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
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 2nd 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 2nd generation i2MOS™ SEE testing this summer**

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

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.
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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JESD57 Content Revision

- Key content updates:
  - Basic effects expanded to better address:
    - SEB, SEFI, 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

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.
### 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 (1200 V)</td>
<td>SemiSouth</td>
<td>SJEP120R100</td>
<td>Sum 2012</td>
</tr>
<tr>
<td>JFET, normally off (1700 V)</td>
<td>SemiSouth</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
GB20SLT12 Current Signatures

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

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

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

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
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

\[ \text{Xe: } 650 \text{ V}_{DS}; 0 \text{ V}_{GS} \]
avg. flux = 17 /cm\(^2\)/s

\[ \text{Xe: } 300 \text{ V}_{DS}; 0 \text{ V}_{GS} \]
avg. flux = 13.5 /cm\(^2\)/s

996 MeV Xe ions:
\[ \text{LET} = 65 \text{ MeV-cm}^2/\text{mg}, \text{ Range} = 49 \mu\text{m} \]

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Cree Gen. 2.0 Signatures: Drain-Source Damage

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

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

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Cree Gen. 1.5 Signatures: Gate-Drain damage

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

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

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

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

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Cree Gen. 1.5 Details:
“Protective Mode” Test

Xe: 500 V_{DS}
avg. flux = 5 /cm^{2}/s
Unprotected test

Xe: 500 V_{DS}
avg. flux = 5 /cm^{2}/s
1 M\Omega on drain node

With protective resistor:
- \Delta I_D > \Delta I_G
- I_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**

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