



Single-Event Effects in Silicon Carbide Power Devices

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

**Stanley Ikpe
NASA Langley Research Center**

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

List of Acronyms



BJT – Bipolar Junction Transistor

BV_{dss} – Drain-to-Source Breakdown Voltage

ESA – European Space Agency

ETW – Electronic Technology Workshop

FY – Fiscal Year

GE – General Electric

GRC – Glenn Research Center

GSFC – Goddard Space Flight Center

I_D – Drain current

I_G – Gate current

JAXA – Japan Aerospace Exploration Agency

JEDEC – (not an acronym)

JESD – JEDEC Standard

JFET – Junction Field Effect Transistor

JPL – Jet Propulsion Laboratory

JSC – Johnson Space Center

LaRC – Langley Research Center

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

RHA – Radiation Hardness Assurance

SEB – Single-Event Burnout

SEE – Single-Event Effect

SEGR – Single-Event Gate Rupture

SEP – Solar Electric Propulsion

TAMU – Texas A&M University

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

NEPP Program Goals & Collaborations



- **Assess SiC power devices for space applications**
 - Develop relationships with SiC device manufacturers
 - Investigate SEE susceptibility of currently available products
 - Understand SEE mechanisms to enable radiation hardening
- **Work presented here has been sponsored in part by:**
 - NASA Electronics, Parts, and Packaging Program (primary sponsor)
 - NASA Solar Electric Propulsion Program
 - NASA High-Temperature Boost Power Processing Unit Project
- **SiC integrated circuits are also under study**
 - This work is not presented here



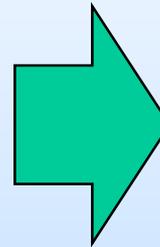
Why SiC?

High Breakdown Voltage
(~ 10x vs. Si)

Low On-State Resistance
(~ 1/100 vs. Si)

High Temperature Operation
(~ 3x vs. Si)

High Thermal Conductivity
(~ 10x vs. Si)

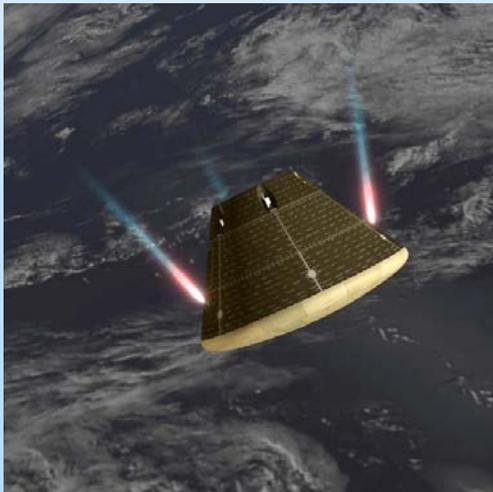


Mass Savings
Power Savings
Cost Savings



NASA Interests in SiC

Program/Project	Primary Benefit
Orion Spacecraft	Power
Advanced Space Power Systems	Mass
High-Temperature Boost Power Processing Unit	Extreme Environments
Venus Mobile Explorer (concept mission)	Extreme Environments



Images: NASA

A Closer Look at Mass Savings



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

2457 kg

- **With derating, require 400 V power MOSFETs**
 - Silicon radiation-hardened MOSFETs have power penalty
- **Higher voltages will result in additional mass savings**
 - SiC is a potentially enabling technology



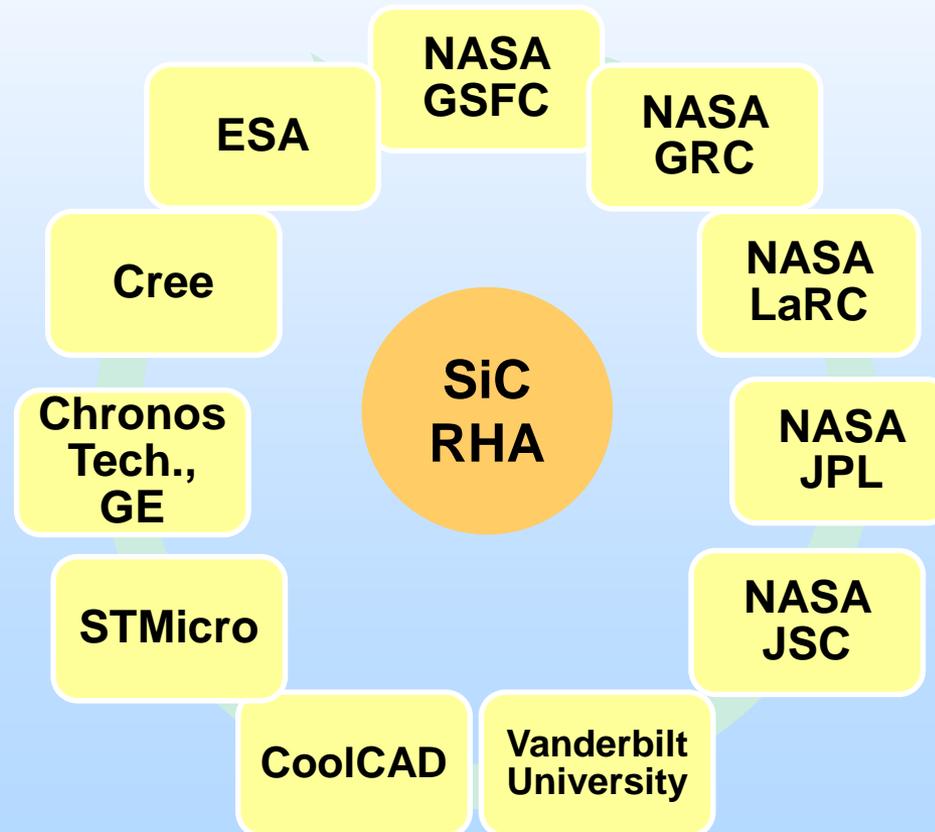
*Mass savings from:
Mercer, AIAA 2011-7252*

*Fig: Rei-artur,
Creative Commons*



FY15 Partnerships

- As the awareness of SiC power device vulnerability to heavy-ion induced single-event effects has grown, so too has the momentum to find a solution:



Status of SiC Power Devices for Space Applications



- Testing by NASA has been performed on a wide range of SiC power devices rated 650 V to 3300 V

Part Type	Number of Parts/Manufacturers
Power MOSFET	7/4
Diode	4/4
JFET	2/1
BJT	1/1

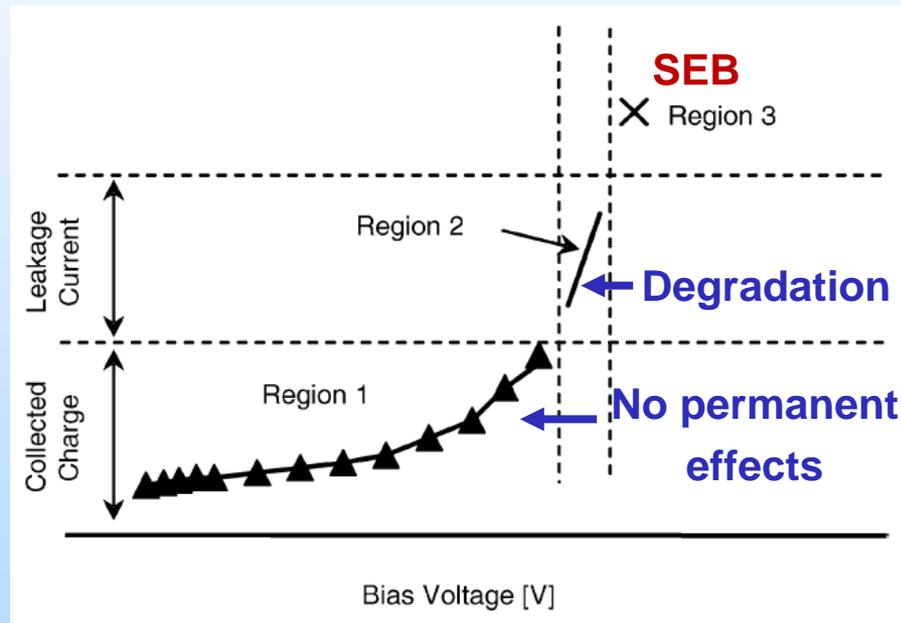
- Additional testing has been performed by ESA, JAXA, and other non-government parties

Serendipitously SEE-hard commercial SiC power devices are rare or non-existent

SEE Performance: Power Diodes



- As V_R increases, response to heavy ions goes from no effect to leakage current degradation to sudden catastrophic single-event burnout (SEB)



Modified from: Kuboyama, et al., IEEE TNS, 2006

SEE Performance: Power Diodes (cont'd)



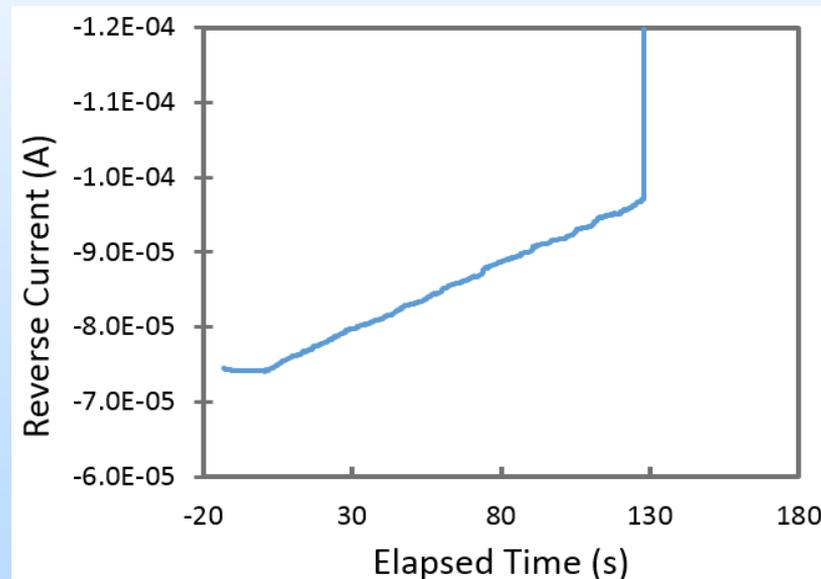
Ion	Device	Max V_R No Degradation	Min V_R Sudden SEB
1289 MeV Ag	D1 _{650V}	150 (23%)	300 (46%)
	D2 _{1200V}	100-150 (8% - 13%)	500 (42%)
	D3 _{1200V}	--	500 (42%)
	D4 _{1200V}	350 (29%)	450-500 (38% - 42%)
1512 MeV Xe	D1 _{650V}	150 (23%)	--
	D2 _{1200V}	150 (13%)	--
1233 MeV Xe	D4 _{1200V}	350 (29%)	450-475 (38% - 40%)
278 MeV Ne	D3 _{1200V}	600 (50%)	600 (50%)

- Percentages are based on RATED breakdown voltage
- D1, D2, D3 = Schottky diodes; D4 = pn diode

Degradation Not Unique to SiC



- Recent work by Megan Casey/GSFC on silicon Schottky diodes reveals susceptibility of many diodes to heavy-ion induced degradation in addition to SEB

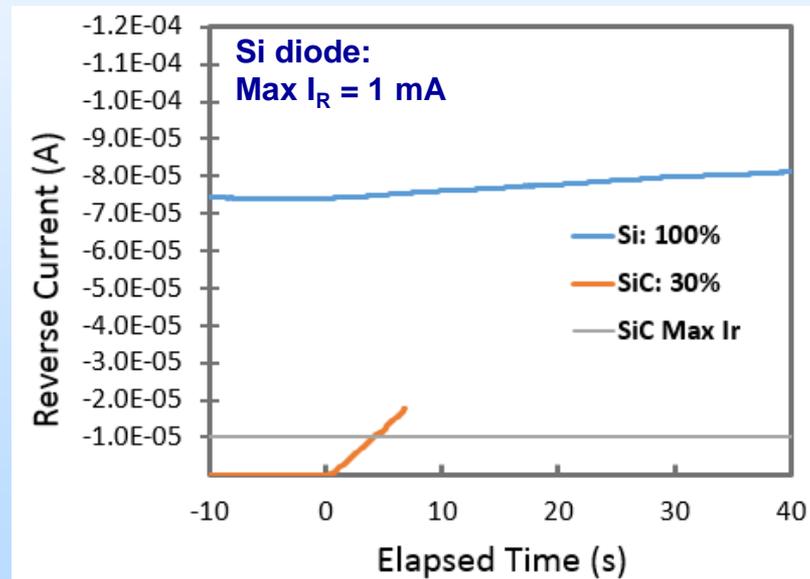


Si diode biased at 100% of rated value
Ion beam: 1233 MeV xenon

Degradation Not Unique to SiC



- Recent work by Megan Casey/GSFC on silicon Schottky diodes reveals susceptibility of many diodes to heavy-ion induced degradation in addition to SEB
 - Degradation is small compared to SiC diodes



**Si diode biased at 100%, SiC at 30%, of rated values
Flux for SiC = 1/10 of flux for Si**

SEE Performance: Power MOSFETs



Ion	Device	Max VDS No Damage	Degradation Currents During Run	Min V_R Sudden SEB/SEGR
1233 MeV Xe	M1 _{1200V}	40	$I_D \geq I_G$	600 < SEB < 700
	M2 _{1200V}	50	$I_D > I_G$	SEB > 500
	M3 _{3300V}	50	$I_D \gg I_G$ at 350 V _{DS}	650 < SEB < 800
	M4 _{1200V}	Not found	$I_D > I_G$	SEB > 500
	M5 _{1200V}	40	$I_D > I_G$	400 ≤ SEB < 600
	M6 _{1200V}	50 < V _{DS} < 75	$I_D = I_G$; $I_D > I_G$ at 425 V _{DS}	475 < SEB < 500
1289 MeV Ag	M4 _{1200V}	25 < V _{DS} < 50	--	100 < SEB < 600
	M6 _{1200V}	50 < V _{DS} < 75	$I_D = I_G$ at 225 V _{DS} $I_D > I_G$ at 400 V _{DS}	500 < SEB < 600
659 MeV Cu	M5 _{1200V}	70	$I_D = I_G$	400 < SEB < 600

- All results shown here conducted at 0 V_{GS}

SiC Power Devices: Collaborative Studies In Progress



- **Ongoing efforts to understand degradation and SEE failure mechanisms include:**
 - Failure analysis work performed at NASA GRC on Schottky diodes
 - Modeling studies in progress at Vanderbilt University
 - Continued heavy-ion testing conducted by NASA GSFC & LaRC and ESA
- **NASA Science and Technology Mission Directorate Early Stage Innovations NASA Research Announcement**
- **Potential NASA SBIR Phase II-X effort on process and design changes on SEE hardening of power SiC MOSFETs and diodes**

Efforts reflect a coordinated commitment to enable SiC technology for space applications

Conclusions and Path Forward



- **The NEPP Program has been an early and constant supporter of SiC power device radiation hardness assurance**
- **SiC devices show high TID tolerance, but low SEE tolerance**
- **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
- **Most space applications will require SiC power devices that have been hardened to SEE**
- **Interest in hardening SiC power devices is growing:**
 - Manufacturers will require partnerships to help fund development efforts