiC and GaN

Markets:

• **Automotive industry forecasted to drive the SiC power market**
  – Almost all carmakers are working to implement SiC in their main inverter
  – SiC transistor forecasted compound annual growth rate for 2017-2023: 50%
  – Source: Yole Power SiC 2018 Market & Technology Report

• **Largest growth in GaN market size will be power supply applications**
  – Over 2 orders of magnitude growth expected by 2021
    • Source: Yole Power GaN 2017: Epitaxy, Devices, Applications, and Technology Trends

R&D efforts

• **Vertical GaN power devices for higher current and voltage**
• **Increased GaN reliability**
• **Increased SiC reliability**

To be presented by J.-M. Lauenstein at the Radiation Effects on Components and Systems (RADECS) Topical Day, Gothenburg, Sweden, September 16, 2018
Ultra WBG: Diamond

• Benefits:
  – Best of everything (see plot)
  – High electron and hole mobilities
  – Electron emissivity
• Target applications: “Ultra-high power” market (1 kW or more)
  – Radar
  – Communication satellites
  – Vacuum electronics (driver, cathode)
• Status:
  – 10 mm x 10 mm wafers commercially available
  – Vertical SBDs, MESFETs, and MOSFETs have been developed
• Challenges for maturation
  – Crystal quality and size
  – Absence of n-doping

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Ultra WBG: $\text{Ga}_2\text{O}_3$

- **Benefits:**
  - Power-Frequency figure of merit (FOM) > 2x GaN
  - Specific on-resistance in vertical drift region > 10x SiC
  - High-quality native substrate
  - Wafer costs are comparable to GaN

- **Target applications:** “Ultra-high power” market (1 kW or more)
  - Radar
  - Communication satellites
  - LED market

- **Status:**
  - Least mature of the ultra-WBG technologies
  - 2" Wafers commercially available
  - Vertical SBDs, MESFETs, and MOSFETs have been developed

- **Challenges for maturation**
  - Crystal quality
  - Absence of p-doping; self-trapping of holes
  - High contact resistance
  - Thermal management: poor heat dissipation

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Thank you for your attention!