JOHNS HOPKINS
APPLIED PHYSICS LABORATORY

LSIC Surface Power Telecon

March 16th, 2023

Begins at 11:03

Lunar Surface Innovation
CONSORTIUM

Dr. Matt Clement, Dr. James Mastandrea, Dr. Sean Young,
Sam Andrade, Julie Peck, Dr. Joseph Kozak, Claire Trop
Johns Hopkins Applied Physics Laboratory
Space Exploration Sector

LSIC Surface Power Facilitator POC: matt.clement@jhuapl.edu

LSIC | Agenda

- Community Updates
  - Solicitations and Awards
  - Conferences/Workshops
    - LSIC Spring Meeting
  - April Telecon: Off schedule again (April 13)
  - July 26-27: LSIC Surface Power Reliability Workshop

- Presentation: Akin Akturk (CoolCAD Electronics, Vice President)

- Q&A

LSIC | Solicitations and Awards

Space Tech Solicitations (https://www.nasa.gov/directorates/spacetech/solicitations)

MUREP Space Technology Artemis Research (M-STAR)
Proposals Due: April 10, 2023

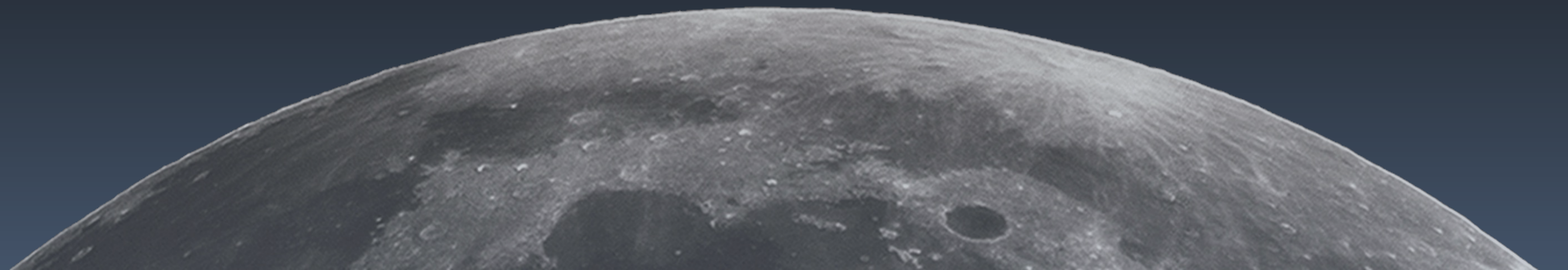
LuSTR 2023 Opportunities
NOIs due March 23
Full proposals due April 24

NASA Innovation Corps Pilot
Next deadline for review: March 29

NASA Innovative Advanced Concepts (NIAC) Phase III Call for Proposals
Final Proposals Due: May 17

Early Career Faculty STMD Research Grants
Notices of Intent Due: **TODAY**
Proposals Due April 13

Early Stage Innovation Solicitation
Solicitation release planned in April 2023



LSIC | Upcoming Meetings and Workshops

Applied Power Electronics Conference (APEC)
March 19-23, Orlando, FL

ASCENDx
March 29-30, Houston, TX

Space Resources Week 2023
April 19-21, Luxembourg

LSIC Spring Meeting
April 24-25, Laurel, MD

Nuclear and Emerging Technologies for Space (NETS 2023)
May 7-11, Idaho Falls, ID

More complete calendar on LSIC website, email with additional events!

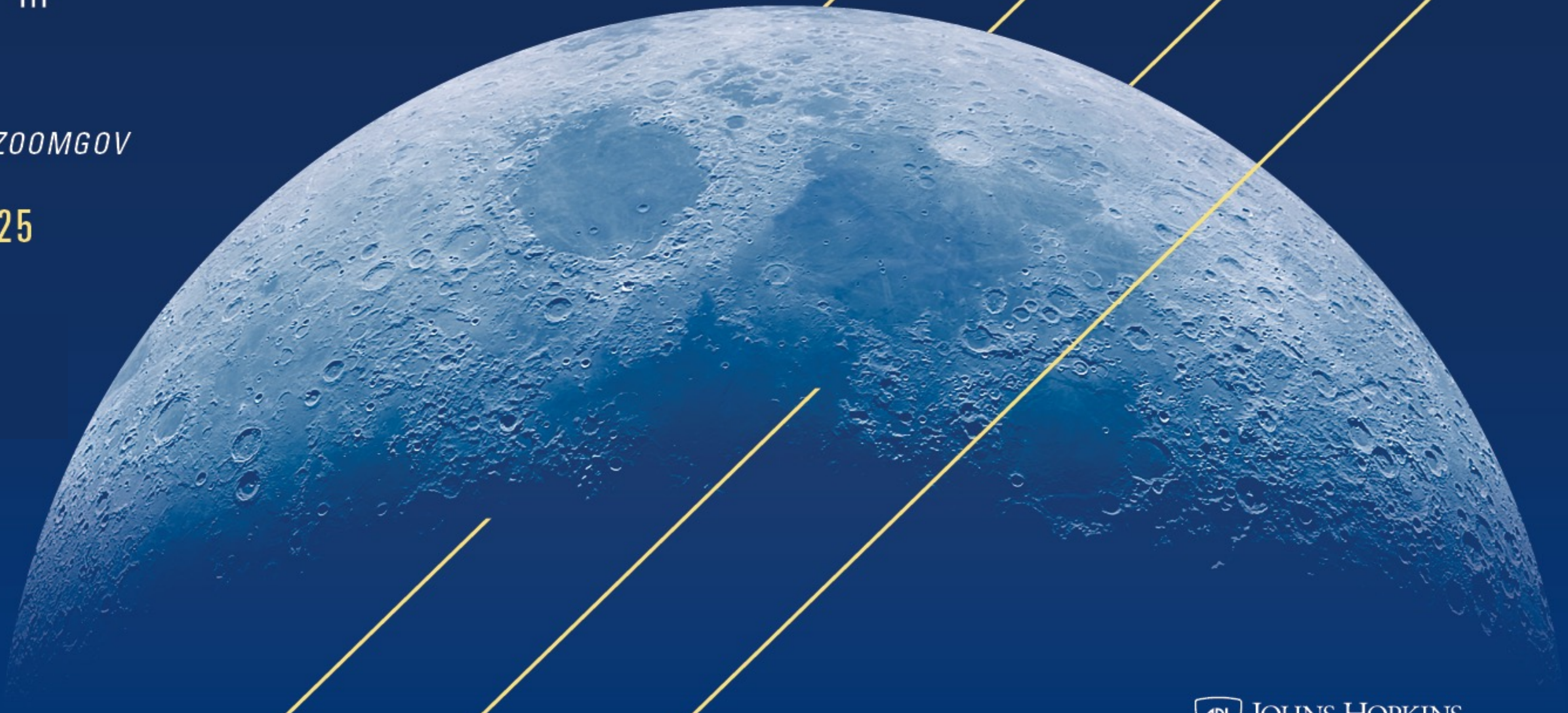
Lunar Surface Innovation
CONSORTIUM

ONSITE AT JOHNS HOPKINS APL & ONLINE VIA ZOOMGOV

SPRING MEETING 2023 • APRIL 24–25

REGISTRATION IS OPEN!!!

Scan for more info



JOHNS HOPKINS
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LSIC | April Telecon

We hope to see you all at our next telecon, which will take place on **Thursday April 13th, 2023 at 11:00AM ET.**

Prof. Witulski

Prof. Wang

Prof. Lubin

Theme: LuSTR 2020 Power Awardees

Speakers:

Art Witulski (Vanderbilt): “SiC Power Components for NASA Lunar Surface Applications”

Jin Wang (OSU): “Flexible DC Energy Router based on Energy Storage Integrated Circuit Breaker”

Phillip Lubin (UCSB): “Moonbeam-Beamed Lunar Power”

LSIC | Surface Power Reliability Workshop

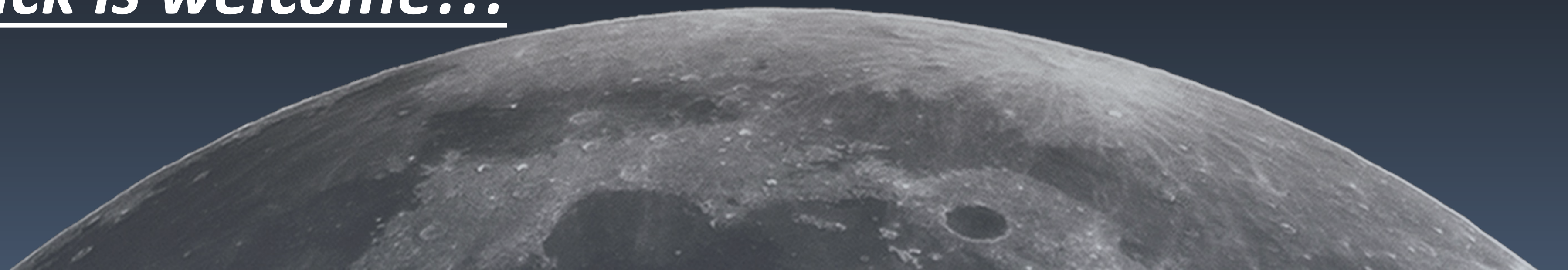
- July 26-27
    - 11:00AM – 3:30 PM ET

- What is Reliability?
    - Redundancy? Resiliency? Interoperability? Maintenance Free?

- How do we approach reliability from the system/grid level and how should this affect the early-TRL development at the component level?

- Bring in Different Perspectives
    - ESDMD, STMD, Industry, Terrestrial Grids, Microgrids, DoD, USN SUBSAFE, and you!

- ***Feedback is welcome!!!***



LSIC | Presentation

- Speaker: Akin Akturk, CoolCAD
  - Vice President

Radiation Response and Hardening of Silicon Carbide Power MOSFETs.

Akin Akturk

akin.akturk@coolcadelectronics.com

CoolCAD Electronics

- Electronics & Design Software for Niche Applications
- Founded in 2009 by Akin Akturk & Neil Goldsman
- Spinoff of Modeling and Design Group at the University of Maryland
  - (100+ years, 200+ publications, devices, circuits, chips, and software)
- Core Technologies:
  - **Modeling and design for new energy efficient SiC power electronics.**
  - **Power electronics.**
  - **Measurements, Models, Design, Software, Fabrication: Electronics in extreme environments.**
  - **UV optical detectors.**
- Member: UMD MTECH, PowerAmerica…..
- Work with ARL, DARPA, NASA, NAVY, …..

5000 College Avenue, Suite 2105,
College Park, MD 20740
https://coolcadelectronics.com/
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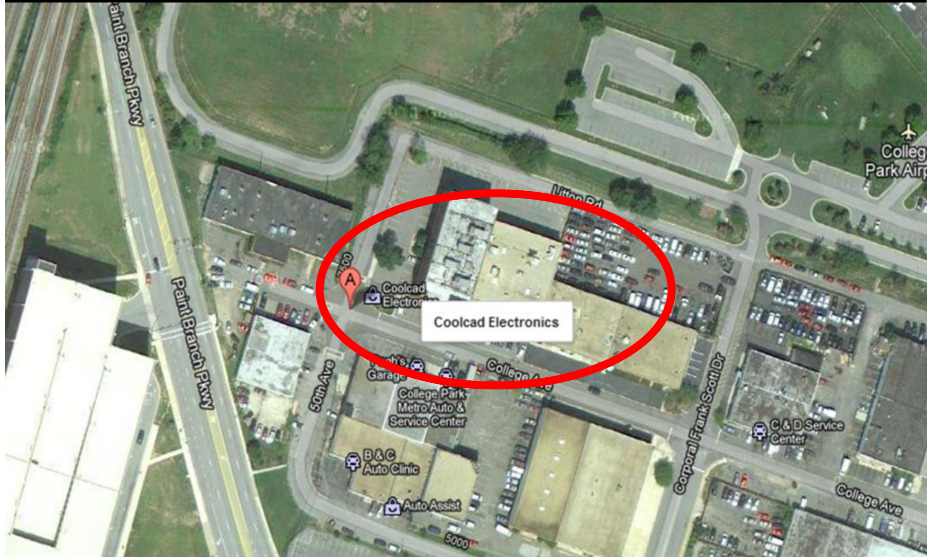
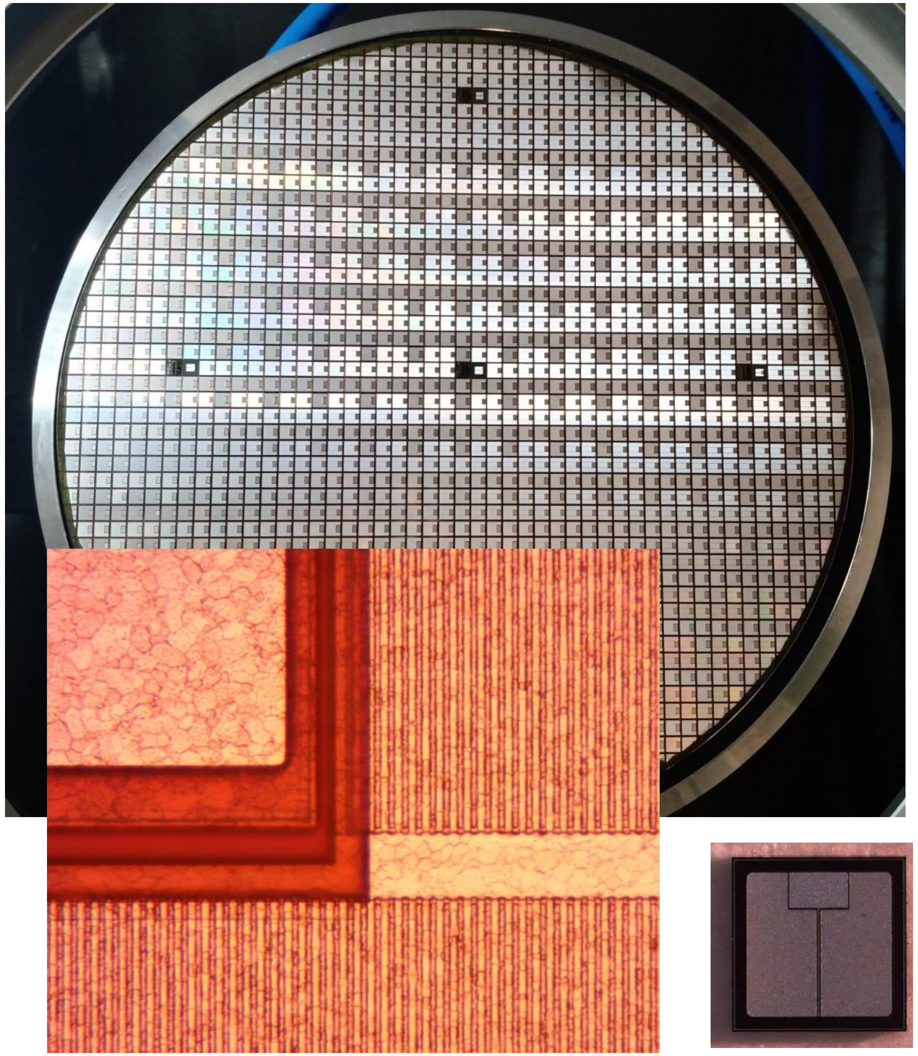
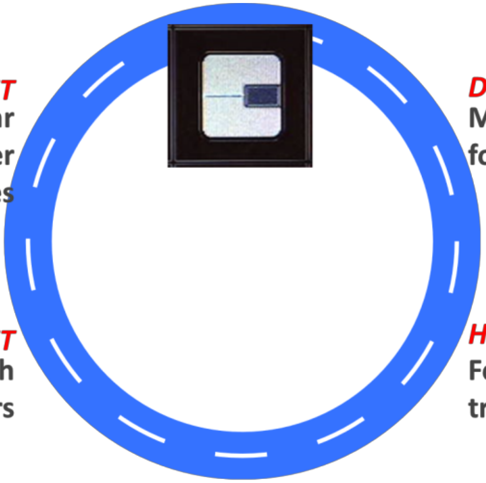
- **Manufactures SiC components**
- **Works with commercial foundries**
- **Runs a prototyping fab for SiC components**



akin.akturk@coolcadelectronics.com

Silicon Carbide Device Fabrication: 650V to 3300V





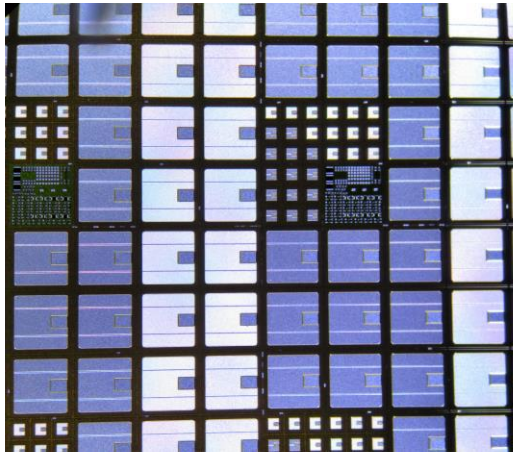
MOSFET
For efficient solar converters and power supplies

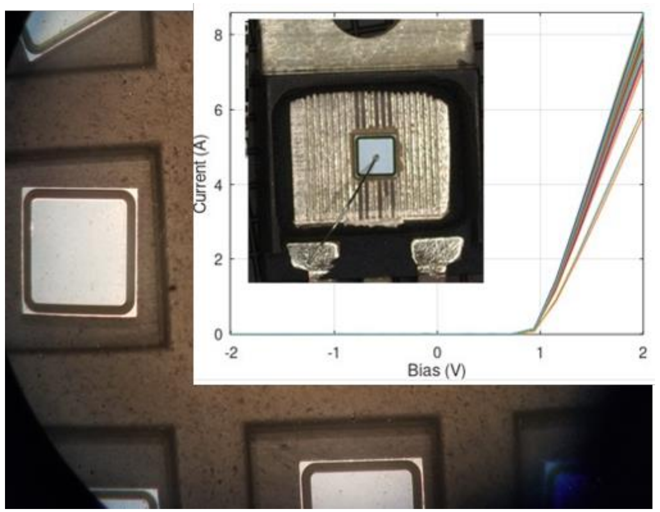
Diode
Minimal reverse recovery time for reduced power loss

LVFET
For on chip integration with controllers

HVFET
For high voltage systems and transmission line connectivity

Module





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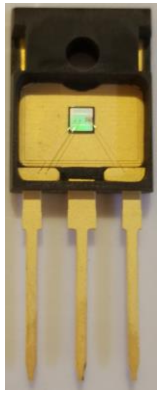
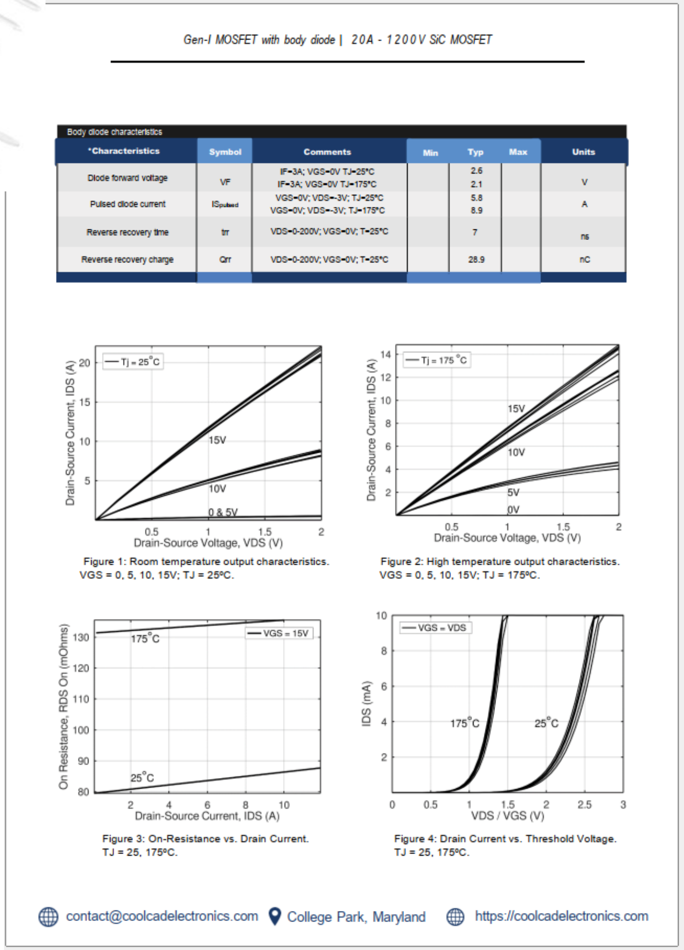
Silicon Carbide Power Device Design and Fabrication Activity





Gen-I MOSFET with body diode | 20A - 1200V SiC MOSFET

Body diode characteristics

*Characteristics	Symbol	Comments	Min	Typ	Max	Units
Diode forward voltage	VF	IF=3A; VGS=0V TJ=25°C IF=3A; VGS=0V TJ=175°C		2.6 2.1		V
Pulsed diode current	IS_{pulsed}	VGS=0V; VDS=-3V; TJ=25°C VGS=0V; VDS=-3V; TJ=175°C		5.8 8.9		A
Reverse recovery time	trr	VDS=0-200V; VGS=0V; T=25°C		7		ns
Reverse recovery charge	Qrr	VDS=0-200V; VGS=0V; T=25°C		28.9		nC

Figure 1: Room temperature output characteristics. VGS = 0, 5, 10, 15V; TJ = 25ºC.

Figure 2: High temperature output characteristics. VGS = 0, 5, 10, 15V; TJ = 175ºC.

Figure 3: On-Resistance vs. Drain Current. TJ = 25, 175ºC.

Figure 4: Drain Current vs. Threshold Voltage. TJ = 25, 175ºC.

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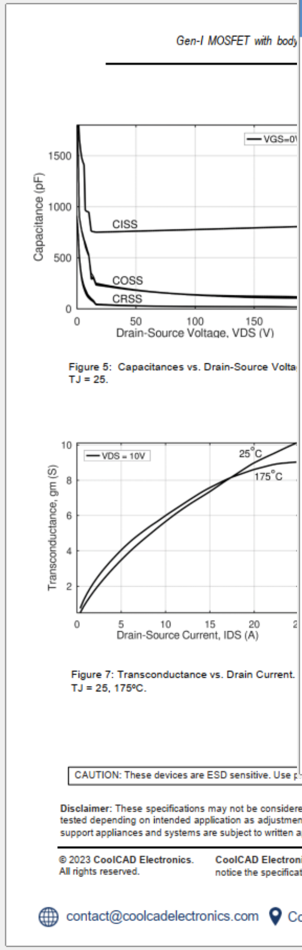

Gen-I MOSFET with body

Figure 5: Capacitances vs. Drain-Source Volta
TJ = 25.

Figure 7: Transconductance vs. Drain Current. TJ = 25, 175ºC.

CAUTION: These devices are ESD sensitive. Use p

Disclaimer: These specifications may not be considered as a guarantee of components characteristics. Components have to be tested depending on intended application as adjustments may be necessary. The use of CoolCAD Electronics components in life support appliances and systems are subject to written approval of CoolCAD Electronics.

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Page 4 of 4. Revision 1 Feb-07

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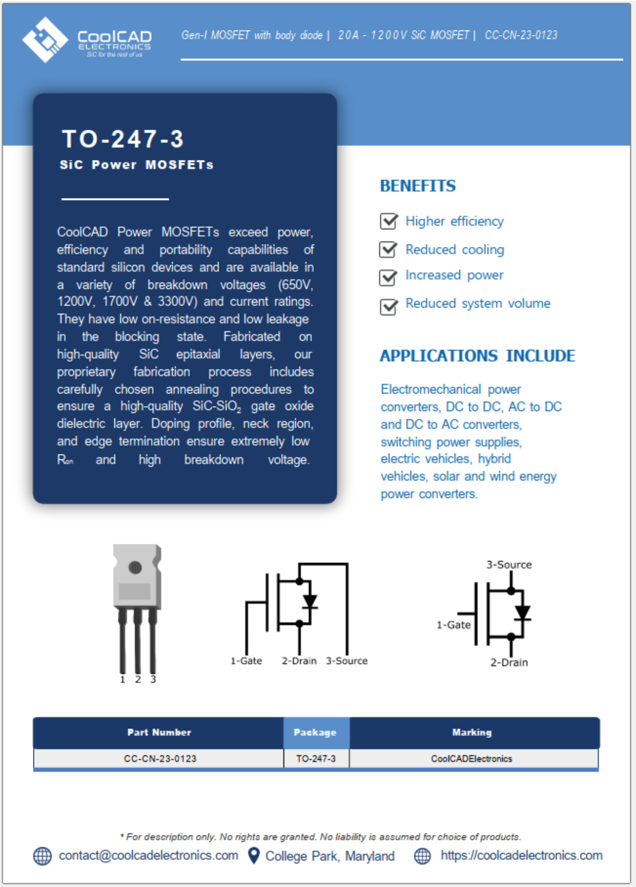

CoolCAD ELECTRONICS SiC for the rest of us

Gen-I MOSFET with body diode | 20A - 1200V SiC MOSFET | CC-CN-23-0123

TO-247-3

SiC Power MOSFETs

CoolCAD Power MOSFETs exceed power, efficiency and portability capabilities of standard silicon devices and are available in a variety of breakdown voltages (650V, 1200V, 1700V & 3300V) and current ratings. They have low on-resistance and low leakage in the blocking state. Fabricated on high-quality SiC epitaxial layers, our proprietary fabrication process includes carefully chosen annealing procedures to ensure a high-quality SiC-SiO$_2$ gate oxide dielectric layer. Doping profile, neck region, and edge termination ensure extremely low R$_{on}$ and high breakdown voltage.

BENEFITS

- ☑ Higher efficiency
- ☑ Reduced cooling
- ☑ Increased power
- ☑ Reduced system volume

APPLICATIONS INCLUDE

Electromechanical power converters, DC to DC, AC to DC and DC to AC converters, switching power supplies, electric vehicles, hybrid vehicles, solar and wind energy power converters.

Part Number	Package	Marking
CC-CN-23-0123	TO-247-3	CoolCADElectronics

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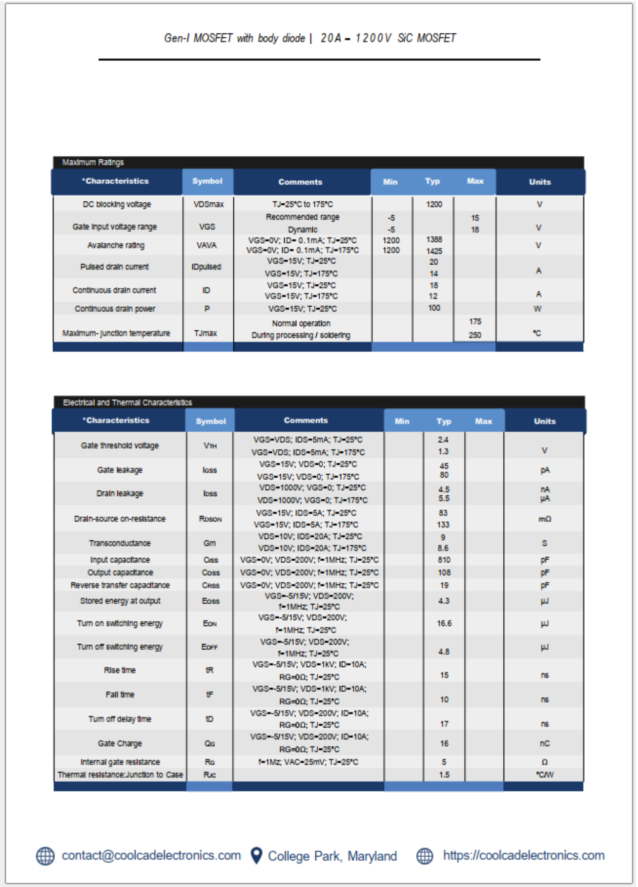

Gen-I MOSFET with body diode | 20A - 1200V SiC MOSFET

Maximum Ratings

*Characteristics	Symbol	Comments	Min	Typ	Max	Units
DC blocking voltage	VDSmax	TJ=25°C to 175°C		1200		V
Gate input voltage range	VGS	Recommended range Dynamic	-5 -5		15 18	V
Avalanche rating	VAVA	VGS=0V; ID= 0.1mA; TJ=25°C VGS=0V; ID= 0.1mA; TJ=175°C	1200 1200	1388 1425		V
Pulsed drain current	IDpulsed	VGS=15V; TJ=25°C VGS=15V; TJ=175°C		20 14		A
Continuous drain current	ID	VGS=15V; TJ=25°C VGS=15V; TJ=175°C		18 12		A
Continuous drain power	P	VGS=15V; TJ=25°C		100		W
Maximum- junction temperature	TJmax	Normal operation During processing / soldering			175 250	°C

Electrical and Thermal Characteristics

*Characteristics	Symbol	Comments	Min	Typ	Max	Units
Gate threshold voltage	V_{TH}	VGS=VDS; IDS=5mA; TJ=25°C VGS=VDS; IDS=5mA; TJ=175°C		2.4 1.3		V
Gate leakage	I_{GSS}	VGS=15V; VDS=0; TJ=25°C VGS=15V; VDS=0; TJ=175°C		45 80		pA
Drain leakage	I_{DSS}	VDS=1000V; VGS=0; TJ=25°C VDS=1000V; VGS=0; TJ=175°C		4.5 5.5		nA µA
Drain-source on-resistance	R_{DSON}	VGS=15V; IDS=5A; TJ=25°C VGS=15V; IDS=5A; TJ=175°C		83 133		mΩ
Transconductance	Gm	VDS=10V; IDS=20A; TJ=25°C VDS=10V; IDS=20A; TJ=175°C		9 8.6		S
Input capacitance	C_{ISS}	VGS=0V; VDS=200V; f=1MHz; TJ=25°C		810		pF
Output capacitance	C_{OSS}	VGS=0V; VDS=200V; f=1MHz; TJ=25°C		108		pF
Reverse transfer capacitance	C_{RSS}	VGS=0V; VDS=200V; f=1MHz; TJ=25°C		19		pF
Stored energy at output	E_{OSS}	VGS=-5/15V; VDS=200V; f=1MHz; TJ=25°C		4.3		µJ
Turn on switching energy	E_{ON}	VGS=-5/15V; VDS=200V; f=1MHz; TJ=25°C		16.6		µJ
Turn off switching energy	E_{OFF}	VGS=-5/15V; VDS=200V; f=1MHz; TJ=25°C		4.8		µJ
Rise time	tR	VGS=-5/15V; VDS=1KV; ID=10A; RG=0Ω; TJ=25°C		15		ns
Fall time	tF	VGS=-5/15V; VDS=1KV; ID=10A; RG=0Ω; TJ=25°C		10		ns
Turn off delay time	tD	VGS=-5/15V; VDS=200V; ID=10A; RG=0Ω; TJ=25°C		17		ns
Gate Charge	Q_G	VGS=-5/15V; VDS=200V; ID=10A; RG=0Ω; TJ=25°C		16		nC
Internal gate resistance	R_G	f=1Mz; VAC=25mV; TJ=25°C		5		Ω
Thermal resistance:Junction to Case	R_{JC}			1.5		°C/W

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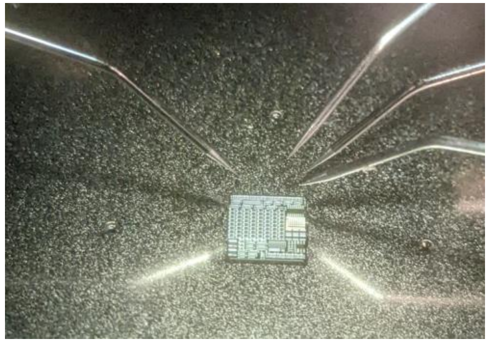
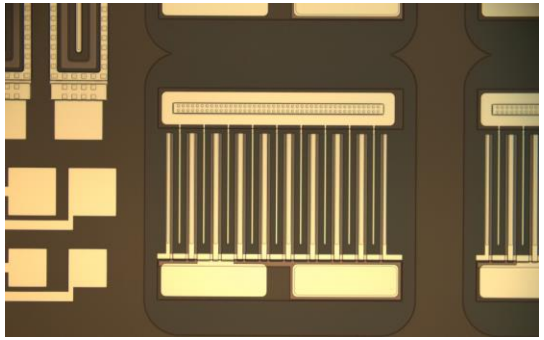
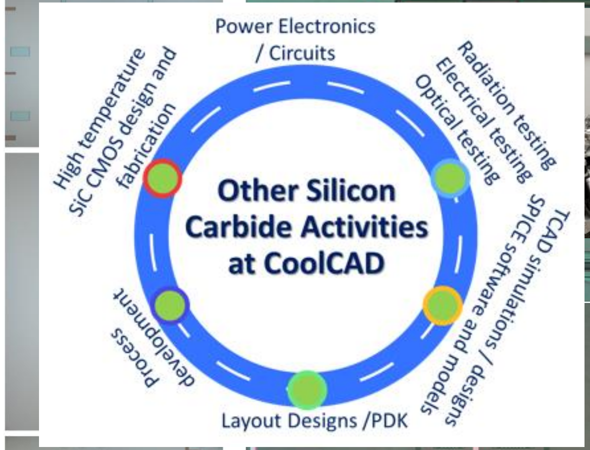
Silicon Carbide Fabrication and Process Development: CMOS (nMOS and pMOS), diode, JFET, etc.

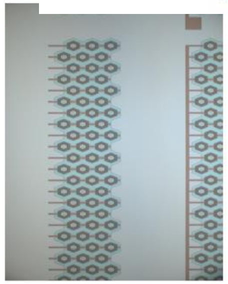


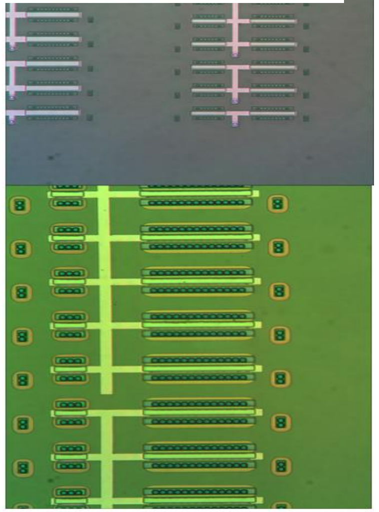


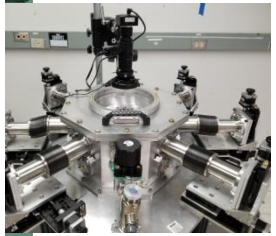
High temperature SiC CMOS

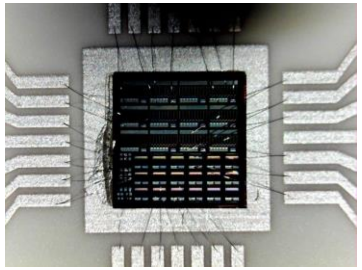


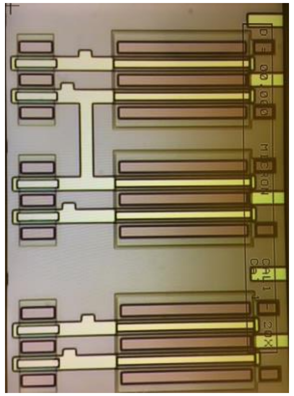
Other Silicon Carbide Activities at CoolCAD











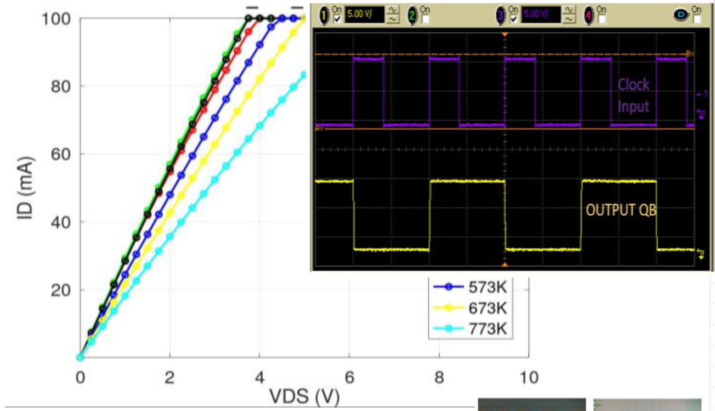
SiC Processing:

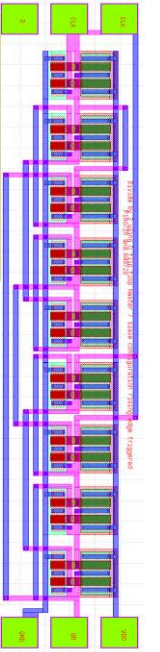
Thermal Oxidation

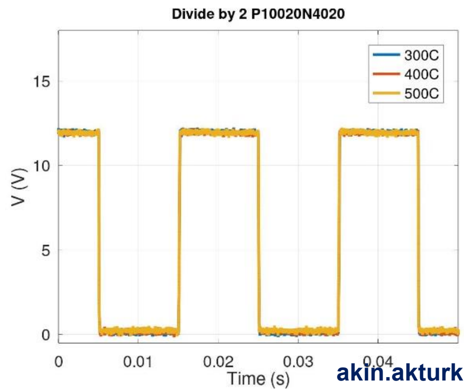
Ion Activation

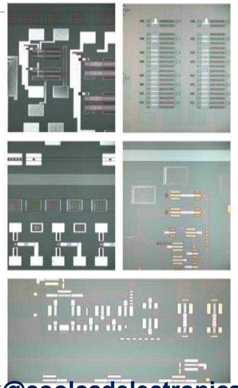
Rapid Thermal Annealing

Metal Contact Silicide



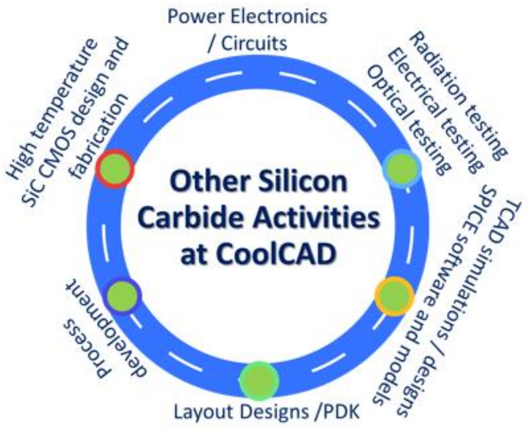






akin.akturk@coolcadelectronics.com

Power Electronics



Other Silicon Carbide Activities at CoolCAD

Power Electronics / Circuits

Radiation testing

Electrical testing

Optical testing

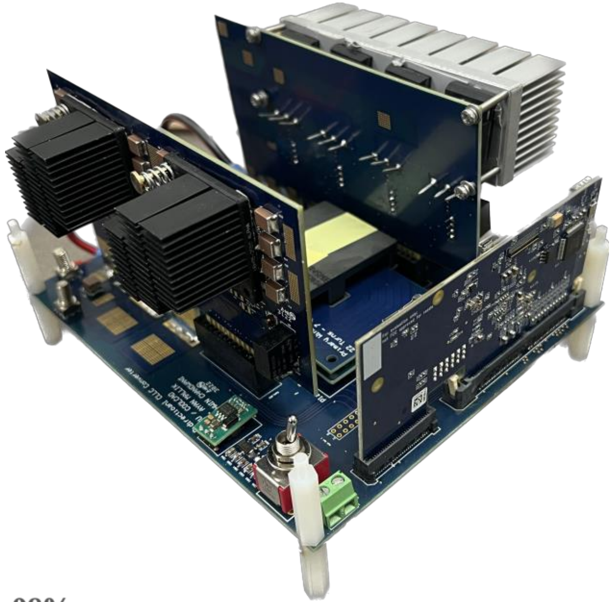
TCAD simulations / designs

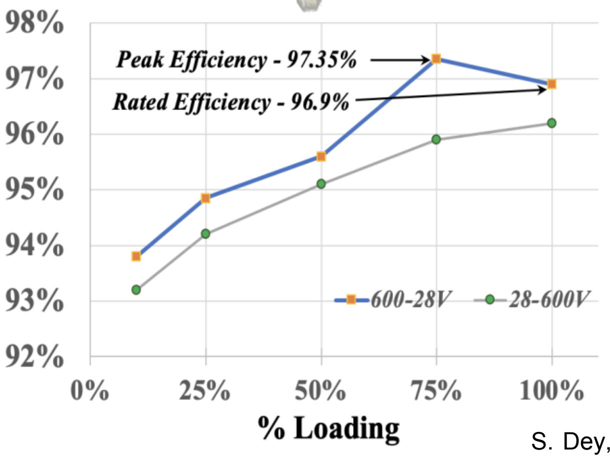
SPICE softwares and models

Layout Designs /PDK

Process development

High temperature SiC CMOS design and fabrication





- Leakage integrated High Frequency Planar Transformer (HFPT) is designed and implemented with optimized winding configuration to ensure reduced winding losses, enabling a power dense yet efficient magnetic solution.

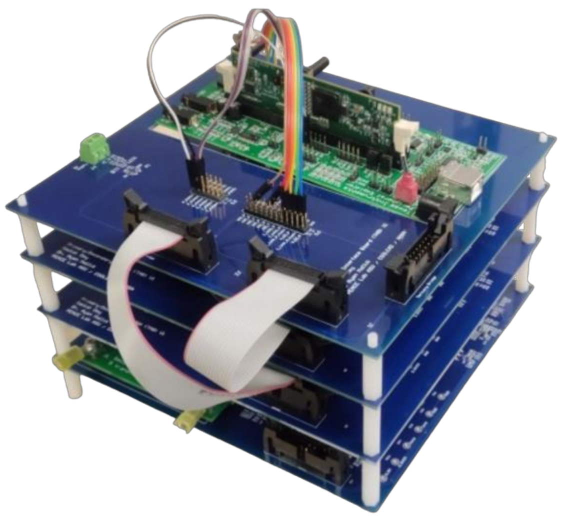
- Zero Voltage Switching (ZVS) based turn on is obtained for the primary side switches during forward power flow, as well as ZVS based turn on is obtained for the primary and secondary side switches during reverse power flow, for a wide gain and load range for efficient power conversion.

- Synchronous Rectification (SR) based switching is achieved for the secondary side during forward power flow to ensure significantly reduced turn-off losses.

- Peak efficiency is measured at 97.35% for forward power flow and 95.93% for reverse power flow operation.

- Conducted EMI compliance is met according to MIL-STD-461G for both forward and reverse power flow.

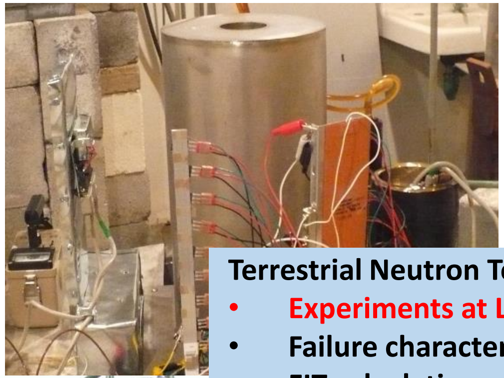
- Terminal voltage ripple and overshoot/undershoot are designed and measured to comply with MIL – PRF – GCS600A (for 600V) and MIL – STD – 1275D (for 28V).

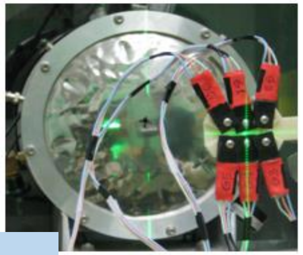


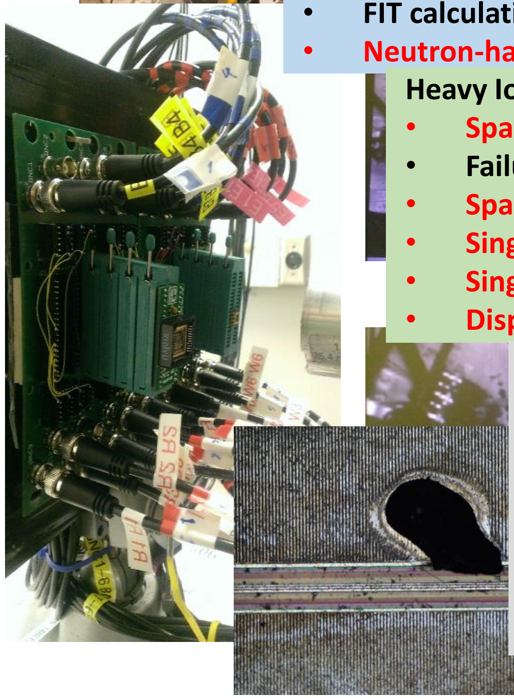
S. Dey, A. Mallik, **A. Akturk**, "Investigation of ZVS criteria and Optimization of Switching Loss in a Triple Active Bridge Converter using Penta-Phase-Shift Modulation," IEEE Journal of Emerging and Selected Topics in Power Electronics, 10(6) 7014-7028, 2022.

akin.akturk@coolcadelectronics.com

Radiation Services: Testing, modeling, failure analysis







Terrestrial Neutron Tests

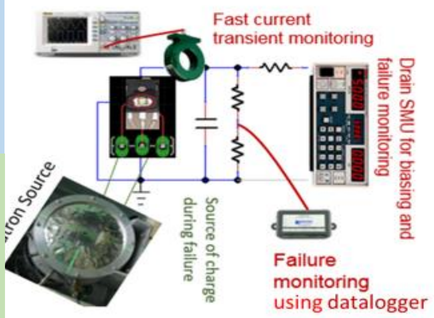
- Experiments at Los Alamos Neutron Science Center
- Failure characterization
- FIT calculations
- Neutron-hard device and circuit design

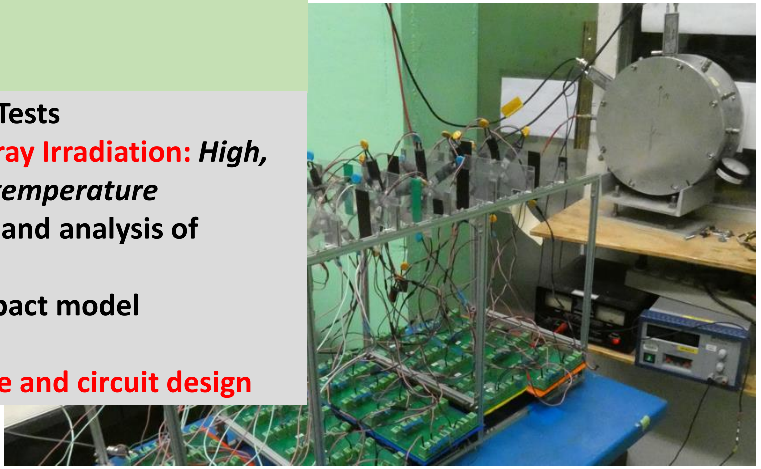
Heavy Ion and Proton Tests

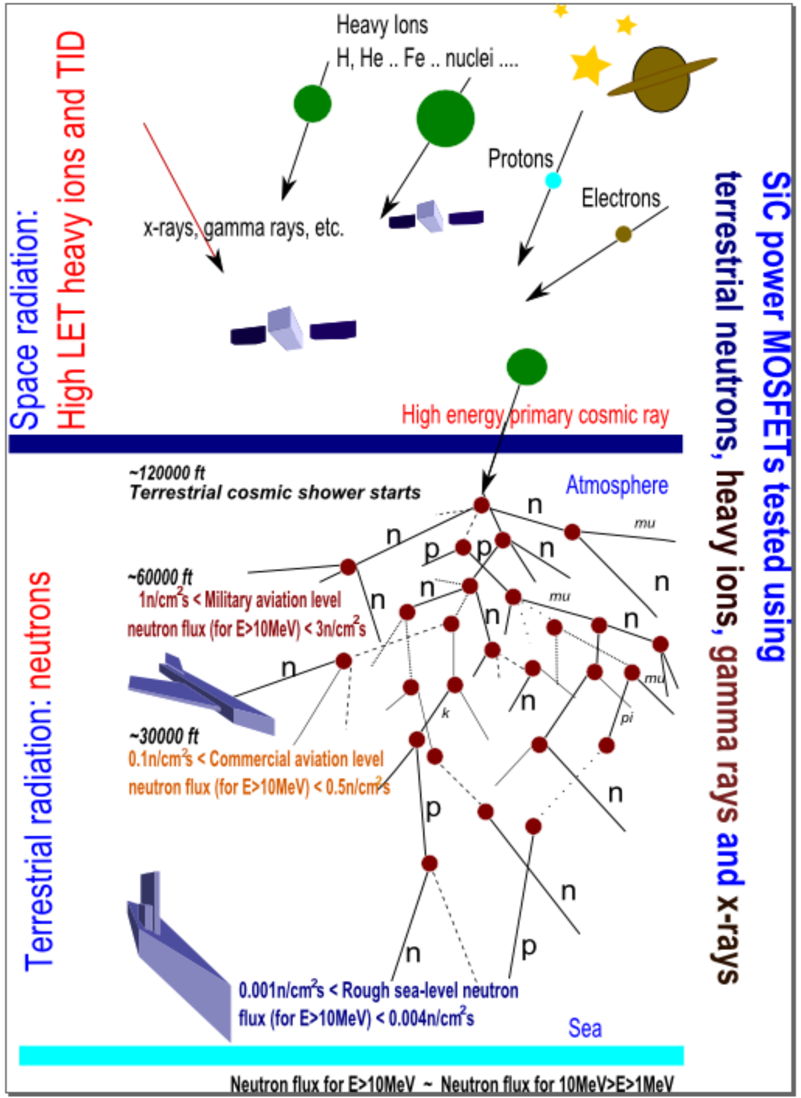
- Space radiation hardness characterization
- Failure analysis
- Space-hard device and circuit design
- Single event effects
- Single event transients
- Displacement damage

Total Ionizing Dose Tests

- Gamma and X-ray Irradiation: *High, low and room temperature*
- Understanding and analysis of measured data
- TCAD and compact model development
- Rad-hard device and circuit design







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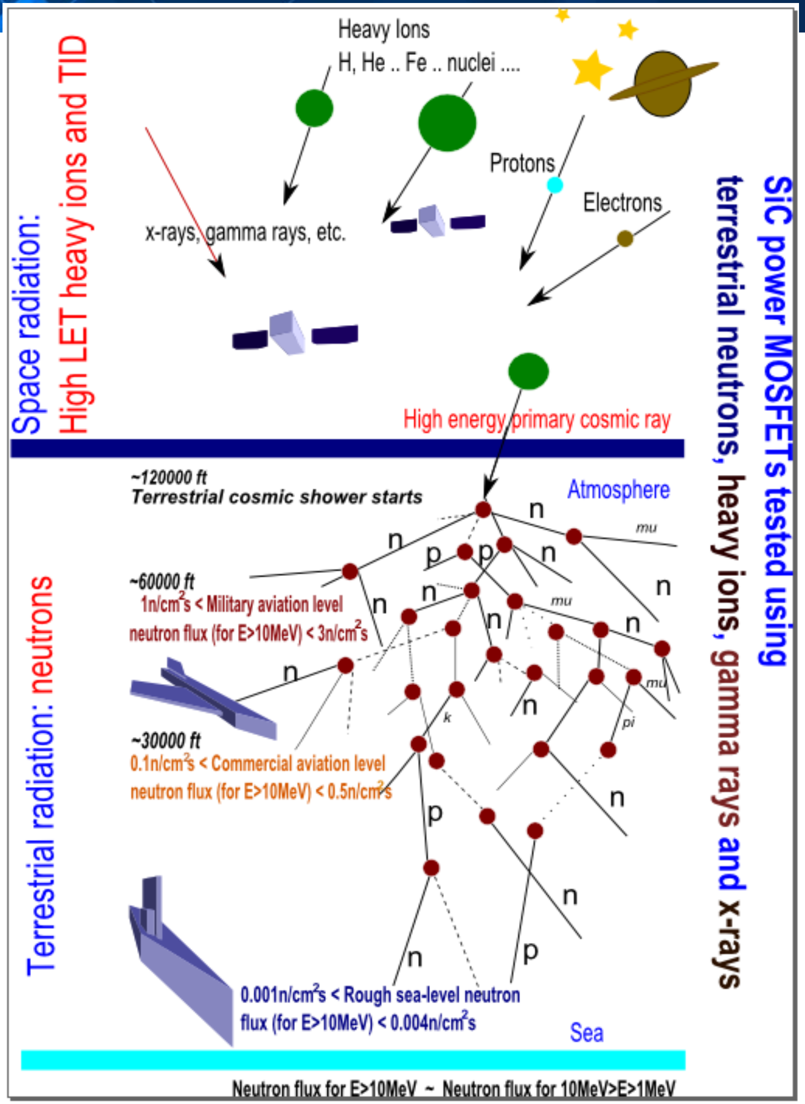
Terrestrial Radiation



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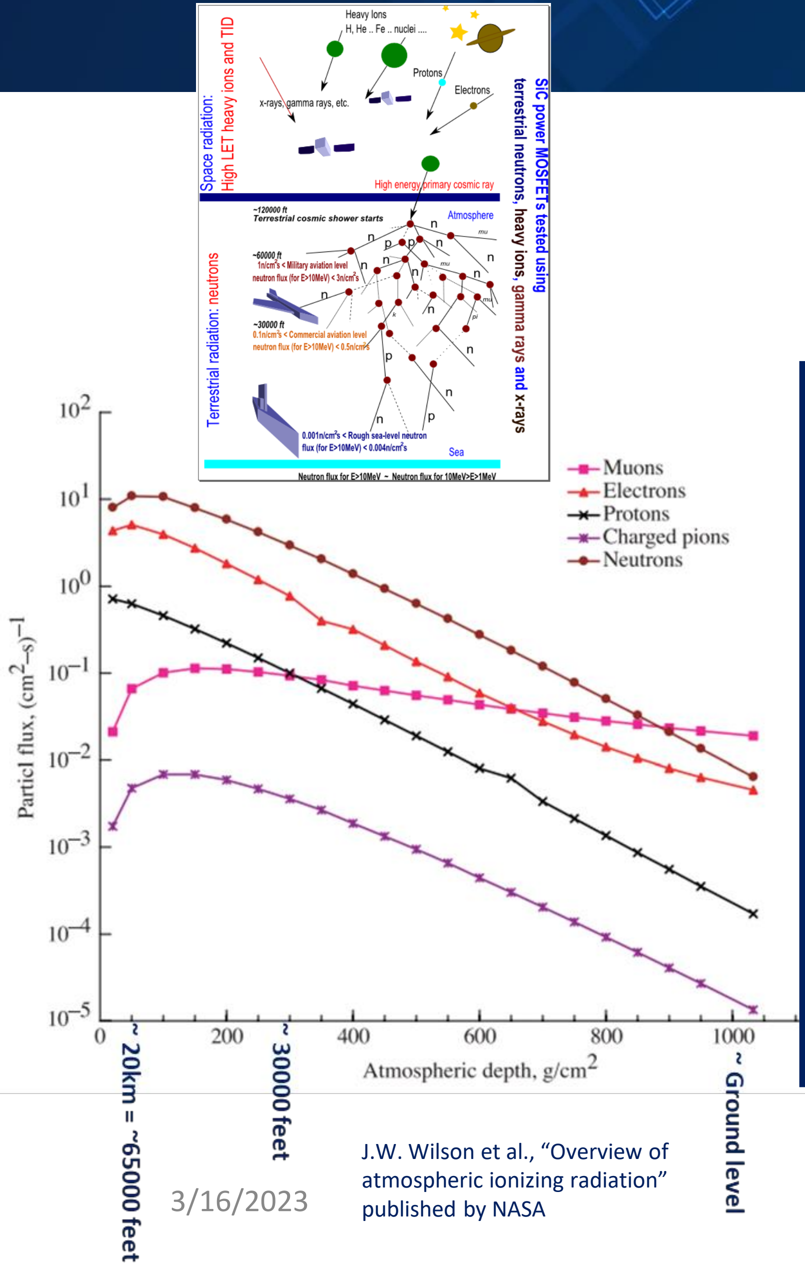
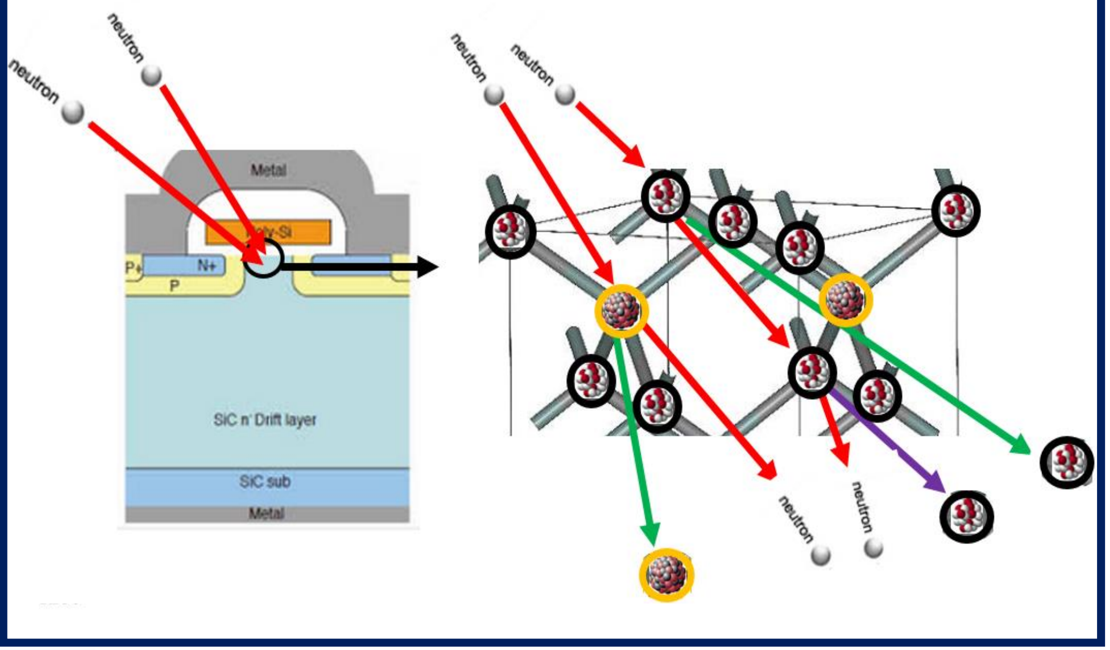
Power Device Failures due to Atmospheric Neutrons

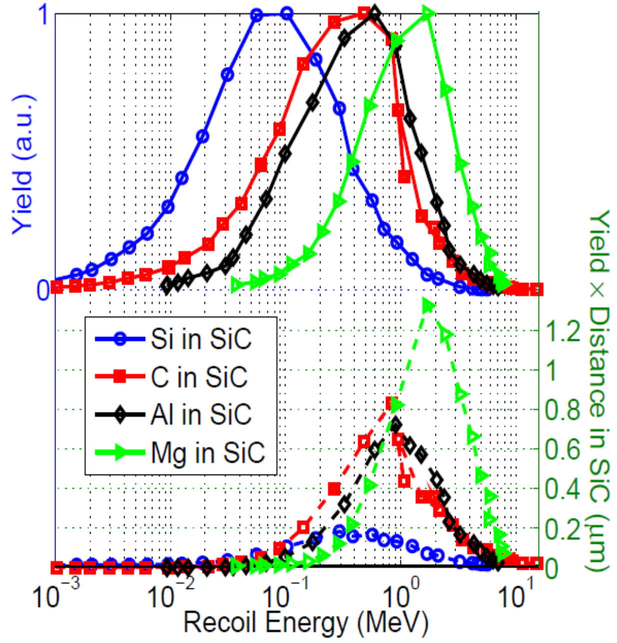


J.W. Wilson et al., “Overview of atmospheric ionizing radiation” published by NASA

Concern: Terrestrial neutrons are relatively abundant, can have high energies and interact with lattice atoms.

Power Device Failures due to Terrestrial Neutrons

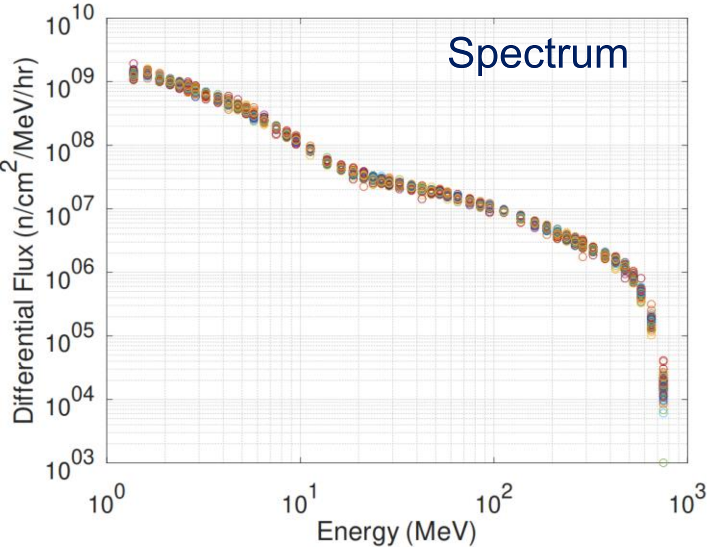


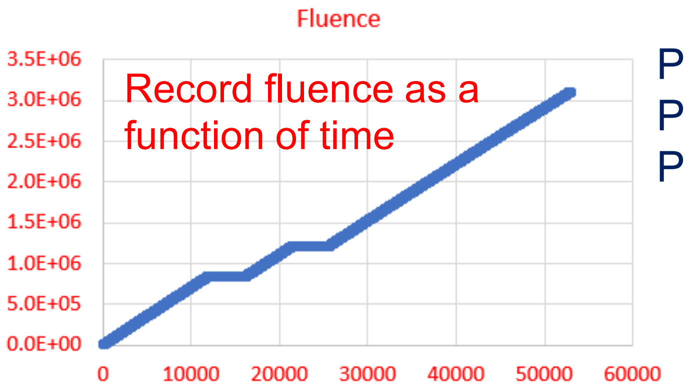


A. Akturk, J. McGarrity, N. Goldsman, D. Lichtenwalner, B. Hull, D. Grider, R. Wilkins, “Terrestrial neutron-induced failures in silicon carbide power MOSFETs and diodes,” *IEEE Transactions on Nuclear Science* **65(6)**, 1248-1254 (2018).

akin.akturk@coolcadelectronics.com

Terrestrial Neutron Experiments



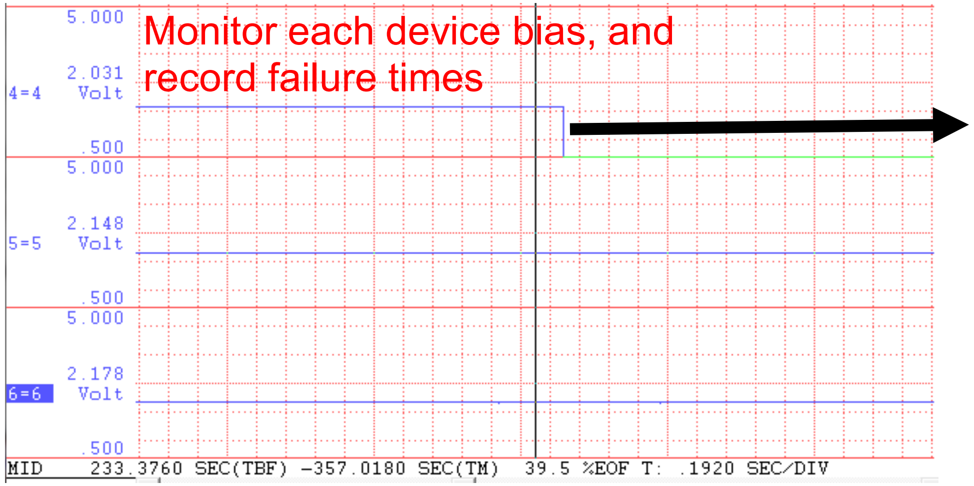


Record fluence as a function of time

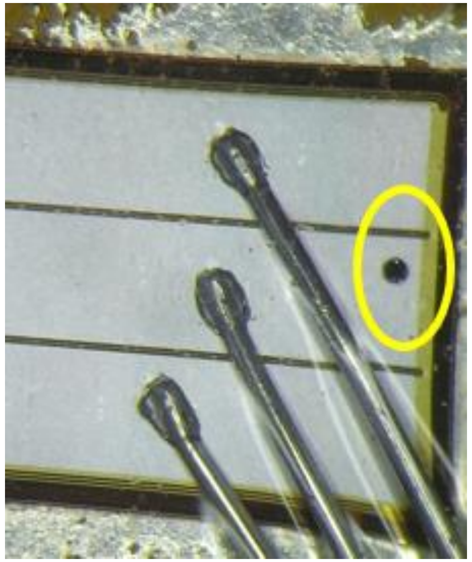
Post Exp: Calculate and plot FIT curves

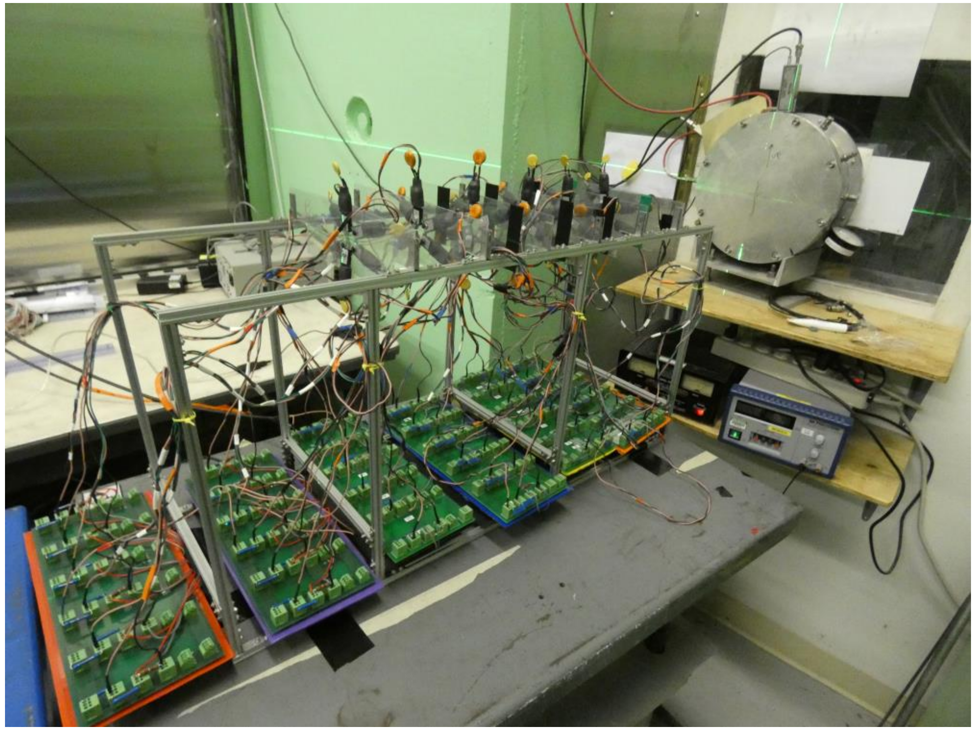
Post Exp: Post-electrical characterization of survived parts

Post Exp: Post failure analysis

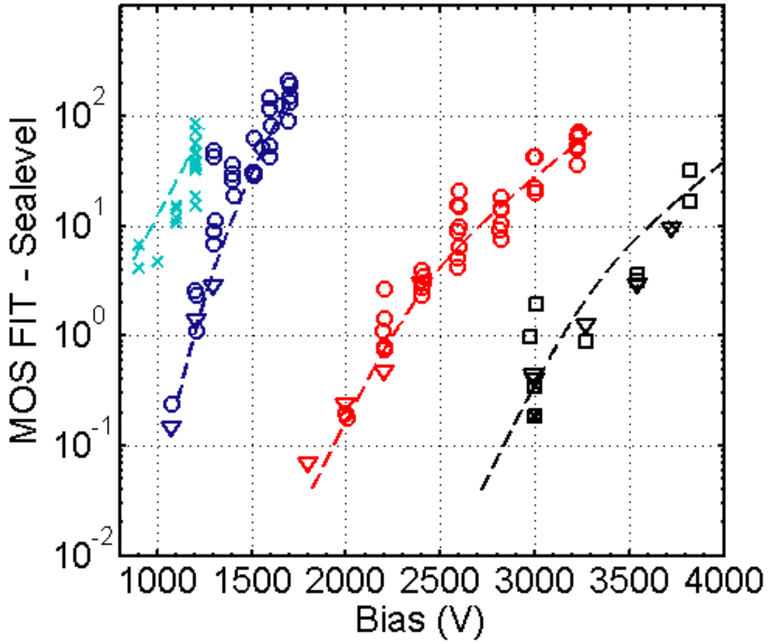


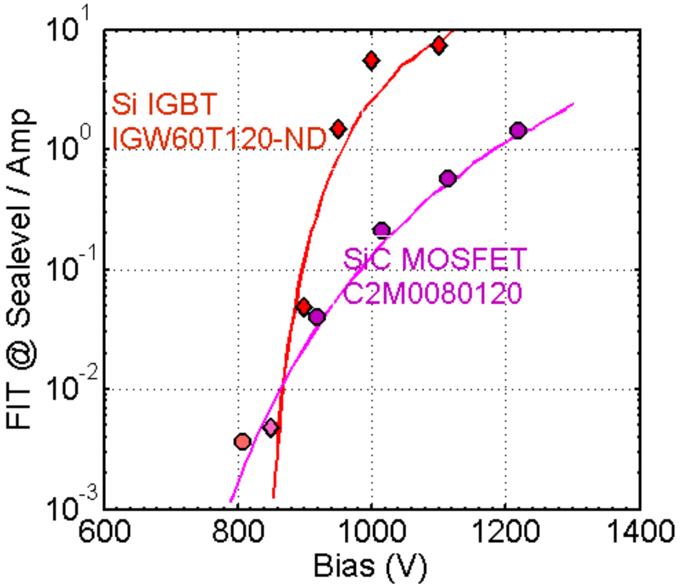
Monitor each device bias, and record failure times

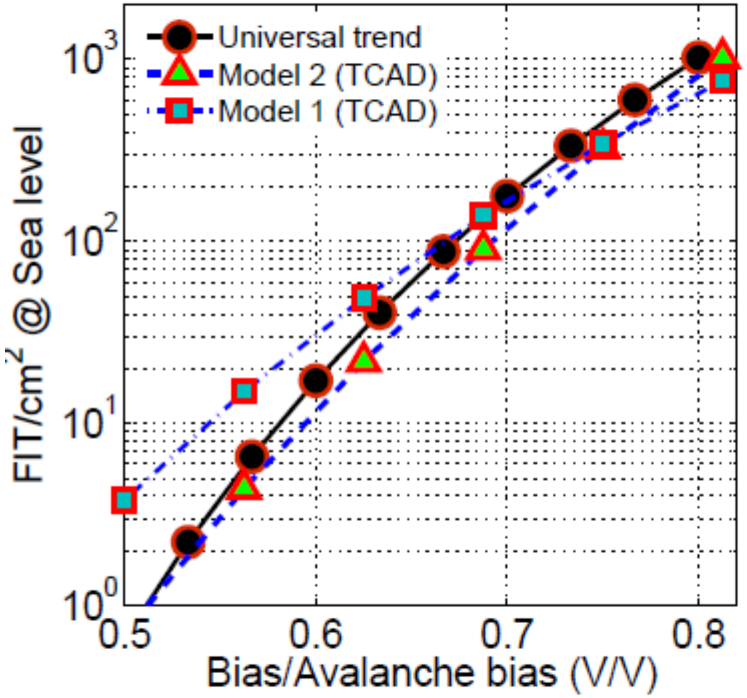




Failure In Time Curves of SiC Devices







SiC power MOSFET sea-level FIT curves for 1.2 (light blue), 1.7 (blue), 3.3 (red) and 6.5 (black) kV rated MOSFETs.

A. Akturk, R. Wilkins, J. McGarrity, B. Gersey, "Single event effects in Si and SiC Power MOSFETs due to terrestrial neutrons," *IEEE Transactions on Nuclear Science* **64(1)**, 529-535 (2017).

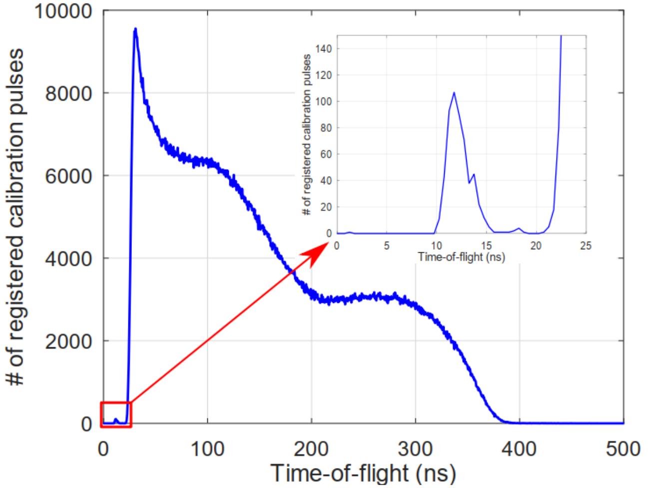
A. Akturk, J. McGarrity, N. Goldsman, D. Lichtenwalner, B. Hull, D. Grider, R. Wilkins, "Predicting cosmic ray-induced failures in silicon carbide power devices," IEEE Transactions on Nuclear Science 66(7), 1828-1832 (2019).

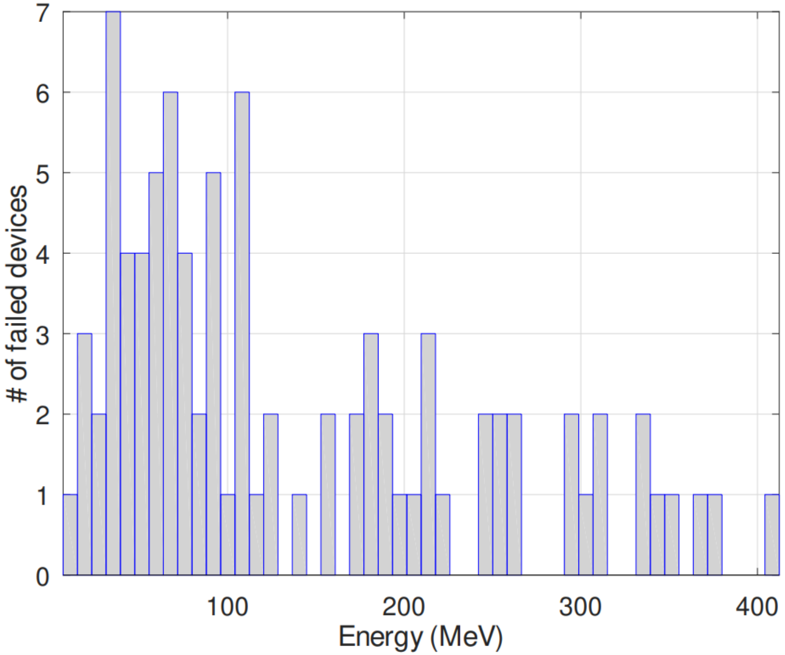
A. Akturk, J. McGarrity, N. Goldsman, D. Lichtenwalner, B. Hull, D. Grider, R. Wilkins, "Terrestrial neutron-induced failures in silicon carbide power MOSFETs and diodes," IEEE Transactions on Nuclear Science 65(6), 1248-1254 (2018).

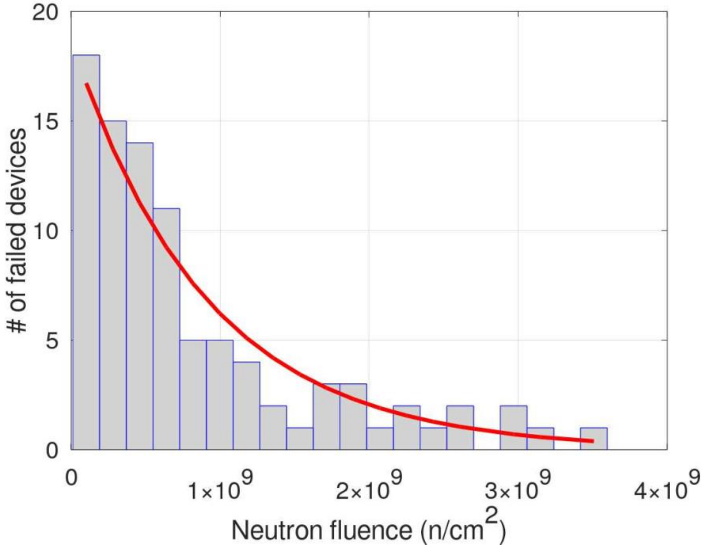
FIT : Failure in one billion device hours

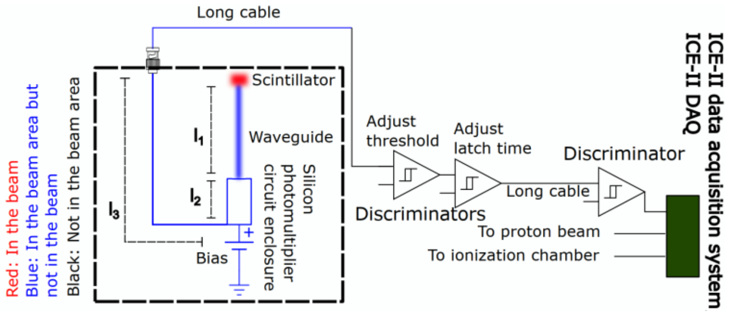
akin.akturk@coolcadelectronics.com

Time of flight measurements

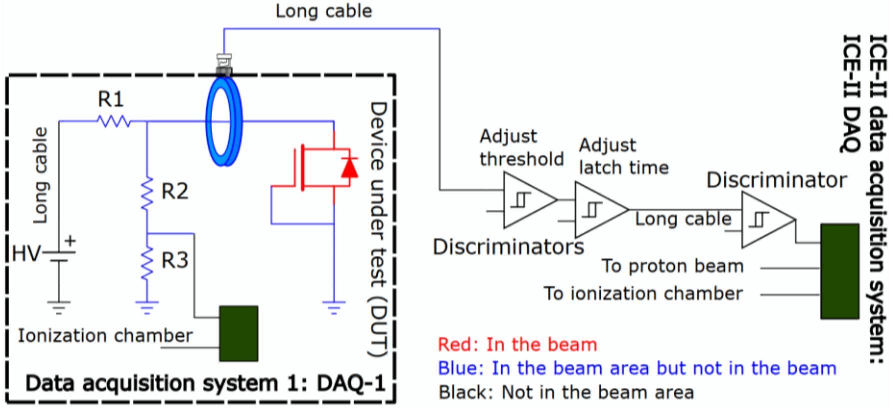


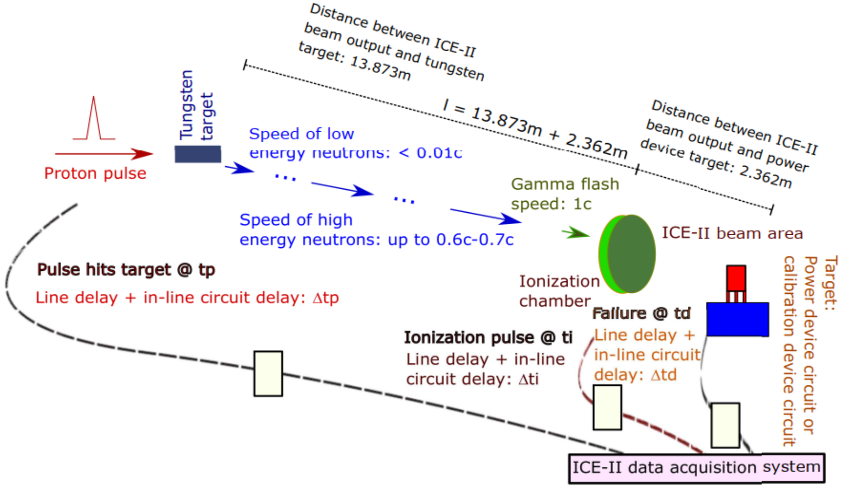






A. Akturk, R. Wilkins, K. Gunthoti, S. A. Wender, N. Goldsman, "Energy Dependence of Atmospheric Neutron-Induced Failures in Silicon Carbide Power Devices," IEEE Transactions on Nuclear Science 69(4), 900-907 (2022).



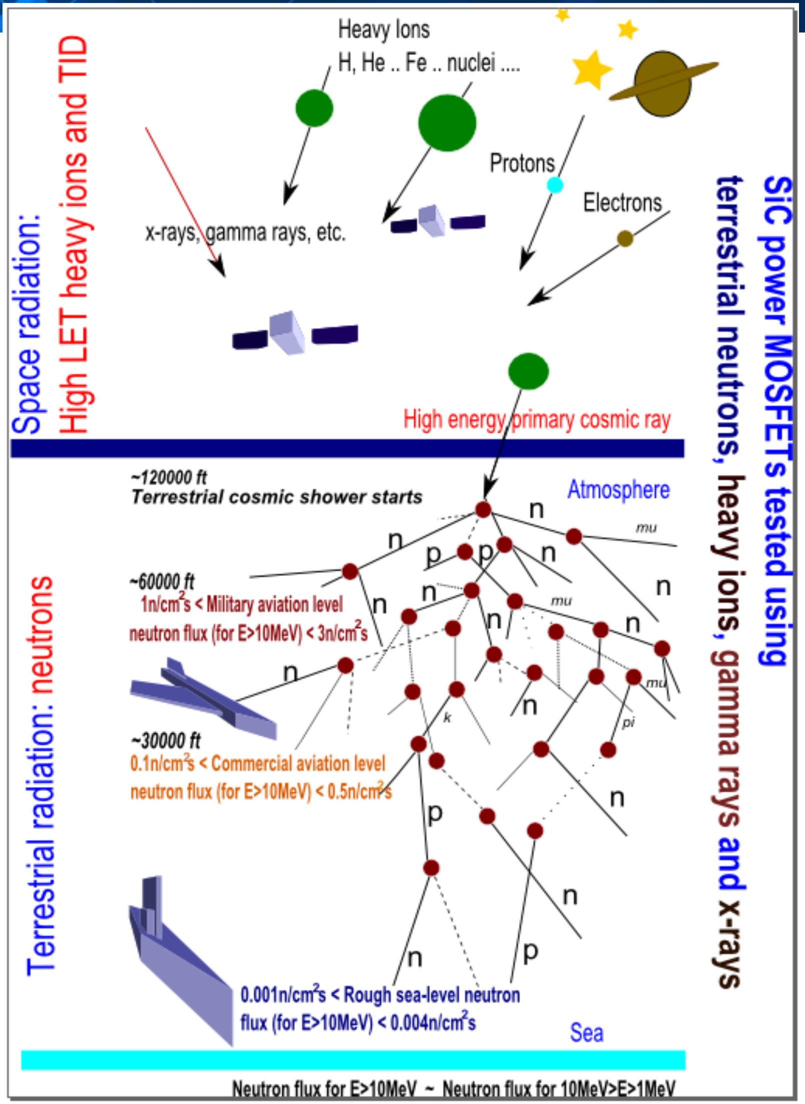


Space Radiation

Total ionizing dose

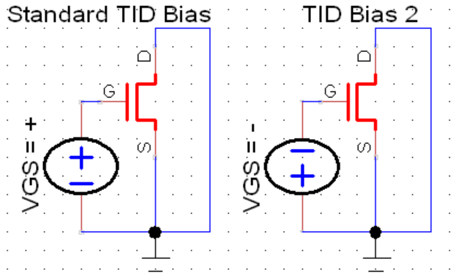
Single event effects

Displacement damage



akin.akturk@coolcadelectronics.com

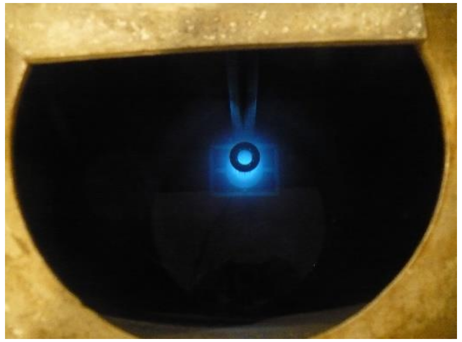
Total Ionizing Dose

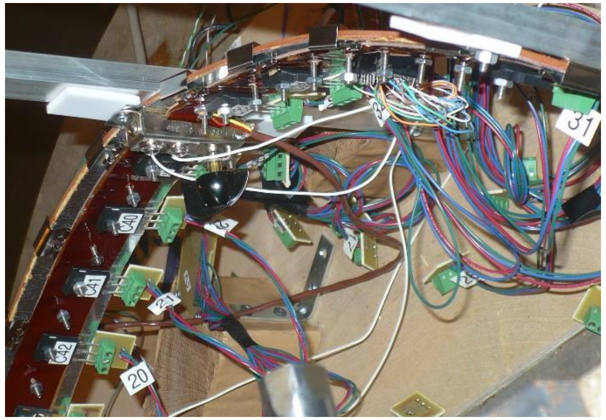


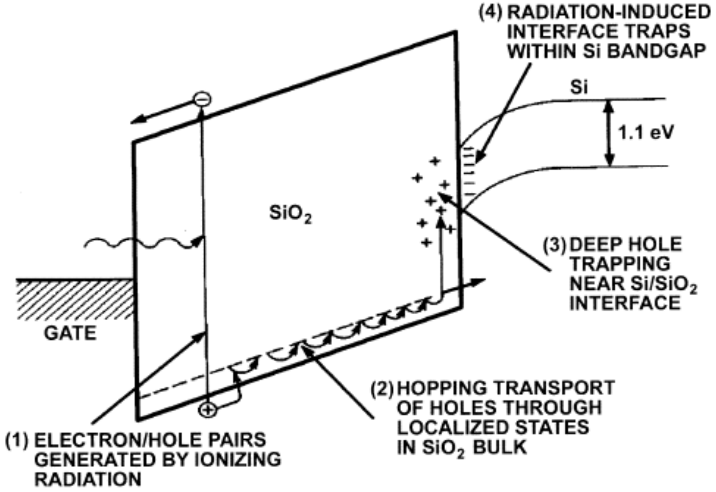
1- Positive charging of the oxide due to ionizing dose radiation (gamma, x-ray, e-beam etc.)

2- Increases in interface state densities over time

Most commonly used source for TID testing is Co60



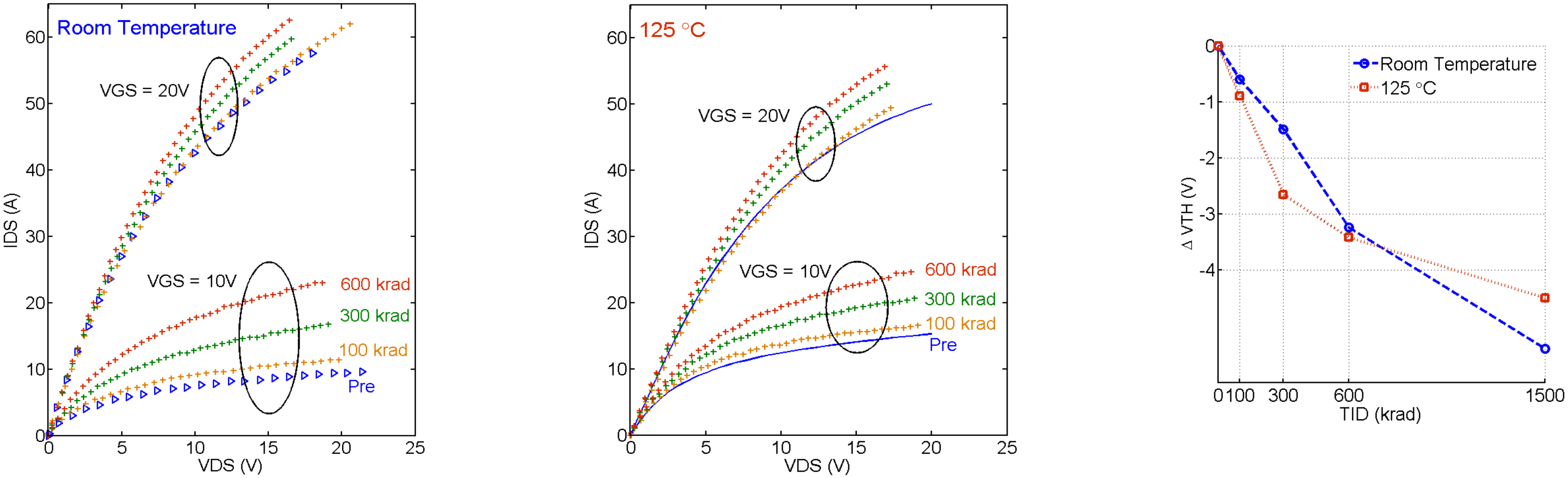




T. R. Oldham and F. B. McLean, IEEE TNS, 50(3,3), 483-499, (2003)

We are experts in pursuing TID experiments to measure bulk trap densities.

Response of Earlier Generation MOSFETs



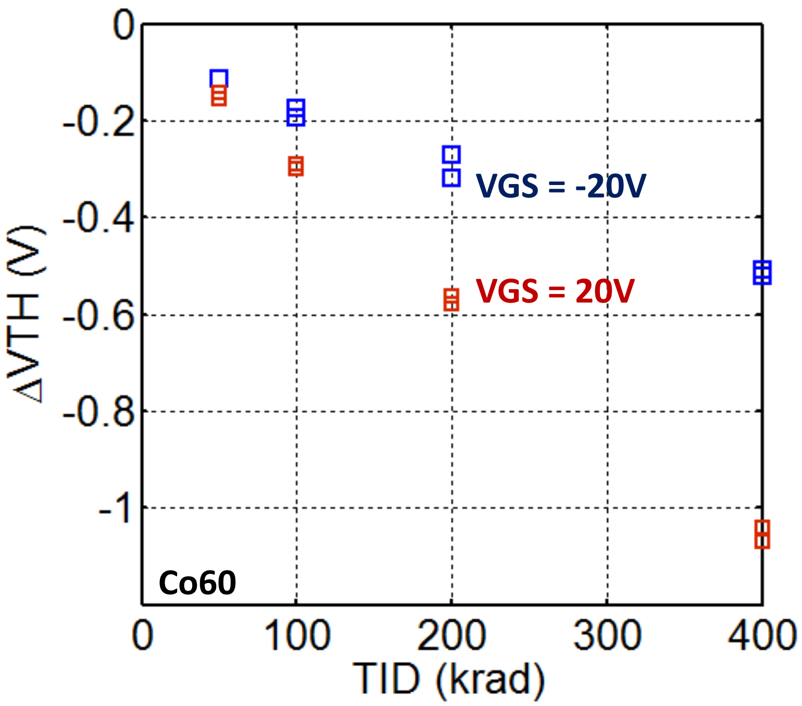
$\Delta VTH = -3.8\times10^{-8}\times D$ (rads)$\times Tox^2$ (nm^2) *if all holes trap at the interface and all electrons are swept out*

<5 % hole trapping

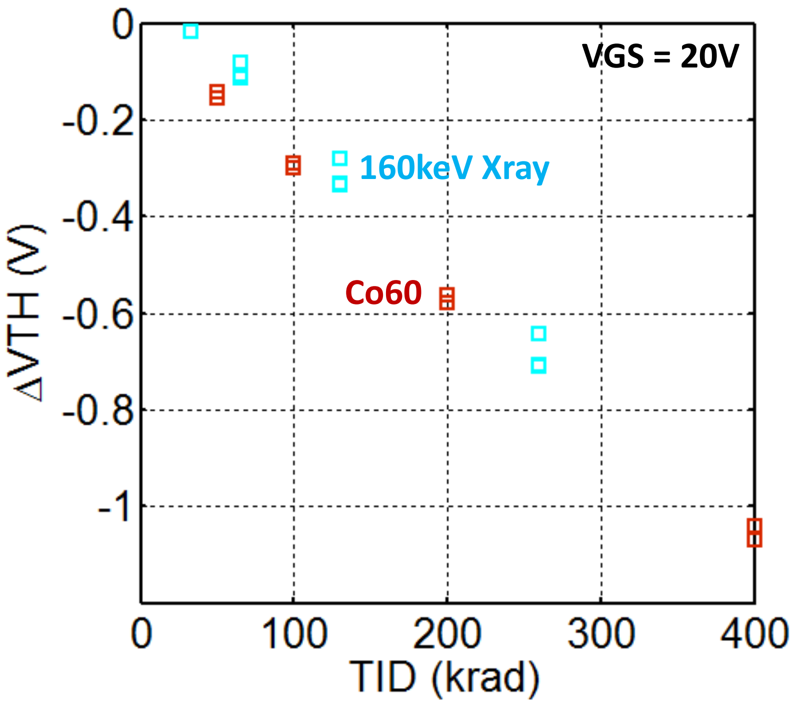
Excellent result for an unhardened thick oxide

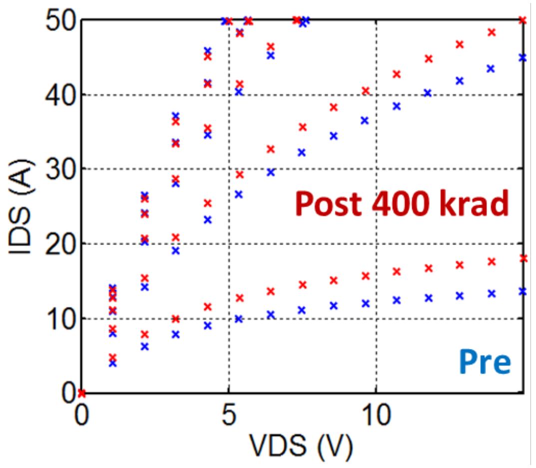
akin.akturk@coolcadelectronics.com

Response of Later Generation MOSFETs



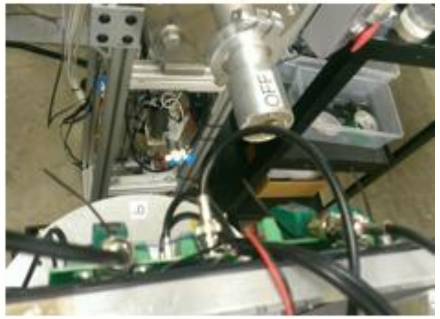
Gen3

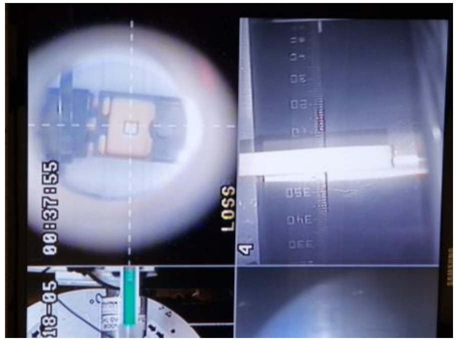


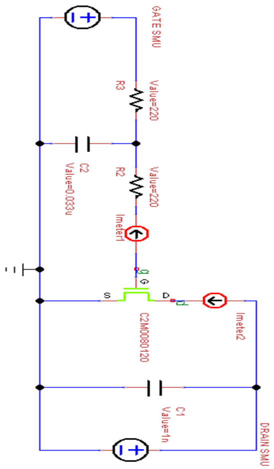


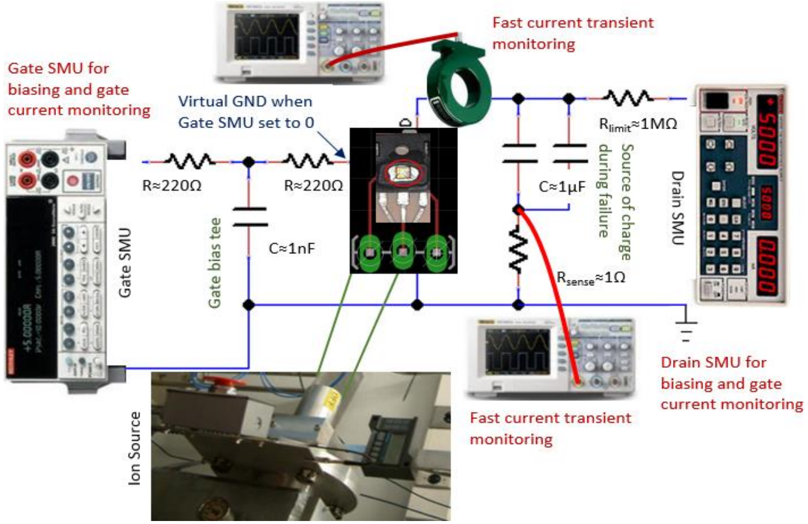
akin.akturk@coolcadelectronics.com

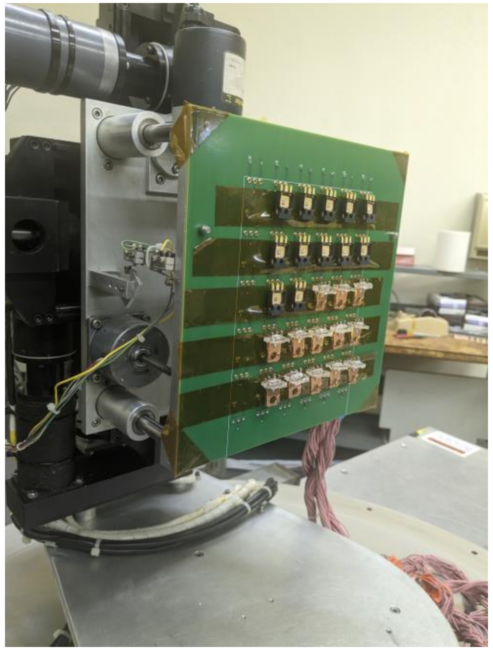
Heavy Ion Tests

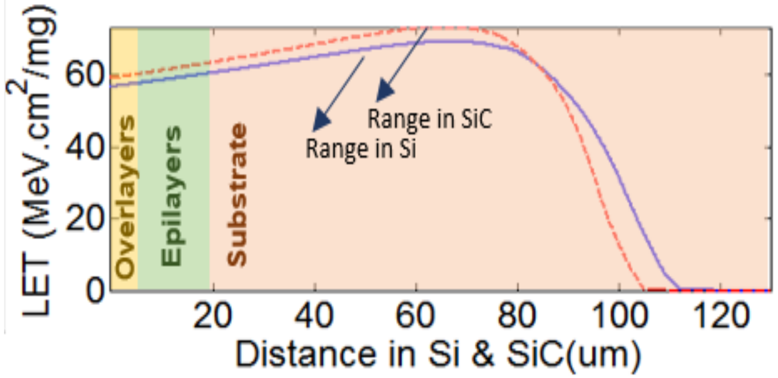










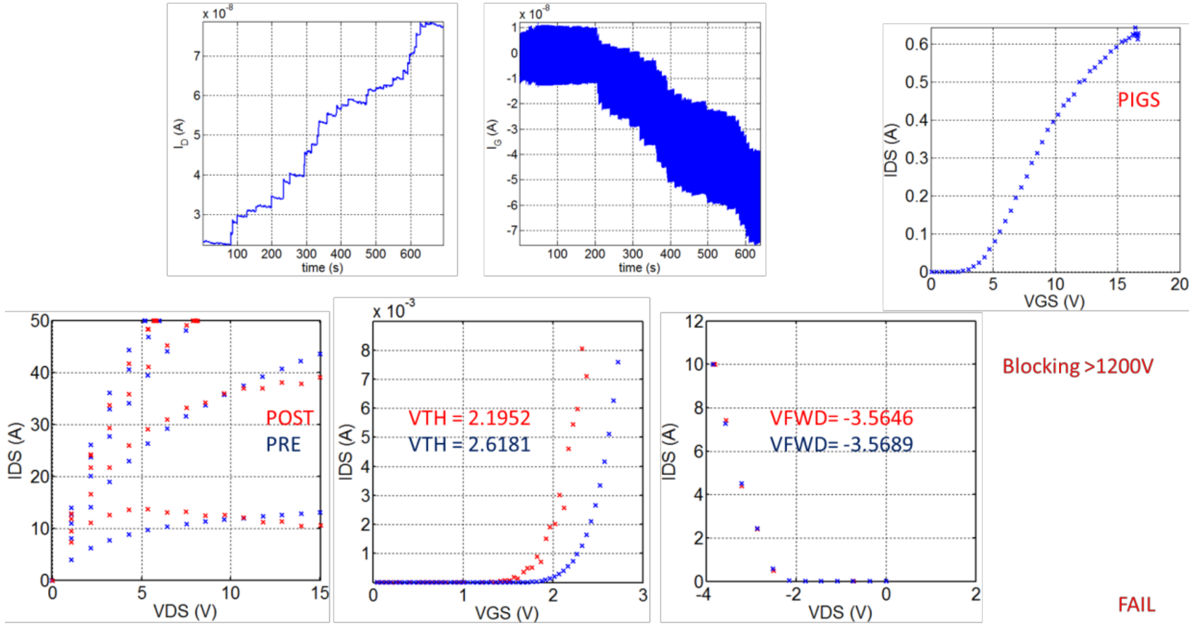


akin.akturk@coolcadelectronics.com

Single Event Effects: Commercially available SiC MOSFETs

LET(Si) ~ 45
Fluence in the 10^3-10^5 ions/cm^2 range
Flux ≈ 10 – 10^3 ions/cm^{2}s
Pre and Post Tests

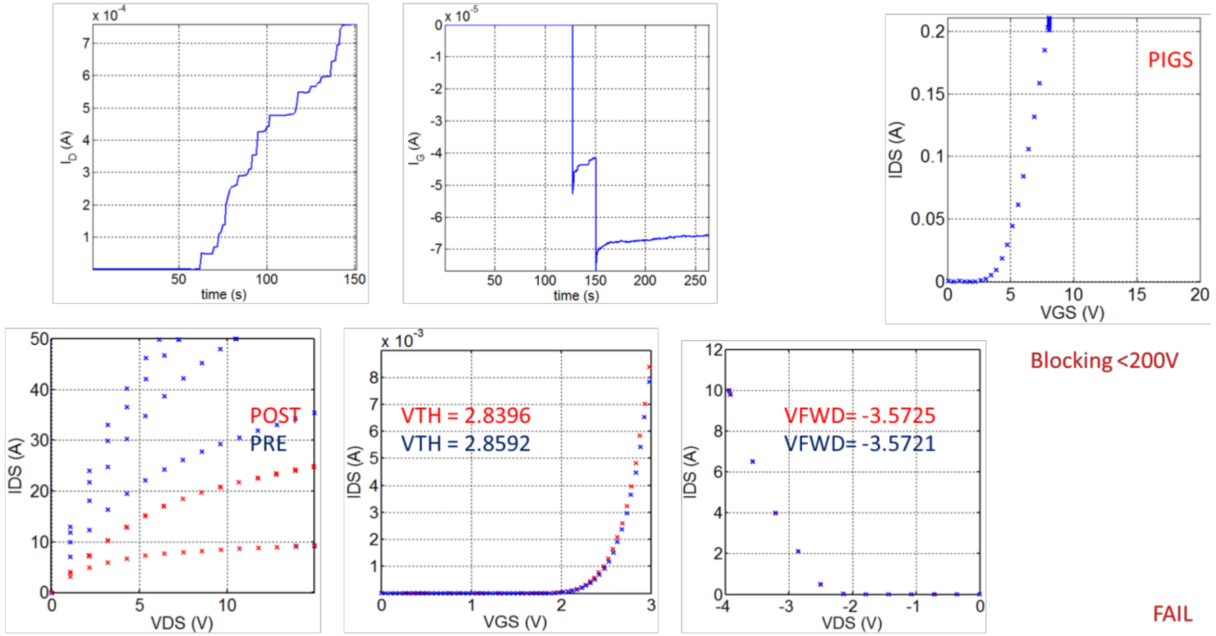
Dev # 70 300V VDS 0V VGS ~1e4 ions/cm2 22.7 ions/cm2s 8.9rad



Blocking >1200V

FAIL

Dev # 91 500V VDS 0V VGS ~1e3 ions/cm2 21.5 ions/cm2s 0.89rad

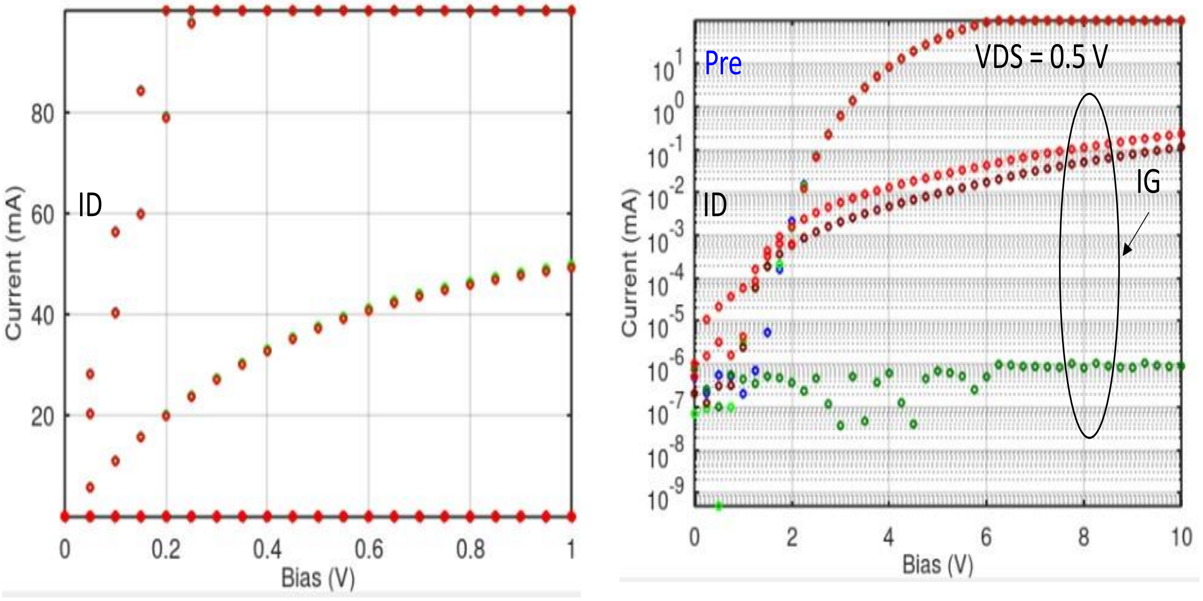


Blocking <200V

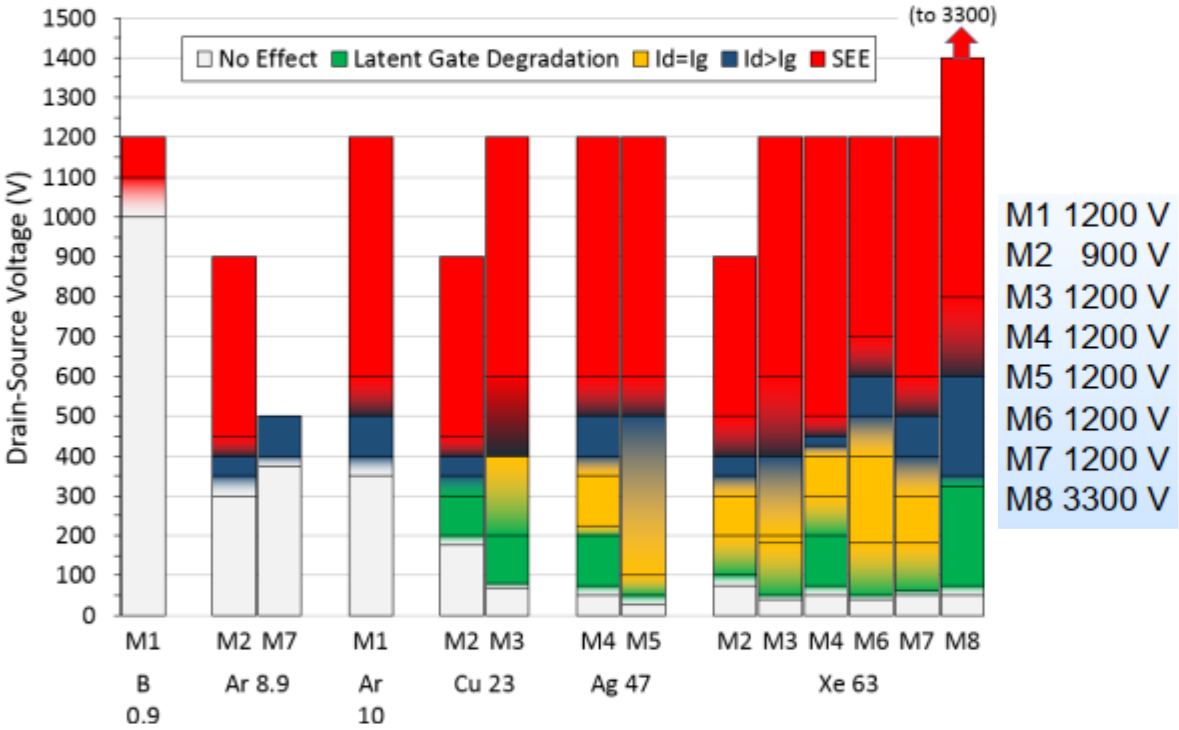
FAIL

akin.akturk@coolcadelectronics.com

Single Event Effects: Commercially available SiC MOSFETs



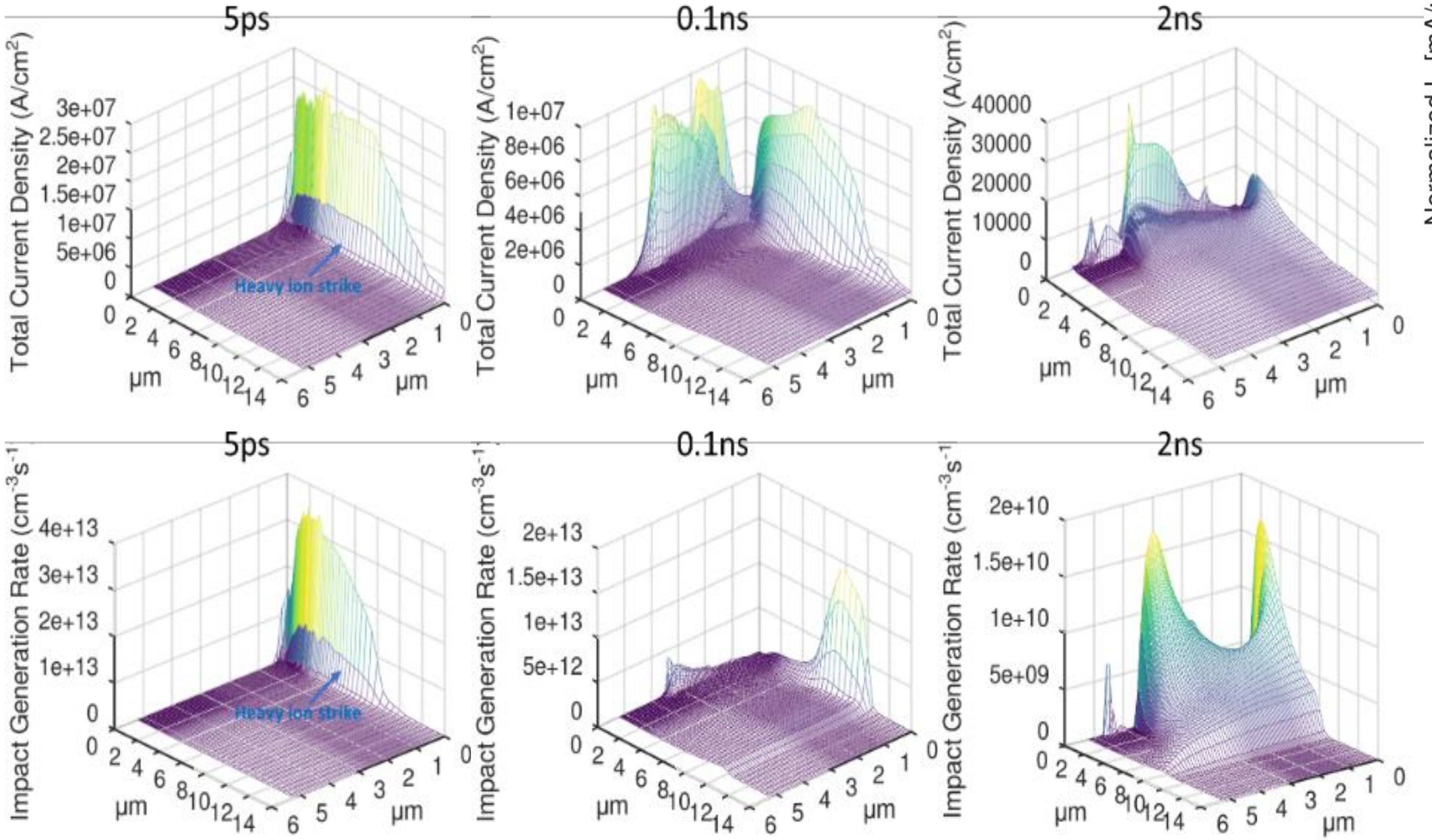
Post 1; 200 V; Ho Fluence ≈ $2\mathrm{x}10^4$ ions/cm^2; Flux ≈ 100 ions/cm^2/s; Dose ≈ 24 rad
Post 2; 400 V; Ho Fluence ≈ $1\mathrm{x}10^4$ ions/cm^2; Flux ≈ 100 ions/cm^2/s; Dose ≈ 12 rad

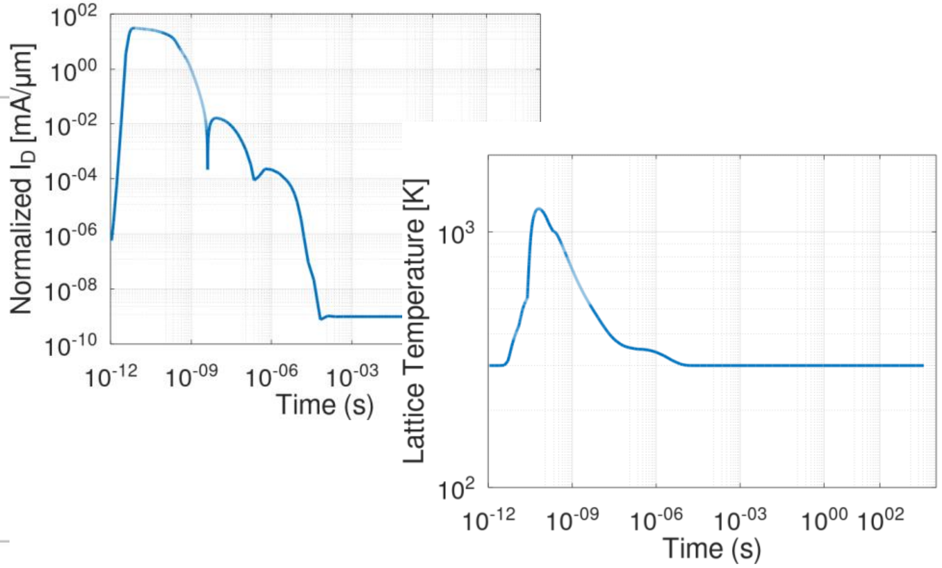


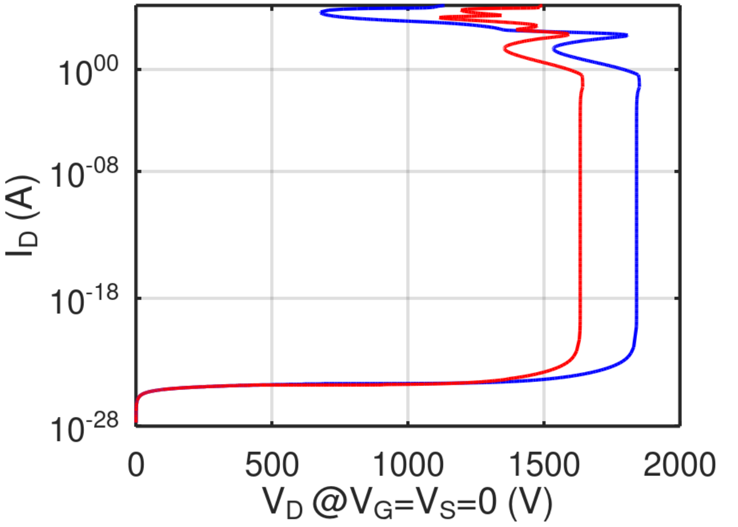
Jean-Marie Lauenstein and Megan Casey, “Taking SiC Power Devices to the Final Frontier: Addressing Challenges of the Space Radiation Environment” NEPP 2017

Simulations

LET~40



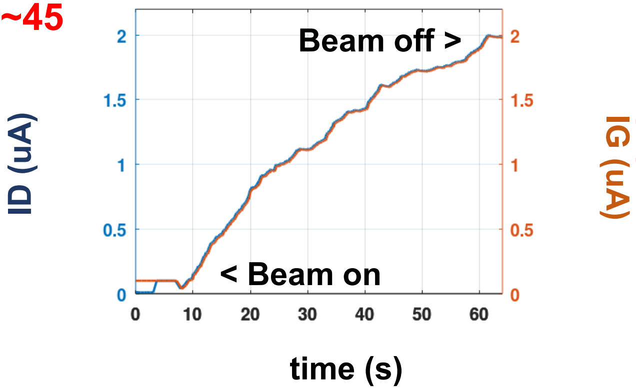




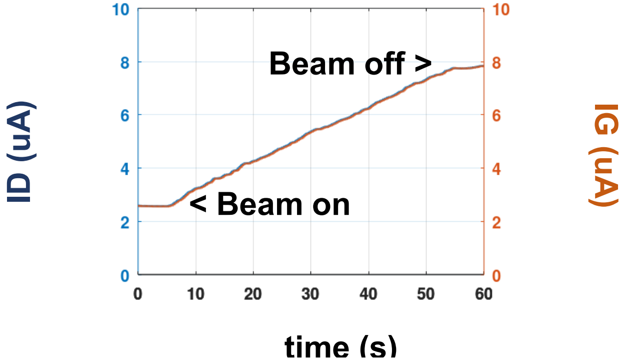
akin.akturk@coolcadelectronics.com

Single Event Effects: CoolCAD SiC MOSFETs - 650V

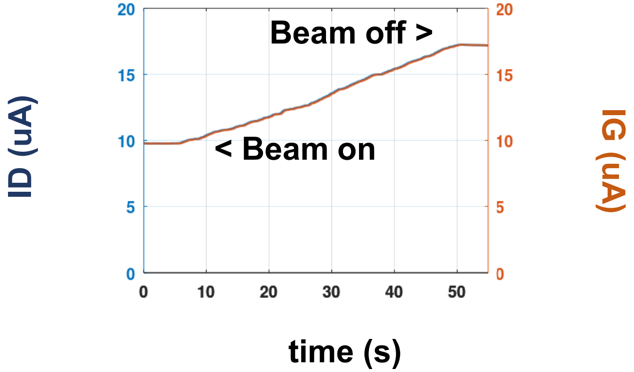
LET~45



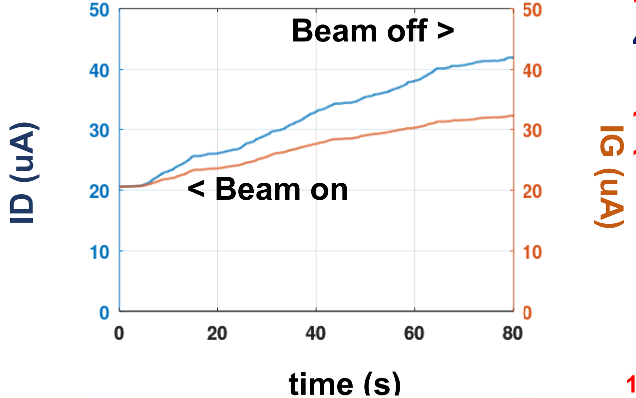
14_R148
300V
~1.87x 10^3
~10^5



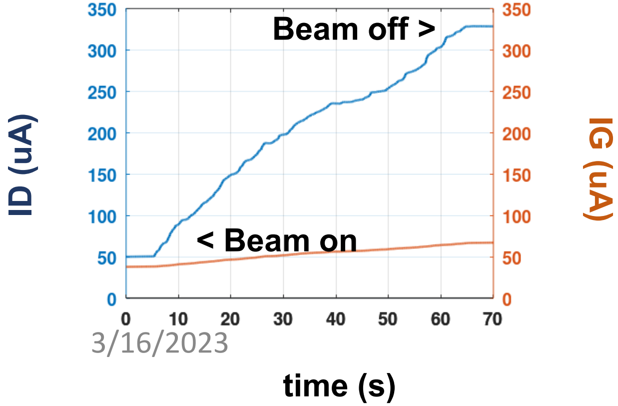
14_R149
350V
~1.83x 10^3
~10^5



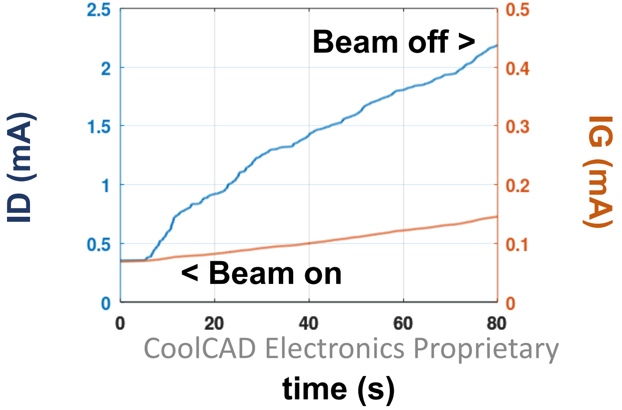
14_R150
400V
~2.25x10^3
~10^5



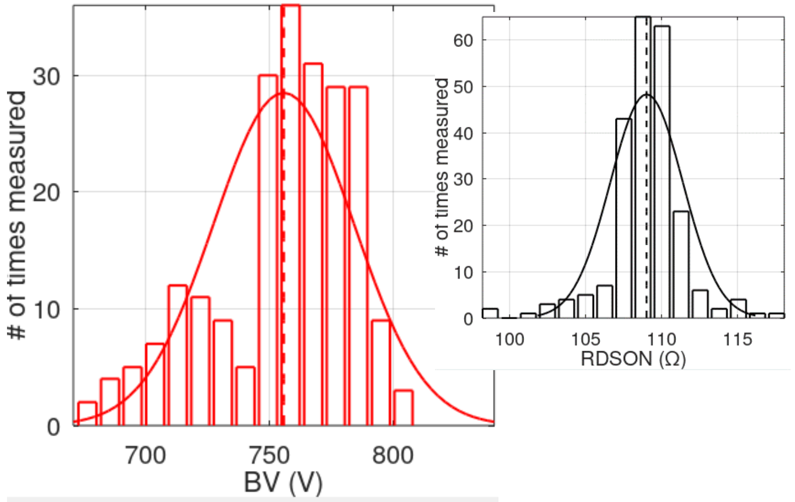
14_R151
450V
~1.34x10^3
~10^5

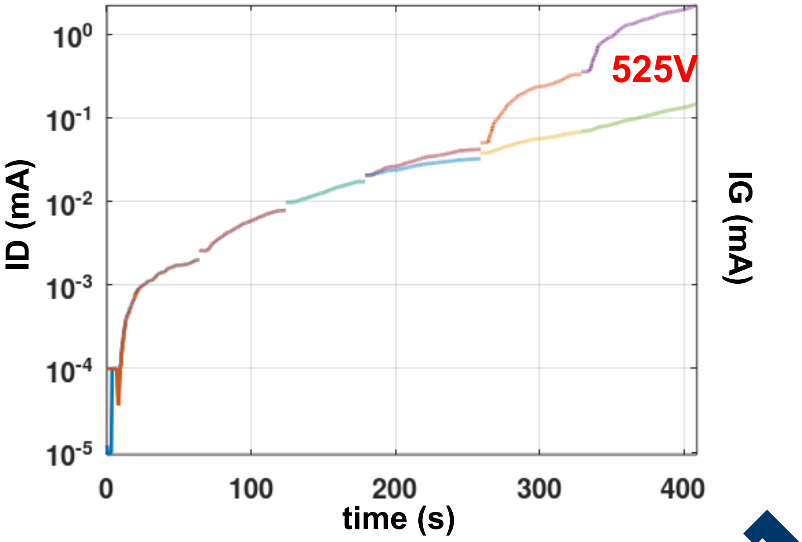


14_R152
500V
~1.65x10^3
~10^5



14_R153
525V
~1.26x10^3
~10^5

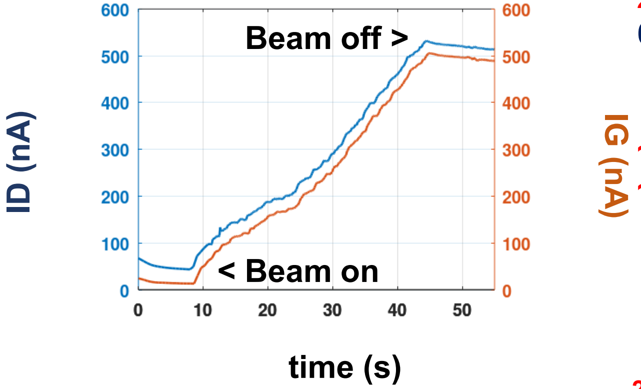




akin.akturk@coolcadelectronics.com

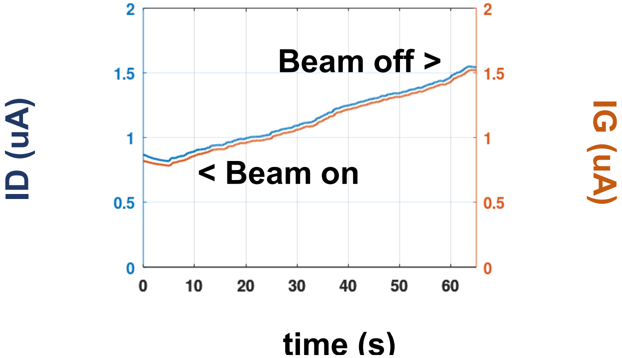
Single Event Effects: CoolCAD SiC MOSFETs – 1200V

LET~60



22_R165
600V

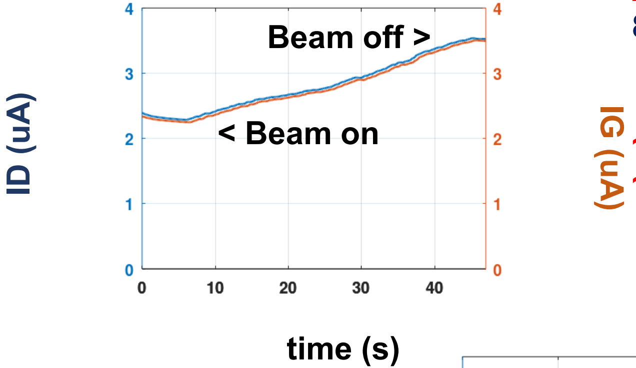
~2.78x 10^3
~10^5



22_R166
700V

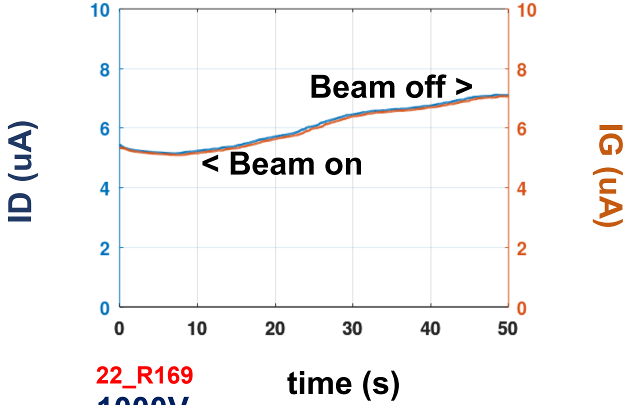
~1.72x 10^3
~10^5

Breakdown ~1700V



22_R167
800V

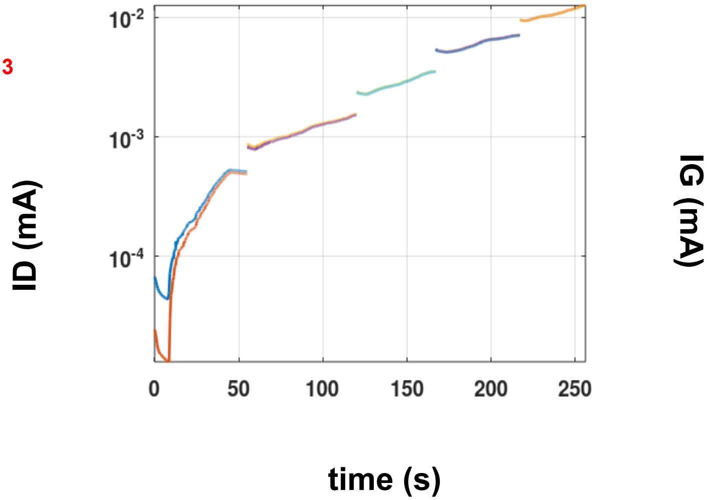
~2.56x10^3
~10^5



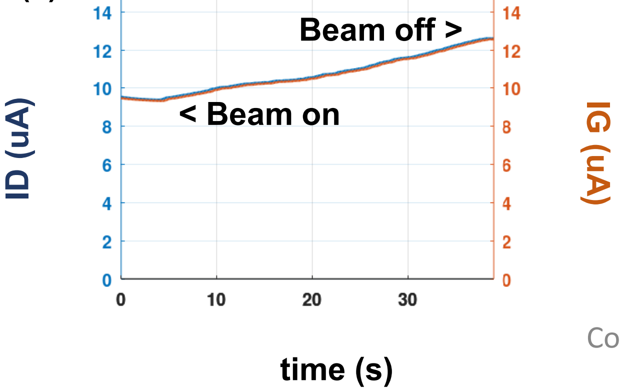
22_R168
900V

~2.43x10^3
~10^5

1000V



22_R169
1000V



~2.94x10^3
~10^5

akin.akturk@coolcadelectronics.com

Summary

- CoolCAD is specialized in silicon carbide device designs, modeling and fabrication.
- We fabricate devices in-house and also at commercial fabrication clearing houses.
- CoolCAD is making and commercializing silicon carbide power devices.
- We are experts on modeling and designing silicon carbide power devices.
- Silicon carbide MOSFETs are relatively radiation hard when it comes to total ionizing dose and displacement damage
- Silicon carbide MOSFETs are susceptible to single event effects; however, they can be hardened

We offer reliability, customization, flexibility………

- Silicon carbide know-how
- Silicon carbide power device designs for reliable and predictable operation
- Silicon carbide power device manufacturing
- Tailored niche designs: Custom current / voltage, radiation tolerance, high temperature operation
- Power circuits that take advantage of wide bandgap devices

akin.akturk@coolcadelectronics.com

APL

JOHNS HOPKINS
APPLIED PHYSICS LABORATORY