NEPP Electronic Technology Workshop
June 17-19, 2014

National Aeronautics
and Space Administration

Single-Event Effects in Silicon and Silicon Carbide Power Devices

Jean-Marie Lauenstein, Megan C. Casey, and Kenneth A. LaBel
Code 561, NASA Goddard Space Flight Center

Alyson D. Topper, Edward P. Wilcox, Hak Kim, and Anthony M. Phan
ASRC Space & Defense

To be published on nepp.nasa.gov previously presented by Jean-Marie Lauenstein at the NASA Electronic Parts and Packaging (NEPP) Electronics Technology Workshop (ETW), Greenbelt, MD, June 17-19, 2014.

List of Acronyms

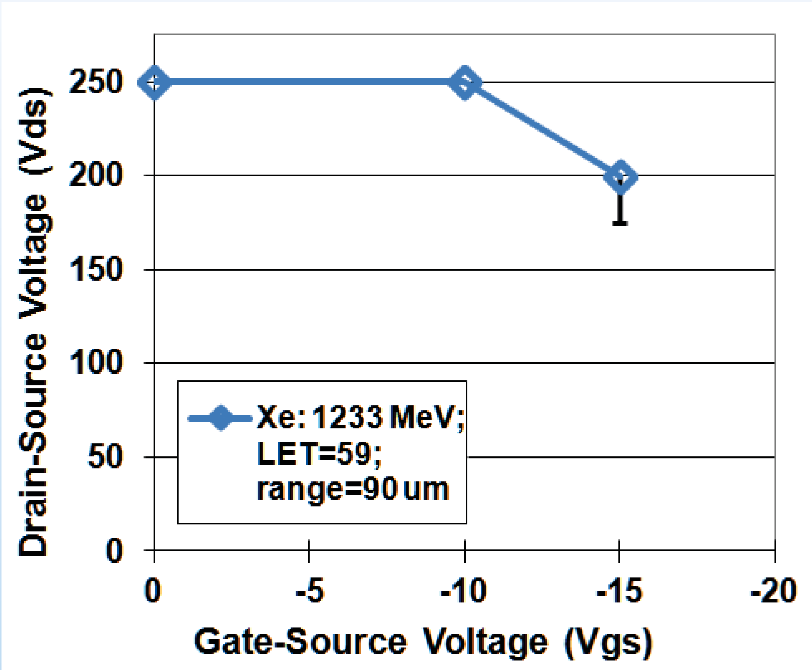
BJT – Bipolar Junction Transistor
BVdss – Drain-to-Source Breakdown Voltage
ETW – Electronic Technology Workshop
FY – Fiscal Year
GRC – Glenn Research Center
GSFC – Goddard Space Flight Center
HEMT – High Electron-Mobility Transistor
I_D – Drain current
I_G – Gate current
JEDEC – (not an acronym)
JESD – JEDEC Standard
JFET – Junction Field-Effect Transistor
JJAP – Japanese Journal of Applied Physics
JPL – Jet Propulsion Laboratory
LBNL – Lawrence Berkeley National Laboratory 88-Inch cyclotron
LET – Linear Energy Transfer
MOSFET – Metal Oxide Semiconductor Field Effect Transistor
NEPP – NASA Electronic Parts and Packaging program
PIGS – Post-Irradiation Gate Stress
RF – Radio Frequency
SEB – Single-Event Burnout
SEE – Single-Event Effect
SEFI – Single-Event Functional Interrupt
SEGR – Single-Event Gate Rupture
SEP – Solar Electric Propulsion
SET – Single-Event Transient
SOA – State-Of-the-Art
TID – Total Ionizing Dose
VDMOS – vertical, planar gate double-diffused power MOSFET
V_{DS} – Drain-source voltage
V_{GS} – Gate-source voltage
V_R – Reverse-bias Voltage

Goals

- **Assess SiC power devices for space applications**
  – Develop relationships with SiC device suppliers
  – Investigate SEE susceptibility of currently available products
  – Understand SEE mechanisms to enable radiation hardening
- **Participate in test method revisions:**
  – Lead JEDEC JESD57 revision: "Test Procedure for the Measurements of Single-Event Effects in Semiconductor Devices from Heavy Ion Irradiation" – current version is from 1996
- **Evaluate alternative silicon power MOSFETs for space applications**
  – Winding down focus on Si VDMOS: We've gone from 1 to 6 manufacturers offering independently verified SEE radiation-hardened discrete silicon power MOSFETs!
  – Thank you to all manufacturers who partnered with us over the years to provide this critical product to the aerospace community
  – *We are always interested in SOA high-performance Si MOSFETs..*

Si Power MOSFETs

- **FUJI advanced 2nd generation radiation-hardened VDMOS:**
  - Developed to withstand PIGS test
  - Hardness of 250 VDMOS evaluated at LBNL – failures only at -15 Vgs
  - 500 V device in development



Single-event effect response curve of FUJI engineering samples of new 250 VDMOS

- **NEPP (JPL) invited to observe Microsemi 2nd generation i2MOS™ SEE testing this summer**

JEDEC Standard No. 57 (JESD57) Revision Efforts

JESD57: "Test Procedures for the Measurement of Single-Event Effects in Semiconductor Devices from Heavy Ion Irradiation"

- **FY13 efforts: update SEGR test method within JESD57**
  - Current understanding of ion species and energy effects
    - Guidance for beam selection based on species
  - Scope expanded:
    - Discrete MOSFETs of various topologies
    - Microcircuits
- **FY14 efforts include complete JESD57 update**
  - Document reorganization
  - Addition of SEB, SET
  - Expansion of SEFI understanding
  - and more

JESD57 Content Revision

- **Key content updates:**
  - **Basic effects expanded to better address:**
    - SEB, SEFIs, SEGR, SETs
    - Effects not well understood to be addressed as “notes”:
      - SiC and Si Schottky burnout-like failures
      - RF SEE challenges, including on-state catastrophic failures in GaN HEMTs
  - **Definitions updated to current JESD88**
    - Some definitions are still out-of-date – need to be expanded to reflect current understanding of effects
      - SEFI, SEU
  - **DUT preparation expanded**
    - Die thinning
    - High-voltage die arcing after decapsulation
  - **Dosimetry practices updated**
  - **Document reorganized for improved readability**

SiC Power Devices Evaluated to Date

Part Type	Manufacturer	Part Number	Date Tested
Schottky (1200 V)	Cree	C4D40120D*	Spr 2013
	GeneSiC	GB20SLT12*	Sum 2013
Schottky (650 V)	Infineon	IDW40G65C5*	Sum 2013
MOSFET (1200 V)	Cree	Gen 2.0*	Fall 2013
		Gen 1.5 (prototype)*	Fall 2013
		Gen 1.0	Fall 2012
	Cissoid	CHT-PLA8543C*	Sum/Fall 2013
NPN BJT (1200 V)	TranSiC (now Fairchild)	BT1206AA-P1	Sum 2012
JFET, normally off (1200 V)	SemiSouth	SJEP120R100	Sum 2012
JFET, normally off (1700 V)	SemiSouth	SJEP170R550	Fall 2012

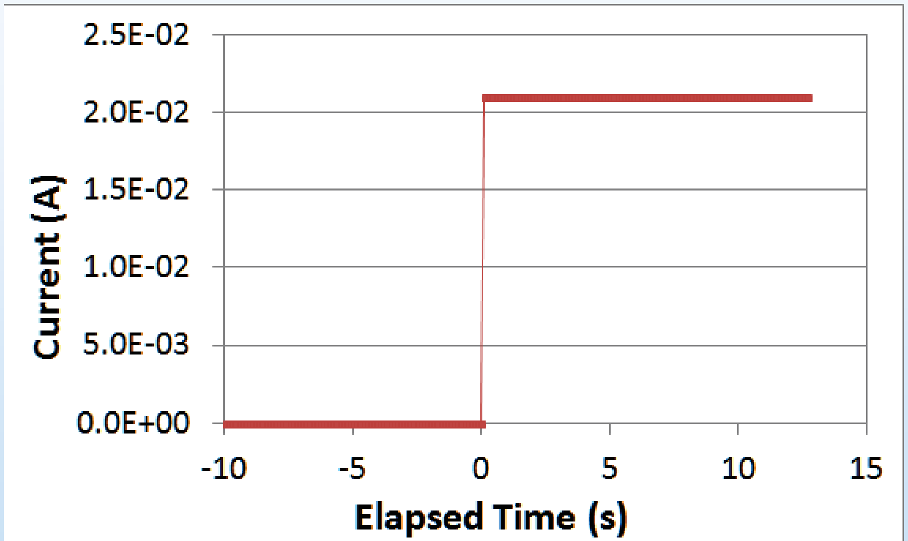
**** Evaluated under the NASA SEP Program with support from NEPP***

SiC Schottky Diodes

- **Two modes of SEE effects, both reported previously in the literature**
  - Degradation
  - Catastrophic failure
- **Degradation (increasing reverse-bias leakage current) prevents identification of onset bias for single-event catastrophic failure**
- **As previously reported, catastrophic failure can occur under proton irradiation**
- **Failure location within active region (as opposed to field termination region)**
  - To be verified via failure analysis

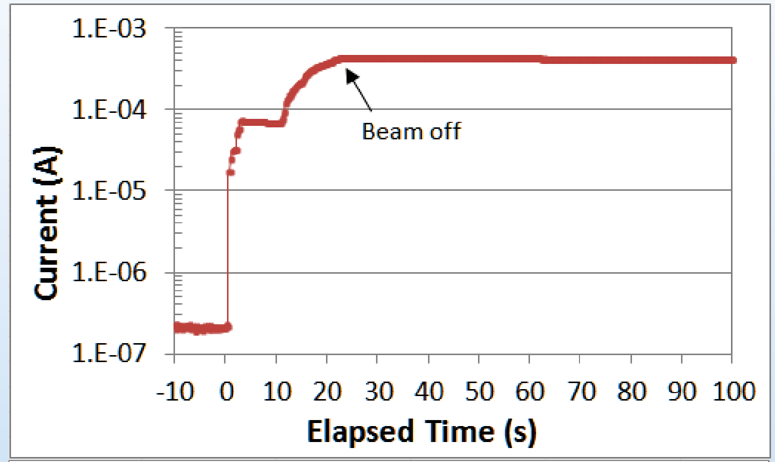
GB20SLT12 Current Signatures

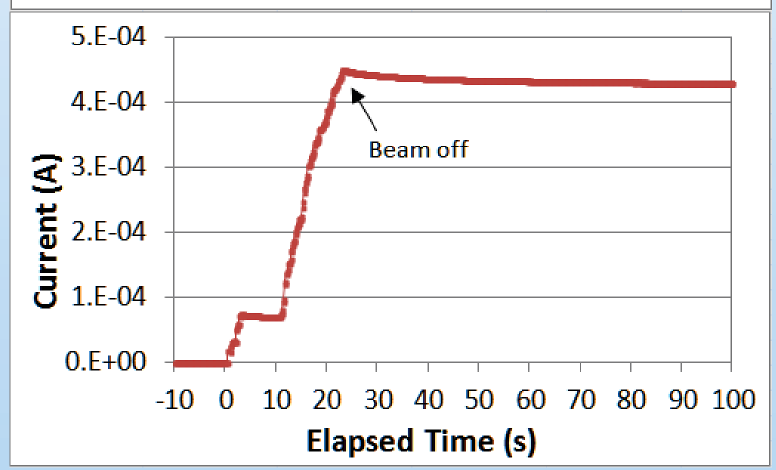
Ag: V_R = 500 V
avg. flux = 24 /cm²/s:
Immediate catastrophic failure



1110 MeV Ag ions:
LET = 66 MeV-cm²/mg
Range = 49 μm

Ag: V_R = 350 V
avg. flux = 589 /cm²/s:
Degradation

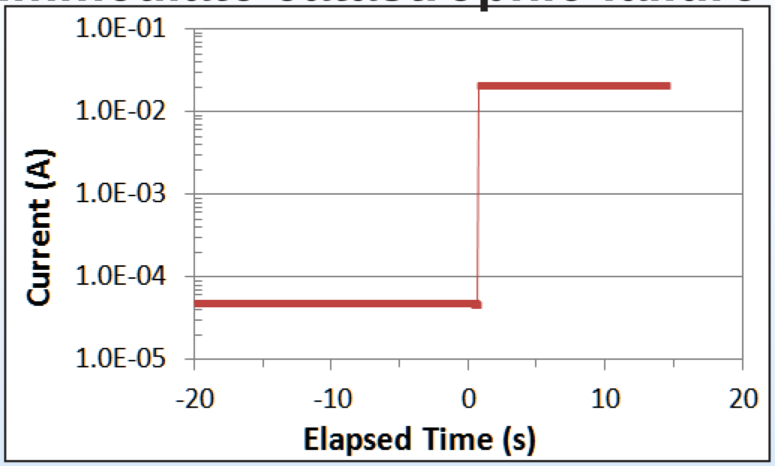




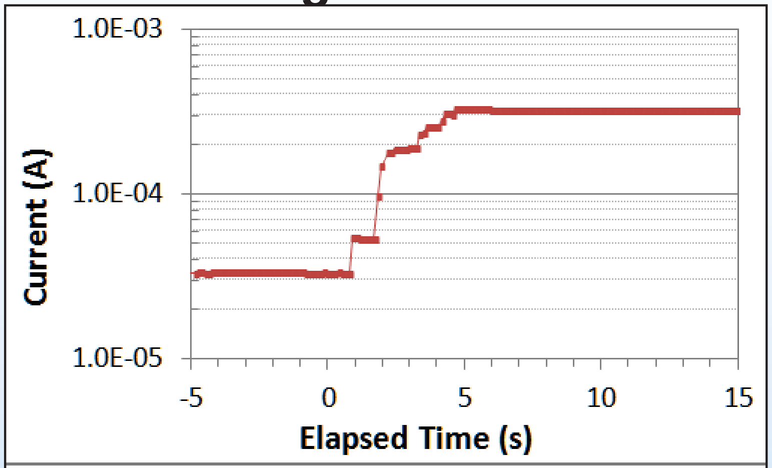
To be published on nepp.nasa.gov previously presented by Jean-Marie Lauenstein at the NASA Electronic Parts and Packaging (NEPP) Electronics Technology Workshop (ETW), Greenbelt, MD, June 17-19, 2014.

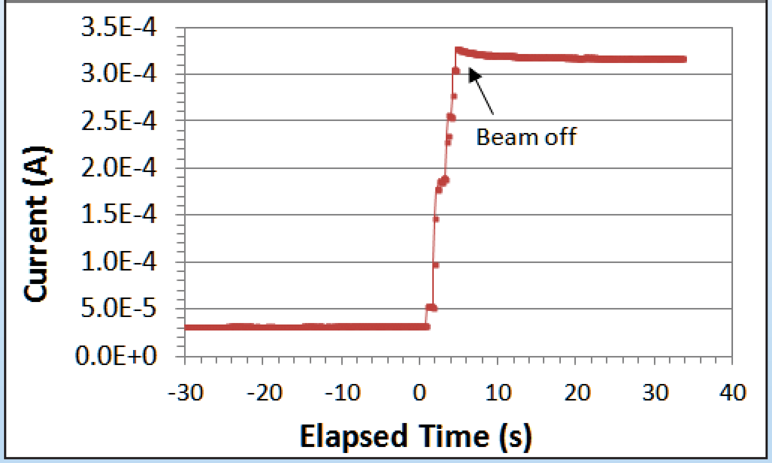
C4D40120D Current Signatures

Ag: V_R = 650 V
avg. flux = 1088 /cm²/s:
Immediate catastrophic failure

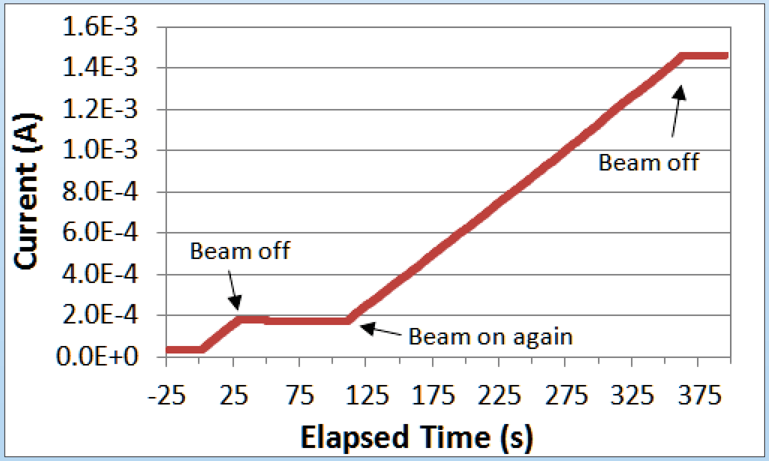


Ag: V_R = 450 V
avg. flux = 63 /cm²/s:
Degradation





Ag: V_R = 300 V
ave flux = 1088 /cm²/s:
Degradation



1110 MeV Ag ions:
LET = 66 MeV-cm²/mg; Range = 49 μm

SiC Schottky Diode Damage Signatures

- **Degradation of reverse current:**
  - Influenced by ion/energy
    - Have not looked at multiple energies for single ion species to isolate energy effects
  - Influenced by reverse bias voltage
  - Does not recover after irradiation
    - Failure analyses to be done to see extent of damage

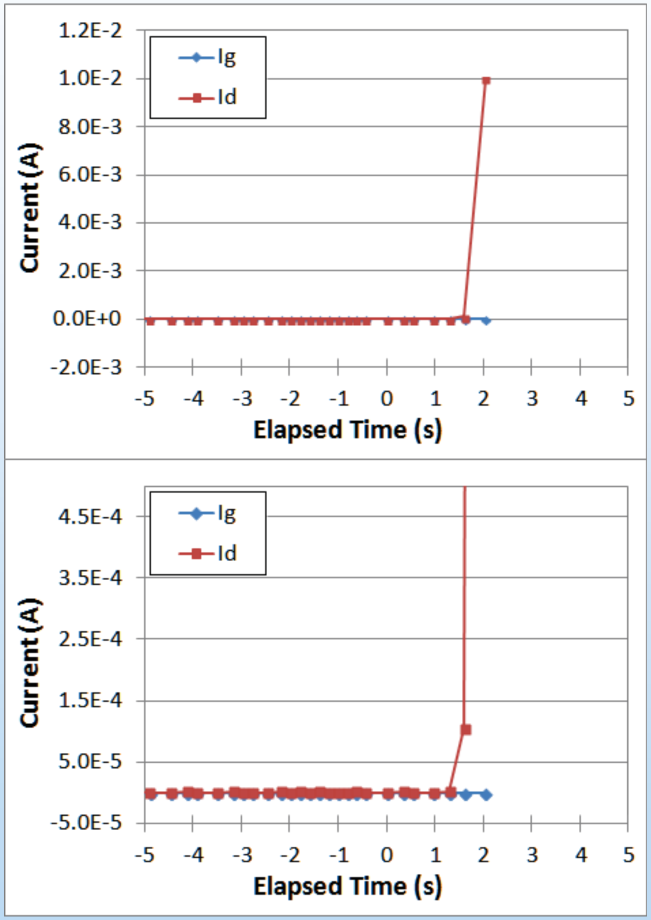
SiC Power MOSFETs

- **Two modes of SEE effects as with Schottkys**
  - Degradation
  - Catastrophic failure
- **Unclear what the primary failure mode is**
  - Both gate and drain current increases
  - Substantially thinner gate oxide in Cree generation 2.0 does not result in increased SEGR susceptibility
    - Cree Gen 1.5 shows predominately SEGR signatures
    - Cree Gen 2 shows predominately burnout-like damage
- **Susceptibility falls off with angle of incidence**
  - assessed only in Cree Gen 1 parts
- **Titus-Wheatley critical V_{GS} at 0 V_{DS} holds (unchanged) for Cree MOSFETs (established on gen 1.0)**

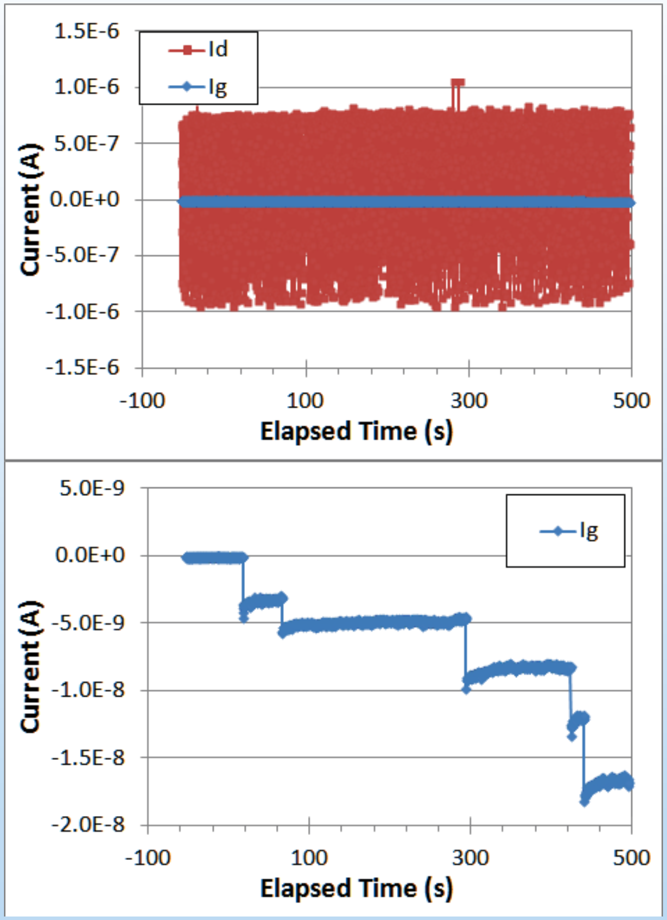
$$V_{gs(crit)} = \frac{10^7 \times t_{ox}}{1 + \frac{Z}{44}}$$

Cree Gen. 2.0 Signatures: Catastrophic Failure; Gate Degradation

Xe: 650 V_{DS}; 0 V_{GS}
avg. flux = 17 /cm^2/s



Xe: 300 V_{DS}; 0 V_{GS}
avg. flux = 13.5 /cm^2/s



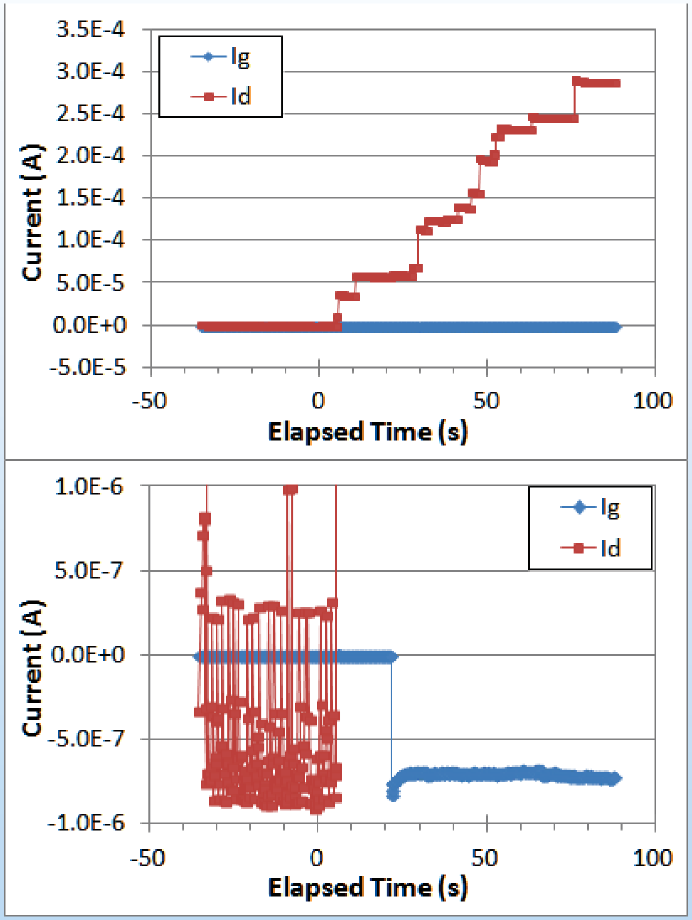
996 MeV Xe ions:

LET = 65 MeV-cm^2/mg, Range = 49 μm

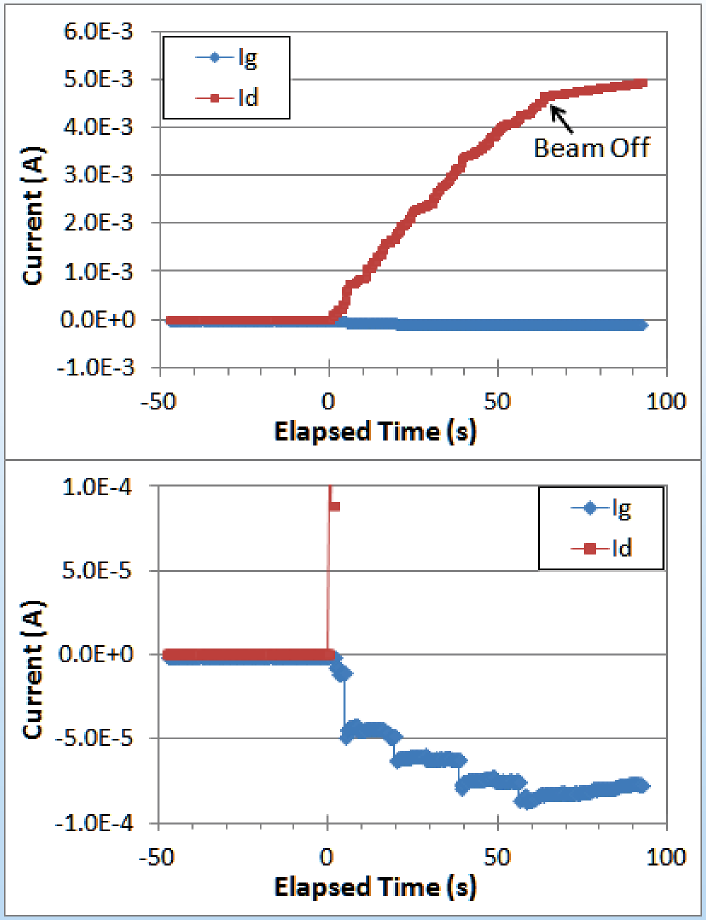
To be published on nepp.nasa.gov previously presented by Jean-Marie Lauenstein at the NASA Electronic Parts and Packaging (NEPP) Electronics Technology Workshop (ETW), Greenbelt, MD, June 17-19, 2014.

Cree Gen. 2.0 Signatures: Drain-Source Damage

Xe: 500 V_{DS}
avg. flux = 6 /cm²/s



Xe: 500 V_{DS}
avg. flux = 162 /cm²/s



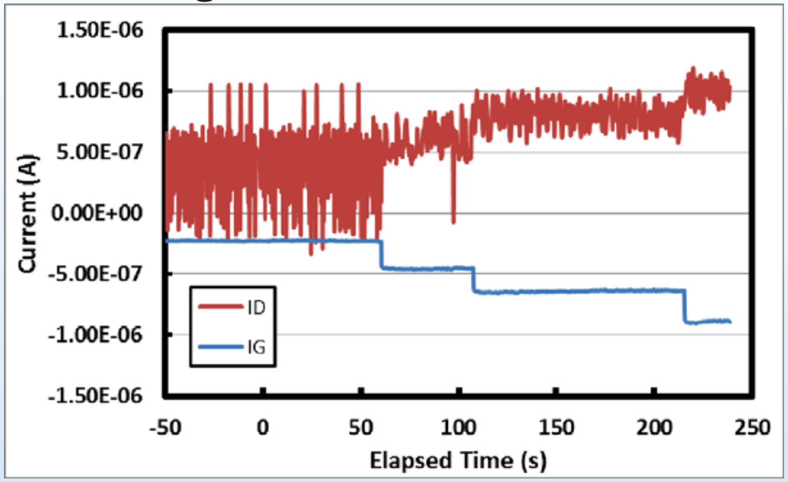
996 MeV Xe ions:

LET = 65 MeV-cm²/mg, Range = 49 μm

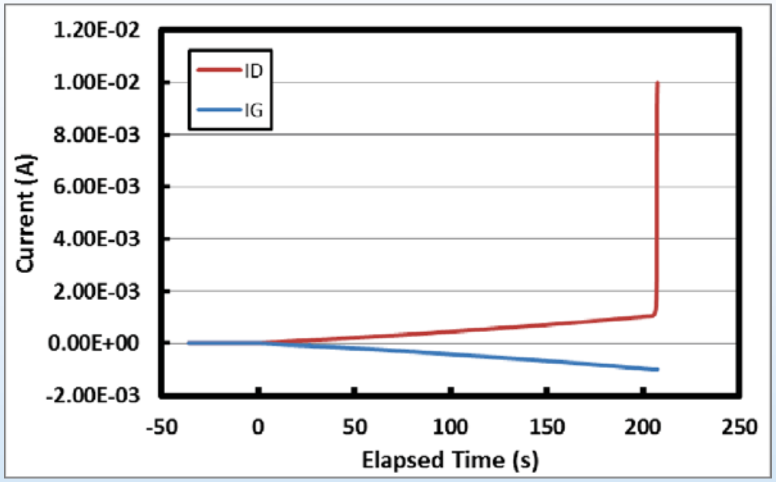
To be published on nepp.nasa.gov previously presented by Jean-Marie Lauenstein at the NASA Electronic Parts and Packaging (NEPP) Electronics Technology Workshop (ETW), Greenbelt, MD, June 17-19, 2014.

Cree Gen. 1.5 Signatures: Gate-Drain damage

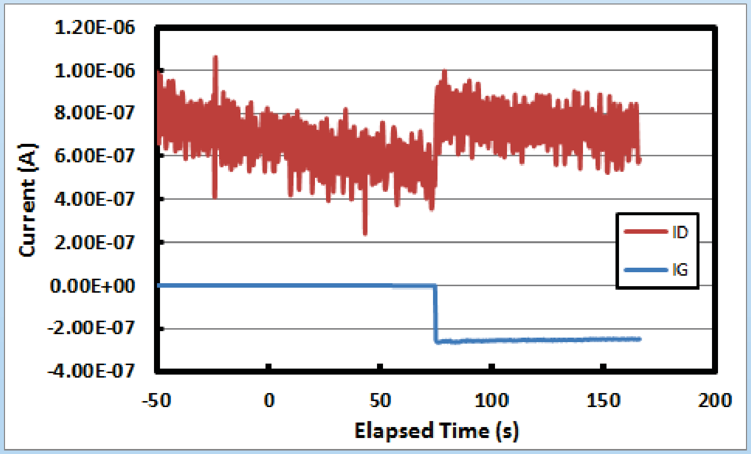
Xe: 182 V_{DS}
avg. flux = 45 /cm²/s



Xe: 400 V_{DS}
avg. flux = 484 /cm²/s



Xe: 182 V_{DS}
ave flux = 68 /cm²/s

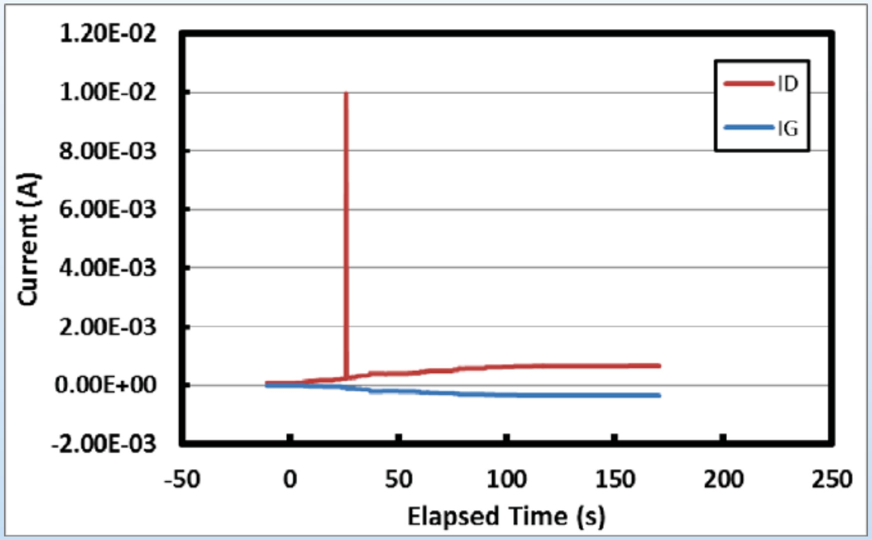


After run on left. BVdss = 912 V (BVdss defined at I_D = 100 μA). PIGS = 40 μA at 18 V_{GS}, 0 V_{DS}.

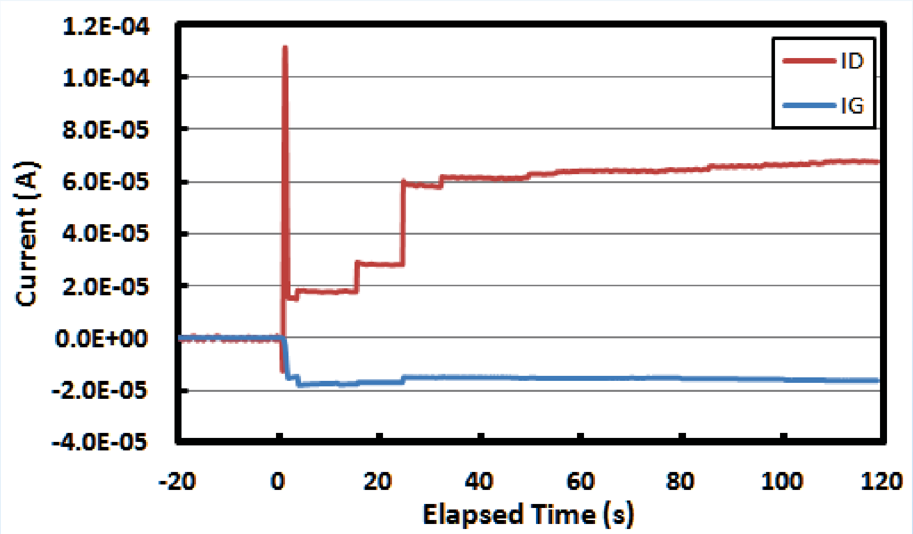
To be published on nepp.nasa.gov previously presented by Jean-Marie Lauenstein at the NASA Electronic Parts and Packaging (NEPP) Electronics Technology Workshop (ETW), Greenbelt, MD, June 17-19, 2014.

Cree Gen. 1.5 Details: "Protective Mode" Test

Xe: 500 V_{DS}
avg. flux = 5 /cm²/s
Unprotected test



Xe: 500 V_{DS}
avg. flux = 5 /cm²/s
1 MΩ on drain node



With protective resistor:

- $\Delta I_D > \Delta I_G$
- I_G shows some temporary recovery
- Failure mode is not pure SEGR

To be published on nepp.nasa.gov previously presented by Jean-Marie Lauenstein at the NASA Electronic Parts and Packaging (NEPP) Electronics Technology Workshop (ETW), Greenbelt, MD, June 17-19, 2014.

Power MOSFETs (cont'd)

- **Revisit protective mode:**
  - Apply lower V_{DS} conditions
  - Examine Cree Gen 2 where drain current effects predominate
- **Revisit Cree Gen 1 test data to assess predominate failure signature**
- **STMicro SiC power MOSFETs to be evaluated June 29th**
  - Designer will be present
- **Negotiating with GeneSiC to obtain samples of their SiC Junction Transistor**

Conclusions and Path Forward

- **SiC devices show high TID tolerance, but low SEE tolerance**
  - Degradation occurs well below rated bias voltage
  - Increased leakage currents with ion fluence are a function of LET and bias voltage on the part
- **Identification of a safe operating condition is extremely difficult**
  - Degradation interferes with adequate sampling of the die with ions – many samples would be required
  - Degradation may impact part reliability
- **Signatures are similar across manufacturers and part types:**
  - Mechanism is more fundamental than geometry or process quality
  - Recent research (Shoji, *JJAP*, 2014) suggests impact ionization at the epi/substrate interface due to the space-charge induced increase in the electric field results in thermal damage (SEB)
    - **Vulnerability tied to much higher heat generation density in SiC vs. Si**