LET Dependence of SEB in 1200V SiC Power MOSFETs: Data and TCAD Results

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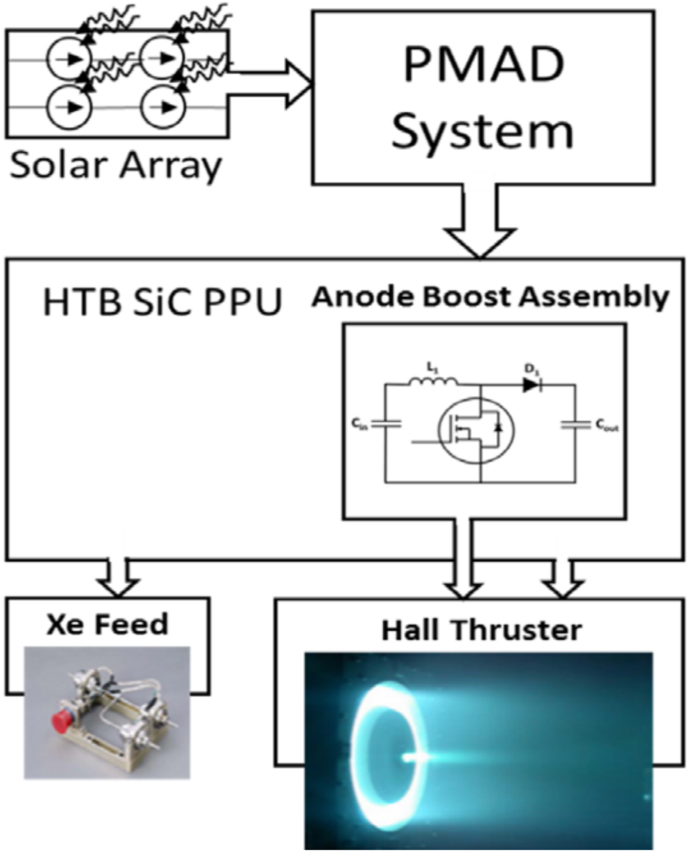
Why Silicon Carbide Power Devices for Space?

SiC vs Silicon Power Devices:

- **Higher Breakdown Voltage**
- **Lower On-State Resistance**
- **Higher Temperature Operation**
- **High Thermal Conductivity**
- **Mass, cost, power savings**

Example: Solar Electric Propulsion (SEP)

- **Deep space transfer for human missions to Near Earth Objects [1]**
- **Desired power levels ~400 kW**
- **Change from 120 V bus voltage to 300 V**



[1] Hoffman, et al, NASA/TM—2011-217281

Why Silicon Carbide Power Devices for Space?

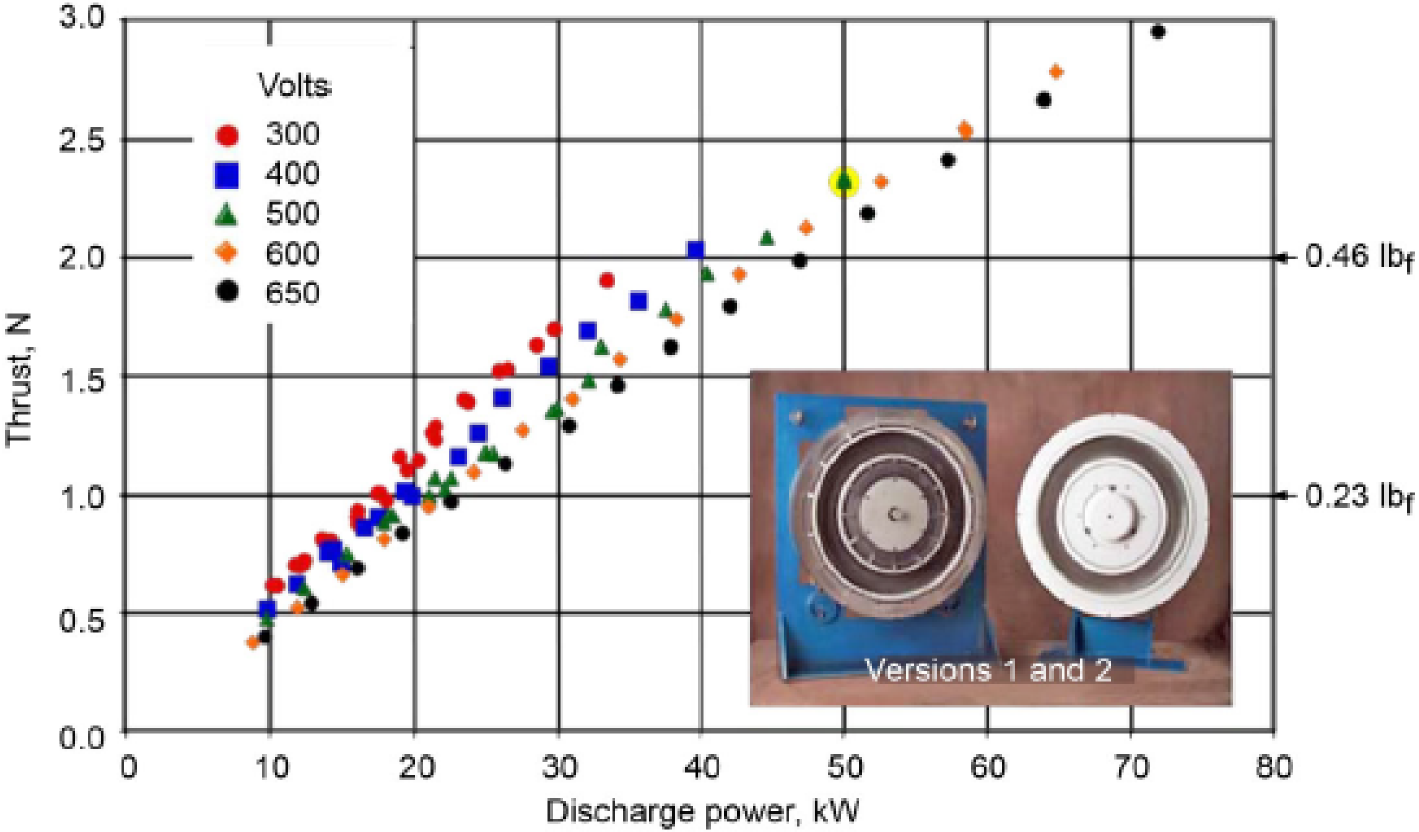
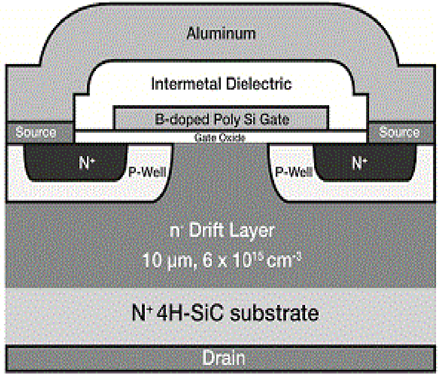


Figure 6.—Operating characteristics of the NASA 457M Hall thruster.

[1] Hoffman, et al, NASA/TM—2011-217281

SEB Failure Mechanism in SiC Power MOSFET

Structure SiC MOSFET [5]



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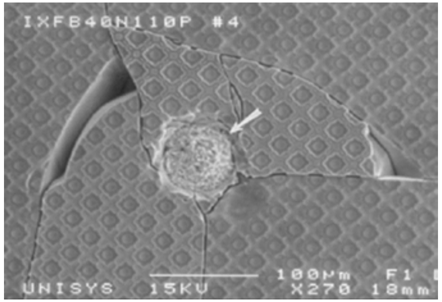
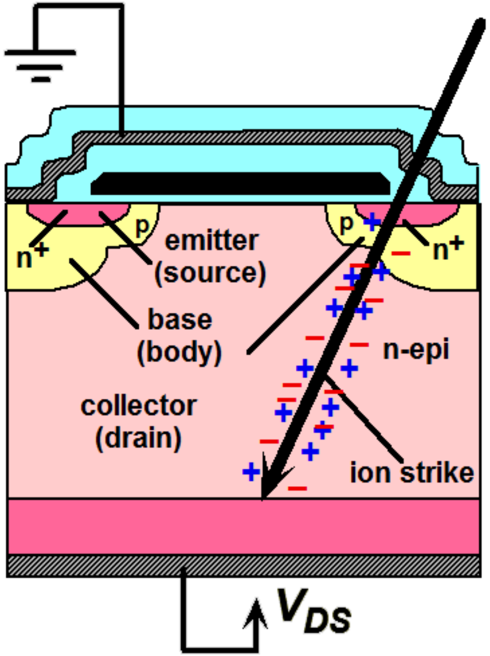


Parasitic BJT

- Ion activates bipolar
- Destructive thermal effects



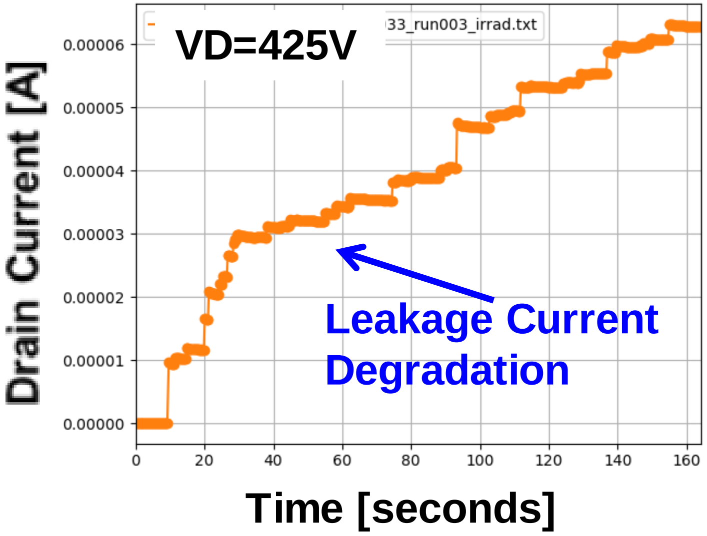
- NASA tests performed on SiC power devices rated 650 V to 3300 V [1,2]
- Additional testing by ESA, JAXA, others [3,4]
- "SEE-hard commercial SiC power devices are rare or non-existent" [1]
- Single-event burnout (SEB) typically ½ rated VDS
- Ion-induced degradation in gate, drain leakage currents

[1] J-M. Lauenstein *et al*., NEPP Electronic Technology Wkshp., 2015.
[2] J-M. Lauenstein *et al*., IEEE NSREC, 2015.
[3] E. Mizuta *et al*., IEEE Trans. Nucl. Sci., 2014.
[4] A. Witulski *et al.*, RADECS, 2017 (submitted)
[5] P. Zuk, Vishay Siliconix, EDN Network 2012
[6] J. van Duivenbode, ASML, Vermogen. Event 2012

Operating Areas in SiC Power MOSFETs

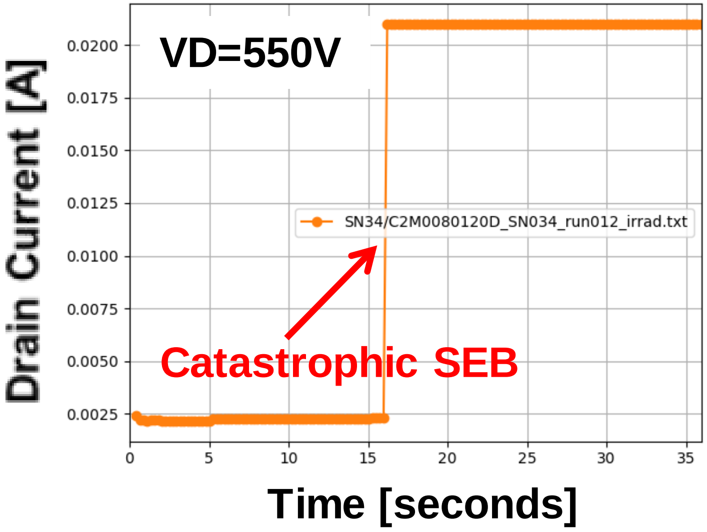
- SiC Power MOSFETs show three distinct operating areas:
  - Usable Operating Area
  - Latent gate damage
  - Drain Leakage Degradation
    - Gate to Drain leakage $I_G > I_S$
    - Source to Drain leakage $I_S > I_G$
  - Catastrophic SEB

Example: Data taken at RADEF for 1200 V Wolfspeed SiC power MOSFETs, irradiated with 1217 MeV Xe, LET(SiC)=62 MeV-cm^2/mg, fluence of 13 particles per second



VD=425V

Leakage Current Degradation



VD=550V

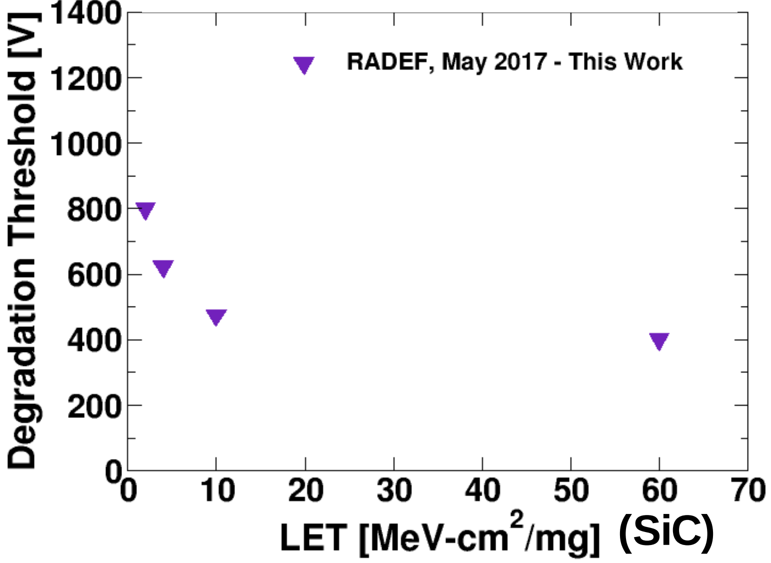
Catastrophic SEB

Heavy Ion Parametric Degradation and SEB Data for SiC Power MOSFETs

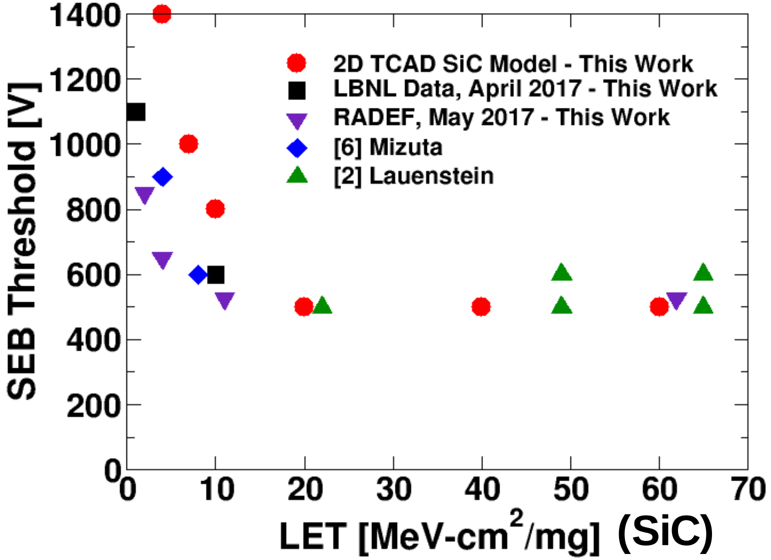
- Data for 1200 V Wolfspeed Gen 2 SiC Power MOSFETs
  - Drain Leakage degradation data taken at RADEF ion facility
  - SEB data taken at RADEF ion facility and LBNL cyclotron
- Previously published SEB SiC data compiled from literature
- 2D TCAD simulation results for SEB compared to SEB data

Abstract accepted for RADECS 2017

Drain Leakage Degradation

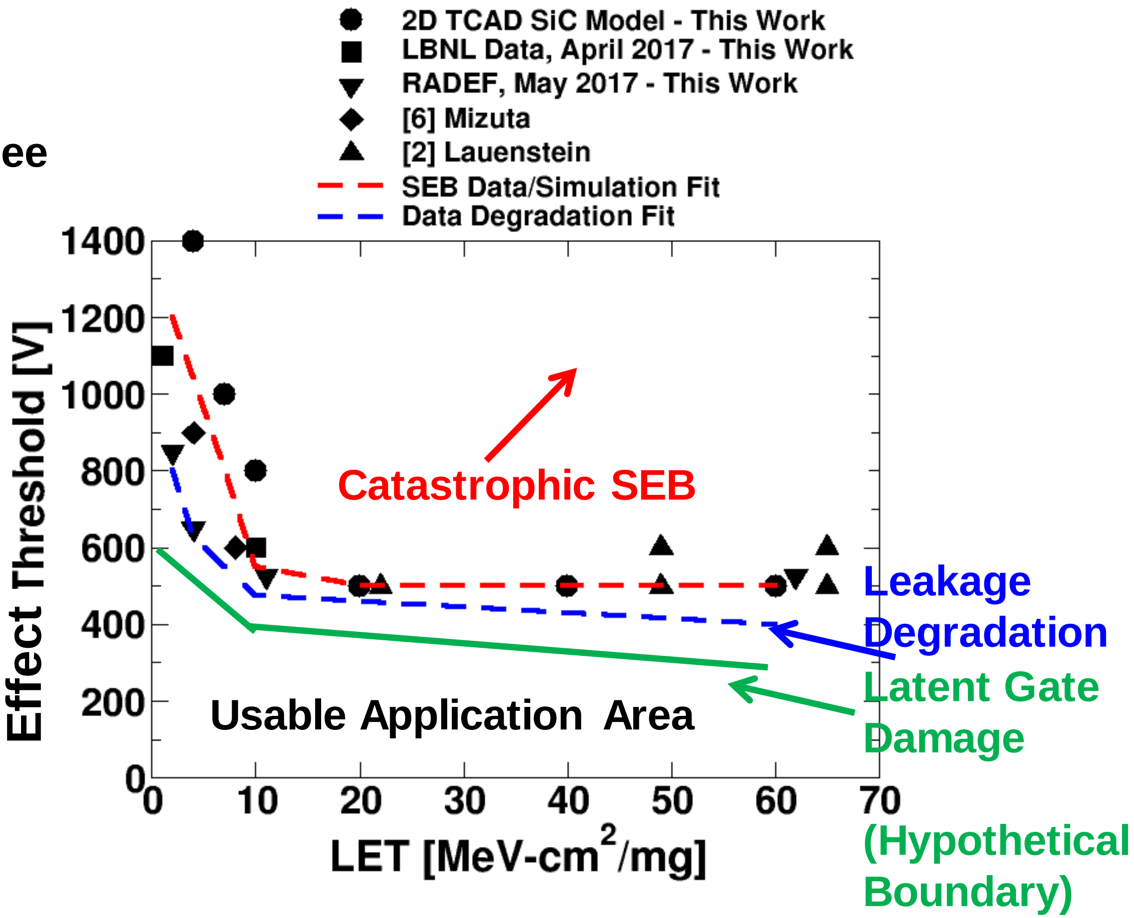


Single Event Burnout



Degradation Modes for SiC Power MOSFETs

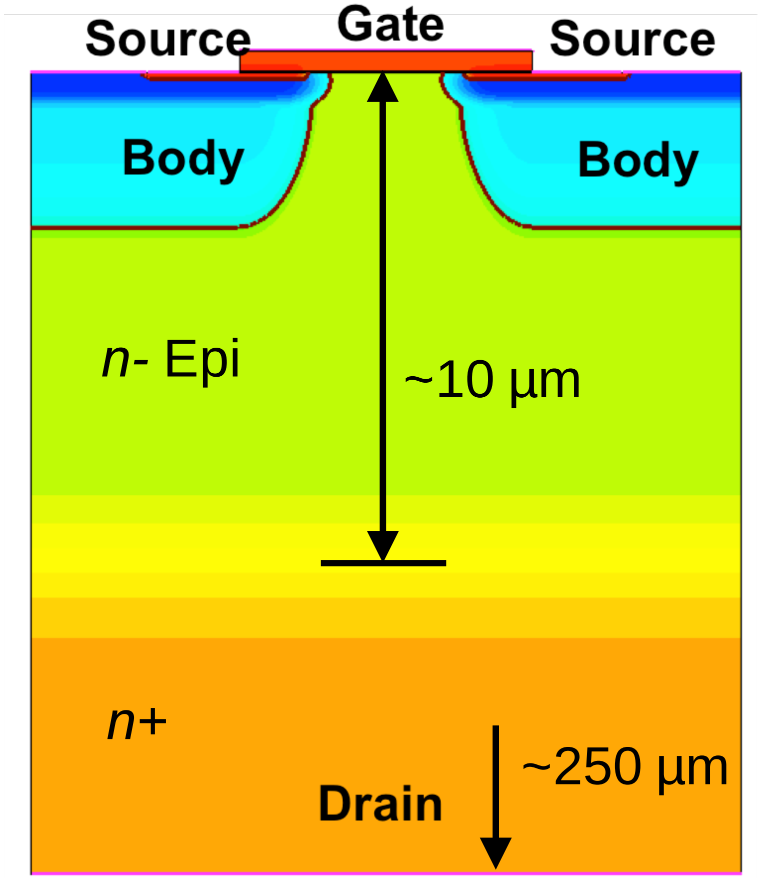
- SiC Power MOSFETs show three distinct operating areas:
  - Usable Operating Area
  - Latent gate damage
  - Drain Leakage Degradation
    - Gate to Drain leakage
    - Source to Drain leakage
  - Catastrophic SEB
- Small Remaining Usable Application Space!



SiC Power MOSFET Simulation TCAD Model

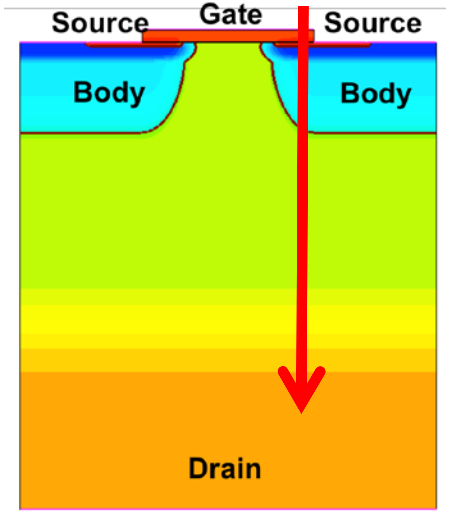
- **2D TCAD model built in Synopsys Sentaurus**
- **Electrical (I-V, breakdown) and single event simulations were performed**

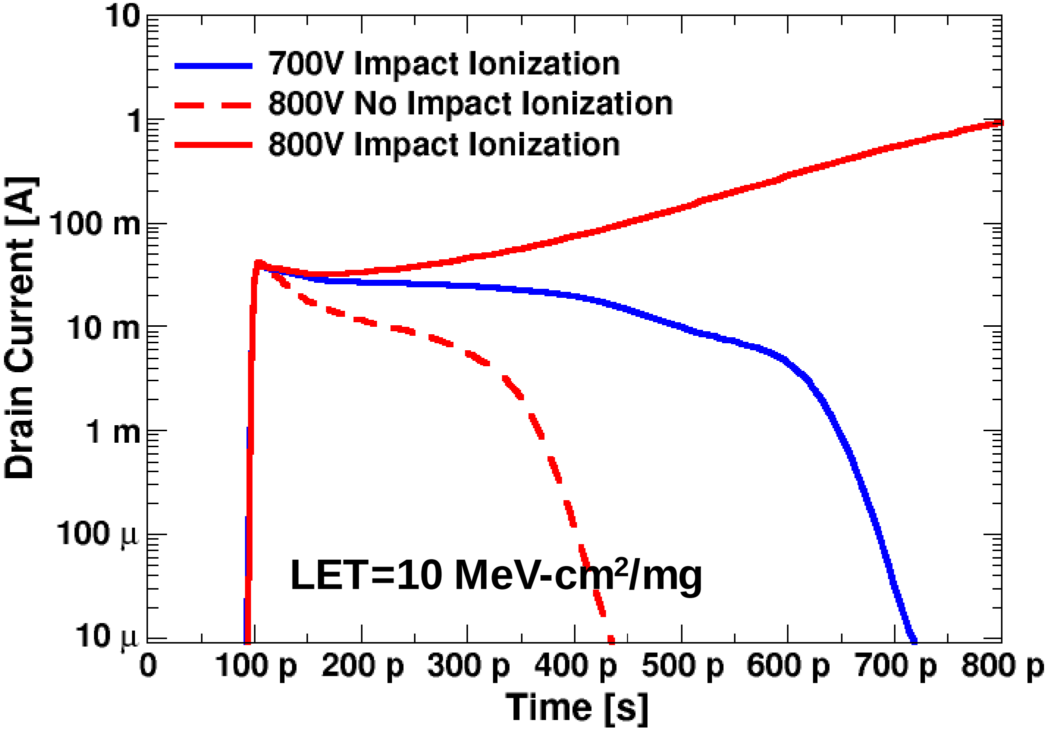
Parameter	Value
4H-SiC	Bandgap = 3.26 eV
N-Epi Doping/Depth	1e15 cm^{-3}, 10um
Body Doping/Depth	1e18 cm^{-3}, 3um
N+ Drain Doping	1e19 cm^{-3}
Ion Track Radius/Length	50nm, 15um
Impact Ionizaton Model	Anisotropic avalanche



Key Mechanism: Impact Ionization

- Ion passes through Source/Body/Drain
- SEB occurs at VD=800V with Impact Ionization turned on for LET=10 MeV-cm^2/mg

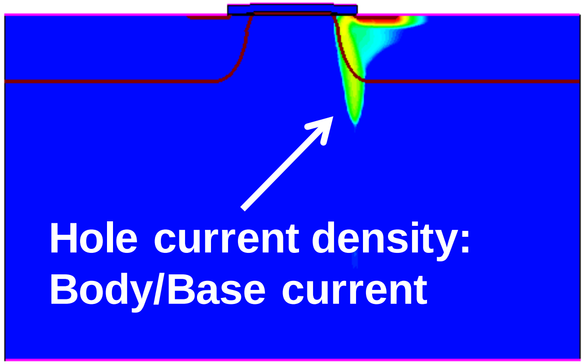


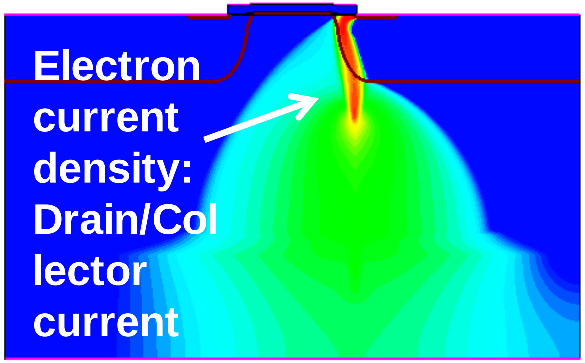


Impact Ionization critical for SEB in SiC Power MOSFETs

Key Mechanism: Parasitic BJT Turn-On

Impact Ionization OFF





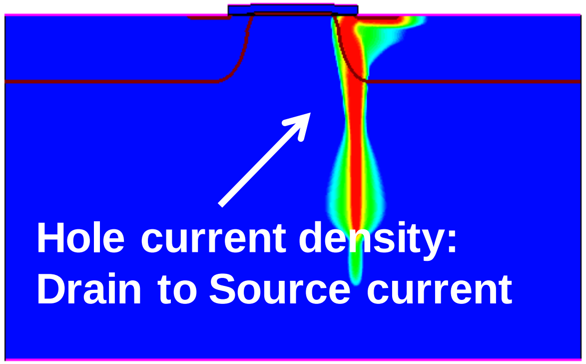
Impact Ionization OFF

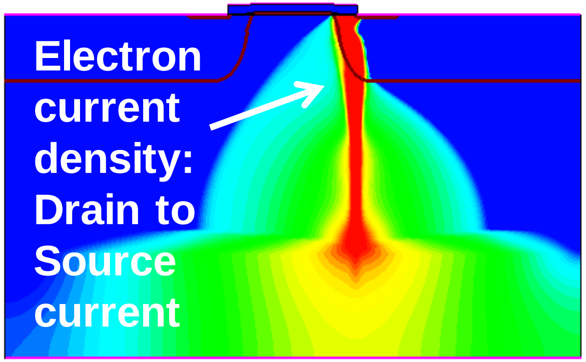
- Parasitic BJT turn-on
- Charge recombines
- Device recovers

Impact Ionization ON

- Parasitic BJT turn-on
- Avalanche multiplication dominates
- Current runs away
- Device shows SEB

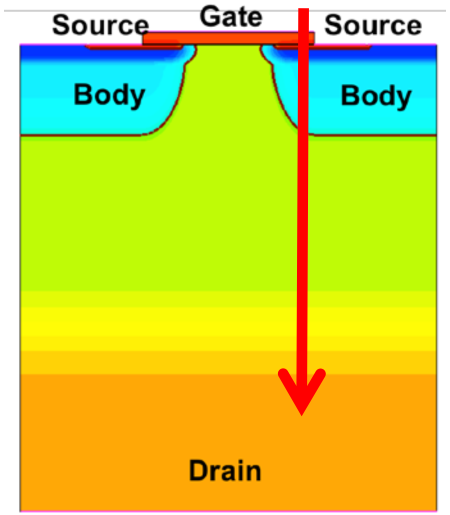
Impact Ionization ON

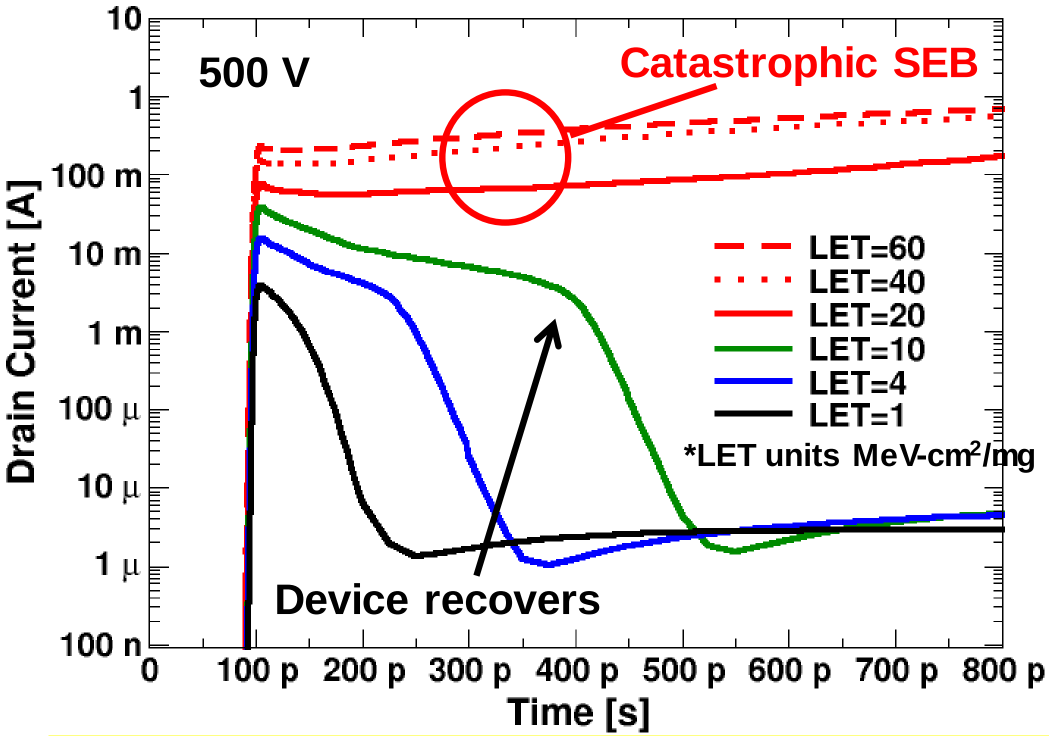




Single Event Induced Drain Current Transients Versus LET

- Ion passes through Source/Body/Drain
- Drain current transient increases as function of LET
  - Peak current
  - Duration

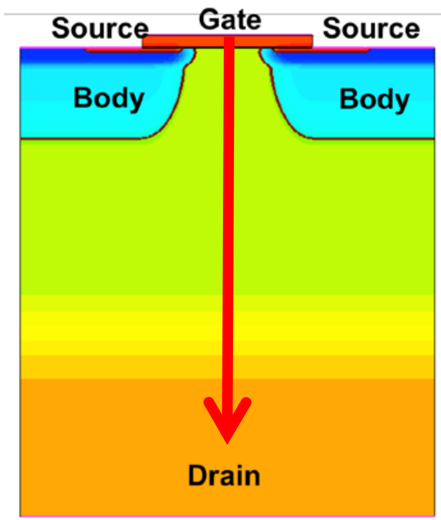




Catastrophic SEB is a function of ion LET and device bias

Single Event Burnout – Strike Location Dependence

- SiC power MOSFET TCAD simulation indicates strike location dependence
- Deposited charge must be able to turn on parasitic BJT to cause SEB



SEB occurrence as a function of hit location, drain bias, and LET

Location	Center Gate	Source/Body	Body
LET=4 @ 1400 V	No	Yes	No
LET=10 @ 800 V	No	Yes	No
LET=20 @ 500 V	No	Yes	No
LET=60 @ 500 V	SEB	Yes	Yes

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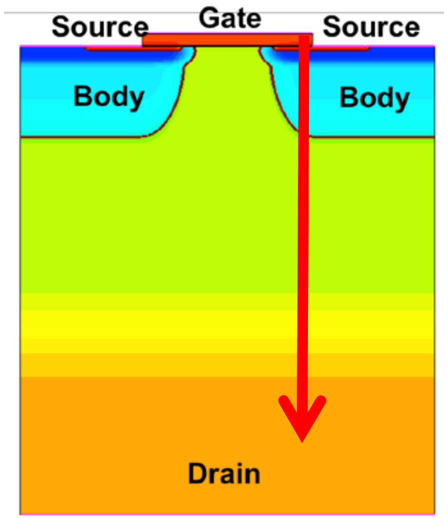

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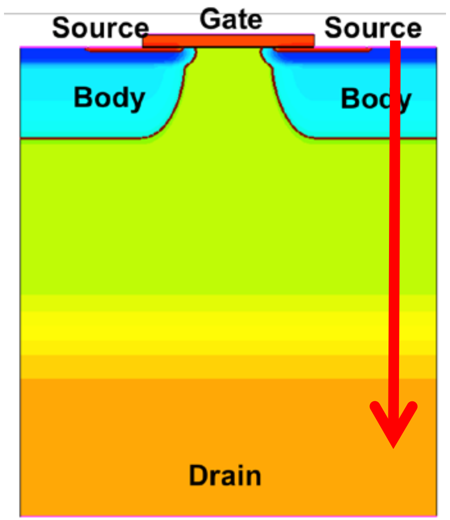

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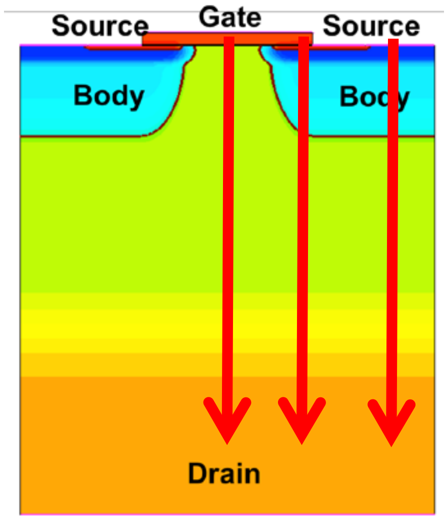
Single Event Burnout – Strike Location Dependence

- **SiC power MOSFET TCAD simulation indicates strike location dependence**
- **Deposited charge must be able to turn on parasitic BJT to cause SEB**
- **For a given bias, increasing LET over the threshold value leads to an increasing sensitive area**



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LET=10 @ 800 V	No	SEB	No
LET=20 @ 500 V	No	SEB	No
LET=60 @ 500 V	SEB	SEB	SEB

Summary: ESI Results on SEE and SiC So Far

- **Pre-rad electrical SiC power MOSFET capability highly desirable for space applications**
- **SiC power MOSFETs exhibit latent gate damage, drain leakage current degradation, and burn-out in heavy-ion environments**
- **Location of SEE Effects can be mapped in Drain Current-LET plane,**
    - **Boundaries depend on off-state drain bias voltage and LET**
    - **Only small portion of ideal Id-LET plane allowable for application in space**
- **Parasitic bipolar action likely explanation for SEB in SiC MOSFETS**
- **TCAD results appear to match experimental results**
    - **Impact ionization is important mechanism in SEB**
    - **Burnout is sensitive to strike location**
    - **Higher LET leads to greater sensitive volume**
- **Experimental and theoretical work is continuing**