Single-Event Effects in Silicon and Silicon Carbide Power Devices

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List of Acronyms

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

To be published on nepp.nasa.gov previously presented by Jean-Marie Lauenstein at the NASA Electronic Parts and Packaging (NEPP) Electronics Technology Workshop (ETW), Greenbelt, MD, June 17-19, 2014.
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.*

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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**

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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

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Key content updates:

- Basic effects expanded to better address:
  - SEB, SEFIs, 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
# 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>
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<tr>
<td>JFET, normally off</td>
<td>SemiSouth</td>
<td>SJEP120R100</td>
<td>Sum 2012</td>
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<tr>
<td>(1200 V)</td>
<td></td>
<td>SJEP170R550</td>
<td>Fall 2012</td>
</tr>
</tbody>
</table>

* 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: \( V_R = 650 \text{ V} \)
ave flux = 1088 /cm²/s:
Immediate catastrophic failure

Ag: \( V_R = 450 \text{ V} \)
ave flux = 63 /cm²/s:
Degradation

Ag: \( V_R = 300 \text{ V} \)
ave flux = 1088 /cm²/s:
Degradation

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

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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
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)

$$V_{gs(crit)} = \frac{10^7 \times t_{ox}}{1 + \frac{Z}{44}}$$

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Cree Gen. 2.0 Signatures: Catastrophic Failure; Gate Degradation

Xe: $650 \, V_{DS}; \, 0 \, V_{GS}$

avg. flux = $17 \, /cm^2/s$

Xe: $300 \, V_{DS}; \, 0 \, V_{GS}$

avg. flux = $13.5 \, /cm^2/s$

996 MeV Xe ions:

$LET = 65 \, MeV \cdot cm^2/mg$, $Range = 49 \, \mu m$

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Cree Gen. 2.0 Signatures: Drain-Source Damage

Xe: $500 \, V_{DS}$

avg. flux = 6 /cm$^2$/s

Xe: $500 \, V_{DS}$

avg. flux = 162 /cm$^2$/s

996 MeV Xe ions:

$LET = 65 \, MeV \cdot cm^2/mg$, $Range = 49 \, \mu m$

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Cree Gen. 1.5 Signatures: Gate-Drain damage

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

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

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

After run on left. BVdss = 912 V (BVdss defined at I\textsubscript{D} = 100 \(\mu\)A). PIGS = 40 \(\mu\)A at 18 V\textsubscript{GS}, 0 V\textsubscript{DS}.

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Cree Gen. 1.5 Details: “Protective Mode” Test

With protective resistor:
- $\Delta I_D > \Delta I_G$
- $I_G$ shows some temporary recovery
- Failure mode is not pure SEGR

Unprotected test

Xe: $500 \ V_{DS}$
avg. flux = $5 \ /\text{cm}^2/\text{s}$

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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