Silicon Carbide Power Devices and Integrated Circuits

Jean-Marie Lauenstein, Megan Casey, Ted Wilcox, and Ken LaBel – NASA/GSFC

Kristen Boomer – NASA GRC

Anthony Phan, Hak Kim, and Alyson Topper – AS&D, Inc.

Ahmad Hammoud – Vantage Partners, LLC

Acknowledgment:

This work was sponsored by:

NASA Office of Safety & Mission Assurance

in collaboration with:

NASA Space Technology Mission Directorate

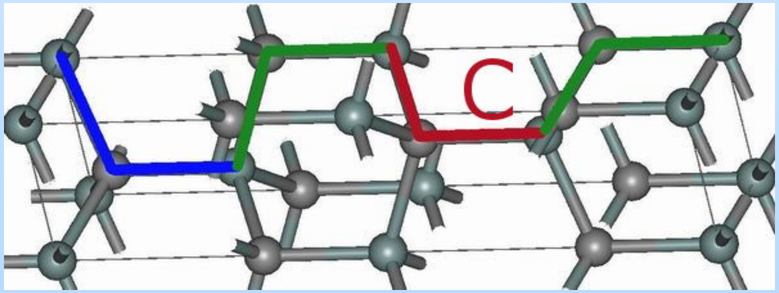
Abbreviations & Acronyms

Acronym	Definition
BOK	Body of Knowledge
BV_{DSS}	Drain-Source Breakdown Voltage
COR	Contracting Officer Representative
COTS	Commercial Off The Shelf
ESA	European Space Agency
ETW	Electronics Technology Workshop
FY	Fiscal Year
GCR	Galactic Cosmic Ray
I_D	Drain Current
I_{DSS}	Drain-Source Leakage Current
I_G	Gate Current
IC	Integrated Circuit
JAXA	Japan Aerospace Exploration Agency
JFET	Junction Field Effect Transistor
LBNL	Lawrence Berkeley National Laboratory cyclotron facility
MOSFET	Metal Oxide Semiconductor Field Effect Transistor

Acronym	Definition
NESC	NASA Engineering & Safety Center
RHA	Radiation Hardness Assurance
RHBP	Radiation Hardened By Process
Si	Silicon
SiC	Silicon Carbide
SJ	Super Junction
SMD	Science Mission Directorate
SME	Subject Matter Expert
SOA	State Of the Art; Safe Operating Area
STMD	Space Technology Mission Directorate
SWAP	Size, Weight, And Power
TAMU	Texas A&M University cyclotron facility
TID	Total Ionizing Dose
VDMOS	Vertical Double-diffused MOSFET
V_{DS}	Drain-Source Voltage
V_{GS}	Gate-Source Voltage
V_{OUT}	Output Voltage
V_{TH}	Gate Threshold Voltage

Outline

- SiC Task Motivation & Technology Focus
- Vehicles for Collaborative Efforts
- Recent Results
  - The Radiation-Induced Leakage Current Dilemma
- Additional Activities
  - Gate drivers
  - SiC integrated circuits
  - State-of-the-Art radiation-hardened silicon MOSFET

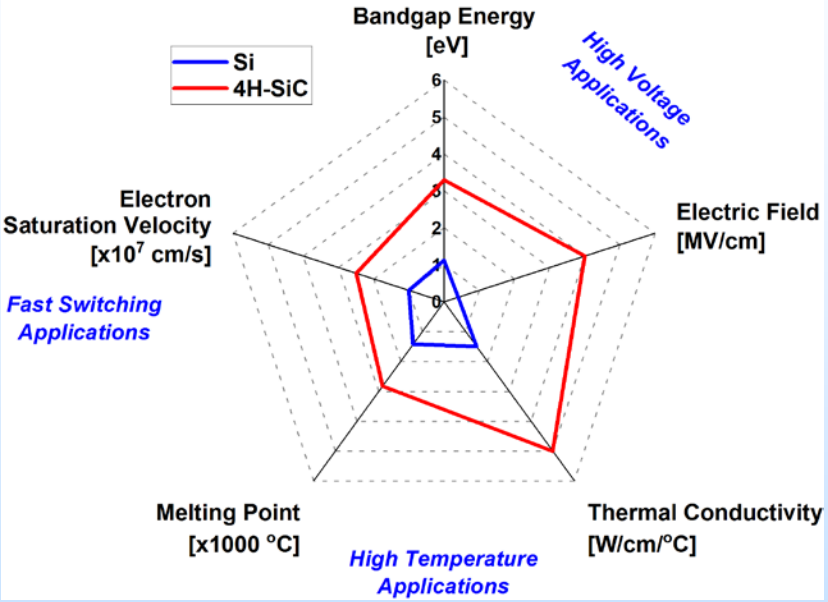


4H-SiC Polytype

Creative Commons Attribution-Share Alike 3.0 Unported license.
Attribution: User:Materialscientist

Motivation

SiC Advantages vs. Si



Material properties from:
P. J. Wellmann, *Z Anorg Allg Chem,* 2017

- **Game-changing NASA approaches are demanding higher-performance power electronics**
  - *SEE rad-hardened high-current MOSFETs > 250 V do not exist*
- **SWAP benefits for existing technologies**
  - *SiC power devices are flying now (Orion, MMS)*

SiC devices are well-suited for high-voltage, high-temperature, and/or fast-switching applications

Motivation: NASA Tech Roadmaps

Technology Area	Capability Needed	Challenges	Mission	Launch Date
TA 4: Robotics and Autonomous Systems	4.3.1.3: Integrated control and power electronics for motor controllers and actuators	Small form factor, more efficient power, and extreme space environment	New Frontier: Lunar Sample Return Planetary Flagship: Mars Sample Return Exploration: Crewed to Lunar Surface Exploration: Crewed to Mars Moons	2024 2026 2027 2027
TA 3: Space Power and Energy Storage	3.3.5: Advanced power processing units and high voltage, high temperature, rad hard power switches, diodes, and passive devices	Reliable, high voltage, low loss, rad hard devices for high-power electric propulsion system and space environment	Into Solar System: Asteroid Redirect Planetary Flagship: Europa Exploration: Crewed to Lunar Surface Exploration: Crewed to Mars Moons New Frontier: Io Observer	2022 2022 2027 2027 2029
TA 10: Nanotechnology	10.4.2.3: Fault-tolerant, extreme-environment Schottky diodes, switches for computing, logic gates, and memories	High speed, robust Schottky diodes and electronics for long-term operation in harsh environment	New Frontier: New Frontier Program 4 Planetary Exploration: Crewed Mars Orbital	2024 --
TA 15: Aeronautics	15.4.2.1: Alternative propulsion system (hybrid/electric)	High power, high density motors, and wide temperature range electronics and controllers	Ultra-efficient, environment-friendly vehicles	--

Table from: K. Boomer, “Body Of Knowledge For Silicon Carbide Power Electronics,” *NASA NEPP Report*, May 2017.

FY19 Wide Bandgap & SOA Si Power Devices
(Continuation)

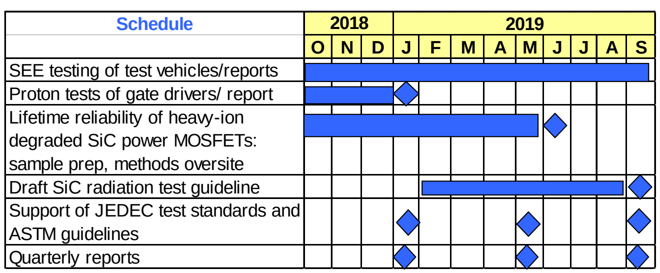
Description:

- Evaluate suitability for space applications emerging wide bandgap (WBG) power devices, and state-of-the-art (SOA) radiation-hardened and promising commercial Si power MOSFETs
  - NASA roadmap calls out need for high power (high current, high voltage) discrete power devices (TA 3, 4, 10, 15)
- Investigate WBG radiation failure mechanisms
- Support WBG radiation test method standards and guidelines
- Leverage with other NASA Centers, government agencies, industry, and universities in coordinated effort to meet goals

FY19 Plans:

- **SiC Test Vehicles:**
  - Wolfspeed power MOSFET and diode variants (goal: test method development/RHA guideline development)
  - Infineon and/or USCi JFETs (goal: test method development/RHA guideline development)
  - Radiation hardened engineering designs: various manufacturers as available (goal: feedback and support of hardening efforts)
  - Avago optocoupler SiC MOSFET gate drivers (goal: hardness eval)
- **RF GaN Test Vehicles:**
  - Wolfspeed RF GaN HEMTs (goal: test method guidance)
- **Si Test Vehicles:** (goal: independent rad hardness eval)
  - Infineon rad-hardened high-voltage SJ MOSFETs
  - Fuji rad-hardened high-voltage MOSFETs
- **SiC radiation test guideline development**

Schedule:



Lead Center/PI: GSFC/Jean-Marie Lauenstein

Sister tasks:
1) JPL for GaN power devices (GSFC GaN plans are complementary in coordination with this task).
2) GRC/ K. Boomer to lead Lifetime reliability of irradiated SiC

Deliverables:

- Quarterly and test reports
- Draft SiC test guideline October 2019
- Summary report due October 2019

Partners (NASA and Non-NASA Organizations):

NASA GRC, JSC, JPL; STMD ESI program
ESA, LANL, AFRL, NRL;
Wolfspeed, GE, USCi, ST Micro, Infineon, Fuji

Procurements:

Beam procurements: TAMU, LBNL, NW Proton (Chicago)
Travel to facilities, technical meetings, and 1 conference;
NRE costs for test set development, sample prep, and test support

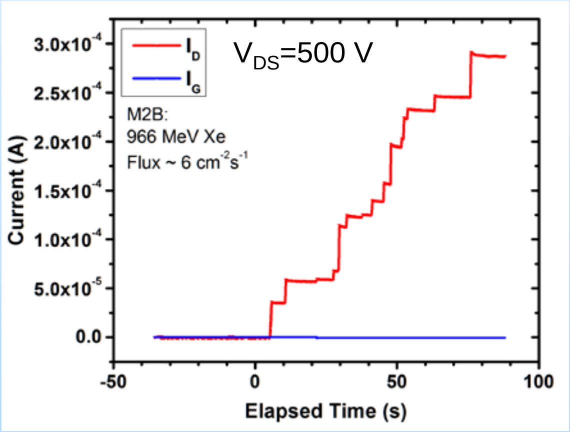
NEPP Collaborations

Vehicle	Agency(ies)/Industry	Description
SBIR	(In coordination with: NASA GRC, GSFC LaRC, JPL, DOE, NRL, ARL)	Identification of SEE failure mechanisms, Development of radiation-hardened devices (SBIR subtopic managed by NEPP SiC Lead)
STMD ESI	Rensselaer Polytechnic Inst., Vanderbilt Univ., GE, Wolfspeed, NASA GRC, GSFC	SEE failure mechanisms through modeling (NEPP SiC lead serving as Research Collaborator)
NEPP WBG Working Group	High Reliability Virtual Electronics Center (HiREV) - AFRL DMEA; NRL; NASA JPL, JSC, GRC, GSFC	Coordinated efforts in radiation and reliability work on both GaN and SiC wide bandgap technology devices.
JEDEC JC13 Gov't Liaison Committee	JC13.1, JC13.7, SAE CE-12 communities, AFRL, DLA	JC-13.1/JC-13.7/SAE CE-12 SiC Tech Insertion Subcommittee meetings to develop test standards and address reliability concerns

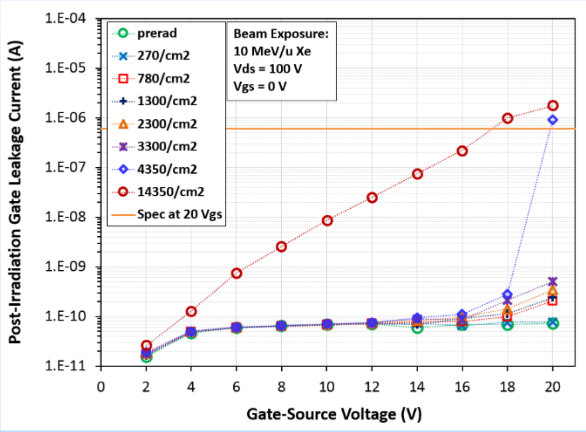
+ Informal relationships to share data, subject matter expertise, and to track and/or evaluate industry developments

Goals of Collaborative SiC Efforts

- **Understand heavy-ion induced degradation and failure**
  - Both catastrophic and non-catastrophic effects
  - In a level of detail that enables:
    - Device hardening
    - On-orbit susceptibility/rate prediction
    - Test method guidelines
- **Develop SEE-hardened power devices**
  - Design, fabrication, and test validation

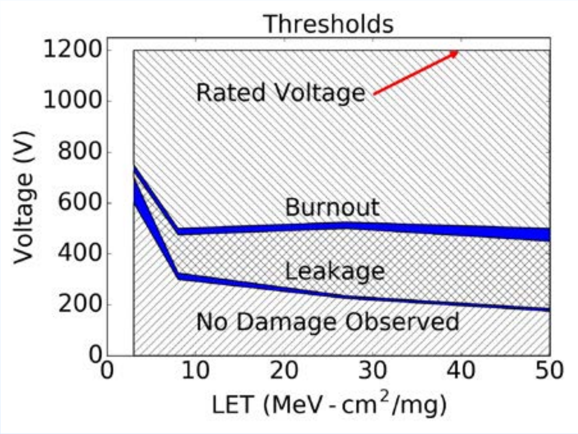


1200V MOSFET biased at 500V: increasing permanent drain leakage current with ion fluence

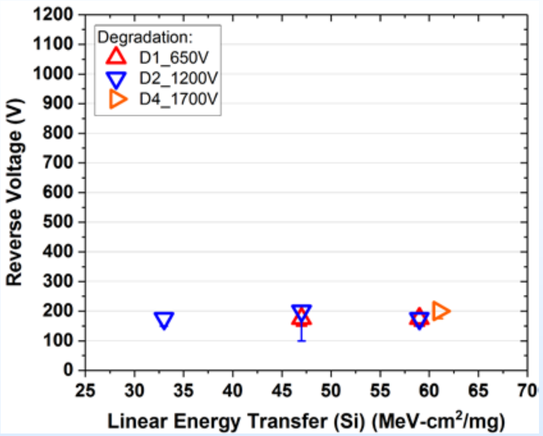


Same part type at 100V: permanent degraded gate leakage current with ion fluence (as measured post-irradiation)

The Problem of Leakage Current Degradation



Witulski, IEEE TNS, 2018



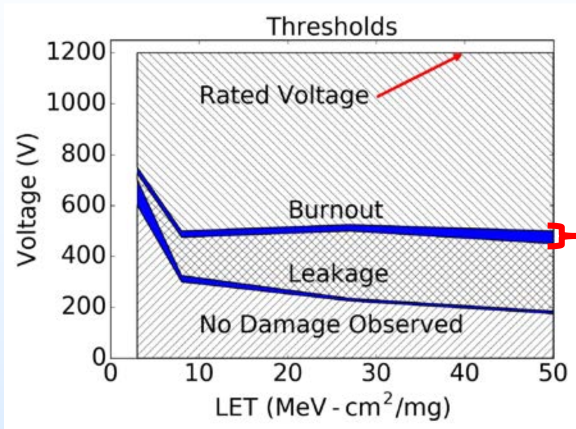
Lauenstein, MRQW 2018

Ion-induced diode leakage current (I_R) findings:

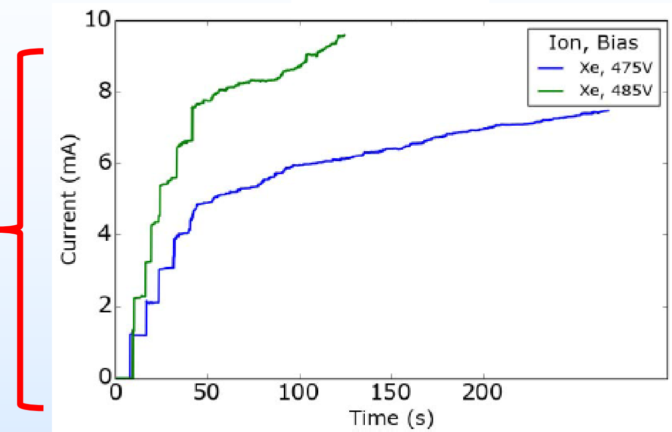
- **Degradation can be non-Poisson process:**
  - ΔI_R can saturate with fluence
- **Onset voltage (V_R) saturates quickly with LET**
  - Saturation V_R is similar for 650 V – 1700 V Schottky diodes

Saturation occurs before the high flux iron knee of the GCR spectrum: Mission orbit will have less influence on risk

The Problem of Leakage Current Degradation



Witulski, IEEE TNS, 2018



Witulski, IEEE TNS, 2018

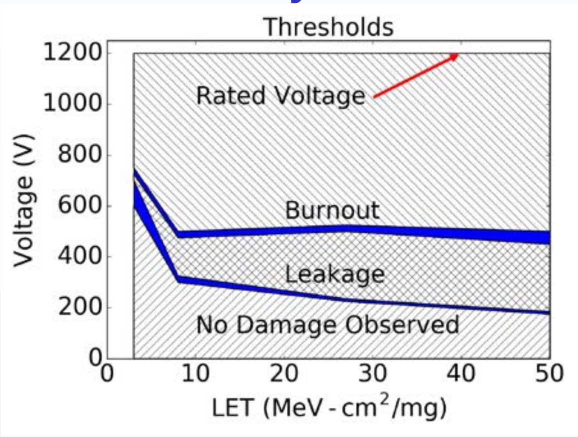
Thresholds for SEB have uncertainty:

- **At V_R = 485 V, after < 10^4 Xe/cm^2, I_R = 10 mA with non-linearity of ΔI_R occurring before that**
  – Is this fluence adequate to rule out SEB? (No)

Be wary of SEB "Safe Operating Areas"

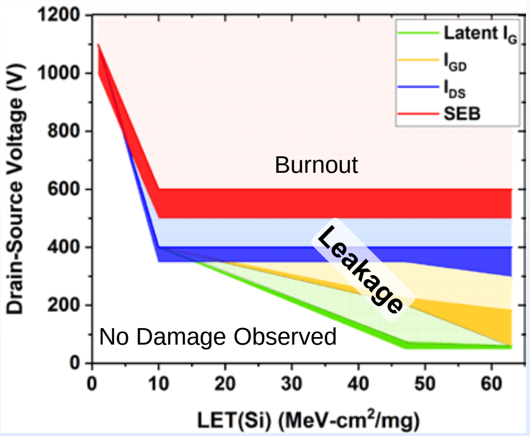
The Problem of Leakage Current Degradation

Schottky Diode



Witulski, IEEE TNS, 2018

MOSFET



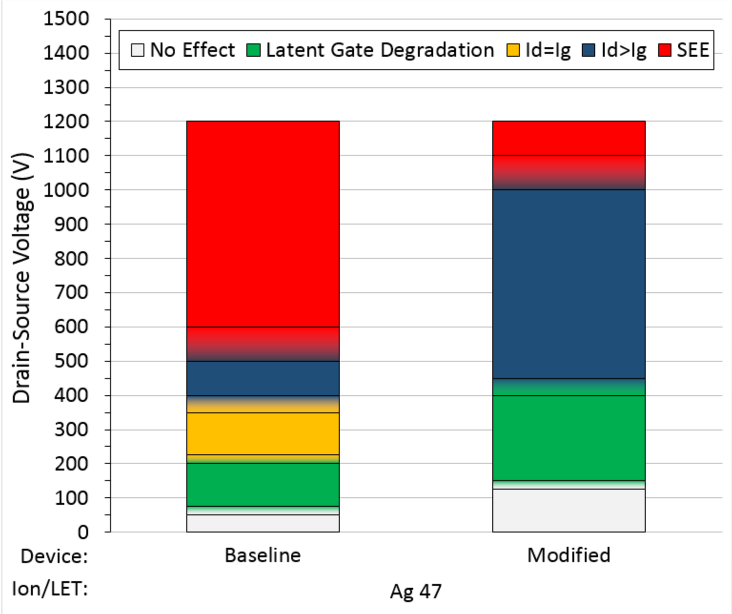
MOSFETs add additional leakage current pathways:

- **Gate-Source leakage measurable only with PIGS test**
  - (not shown: At higher V_{DS}, device can/will fail PIGS test)
  - No damage from lighter ions
- **Gate-Drain leakage increasing with beam exposure**
- **Drain-Source leakage: Similar to diode I_R leakage**

How do we test? How do we harden?

How is lifetime reliability impacted?

SiC Radiation Hardness by Process: 1200 V MOSFET



After Zhu, X., et al., 2017 ICSCRM

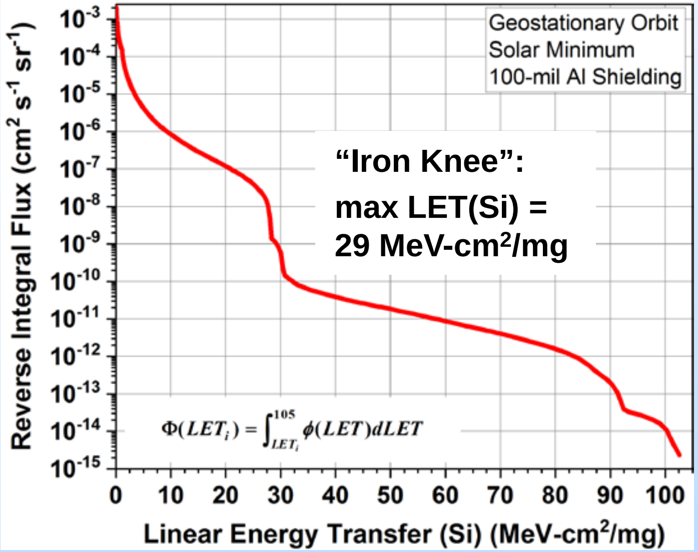
Color gradients span between known V_{DS} for given response types

- **Reduced SEB susceptibility**
  - Thicker epilayer
- **Degradation of I_{DG} eliminated**
  - Drain neck width reduction
- **BUT minimal change in onset of other degradation effects:**
  - $\Delta I_D >> \Delta I_G$
  - latent gate damage

Continued research and development efforts are necessary to understand residual degradation mechanisms

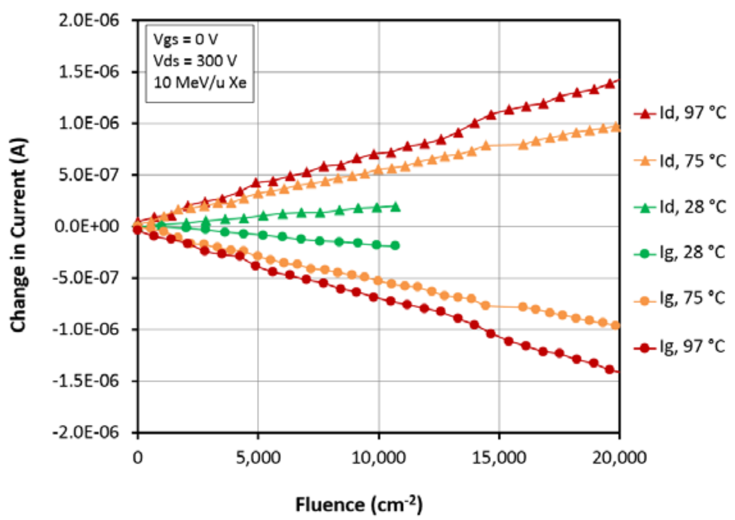
SiC Summary & RHA Conclusions

- **SEB safe operating area is difficult to reliably define**
  - Susceptibility quickly saturates before the high-flux iron knee of the GCR spectrum
    - **Mission orbit will have less influence on risk**



SiC Summary & RHA Conclusions

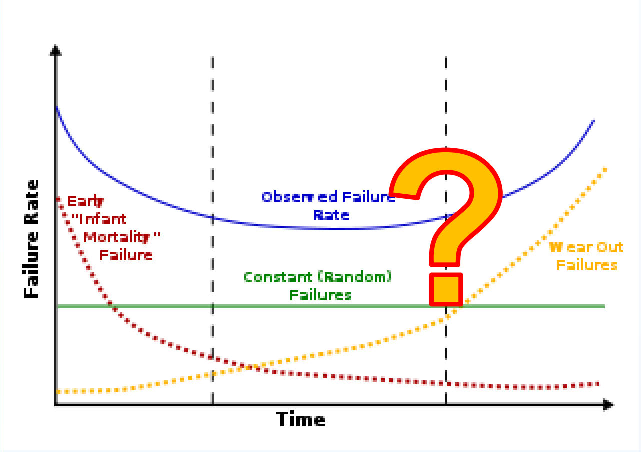
- **SEB safe operating area is difficult to reliably define**
  - Susceptibility quickly saturates before the high-flux iron knee of the GCR spectrum
    - **Mission orbit will have less influence on risk**
- **Application-specific temperature testing may be necessary**
  - Dopants not fully ionized at room temperature
  - Effects of temperature on SEB susceptibility must be established



Rate of leakage current degradation in MOSFET increases with temperature

SiC Summary & RHA Conclusions

- **SEB safe operating area is difficult to reliably define**
  - Susceptibility quickly saturates before the high-flux iron knee of the GCR spectrum
    - **Mission orbit will have less influence on risk**
- **Application-specific temperature testing may be necessary**
  - Dopants not fully ionized at room temperature
  - Effects of temperature on SEB susceptibility must be established
- **Some degradation mechanisms may persist despite RHBP efforts**
  - Impact on device long-term reliability must be established



SiC Summary & RHA Conclusions

- **SEB safe operating area is difficult to reliably define**
  - Susceptibility quickly saturates before the high-flux iron knee of the GCR spectrum
    - **Mission orbit will have less influence on risk**
- **Application-specific temperature testing may be necessary**
  - Dopants not fully ionized at room temperature
  - Effects of temperature on SEB susceptibility must be established
- **Some degradation mechanisms may persist despite RHBP efforts**
  - Impact on device long-term reliability must be established
- **Radiation hardening comes with a cost**
  - As with Si power MOSFETs, electrical performance will suffer from hardening techniques

SiC Summary & RHA Conclusions (Cont'd)

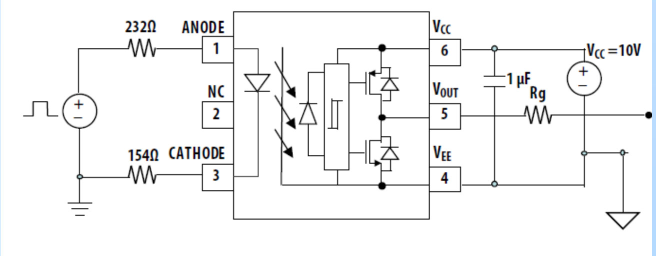
- **Lighter ion/lower LET tests will reveal nuances between designs and aid on-orbit degradation predictions**
  - Responses are saturated at LETs dictated by typical mission destructive-SEE radiation requirements
  - LET should be specified in terms of LET(Si) but penetration range must be for SiC

SiC Summary & RHA Conclusions (Cont'd)

- **Lighter ion/lower LET tests will reveal nuances between designs and aid on-orbit degradation predictions**
  - Responses are saturated at LETs dictated by typical mission destructive-SEE radiation requirements
  - LET should be specified in terms of LET(Si) but penetration range must be for SiC
    - Space radiation environments and thus mission requirements are given in terms of LET(Si)
- **Characterization data should include identification of voltage conditions at which different effects occur**
  - Richer dataset will include how susceptibility to these effects changes with ion species/LET

Associated Activities: Gate Driver Thermal Stress Testing

- **Broadcom ACPL-P346 optocoupler SiC MOSFET gate driver was evaluated under extreme temperatures and thermal cycling**
  - Temperature effects on performance evaluated from -180 °C to +120 °C, well beyond -40 °C to + 105 °C rating: Parts continued to function
  - Successful restart capability at the extreme temperatures
  - No effects from 500 thermal cycles between -180 °C and +120 °C
  - **See NASA NEPP Report, April 2018:**
    K. Boomer, *et al.*, "Performance of SiC MOSFET Gate Drive Optocoupler, ACPL-P346, Over Extended Temperature Range."
- **Preliminary SEE testing planned this Fall:**
  - 200-MeV proton testing in lieu of heavy ions due to package constraints

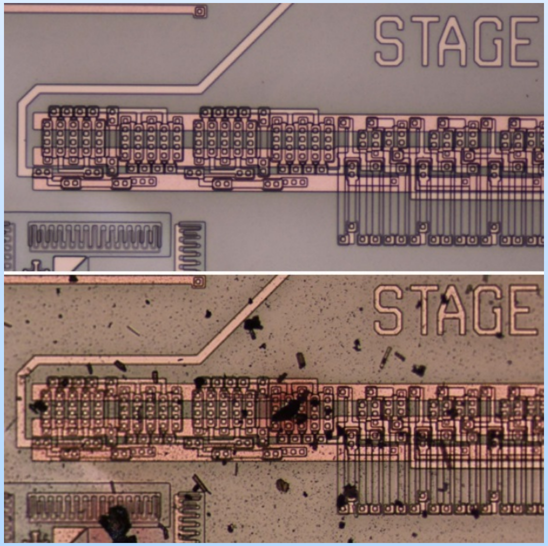


ACPL-P346:
2.5 A, rail-rail V_{out}

https://www.broadcom.com/products/optocouplers/industrial-plastic/isolated-gate-drive-optocouplers/gate-drives/acpl-p346-000e

Associated Activities: SiC IC Testing

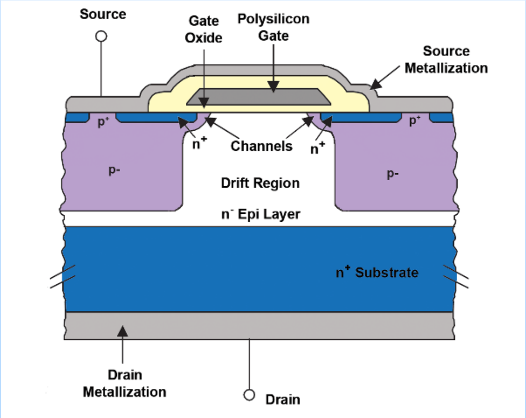
- **NASA GRC-developed Venus-worthy SiC integrated circuits will be radiation-tested in collaboration with GRC High-Temperature SiC IC team**
  - Both TID and SEE tests to be performed this summer
  - Preliminary SEE tests suggest no catastrophic failures



NASA GRC SiC IC before and after 521 hours at Venus surface temperature and atmospheric conditions

Associated Activities: High Voltage Silicon SJ MOSFET

- **Infineon BUY65CS05J rad-hardened 650-V SJ MOSFET heavy-ion SEE verification testing**
  - To be completed this summer: engineering samples received
  - May fill some high-voltage/high power needs:
    - **650 V, 5.3 A, 1 Ω**
    - SMD 0.5 hermetic package



Cartoon example of SJ MOSFET