Silicon Carbide Power Devices and Integrated Circuits

Jean-Marie Lauenstein, Megan Casey, Isaak Samsel, and Ken LaBel - NASA/GSFC

Yuan Chen and Stanley Ikpe – NASA LaRC

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

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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
ICSCRM	International Conference on SiC and Related Materials
JAXA	Japan Aerospace Exploration Agency
JFET	Junction Field Effect Transistor
LBNL	Lawrence Berkeley National Laboratory cyclotron facility

Acronym	Definition
MOSFET	Metal Oxide Semiconductor Field Effect Transistor
NESC	NASA Engineering & Safety Center
RADECS	Radiation and its Effects on Components and Systems
RHA	Radiation Hardness Assurance
Si	Silicon
SiC	Silicon Carbide
SMD	Science Mission Directorate
SME	Subject Matter Expert
SOA	State Of the Art
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_{TH}	Gate Threshold Voltage

Outline

- **SiC Task & Technology Focus**
- **Task Roadmap & Partners**
- **Recent Results**
- **Future Plans**

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

2.7 tons!!

*(*Mercer, AIAA 2011-7252*)*

One-Ton Weight by Rei-Artur.

SiC Power Technology

- Prior work by NEPP, NASA STMD GCD, and others has shown that serendipitously SEE-hard commercial SiC power devices are rare or non-existent
- Current NEPP SiC focus areas:
  - SEE hardening efforts
  - Reliability assessments
  - Body of Knowledge (BOK) document
  - Test guidelines

TID hardness came for "free"; SEE hardness will not!

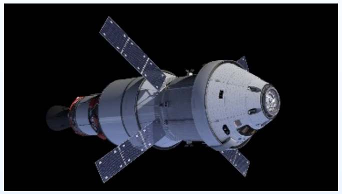
SiC parts evaluated with support from NEPP:

Device Type	# COTS Parts/ # Manufacturers
Diode	5/4
MOSFET	10/4
JFET	4/2
BJT	1/1

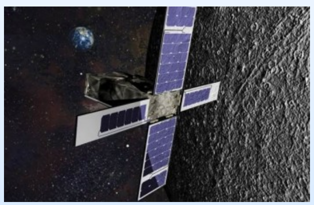
Motivational Factors

Images courtesy of NASA

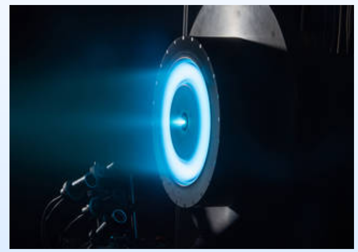
High Voltage Instruments



Orion



SmallSats



Solar Electric Propulsion

Commercial Space

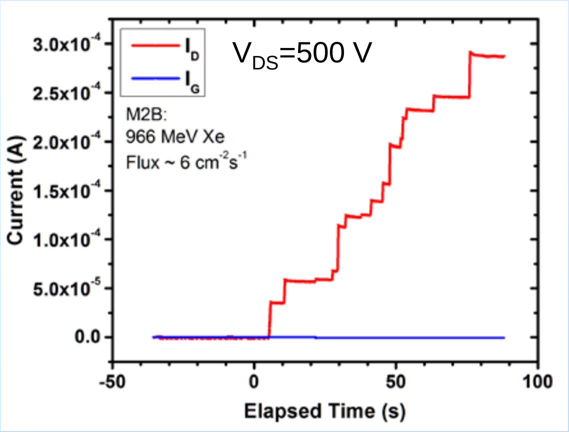
- **Game-changing NASA approaches are demanding higher-performance power electronics**
  - *SEE rad-hardened high-current MOSFETs > 250 V do not exist*
- **SWAP benefits for existing technologies**
  - *SiC power devices are flying now (Orion, MMS)*

Conclusions: We must understand the risk of damaged parts

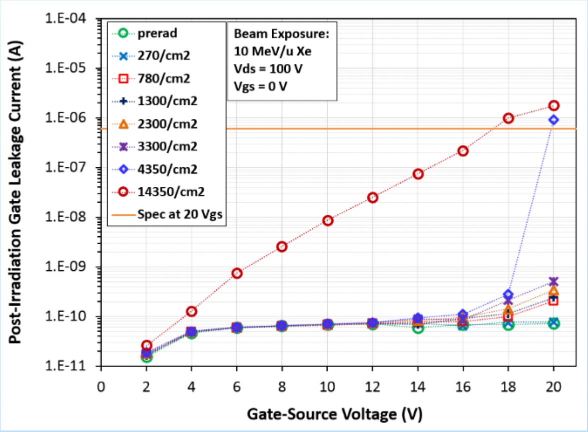
We must form industry/government/academic partnerships to expand SEE hardening efforts

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

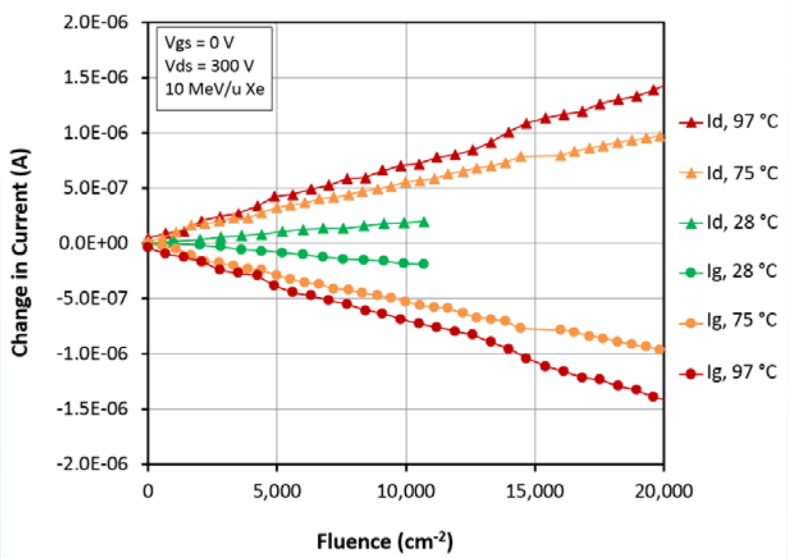


1200V MOSFET biased at 500V: increasing permanent drain leakage current with ion fluence



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

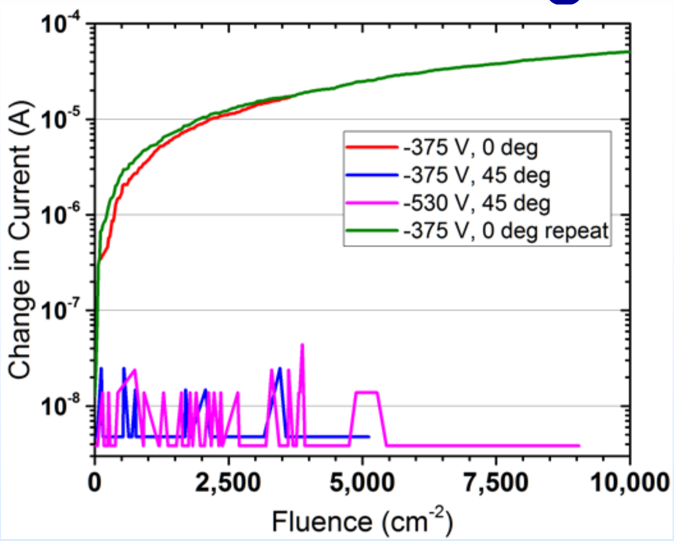
Understanding the Parameter Space



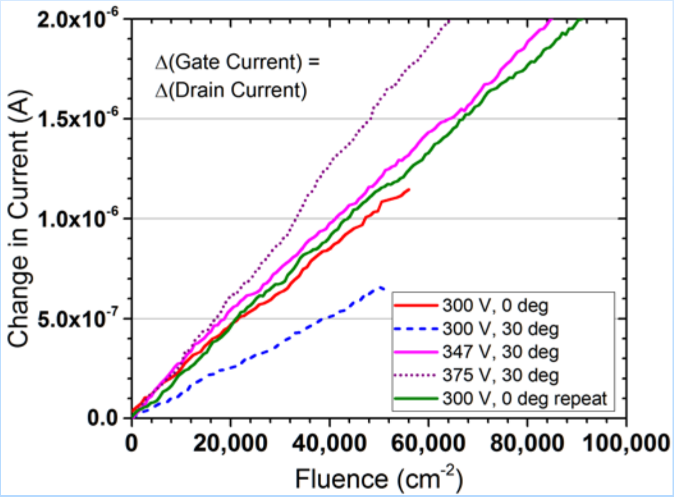
Degradation of both drain and gate currents during irradiation with xenon while biased at 0 V_{GS} and 300 V_{DS} is very linear with ion fluence. The degradation rate during irradiation increases with increasing case temperature.

- **COTS SiC power devices show similar behavior across part types and manufacturers**
  - ***One part or device type does not stand out from another in terms of SEE hardness***
- **Recent efforts:**
  - **What test data do we need to predict on-orbit degradation?**
    - What parameters are most important to the degradation mechanisms?
  - **How does degradation impact overall device reliability?**
    - High-temperature reverse bias test
    - High-temperature gate bias test

Understanding the Parameter Space: Angular Dependence



SiC Schottky Diode



SiC Power MOSFET

- **Diode: Strong angle effect**
  - At given VR, no degradation at 45°
  - Matching vertical component of electric field has no impact
    - Cosine law not followed
- **MOSFET: May follow cosine law when gate-leakage dominated**
  - For $I_G = I_D$ degradation signature, path through gate likely dominates angle effect
  - For drain-source current degradation dominant device, expect behavior similar to diode response

NEPP Collaborations

Vehicle	Agency(ies)/Industry	Description
SBIR	CFDRC, CoolCAD, DOE, Frequency Management Inc., GE, Semicoa, Vanderbilt Univ., Wolfspeed, NASA GRC, GSFC LaRC, JPL	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.
NEPP BOK	NASA GRC, GSFC	Body of knowledge for silicon carbide power electronics (knowledge and gap analysis)
JEDEC JC13 Gov't Liaison Committee	JC13.1, JC13.7, G12 communities, AFRL, DLA	JC-13.1/JC-13.7/G-12 SiC Tech Insertion Subcommittee meetings to develop test standards and address reliability concerns

- **Informal relationships to share data, subject matter expertise, track industry developments**

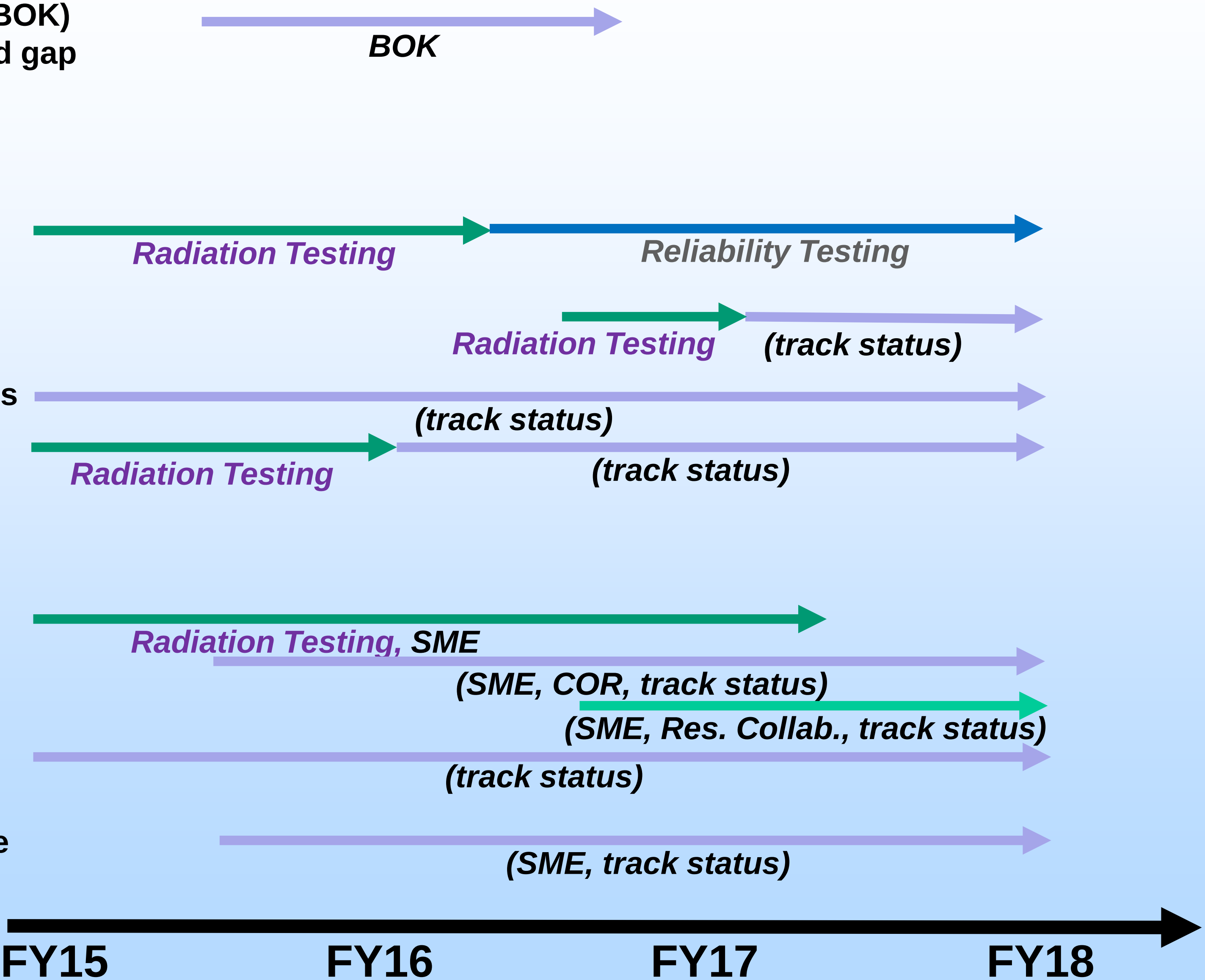
SiC Roadmap

SiC Body of Knowledge (BOK) document (knowledge and gap analysis)

COTS/Engineering
- Wolfspeed Gen 1-3 MOSFETs
- JFETs (normally on & off)
- Other SiC Manufacturers
- Logic ICs

SEE Hardening Effort Collaboration
- SMD SBIR Phase IIX
- STMD SBIR PI & PII
- STMD ESI
- ESA, JAXA

JEDEC SiC Subcommittee Test Standards/Reliability



Recent NEPP SiC Documents

- **“Body of Knowledge for Silicon Carbide Power Electronics” released:**
  - https://nepp.nasa.gov/files/27644/NEPP-BOK-2016-GRC-Boomer-SiC-TN35760.pdf
- **Papers and Conference Submissions:**
  - “Analysis of SEB Physics in SiC Power MOSFETs”, Witulski, et al., submitted to the 2017 RADECS.
  - “Taking SiC Power Devices to the Final Frontier—Addressing Challenges of the Space Radiation Environment,” Lauenstein, invited talk, 2017 ICSCRM.
  - “Heavy Ion Induced Degradation in SiC Schottky Diodes: Bias and Energy Deposition Dependence,” Javanainen, et al., IEEE Trans. Nucl. Sci., 2017.
  - “Long-term reliability of a hard-switched boost power processing unit utilizing SiC power MOSFETs,” Ikpe, et al., IEEE Reliability Physics Symposium, 2016.
- **Test reports:**
  - In progress

Summary and Comments

- **Aerospace community is benefiting from the momentum of the terrestrial SiC power device market's high-reliability needs**
  - Department of Energy grants to increase energy efficiency via WBG
    - Grant to identify cosmic-ray induced failures
  - Electric vehicle industry for SWAP of power control units
    - Toyota research on neutron-induced SEB
  - Other high-power applications requiring many devices in parallel
    - Importance of reliability
- **Years of NEPP and STMD GCD Program partnership have resulted in NASA funding of SiC SEE hardening efforts**
  - ***NEPP continues to support these activities through subject matter expertise and test support as appropriate***
- ***NEPP will continue to work with stakeholders to establish appropriate test guidelines and facilitate the path to reliable insertion of SiC power devices into space missions***