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Single-Event Effects in Silicon Carbide Power Devices

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List of Acronyms

BJT – Bipolar Junction Transistor
BVdss – 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
(200 ^{0}C)

High Thermal Conductivity
(~ 10x vs. Si)

→

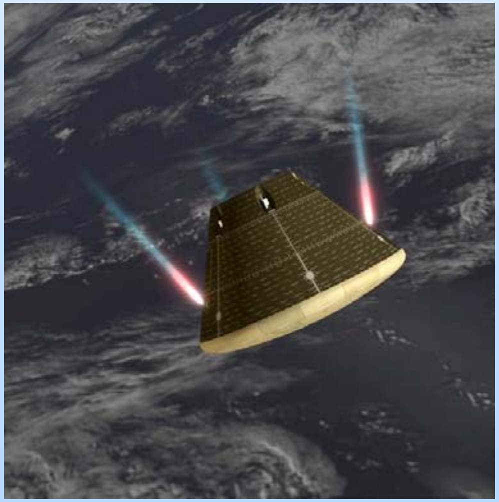
Mass Savings

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

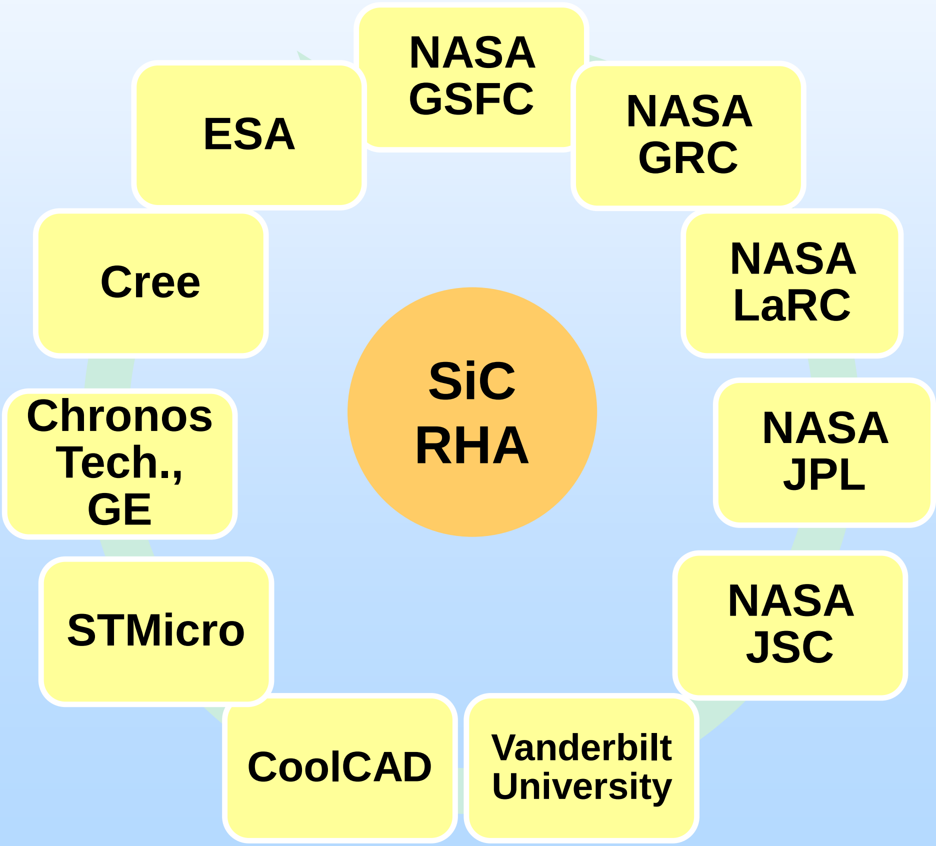
- **With derating, require 400 V power MOSFETs**
  - Silicon radiation-hardened MOSFETs have power penalty
- **Higher voltages will result in additional mass savings**
  - SiC is a potentially enabling technology

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:



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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**

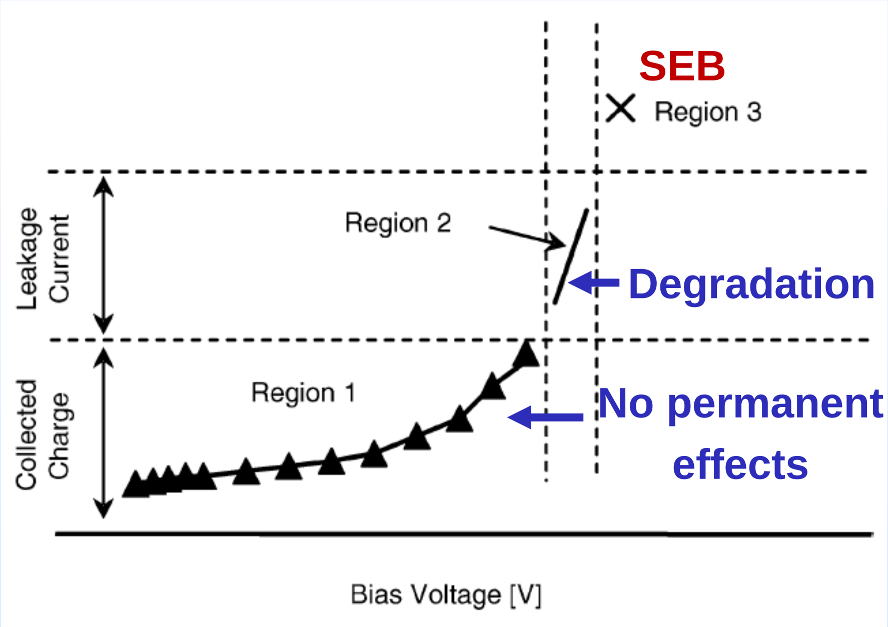
Part Type	Number of Parts/Manufacturers
Power MOSFET	7/4
Diode	4/4
JFET	2/1
BJT	1/1

- **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

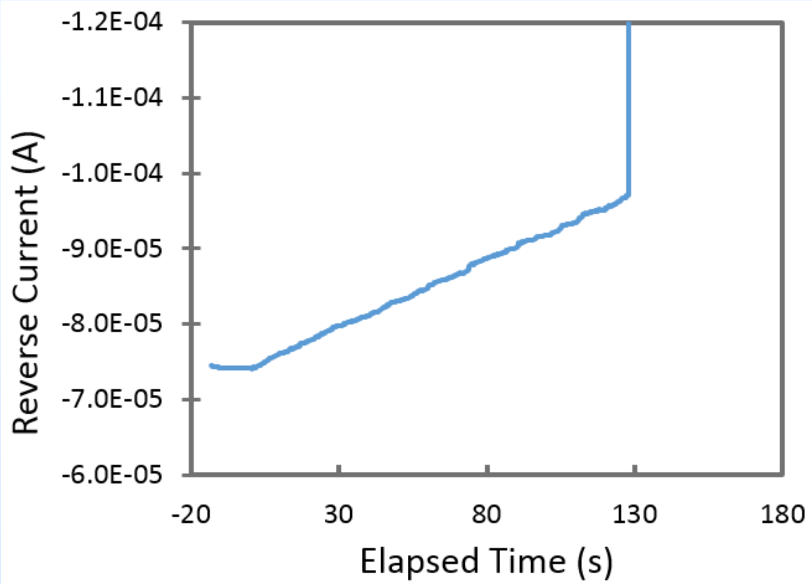
SEE Performance: Power Diodes (cont'd)

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

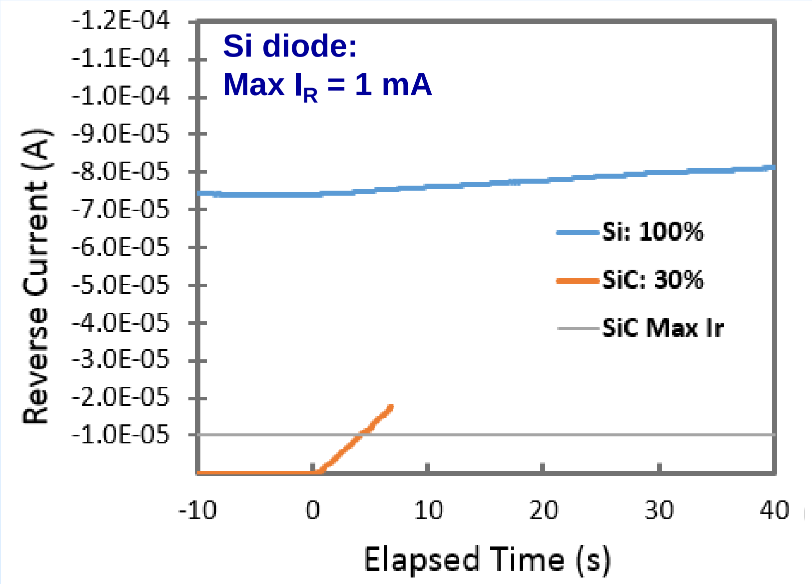
- **Recent work by Megan Casey/GSFC on silicon Schottky diodes reveals susceptibility of many diodes to heavy-ion induced degradation in addition to SEB**



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	$I_D >> I_G$ 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