Single-Event Effects in Silicon and Silicon Carbide Power Devices

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ASRC Space & Defense

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# List of Acronyms

<table>
<thead>
<tr>
<th>Acronym</th>
<th>Definition</th>
</tr>
</thead>
<tbody>
<tr>
<td>BJT</td>
<td>Bipolar Junction Transistor</td>
</tr>
<tr>
<td>BVdss</td>
<td>Drain-to-Source Breakdown Voltage</td>
</tr>
<tr>
<td>ETW</td>
<td>Electronic Technology Workshop</td>
</tr>
<tr>
<td>FY</td>
<td>Fiscal Year</td>
</tr>
<tr>
<td>GRC</td>
<td>Glenn Research Center</td>
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<tr>
<td>GSFC</td>
<td>Goddard Space Flight Center</td>
</tr>
<tr>
<td>HEMT</td>
<td>High Electron-Mobility Transistor</td>
</tr>
<tr>
<td>ID</td>
<td>Drain current</td>
</tr>
<tr>
<td>IG</td>
<td>Gate current</td>
</tr>
<tr>
<td>JEDEC</td>
<td>(not an acronym)</td>
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<tr>
<td>JESD</td>
<td>JEDEC Standard</td>
</tr>
<tr>
<td>JFET</td>
<td>Junction Field-Effect Transistor</td>
</tr>
<tr>
<td>JJAP</td>
<td>Japanese Journal of Applied Physics</td>
</tr>
<tr>
<td>JPL</td>
<td>Jet Propulsion Laboratory</td>
</tr>
<tr>
<td>LBNL</td>
<td>Lawrence Berkeley National Laboratory 88-Inch cyclotron</td>
</tr>
<tr>
<td>LET</td>
<td>Linear Energy Transfer</td>
</tr>
<tr>
<td>MOSFET</td>
<td>Metal Oxide Semiconductor Field Effect Transistor</td>
</tr>
<tr>
<td>NEPP</td>
<td>NASA Electronic Parts and Packaging program</td>
</tr>
<tr>
<td>PIGS</td>
<td>Post-Irradiation Gate Stress</td>
</tr>
<tr>
<td>RF</td>
<td>Radio Frequency</td>
</tr>
<tr>
<td>SEB</td>
<td>Single-Event Burnout</td>
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<tr>
<td>SEE</td>
<td>Single-Event Effect</td>
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<tr>
<td>SEFI</td>
<td>Single-Event Functional Interrupt</td>
</tr>
<tr>
<td>SEGR</td>
<td>Single-Event Gate Rupture</td>
</tr>
<tr>
<td>SET</td>
<td>Single-Event Transient</td>
</tr>
<tr>
<td>SOA</td>
<td>State-Of-the-Art</td>
</tr>
<tr>
<td>TID</td>
<td>Total Ionizing Dose</td>
</tr>
<tr>
<td>VDMOS</td>
<td>vertical, planar gate double-diffused power MOSFET</td>
</tr>
<tr>
<td>VDS</td>
<td>Drain-source voltage</td>
</tr>
<tr>
<td>VGS</td>
<td>Gate-source voltage</td>
</tr>
<tr>
<td>VR</td>
<td>Reverse-bias Voltage</td>
</tr>
</tbody>
</table>

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Goals

• Assess SiC power devices for space applications
  – Develop relationships with SiC device suppliers
  – Investigate SEE susceptibility of currently available products
  – Understand SEE mechanisms to enable radiation hardening

• Participate in test method revisions:

• Evaluate alternative silicon power MOSFETs for space applications
  – Winding down focus on Si VDMOS: We’ve gone from 1 to 6 manufacturers offering independently verified SEE radiation-hardened discrete silicon power MOSFETs!
  – Thank you to all manufacturers who partnered with us over the years to provide this critical product to the aerospace community
  – *We are always interested in SOA high-performance Si MOSFETs.*
Si Power MOSFETs

- **FUJI advanced 2\textsuperscript{nd} generation radiation-hardened VDMOS:**
  - Developed to withstand PIGS test
  - Hardness of 250 VDMOS evaluated at LBNL – failures only at -15 Vgs
  - 500 V device in development

- **NEPP (JPL) invited to observe Microsemi 2\textsuperscript{nd} generation i2MOS\textsuperscript{TM} SEE testing this summer**

Single-event effect response curve of FUJI engineering samples of new 250 VDMOS

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JEDEC Standard No. 57 (JESD57) Revision Efforts


- **FY13 efforts: update SEGR test method within JESD57**
  - Current understanding of ion species and energy effects
    - Guidance for beam selection based on species
  - Scope expanded:
    - Discrete MOSFETs of various topologies
    - Microcircuits

- **FY14 efforts include complete JESD57 update**
  - Document reorganization
  - Addition of SEB, SET
  - Expansion of SEFI understanding
  - and more
JESD57 Content Revision

- **Key content updates:**
  - **Basic effects expanded to better address:**
    - SEB, SEFIIs, SEGR, SETs
    - Effects not well understood to be addressed as “notes”:
      - SiC and Si Schottky burnout-like failures
      - RF SEE challenges, including on-state catastrophic failures in GaN HEMTs
  - **Definitions updated to current JESD88**
    - Some definitions are still out-of-date – need to be expanded to reflect current understanding of effects
      - SEFI, SEU
  - **DUT preparation expanded**
    - Die thinning
    - High-voltage die arcing after decapsulation
  - **Dosimetry practices updated**
  - **Document reorganized for improved readability**

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## SiC Power Devices Evaluated to Date

<table>
<thead>
<tr>
<th>Part Type</th>
<th>Manufacturer</th>
<th>Part Number</th>
<th>Date Tested</th>
</tr>
</thead>
<tbody>
<tr>
<td>Schottky (1200 V)</td>
<td>Cree</td>
<td>C4D40120D*</td>
<td>Spr 2013</td>
</tr>
<tr>
<td></td>
<td>GeneSiC</td>
<td>GB20SLT12*</td>
<td>Sum 2013</td>
</tr>
<tr>
<td>Schottky (650 V)</td>
<td>Infineon</td>
<td>IDW40G65C5*</td>
<td>Sum 2013</td>
</tr>
<tr>
<td>MOSFET (1200 V)</td>
<td>Cree</td>
<td>Gen 2.0*</td>
<td>Fall 2013</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Gen 1.5 (prototype)*</td>
<td>Fall 2013</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Gen 1.0</td>
<td>Fall 2012</td>
</tr>
<tr>
<td></td>
<td>Cissoid</td>
<td>CHT-PLA8543C*</td>
<td>Sum/Fall 2013</td>
</tr>
<tr>
<td>NPN BJT (1200 V)</td>
<td>TranSiC (now Fairchild)</td>
<td>BT1206AA-P1</td>
<td>Sum 2012</td>
</tr>
<tr>
<td>JFET, normally off</td>
<td>SemiSouth</td>
<td>SJEP120R100</td>
<td>Sum 2012</td>
</tr>
<tr>
<td>(1200 V)</td>
<td></td>
<td>SJEP170R550</td>
<td>Fall 2012</td>
</tr>
<tr>
<td>JFET, normally off</td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>(1700 V)</td>
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*Evaluated under the NASA SEP Program with support from NEPP*

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SiC Schottky Diodes

- Two modes of SEE effects, both reported previously in the literature
  - Degradation
  - Catastrophic failure
- Degradation (increasing reverse-bias leakage current) prevents identification of onset bias for single-event catastrophic failure
- As previously reported, catastrophic failure can occur under proton irradiation
- Failure location within active region (as opposed to field termination region)
  - To be verified via failure analysis

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GB20SLT12 Current Signatures

Ag: $V_R = 500$ V  
avg. flux = 24 $/\text{cm}^2/\text{s}$:  
Immediate catastrophic failure

Ag: $V_R = 350$ V  
avg. flux = 589 $/\text{cm}^2/\text{s}$:  
Degradation

1110 MeV Ag ions:  
LET = 66 MeV-$\text{cm}^2$/mg  
Range = 49 $\mu\text{m}$

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C4D40120D Current Signatures

Ag: $V_R = 650$ V
avg. flux = 1088 $\text{cm}^2/\text{s}$:
Immediate catastrophic failure

Ag: $V_R = 450$ V
avg. flux = 63 $\text{cm}^2/\text{s}$:
Degradation

Ag: $V_R = 300$ V
avg flux = 1088 $\text{cm}^2/\text{s}$:
Degradation

1110 MeV Ag ions:
$LET = 66 \text{ MeV-cm}^2/\text{mg}$; Range = 49 $\mu\text{m}$

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SiC Schottky Diode Damage Signatures

- Degradation of reverse current:
  - Influenced by ion/energy
    - Have not looked at multiple energies for single ion species to isolate energy effects
  - Influenced by reverse bias voltage
  - Does not recover after irradiation
    - Failure analyses to be done to see extent of damage

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SiC Power MOSFETs

• Two modes of SEE effects as with Schottkys
  – Degradation
  – Catastrophic failure

• Unclear what the primary failure mode is
  – Both gate and drain current increases
  – Substantially thinner gate oxide in Cree generation 2.0 does not result in increased SEGR susceptibility
    • Cree Gen 1.5 shows predominately SEGR signatures
    • Cree Gen 2 shows predominately burnout-like damage

• Susceptibility falls off with angle of incidence
  – assessed only in Cree Gen 1 parts

• Titus-Wheatley critical $V_{GS}$ at 0 $V_{DS}$ holds (unchanged) for Cree MOSFETs (established on gen 1.0)
  \[ V_{gs\text{crit}} = \frac{10^7 \times t_{ox}}{1 + \frac{Z}{44}} \]

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Cree Gen. 2.0 Signatures: Catastrophic Failure; Gate Degradation

Xe: $650 \, V_{DS}; \, 0 \, V_{GS}$
avg. flux = 17 /cm²/s

Xe: $300 \, V_{DS}; \, 0 \, V_{GS}$
avg. flux = 13.5 /cm²/s

996 MeV Xe ions:
LET = 65 MeV-cm²/mg, Range = 49 μm

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Cree Gen. 2.0 Signatures: Drain-Source Damage

**Xe: 500 V\textsubscript{DS}**
avg. flux = 6 /cm\textsuperscript{2}/s

**Xe: 500 V\textsubscript{DS}**
avg. flux = 162 /cm\textsuperscript{2}/s

996 MeV Xe ions:
LET = 65 MeV-cm\textsuperscript{2}/mg, Range = 49 \textmu m

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Cree Gen. 1.5 Signatures: Gate-Drain damage

Xe: 182 V\text{DS}
\text{avg. flux} = 45 /\text{cm}^2/\text{s}

Xe: 400 V\text{DS}
\text{avg. flux} = 484 /\text{cm}^2/\text{s}

Xe: 182 V\text{DS}
\text{ave flux} = 68 /\text{cm}^2/\text{s}

After run on left. BV\text{dss} = 912 V (BV\text{dss}
\text{defined at} I_D = 100 \mu A). PIGS = 40 \mu A at 18 V\text{GS}, 0 V\text{DS.}

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Cree Gen. 1.5 Details:
“Protective Mode” Test

Xe: 500 V\textsubscript{DS}
avg. flux = 5 /cm\textsuperscript{2}/s
Unprotected test

Xe: 500 V\textsubscript{DS}
avg. flux = 5 /cm\textsuperscript{2}/s
1 M\textOmega\ on drain node

With protective resistor:
• ΔI\textsubscript{D} > ΔI\textsubscript{G}
• I\textsubscript{G} shows some temporary recovery
• Failure mode is not pure SEGR

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Power MOSFETs (cont’d)

• Revisit protective mode:
  – Apply lower $V_{DS}$ conditions
  – Examine Cree Gen 2 where drain current effects predominate

• Revisit Cree Gen 1 test data to assess predominate failure signature

• STMicro SiC power MOSFETs to be evaluated June 29th
  – Designer will be present

• Negotiating with GeneSiC to obtain samples of their SiC Junction Transistor

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Conclusions and Path Forward

- SiC devices show high TID tolerance, but low SEE tolerance
  - Degradation occurs well below rated bias voltage
  - Increased leakage currents with ion fluence are a function of LET and bias voltage on the part
- Identification of a safe operating condition is extremely difficult
  - Degradation interferes with adequate sampling of the die with ions – many samples would be required
  - Degradation may impact part reliability
- Signatures are similar across manufacturers and part types:
  - Mechanism is more fundamental than geometry or process quality
  - Recent research (Shoji, *JJAP*, 2014) suggests impact ionization at the epi/substrate interface due to the space-charge induced increase in the electric field results in thermal damage (SEB)
  - Vulnerability tied to much higher heat generation density in SiC vs. Si