Single-Event Effects in Silicon Carbide Power Devices

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List of Acronyms

BJT – Bipolar Junction Transistor
BVdss – Drain-to-Source Breakdown Voltage
ESA – European Space Agency
ETW – Electronic Technology Workshop
FY – Fiscal Year
GE – General Electric
GRC – Glenn Research Center
GSFC – Goddard Space Flight Center
ID – Drain current
IG – Gate current
JAXA – Japan Aerospace Exploration Agency
JEDEC – (not an acronym)
JESD – JEDEC Standard
JFET – Junction Field Effect Transistor
JPL – Jet Propulsion Laboratory
JSC – Johnson Space Center
LaRC – Langley Research Center
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
RHA – Radiation Hardness Assurance
SEB – Single-Event Burnout
SEE – Single-Event Effect
SEGR – Single-Event Gate Rupture
SEP – Solar Electric Propulsion
TAMU – Texas A&M University
TID – Total Ionizing Dose
VDMOS – vertical, planar gate double-diffused power MOSFET
VDS – Drain-source voltage
VGS – Gate-source voltage
VR – Reverse-bias Voltage
NEPP Program Goals & Collaborations

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

- **Work presented here has been sponsored in part by:**
  - NASA Electronics, Parts, and Packaging Program (primary sponsor)
  - NASA Solar Electric Propulsion Program
  - NASA High-Temperature Boost Power Processing Unit Project

- **SiC integrated circuits are also under study**
  - This work is not presented here
Why SiC?

- High Breakdown Voltage (~ 10x vs. Si)
- Low On-State Resistance (~ 1/100 vs. Si)
- High Temperature Operation (200 °C)
- High Thermal Conductivity (~ 10x vs. Si)

Mass Savings
Power Savings
Cost Savings
# NASA Interests in SiC

<table>
<thead>
<tr>
<th>Program/Project</th>
<th>Primary Benefit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Orion Spacecraft</td>
<td>Power</td>
</tr>
<tr>
<td>Advanced Space Power Systems</td>
<td>Mass</td>
</tr>
<tr>
<td>High-Temperature Boost Power Processing Unit</td>
<td>Extreme Environments</td>
</tr>
<tr>
<td>Venus Mobile Explorer (concept mission)</td>
<td>Extreme Environments</td>
</tr>
</tbody>
</table>

*Images: NASA*
A Closer Look at Mass Savings

- Solar Electric Propulsion mass savings by using 300 V solar arrays instead of 120 V arrays:
  
  2457 kg

- With derating, require 400 V power MOSFETs
  - Silicon radiation-hardened MOSFETs have power penalty

- Higher voltages will result in additional mass savings
  - SiC is a potentially enabling technology

Mass savings from:
Mercer, AIAA 2011-7252

Fig: Rei-artur, Creative Commons
FY15 Partnerships

- As the awareness of SiC power device vulnerability to heavy-ion induced single-event effects has grown, so too has the momentum to find a solution:
Status of SiC Power Devices for Space Applications

• Testing by NASA has been performed on a wide range of SiC power devices rated 650 V to 3300 V

<table>
<thead>
<tr>
<th>Part Type</th>
<th>Number of Parts/Manufacturers</th>
</tr>
</thead>
<tbody>
<tr>
<td>Power MOSFET</td>
<td>7/4</td>
</tr>
<tr>
<td>Diode</td>
<td>4/4</td>
</tr>
<tr>
<td>JFET</td>
<td>2/1</td>
</tr>
<tr>
<td>BJT</td>
<td>1/1</td>
</tr>
</tbody>
</table>

• Additional testing has been performed by ESA, JAXA, and other non-government parties

Serendipitously SEE-hard commercial SiC power devices are rare or non-existent
SEE Performance: Power Diodes

- As $V_R$ increases, response to heavy ions goes from no effect to leakage current degradation to sudden catastrophic single-event burnout (SEB)

![Graph showing SEE Performance]

*Modified from: Kuboyama, et al., IEEE TNS, 2006*
## SEE Performance: Power Diodes (cont’d)

<table>
<thead>
<tr>
<th>Ion</th>
<th>Device</th>
<th>Max $V_R$ No Degradation</th>
<th>Min $V_R$ Sudden SEB</th>
</tr>
</thead>
<tbody>
<tr>
<td>1289 MeV Ag</td>
<td>D1&lt;sub&gt;650V&lt;/sub&gt;</td>
<td>150 (23%)</td>
<td>300 (46%)</td>
</tr>
<tr>
<td></td>
<td>D2&lt;sub&gt;1200V&lt;/sub&gt;</td>
<td>100-150 (8% - 13%)</td>
<td>500 (42%)</td>
</tr>
<tr>
<td></td>
<td>D3&lt;sub&gt;1200V&lt;/sub&gt;</td>
<td>--</td>
<td>500 (42%)</td>
</tr>
<tr>
<td></td>
<td>D4&lt;sub&gt;1200V&lt;/sub&gt;</td>
<td>350 (29%)</td>
<td>450-500 (38% - 42%)</td>
</tr>
<tr>
<td>1512 MeV Xe</td>
<td>D1&lt;sub&gt;650V&lt;/sub&gt;</td>
<td>150 (23%)</td>
<td>--</td>
</tr>
<tr>
<td></td>
<td>D2&lt;sub&gt;1200V&lt;/sub&gt;</td>
<td>150 (13%)</td>
<td>--</td>
</tr>
<tr>
<td>1233 MeV Xe</td>
<td>D4&lt;sub&gt;1200V&lt;/sub&gt;</td>
<td>350 (29%)</td>
<td>450-475 (38% - 40%)</td>
</tr>
<tr>
<td>278 MeV Ne</td>
<td>D3&lt;sub&gt;1200V&lt;/sub&gt;</td>
<td>600 (50%)</td>
<td>600 (50%)</td>
</tr>
</tbody>
</table>

- Percentages are based on RATED breakdown voltage
- D1, D2, D3 = Schottky diodes; D4 = pn diode
Degradation Not Unique to SiC

- Recent work by Megan Casey/GSFC on silicon Schottky diodes reveals susceptibility of many diodes to heavy-ion induced degradation in addition to SEB.

Si diode biased at 100% of rated value
Ion beam: 1233 MeV xenon
Degradation Not Unique to SiC

- Recent work by Megan Casey/GSFC on silicon Schottky diodes reveals susceptibility of many diodes to heavy-ion induced degradation in addition to SEB
  - Degradation is small compared to SiC diodes

Si diode biased at 100%, SiC at 30%, of rated values
Flux for SiC = 1/10 of flux for Si

Si diode: Max $I_R = 1 \text{ mA}$
## SEE Performance: Power MOSFETs

<table>
<thead>
<tr>
<th>Ion</th>
<th>Device</th>
<th>Max VDS No Damage</th>
<th>Degradation Currents During Run</th>
<th>Min V&lt;sub&gt;R&lt;/sub&gt; Sudden SEB/SEGR</th>
</tr>
</thead>
<tbody>
<tr>
<td>1233 MeV Xe</td>
<td>M1&lt;sub&gt;1200V&lt;/sub&gt;</td>
<td>40</td>
<td>I&lt;sub&gt;D&lt;/sub&gt; ≥ I&lt;sub&gt;G&lt;/sub&gt;</td>
<td>600 &lt; SEB &lt; 700</td>
</tr>
<tr>
<td></td>
<td>M2&lt;sub&gt;1200V&lt;/sub&gt;</td>
<td>50</td>
<td>I&lt;sub&gt;D&lt;/sub&gt; &gt; I&lt;sub&gt;G&lt;/sub&gt;</td>
<td>SEB &gt; 500</td>
</tr>
<tr>
<td></td>
<td>M3&lt;sub&gt;3300V&lt;/sub&gt;</td>
<td>50</td>
<td>I&lt;sub&gt;D&lt;/sub&gt; &gt;&gt; I&lt;sub&gt;G&lt;/sub&gt; at 350 V&lt;sub&gt;DS&lt;/sub&gt;</td>
<td>650 &lt; SEB &lt; 800</td>
</tr>
<tr>
<td></td>
<td>M4&lt;sub&gt;1200V&lt;/sub&gt;</td>
<td>Not found</td>
<td>I&lt;sub&gt;D&lt;/sub&gt; &gt; I&lt;sub&gt;G&lt;/sub&gt;</td>
<td>SEB &gt; 500</td>
</tr>
<tr>
<td></td>
<td>M5&lt;sub&gt;1200V&lt;/sub&gt;</td>
<td>40</td>
<td>I&lt;sub&gt;D&lt;/sub&gt; &gt; I&lt;sub&gt;G&lt;/sub&gt;</td>
<td>400 ≤ SEB &lt; 600</td>
</tr>
<tr>
<td></td>
<td>M6&lt;sub&gt;1200V&lt;/sub&gt;</td>
<td>50&lt;V&lt;sub&gt;DS&lt;/sub&gt;&lt;75</td>
<td>I&lt;sub&gt;D&lt;/sub&gt; = I&lt;sub&gt;G&lt;/sub&gt;; I&lt;sub&gt;D&lt;/sub&gt; &gt; I&lt;sub&gt;G&lt;/sub&gt; at 425 V&lt;sub&gt;DS&lt;/sub&gt;</td>
<td>475 &lt; SEB &lt; 500</td>
</tr>
<tr>
<td>1289 MeV Ag</td>
<td>M4&lt;sub&gt;1200V&lt;/sub&gt;</td>
<td>25&lt;V&lt;sub&gt;DS&lt;/sub&gt;&lt;50</td>
<td>--</td>
<td>100 &lt; SEB &lt; 600</td>
</tr>
<tr>
<td></td>
<td>M6&lt;sub&gt;1200V&lt;/sub&gt;</td>
<td>50&lt;V&lt;sub&gt;DS&lt;/sub&gt;&lt;75</td>
<td>I&lt;sub&gt;D&lt;/sub&gt; = I&lt;sub&gt;G&lt;/sub&gt; at 225 V&lt;sub&gt;DS&lt;/sub&gt;; I&lt;sub&gt;D&lt;/sub&gt; &gt; I&lt;sub&gt;G&lt;/sub&gt; at 400 V&lt;sub&gt;DS&lt;/sub&gt;</td>
<td>500 &lt; SEB &lt; 600</td>
</tr>
<tr>
<td>659 MeV Cu</td>
<td>M5&lt;sub&gt;1200V&lt;/sub&gt;</td>
<td>70</td>
<td>I&lt;sub&gt;D&lt;/sub&gt; = I&lt;sub&gt;G&lt;/sub&gt;</td>
<td>400 &lt; SEB &lt; 600</td>
</tr>
</tbody>
</table>

- All results shown here conducted at 0 V<sub>GS</sub>
SiC Power Devices: Collaborative Studies In Progress

• Ongoing efforts to understand degradation and SEE failure mechanisms include:
  – Failure analysis work performed at NASA GRC on Schottky diodes
  – Modeling studies in progress at Vanderbilt University
  – Continued heavy-ion testing conducted by NASA GSFC & LaRC and ESA

• NASA Science and Technology Mission Directorate Early Stage Innovations NASA Research Announcement

• Potential NASA SBIR Phase II-X effort on process and design changes on SEE hardening of power SiC MOSFETs and diodes

Efforts reflect a coordinated commitment to enable SiC technology for space applications
Conclusions and Path Forward

- The NEPP Program has been an early and constant supporter of SiC power device radiation hardness assurance
- SiC devices show high TID tolerance, but low SEE tolerance
- 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
- Most space applications will require SiC power devices that have been hardened to SEE
- Interest in hardening SiC power devices is growing:
  - Manufacturers will require partnerships to help fund development efforts