Taking SiC Power Devices to the Final Frontier: Addressing Challenges of the Space Radiation Environment

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<table>
<thead>
<tr>
<th>Acronym</th>
<th>Definition</th>
</tr>
</thead>
<tbody>
<tr>
<td>BJT</td>
<td>Bipolar Junction Transistor</td>
</tr>
<tr>
<td>BV_{DSS}</td>
<td>Drain-Source Breakdown Voltage</td>
</tr>
<tr>
<td>COR</td>
<td>Contracting Officer Representative</td>
</tr>
<tr>
<td>COTS</td>
<td>Commercial Off The Shelf</td>
</tr>
<tr>
<td>ESA</td>
<td>European Space Agency</td>
</tr>
<tr>
<td>ETW</td>
<td>Electronics Technology Workshop</td>
</tr>
<tr>
<td>FY</td>
<td>Fiscal Year</td>
</tr>
<tr>
<td>GCR</td>
<td>Galactic Cosmic Ray</td>
</tr>
<tr>
<td>I_{D}</td>
<td>Drain Current</td>
</tr>
<tr>
<td>I_{DSS}</td>
<td>Drain-Source Leakage Current</td>
</tr>
<tr>
<td>I_{G}</td>
<td>Gate Current</td>
</tr>
<tr>
<td>I_{R}</td>
<td>Reverse-Bias Leakage Current</td>
</tr>
<tr>
<td>IC</td>
<td>Integrated Circuit</td>
</tr>
<tr>
<td>ICSCRM</td>
<td>International Conference on SiC and Related Materials</td>
</tr>
<tr>
<td>JAXA</td>
<td>Japan Aerospace Exploration Agency</td>
</tr>
<tr>
<td>JBS</td>
<td>Junction Barrier Schottky</td>
</tr>
<tr>
<td>JFET</td>
<td>Junction Field Effect Transistor</td>
</tr>
<tr>
<td>LBNL</td>
<td>Lawrence Berkeley National Laboratory cyclotron facility</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Acronym</th>
<th>Definition</th>
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<tbody>
<tr>
<td>MOSFET</td>
<td>Metal Oxide Semiconductor Field Effect Transistor</td>
</tr>
<tr>
<td>Q</td>
<td>Charge</td>
</tr>
<tr>
<td>RADECES</td>
<td>Radiation and its Effects on Components and Systems</td>
</tr>
<tr>
<td>RHA</td>
<td>Radiation Hardness Assurance</td>
</tr>
<tr>
<td>SBD</td>
<td>Schottky Barrier Diode</td>
</tr>
<tr>
<td>SEB</td>
<td>Single-Event Burnout</td>
</tr>
<tr>
<td>Si</td>
<td>Silicon</td>
</tr>
<tr>
<td>SiC</td>
<td>Silicon Carbide</td>
</tr>
<tr>
<td>SMU</td>
<td>Source Measurement Unit</td>
</tr>
<tr>
<td>SOA</td>
<td>State Of the Art</td>
</tr>
<tr>
<td>STMD</td>
<td>Space Technology Mission Directorate</td>
</tr>
<tr>
<td>SWAP</td>
<td>Size, Weight, And Power</td>
</tr>
<tr>
<td>TAMU</td>
<td>Texas A&amp;M University cyclotron facility</td>
</tr>
<tr>
<td>TID</td>
<td>Total Ionizing Dose</td>
</tr>
<tr>
<td>VDMOS</td>
<td>Vertical Double-diffused MOSFET</td>
</tr>
<tr>
<td>V_{DS}</td>
<td>Drain-Source Voltage</td>
</tr>
<tr>
<td>V_{GS}</td>
<td>Gate-Source Voltage</td>
</tr>
<tr>
<td>V_{R}</td>
<td>Blocking Voltage</td>
</tr>
<tr>
<td>V_{TH}</td>
<td>Gate Threshold Voltage</td>
</tr>
</tbody>
</table>
Game-changing NASA approaches are demanding higher-performance power electronics

- SEE rad-hardened high-current MOSFETs > 250 V do not exist
- High-voltage transistors with fast switching speeds are also needed

SWAP benefits for existing technologies

- SiC power devices are flying now (Orion, MMS)

Conclusions: We must understand the risk of damaged parts
We must support industry/government/academic partnerships to expand SEE hardening efforts
Radiation Effects in SiC Power Technology

• Wide-bandgap power electronics are frequently referred to as “inherently radiation hard” – but to what type of radiation?
  – Total ionizing dose (TID)
  – Displacement damage dose (DDD)
  – Heavy-ion induced single-event effects (SEE)

• Prior work by NASA and other researchers has shown that serendipitously SEE-hard commercial SiC power devices are rare or non-existent

<table>
<thead>
<tr>
<th>Device Type</th>
<th># COTS or Engineering Parts/ # Manufacturers</th>
</tr>
</thead>
<tbody>
<tr>
<td>Diode</td>
<td>6/4</td>
</tr>
<tr>
<td>MOSFET</td>
<td>8/4</td>
</tr>
<tr>
<td>JFET</td>
<td>4/2</td>
</tr>
<tr>
<td>BJT</td>
<td>1/1</td>
</tr>
</tbody>
</table>

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Space Radiation Environment

- **Cumulative effects**
  - TID—Total Ionizing Dose (degradation due to charge trapped in device oxides)
  - DDD—Displacement Damage Dose (degradation from damage to semiconductor)

- **Single-particle effects**
  - SEE—Single-Event Effect (change in performance of device resulting from passage of a single energetic particle)

Trapped Particles:
Protons, Electrons, Heavy Ions

After: Nikkei Science Inc. of Japan

Trapped Particles: Protons, Electrons, Heavy Ions

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SEE radiation requirements are derived in part by the environment specified as a function of linear energy transfer (LET) in silicon; SiC test results therefore are in LET(Si)
SiC Power Device Response to Heavy Ion Irradiation

- Heavy-ion radiation effects in SiC power devices are a function of:
  - Applied voltage
    - Reverse voltage ($V_R$) or drain-source voltage ($V_{DS}$) when in the “off” or blocking state
  - Incident ion energy and species
    - Linear energy transfer (LET)
  - Angle of ion strike
    - Tilt/roll angle
  - Device temperature

$\Theta = \text{tilt angle}$
$\Phi = \text{roll angle}$

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Test Circuits

- Per MIL-STD 750, TM1080
  - Stiffening capacitor prevents voltage sagging upon sudden increase in current
  - Gate filter to protect MOSFET oxide from electrically induced transients
    - Filter removed for BJT tests
Applied Voltage and Ion LET:

SCHOTTKY DIODES
Diode Effects as a Function of $V_R$: Degradation

Leakage current increases linearly with ion fluence; Slope increases with increasing $V_R$
Diode Effects as a Function of $V_R$: Degradation

Onset $V_R$ for degradation is similar for 650 V – 1700 V SBD or JBS diodes: Once minimum conditions met, electric field may not matter

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Diode Effects as a Function of $V_R$: SEB

**SEB (sudden high-$I_R$ event)**
- Increasing $I_R \propto$ ion fluence
- Q Collection
- No Measurable Effect

**Catastrophic Failure: Inability to block $V_R$**
- Degraded $I_R$

**Reverse/Blocking Voltage**
- During Irradiation
- Post Run

**Measurement Results**

*After catastrophic single-event burnout (SEB), the diode can no longer block voltage*

**Graph:**
- $V_R = 500$ V
- 1110 MeV Ag
- LET(Si) = 47 MeV-cm$^2$/mg
- Ave. Flux: 23 cm$^2$ s$^{-1}$ (~ 2 ions/s to diode)

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Diode Effects as a Function of $V_R$: Test Challenge

Degradation is non-Poisson process: Prior damage can impact effect of next ions. Threshold for SEB can be affected, preventing accurate identification of “SEB-safe” region of operation*.

Saturation: Heat? or Degraded E-field?

Degradation is non-Poisson process: Prior damage can impact effect of next ions. Threshold for SEB can be affected, preventing accurate identification of “SEB-safe” region of operation*.

Diode Effects as a Function of $V_R$: SEB

SEB: sudden high-$I_R$ event
Catastrophic Failure: Inability to block $V_R$
Increasing $I_R \propto$ ion fluence
Degraded $I_R$
Q Collection
No Measurable Effect

Measurement Results

650 V – 1700 V Schottkys show SEB at similar % of rated $V_R$: Electric field dependent

Max $V_R$ before immediate SEB
Error bars: SEB

<table>
<thead>
<tr>
<th>D1: 650V</th>
<th>D2: 1200V</th>
<th>D3: 1200V</th>
<th>D1</th>
<th>D2</th>
<th>D3</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ag: 47 MeV-cm$^2$/mg</td>
<td>% Rated V</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

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Schottky Diode Effects as a Function of LET

No degradation with neon at LET = 2.8 MeV-cm²/mg but SEB still occurs at 50% of rated $V_R$ despite very low LET. Suggests high-energy protons will cause SEB.

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Applied Voltage and Ion LET:

PIN DIODES
PIN vs. Schottky Diode Effects: Degradation

PIN diode onset $V_R$ for degradation is higher than that for Schottkys. Similar degradation onset $V_R$ for 1200 V and 3300 V PINs

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PIN vs. Schottky Diode Effects: SEB

*PIN and Schottky diode SEB occurs at similar normalized $V_R$ –
Again suggests different mechanisms for SEB vs. degradation*
Applied Voltage:

JFETS
Effects as a Function of $V_{DS}$ at Fixed off $V_{GS}$: Degradation

Degradation in tested normally-on and normally-off JFETs is always drain-gate leakage, likely due to trench design.

Measurement Results

- Increasing $I_{DG}$ $\propto$ ion fluence:
  - $I_D = I_G$
- Degraded leakage
  - $I_D$ & $I_G$
- No Measurable Effect

Q Collection

During Irradiation

Post Run

Drain-Source Voltage

$V_{DS} = 400$ V
361-MeV Ar
LET(Si) = 10 MeV-cm$^2$/mg
Fluence = $1 \times 10^5$ cm$^2$
Flux = $1.3 \times 10^6$ cm$^2$ s$^{-1}$
Effects as a Function of $V_{DS}$ at Fixed off $V_{GS}$: Degradation

**Measurement Results**

Onset $V_{DS}$ for degradation is similar for normally-on and normally-off JFETs. Possibly greater field dependence of degradation mechanism vs. diodes (or due to lower test LET?)
Effects as a Function of $V_{DS}$ at Fixed off $V_{GS}$: SEE

**Measurement Results**

*1200 V – 1700 V JFETs show SEE at similar % of rated $V_{DS}$*

*Normally-on similar to normally-off JFET susceptibility*

**No Measurable Effect**

**Increasing $I_{DG}$**

$\propto$ ion fluence:

$I_D = I_G$

**Catastrophic Failure:**

Shorted Gate and Drain

**Q Collection**

**SEE:** sudden high-$I$ event

**Max $V_R$ no immediate SEE**

Error bars: Onset of degradation or SEE

$J4 \ V_{GS} = -15 \ V$;

$J1$-$J3 \ V_{GS} = 0 \ V$

Drain-Source Voltage

<table>
<thead>
<tr>
<th>$V_{DS}$</th>
<th>$I_D$</th>
<th>$I_G$</th>
</tr>
</thead>
<tbody>
<tr>
<td>1200 V</td>
<td></td>
<td></td>
</tr>
<tr>
<td>1700 V</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

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Applied Voltage and LET:
MOSFETS
Effects as a Function of $V_{DS}$ at $V_{GS} = 0$ V: Latent Gate Damage

**Measurement Results**

Presence of gate oxide introduces a latent-damage mechanism revealed only on post-irradiation gate stress (PIGS) test

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

Gate Leakage Current ($I_{GSS}$) initially increases linearly with fluence but then thermal damage likely occurs.
Latent gate damage is LET/ion species-dependent; Onset is independent of voltage rating at higher LETs.
Effects as a Function of $V_{DS}$ at $V_{GS} = 0$ V: Degradation During Beam Run

- **Measurement Results**
  - Gate oxide degradation is linear with ion fluence.
  - Slope is a function of $V_{DS}$ and ion LET/species.

- **Drain-Source Voltage**
  - $\uparrow I_{DG}$
  - $\Delta I_D = \Delta I_G$
  - Q Collection

- **During Irradiation**
  - $\uparrow I_{GSS}$, $\uparrow I_{DSS}$
  - Failed $I_{GSS}$
  - Q Collection

- **Post Run**
  - No Measurable Effect

**Graph:**
- $V_{DS} = 300$ V
- $996$ MeV Xe
- LET(Si) = $63$ MeV-cm$^2$/mg

- $I_{DSS}$, $I_{GSS}$
- $V_{DS} = 300$ V

**Table:**

<table>
<thead>
<tr>
<th>Current (A)</th>
<th>Elapsed Time (s)</th>
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<tbody>
<tr>
<td>1.5E-06</td>
<td>50</td>
</tr>
<tr>
<td>1.0E-06</td>
<td></td>
</tr>
<tr>
<td>5.0E-07</td>
<td></td>
</tr>
<tr>
<td>0.0E+00</td>
<td></td>
</tr>
<tr>
<td>-5.0E-07</td>
<td></td>
</tr>
<tr>
<td>-1.0E-06</td>
<td></td>
</tr>
<tr>
<td>-1.5E-06</td>
<td></td>
</tr>
</tbody>
</table>
Effects as a Function of $V_{DS}$ at $V_{GS} = 0$ V: Degradation During Beam Run

Measurement Results

Unlike vertical JFET topology, planar-gate MOSFETs show drain-source leakage current. Very low flux reveals damage from individual ion strikes.

Drain-Source Voltage

During Irradiation

Post Run

↑ $I_{DG}$, $I_{DS}$

$\Delta I_D >> \Delta I_G$

$\Delta I_D = \Delta I_G$

Q Collection

↑ $I_{DG}$

Q Collection

No Measurable Effect

↑ $I_{DG}$, $I_{DS}$

$\Delta I_D >> \Delta I_G$

↑ $I_G$

↑ $I_{GSS}$, $I_{DSS}$

or Failed $I_{GSS}$

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

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

Not all MOSFETs suffer drain-gate leakage current degradation: Per ICSCRM MO.DP.14 (Zhu, et al.), likely a “JFET” drain neck width factor

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

SEB: sudden high-I event
- $I_{DG}, I_{DS}$
- $\Delta I_D >> \Delta I_G$
- $I_{DG}$
- $\Delta I_D = \Delta I_G$

Catastrophic Failure:
- $BV_{DSS} < 2$ V
- $I_{DSS}$
- $\Delta I_D, \Delta I_G$
- Failed $I_{GSS}$

Measurement Results
- No Measurable Effect
- $I_{GSS}$

Use of real $BV_{DS}$ will likely strengthen similarity across MOSFETs of different ratings.
SEB vulnerability saturates before the GCR flux “iron knee”.

To be published on nepp.nasa.gov.
Drain-source leakage current degradation is least influenced by electric field and ion LET; it may be more closely linked to material properties.
Angle of Ion Incidence

- **Diode: Strong angle effect**
  - At given $V_R$, no degradation at 45°
  - Matching vertical component of electric field has no impact
  - Cosine law not followed

- **MOSFET: Follows cosine law when gate-leakage dominated**
  - For $I_G = I_D$ degradation signature, path length through gate likely dominates angle effect
  - For drain-source current degradation dominant region/device, expect behavior similar to diode response

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Rate of leakage current degradation in a 1200-V power MOSFET increases with increasing temperature.
Summary & Conclusions

• All discrete, unhardened SiC power devices in this work exhibit catastrophic failure at 50% of rated voltage or below
  – Electric field and ion LET/species are shown to impact this threshold.
  – LET/species effects are quickly saturated below the high-flux iron knee of the GCR spectrum
    • Mission orbit will have a weaker influence on risk

• Non-catastrophic damage occurs at voltages as low as 10% of rated values (gate oxide latent damage effects), and 30% for non-oxide degradation effects.
  – Degradation within the SiC material is not correlated significantly with electric field strength and thus may require other methods than doping or geometry changes.
  – Reliability studies will be important to understand the impact of degradation mechanisms on long-term mission reliability

• Due to saturation effects at high LETs, performance discrimination may best be achieved by testing at LETs below those dictated by typical space mission radiation requirements.
Summary & Conclusions

Angle effects – Diodes and MOSFETs:

• Both Schottky and PIN diodes exhibit faster roll-off of degradation effects with angle of incidence than would be expected if the vertical component of the electric field were the critical component of the mechanism.
  – This lack of strong field dependence is also seen at normal angle of incidence when comparing effects in diodes of different voltage ratings.

• Additional angle studies are needed in transistor devices.
  – Gate oxide leakage effects follow the cosine relationship of the vertical field as expected from historic silicon studies.

Temperature - MOSFETs:

• For case temperatures up to 100 °C, rate of $I_{DG}$ degradation increases.
  – More studies are needed for non-oxide leakage pathways.