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 $20 \times V_{GS} > 10^8$ hours (~ 11,000 years)


What is the Problem?

- 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.

After: G. Consentino et. al, 2014 IEEE Applied Power Electronics Conference and Exposition, Fort Worth, TX.
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 \( \frac{1}{2} \) rated \( V_{DS} \)
- Ion-induced degradation observed in gate, drain leakage currents prior to SEB

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

\[
\text{Failure Rate (FR)} = \text{SEB cross-section (σ)} \int_{\text{LET} > 10 \text{ MeV-cm}^2/\text{mg}} \text{Flux(LET)} \, d\text{LET}
\]

\[\int_{\text{LET} > 10 \text{ MeV-cm}^2/\text{mg}} \text{Flux(LET)} \, d\text{LET} = \text{integral over LET spectrum for LETs greater than 10 MeV-cm}^2/\text{mg using CREME96 or Xapsos et al.}\]


Similar to ………

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

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

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

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

Integral evaluated for all \( \text{LET} > 10 \text{ MeV-cm}^2/\text{mg} \) from the 99% confidence level curve from Xapsos et al. – appropriate a conservative design estimate of the single-event rate due to solar particles

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

\[ \text{FR} = 6.25 \times 10^{-3}/\text{hour} \text{ and } \text{FIT} = 6.25 \times 10^6 \]

\[ \text{MTTF (Mean Time To Failure)} = 160 \text{ hours} \]
Integral LET > 10 MeV-cm\(^2\)/mg, FIT, MTTF for Different Mission and Satellite Scenarios

<table>
<thead>
<tr>
<th>Integral LET (no./cm(^2)-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>
</tr>
<tr>
<td>SPE</td>
<td>10</td>
<td>6.25E+06</td>
</tr>
<tr>
<td>GEO</td>
<td>0.9</td>
<td>5.6E+05</td>
</tr>
<tr>
<td>LEO</td>
<td>1E-04</td>
<td>62.5</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