Reliability Concerns for Flying SiC Power MOSFETs in Space

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Outline

1. Why the interest in SiC power?
2. Electrical reliability.
3. SEB in SiC power MOSFETs.
4. Environment.
5. Estimating failure rate in space.

1200 V SiC Power MOSFET
Why Silicon Carbide Power Devices for Space?

SiC vs Silicon Power Devices:
• Higher Breakdown Voltage (~ 10x vs. Si)
• Lower On-State Resistance (~1/100 vs. Si)
• Higher Temperature Operation (~3x vs. Si)
• High Thermal Conductivity (~10x vs. Si)
• Mass, cost, power savings


Example: Concept Design of High Power Solar Electric Propulsion (SEP) for Human Exploration
• Desired power levels ~400 kW
• Change from 120 V bus voltage to 300 V

After: D.J. Hoffman, et al., NASA/TM—2011-217281

PMAD: Power management and distribution
HTB PPU: High-temperature boost power processing unit
Toyota and Denso Development for Hybrid Vehicles

- Power control units (PCUs) contain multiple power semiconductors – usually silicon technology

- According to Toyota, ~20% of hybrid electric vehicle (HEV) total electrical power loss is associated with power semiconductors

- Goal to improve hybrid vehicle (HV) fuel efficiency by 10% and PCU downsizing of 80%

- SiC technology leads to lower weight, higher efficiency

https://newsroom.toyota.co.jp/en/detail/2656842 (Image used with permission)
http://www.eenewseurope.com/design-center/potential-silicon-carbide-sic-automotive-applications/page/0/3
Accelerated Testing – High-Temperature Reverse Bias

- High-Temperature Reverse Bias (HTRB)
- Wolfspeed 1200 V 20A G2 MOSFETs
- $V_{GS} = 0V$, $V_{DS} = 1460V$, 1540V, 1620V
- Mean failure time at a given $V_{DS}$ predicted by extrapolation
- At $800 \, V_{DS}$, extrapolated failure time is $\sim 3 \times 10^7$ hours ($\sim 3400$ years)


Accelerated Testing – Time-Dependent Dielectric Breakdown

- Time-Dependent Dielectric Breakdown (TDDB)
- Wolfspeed 1200 V 20A G2 MOSFETs
- Mean failure time at a given $V_{GS}$ predicted by extrapolation
- Extrapolated mean failure time at 20 $V_{GS} > 10^8$ hours (~ 11,000 years)


SiC power devices – both diodes and MOSFETs – are susceptible to catastrophic failure in the swift, energetic heavy ion environment encountered in space or neutron environments.
Measurement of SEB in SiC Power MOSFET

- Tests performed on SiC power devices rated 650 V to 3300 V by NASA, ESA, JAXA, and others
- Single-event burnout (SEB) occurs at typically ½ rated $V_{DS}$
- Ion-induced degradation observed in gate, drain leakage currents prior to SEB

![Graph showing SEB threshold vs. LET for different MOSFETs](image)

Lethal Ion Criteria

• Most particles in space are of no consequence to MOSFET catastrophic failure.

• To be lethal, a particle (or one of its recoils), must:
  1. Have sufficient energy deposition
  2. Strike at the proper solid angle
  3. Strike within the sensitive area
  4. Strike when the biases are in a critical state

Estimate of the Failure Rate for 1200 V SiC Power MOSFETs in Space

- Devices show SEB failure at ≈ 500 V for LET > 10 MeV-cm²/mg
- Assume SEB cross-section saturated for LET > 10 MeV-cm²/mg
- Define SEB failure as operation at a reverse voltage > 500 V for any LET > 10

\[
\text{Failure Rate (FR)} = \text{SEB cross-section (}\sigma\text{)} \int \text{Flux(LET) dLET}
\]

\[
\int \text{Flux(LET) dLET} = \text{integral over LET spectrum for LETs greater than 10 MeV-cm²/mg using CREME96 or Xapsos et al.}
\]


Similar to ..........


Hardened Electronics and Radiation Technology (HEART), Tucson, AZ, April 16-20, 2018.
Worst day solar particle event (SPE) from CREME96. GEO and LEO are solar minimum spectra from CREME96. Cumulative solar particle event spectra at the 99% confidence level after Xapsos et al. Results for 100 mils aluminum shielding.

Worst Case Estimate of the Failure Rate (FR) for 1200 V SiC Power MOSFETs in Space

\[ FR = \sigma \int \text{Flux}(\text{LET}) \, d\text{LET} \]

\[ \sigma = \text{base MOSFET SEB cross-section on chip area}, \ 1200V \text{ chip is } \approx 2 \text{ mm} \times 3 \text{ mm} \text{ assume 50% sensitive area and 50% duty cycle} \]

\[ \sigma = 1.5 \times 10^{-2} \text{ cm}^2 \]

Integral evaluated for all LET> 10 MeV-cm²/mg from the 99% confidence level curve from Xapsos et al. – appropriate a conservative design estimate of the single-event rate due to solar particles

\[ \int \text{Flux}(\text{LET}) \, d\text{LET} = 10 \text{ cm}^{-2} \text{ day}^{-1} \]

FR = 6.25x10⁻³/hour and FIT = 6.25x10⁶

MTTF (Mean Time To Failure) = 160 hours
## Integral LET > 10 MeV-cm²/mg, FIT, MTTF for Different Mission and Satellite Scenarios

<table>
<thead>
<tr>
<th></th>
<th>Integral (no./cm²-day)</th>
<th>FIT (1 per billion hours)</th>
<th>MTTF (hours)</th>
</tr>
</thead>
<tbody>
<tr>
<td>SPEW</td>
<td>1000</td>
<td>6.25E+08</td>
<td>1.6</td>
</tr>
<tr>
<td>SPE</td>
<td>10</td>
<td>6.25E+06</td>
<td>160</td>
</tr>
<tr>
<td>GEO</td>
<td>0.9</td>
<td>5.6E+05</td>
<td>1786</td>
</tr>
<tr>
<td>LEO</td>
<td>1E-04</td>
<td>62.5</td>
<td>1.6E+07</td>
</tr>
</tbody>
</table>

**SPEW** = worst day solar particle event from CREME96  
**SPE** = cumulative particle event at 99% confidence level from Xapsos *et al.*  
**GEO** = geostationary orbit during solar min from CREME96  
**LEO** = low Earth orbit during solar min from CREME96  
For all, 100 mils of aluminum shielding assumed.

**FIT**: Failure in time
MTTF on Orbit – 1200 V SiC MOSFET Operated at \( V_{DS} > 500 \) V

- MTTF \(~ 1800\) hours (75 days) – GEO from CREME96
- MTTF \(~ 160\) hours – SPE C = 99% from Xapsos et al.
- MTTF \(~ 1.6\) hours – SPE worst day from CREME96

MTTF \(> 1000\) years – LEO from CREME96

Image from: National Oceanic and Atmospheric Administration
Summary

• SiC power MOSFETs have several performance advantages over Si power MOSFETs and silicon IGBTs
• Current commercial devices are very reliable
• Demonstrated heavy-ion susceptibility
• Failure rate estimates indicate a radiation reliability issue for space electronics
• Any application of commercially available 1200 V SiC MOSFETs in space would require significant voltage de-rating
• Performance advantages may justify use if de-rating and leakage degradation is acceptable
• Careful heavy ion testing of any commercially available SiC MOSFET component proposed for spaceborne electronic systems is recommended