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


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 ½ rated $V_{DS}$
- Ion-induced degradation observed in gate, drain leakage currents prior to SEB

![Graph showing SEB threshold vs. LET for 1200V SiC MOSFET.](image)

\[ \text{LET: linear energy transfer} \]

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

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

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


similar to ...........

Integral LET Spectra

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

\[ FR = \sigma \int Flux(LET) \, dLET \]

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

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

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

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

FR = 6.25x10\(^{-3}\)/hour and FIT = 6.25x10\(^6\)

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 $\sim$ 1800 hours (75 days) – GEO from CREME96
MTTF $\sim$ 160 hours – SPE C = 99% from Xapsos et al.
MTTF $\sim$ 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