Modeling, Testing, and Simulation of Heavy-Ion Basic Mechanisms in Silicon Carbide Power Devices

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Definition of Acronyms

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1D-One Dimensional
BV-Breakdown Voltage of a material
"Epi"-Abbreviation of "Epitaxial"
FIT-Failures in Time
GE-General Electric Corporation
JBS-Junction-Barrier Schottky Diode
LuSTR-Lunar Surface Technology Research
SEB-Single Event Burnout
SEM-Scannng Electron Microscope
SiC-Silicon Carbide
TCAD-Technology Computer-Aided Design Software
VU-Vanderbilt University
WBG-Wide Bandgap semiconductor material

NASA ARTEMIS Lunar Program

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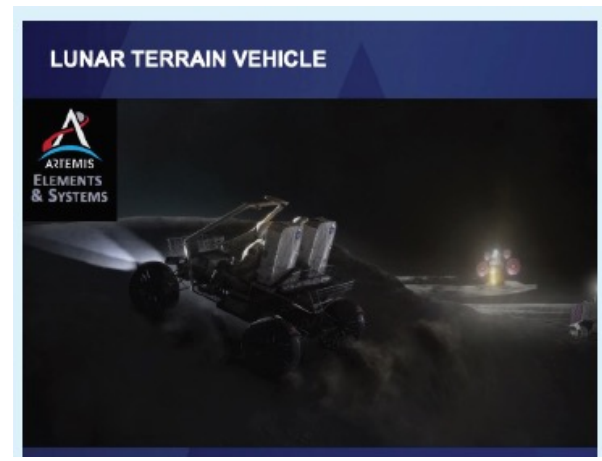

NASA’s Lunar Exploration Program Overview Sept.2020

NASA Lunar Surface Technology Research (LuSTR)

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LuSTR projects for 2021-2023:

Innovative ways to identify and access resources on the moon

- Thermal mining to access and trap water vapor (UTEP)
- Rover-mounted drill for water (WUSL)
- Heated cone percussive penetrometer for soil/regolith study (MTU)

Next-generation energy storage and power distribution technologies

- Wireless transfer feasibility studies for remote power transfer (UCSB)
- Silicon carbide power components for lunar surface applications (VU)
- Flexible energy distribution between multiple power grids (OSU)

https://www.nasa.gov/directorates/spacetech/lustr/US_Universities_to_Develop_Lunar_Tech_for_NASA

Wide Bandgap Power Devices Electrical Performance

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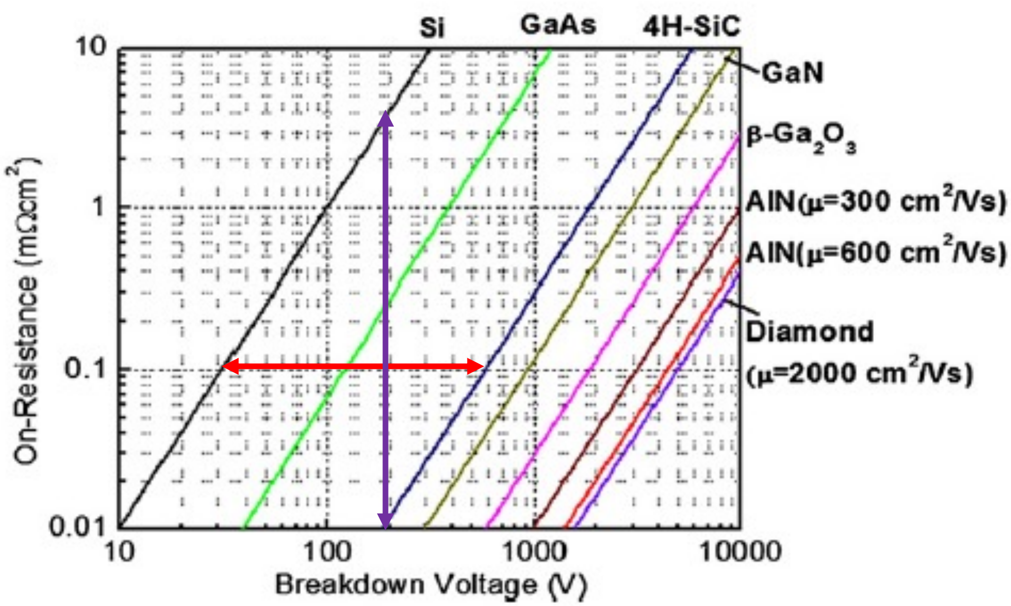
Same R_{on}: WBG > 1 decade higher BV-Well suited to high voltage applications

Same BV: WBT > 2 decades lower R_{on}-Much more efficient than silicon devices



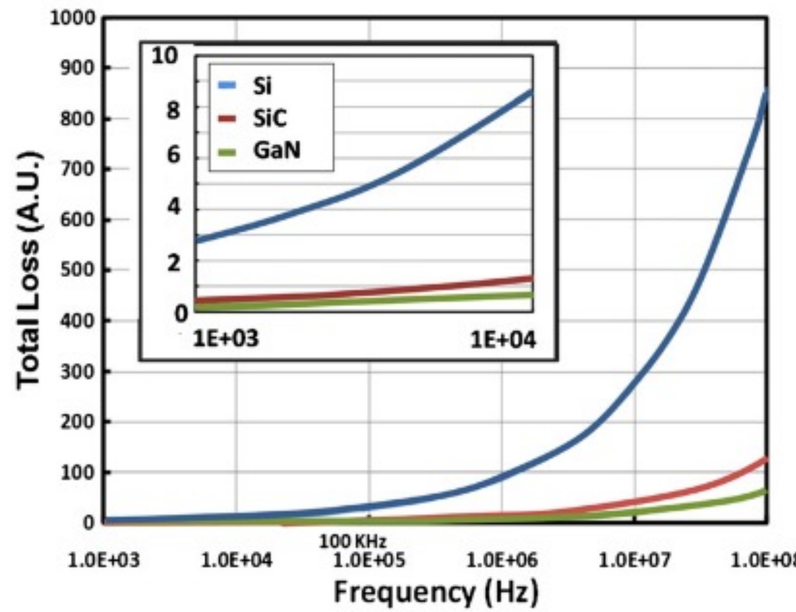


Figure 2. On-resistance versus Breakdown Voltage for wide bandgap materials (*Courtesy Palacios group, MIT*).

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Choudhury, et al, Semiconductor Science and Technology, 2013.

Comparative Structure of SiC and SI Power Devices

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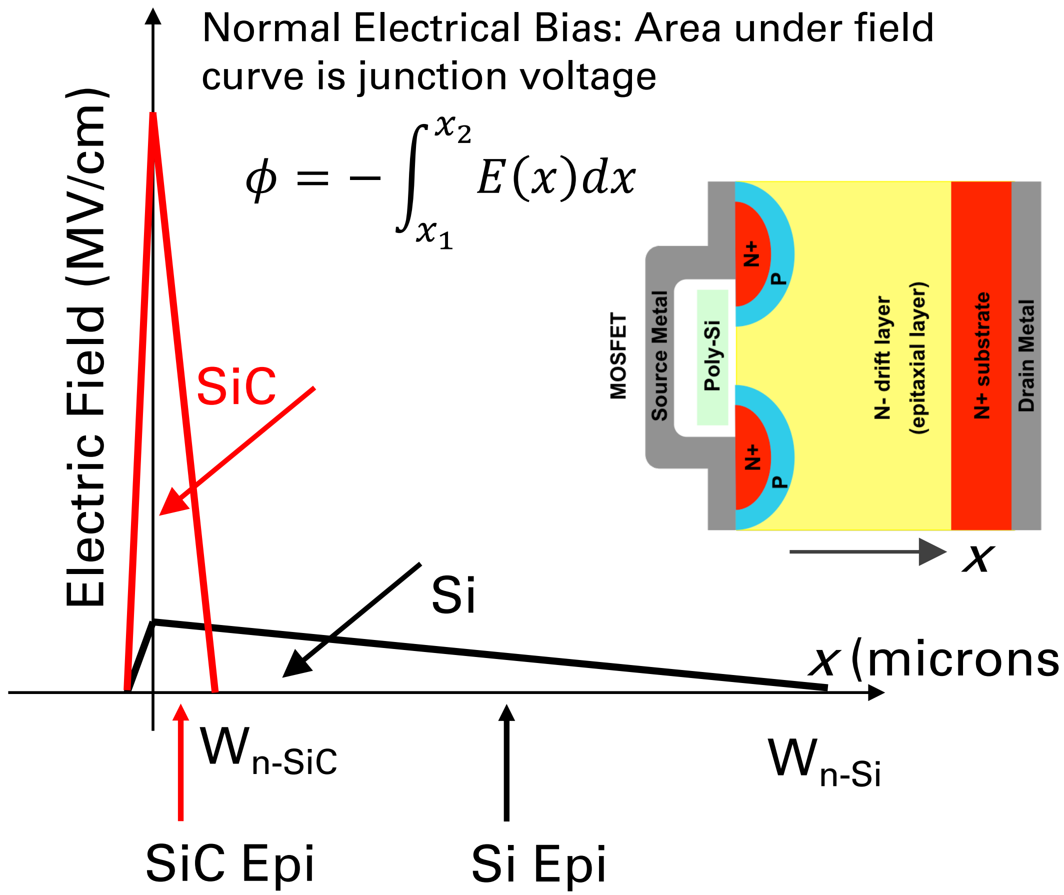
- SiC Critical field ~8x of Si
- Depletion width much smaller for same breakdown voltage
- Smaller depletion region leads to lower on-resistance
- Higher doping in n- “drift” region in SiC devices than Si
- High fields contribute to more severe single event effects in SiC than in Si



LuSTR SiC Device Performance Goals

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Electrical Performance:

- SEE-tolerant SiC power diodes: Minimum 1200 V, 40 A, with maximum recovery time of 40 ns
- SEE-tolerant SiC power transistors: Normally off (enhancement mode), minimum 600 V, 40 A, Rds_on < 24 mOhms while preserving low switching losses.

Radiation Goal:

- No heavy-ion induced permanent destructive effects upon irradiation while in blocking configuration (in powered reverse-bias/off state) with ions having a silicon-equivalent surface incident linear energy transfer (LET) of 40 MeV-cm^2/mg of sufficient energy to maintain a rising LET level throughout the epitaxial layer(s).

Structure of SiC JBS Diodes and MOSFETs

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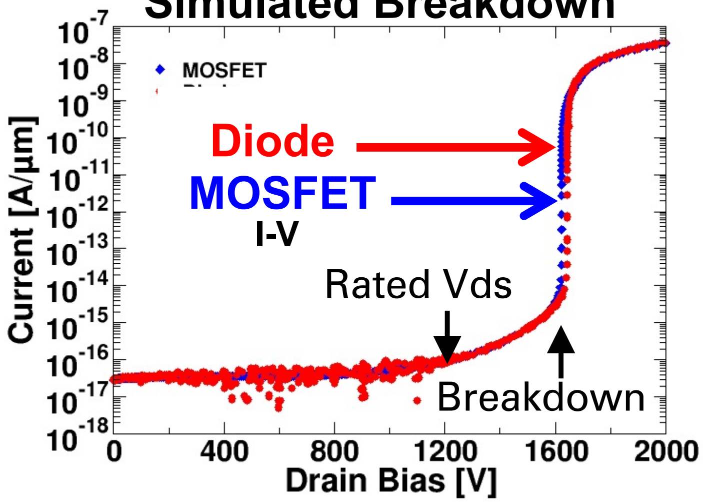
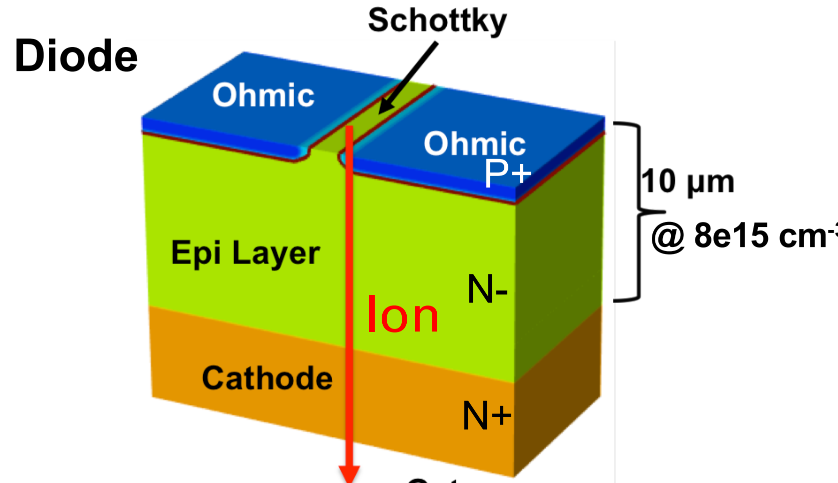
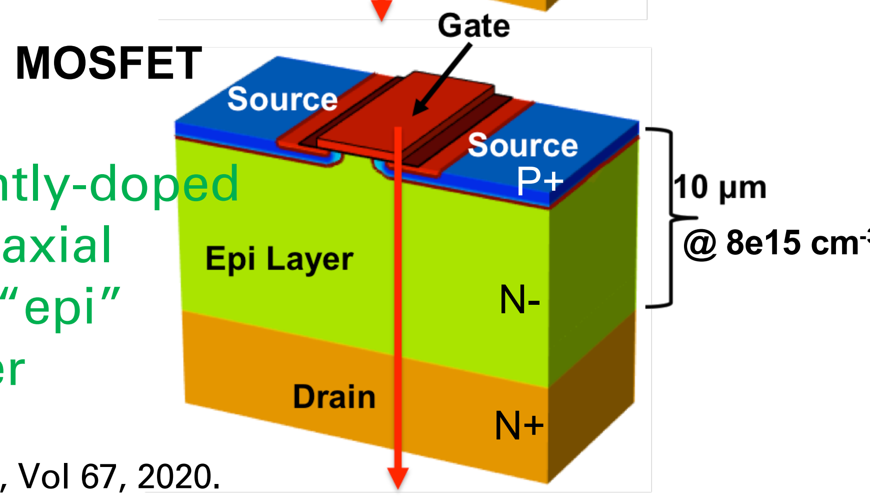
- 3D TCAD models developed
  - 1200 V rated vertical JBS diode
  - 1200 V rated vertical MOSFET
  - Dimensions/dopings based on published literature from Wolfspeed
  - Synopsys Sentaurus tool suite

Simulated Breakdown



D.R. Ball, et al, Trans. Nucl. Sci., Vol 67, 2020.





Lightly-doped Epitaxial Or “epi” layer

SiC Power MOSFET and Diode SEB and Degradation Thresholds

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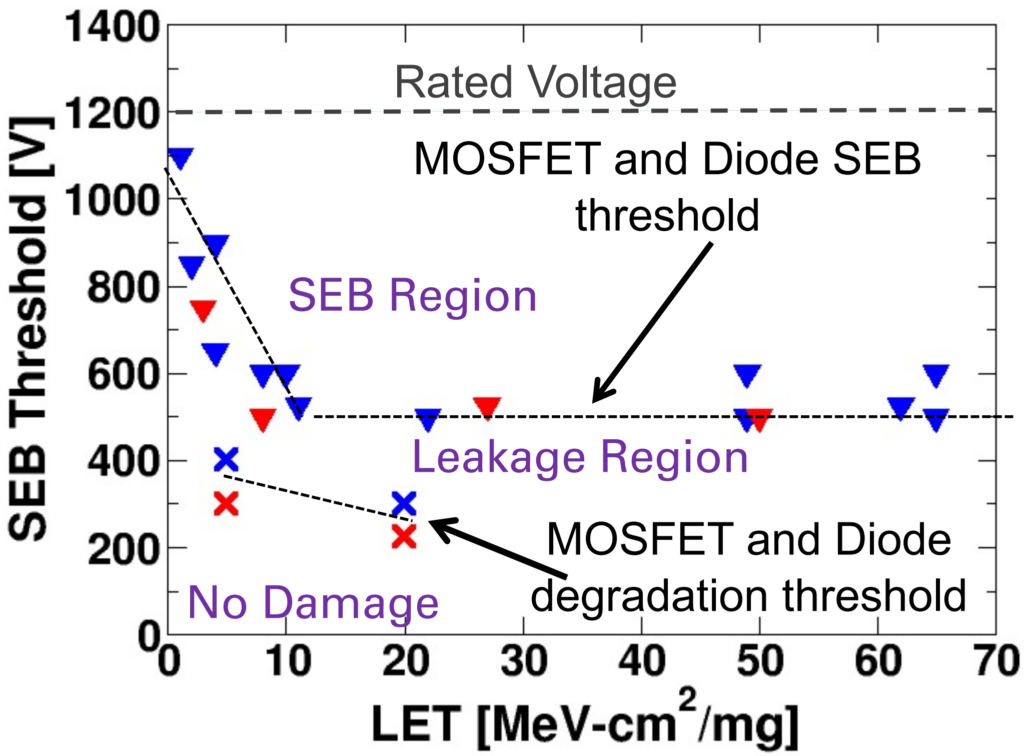
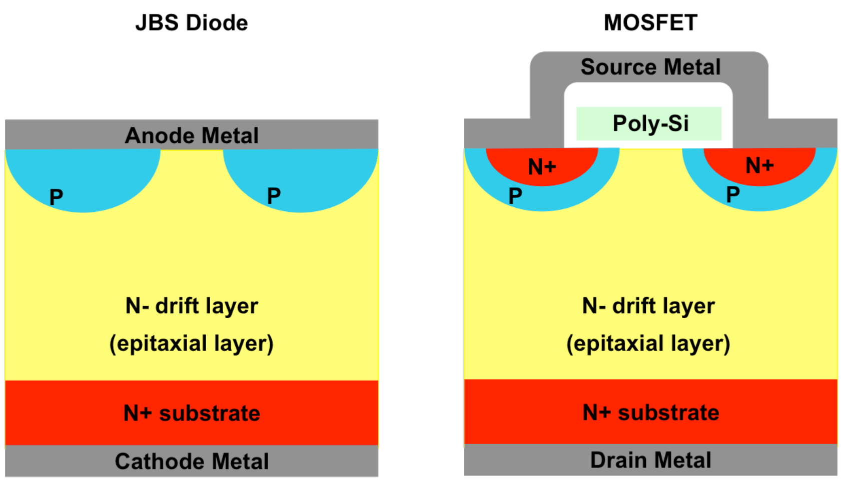
1200 V SiC Power MOSFET and Diode show the same SEB and degradation thresholds



D.R. Ball, et al, Trans. Nucl. Sci., Vol 67, 2020.

All experimentally measured points on 1200 V SiC Devices



Single Event Physical Damage and Failure Analysis

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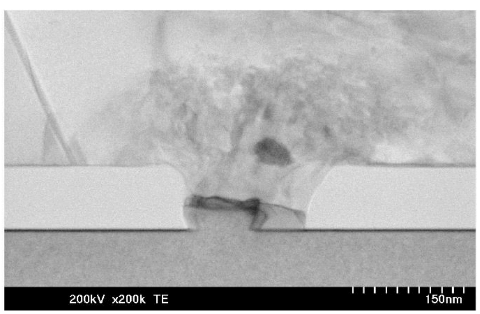
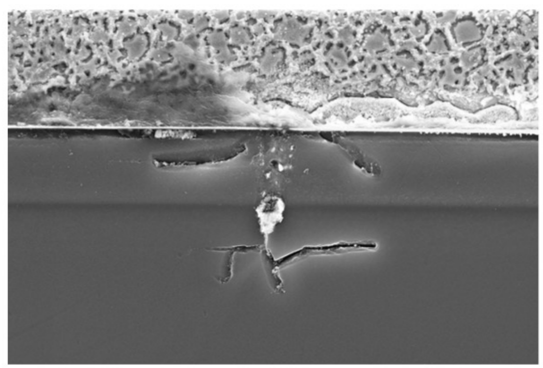
- Happens fast – on the order of picoseconds vs. device natural response time of nanoseconds
- Indirectly observed via
  - Electrical measurements (leakage or short circuit)
  - Physical imaging in failure analysis (SEM, etc.)
- LuSTR Task for Caldwell failure analysis Lab at VU

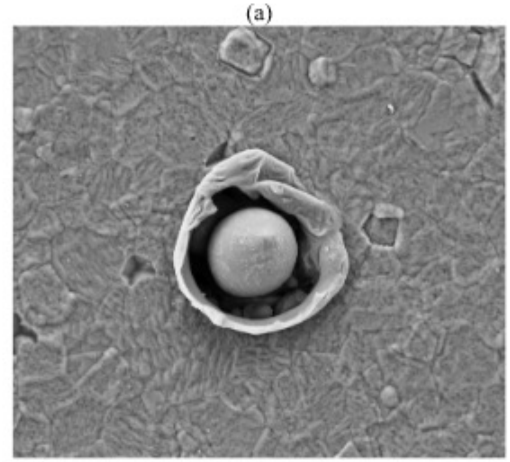


Kuboyama, et. al, RADECS 2018



Casey, et. al, IEEE TNS Jan. 2018

(a)



(b)

Similarity of 1200 V MOSFET and Diode Electrical Breakdown in the Off-State - TCAD

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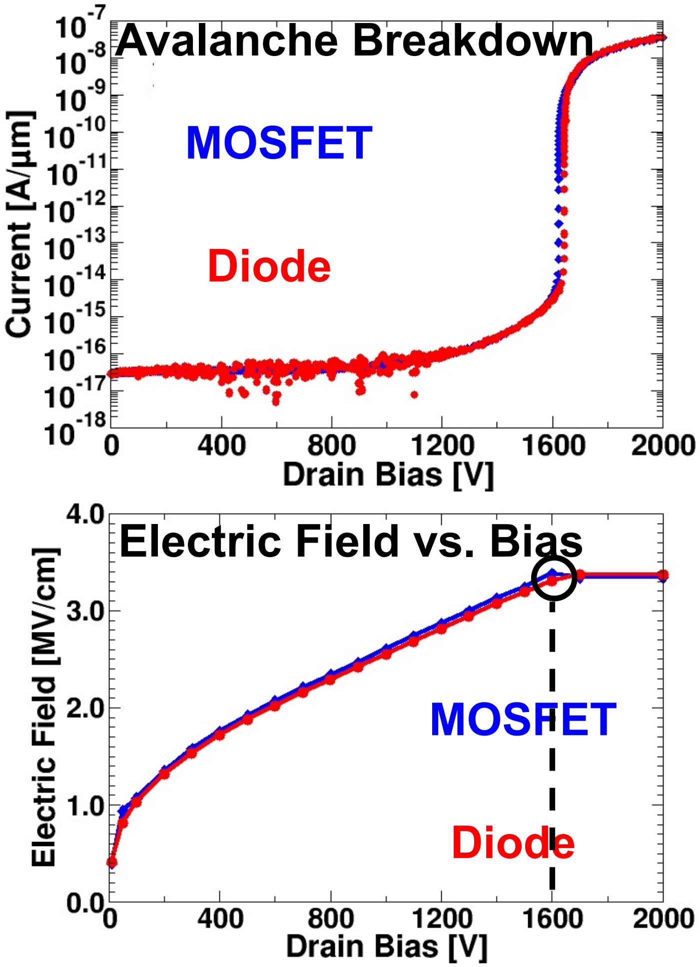
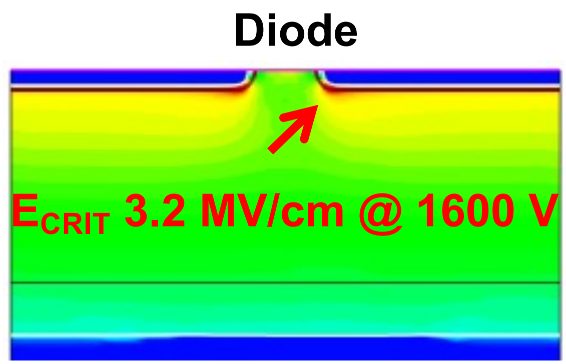
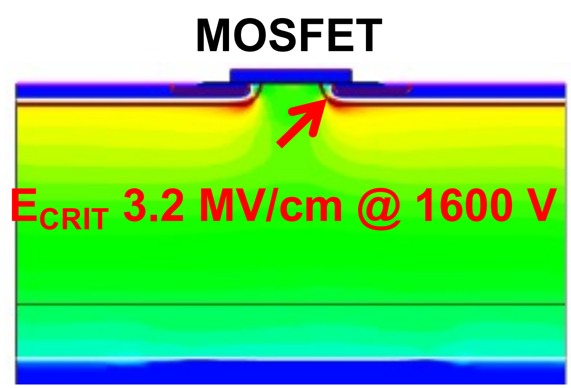
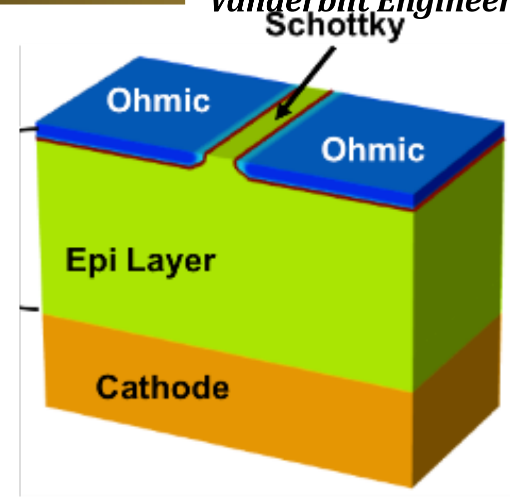
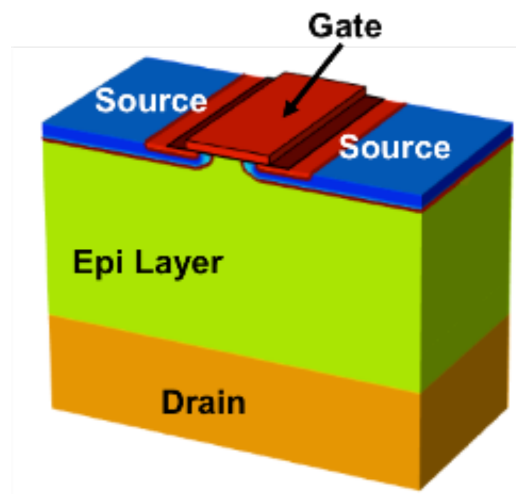




Electric breakdown and internal electric fields consistent between devices







Ion-Induced Re-Distribution of Electric Field During Strike - TCAD

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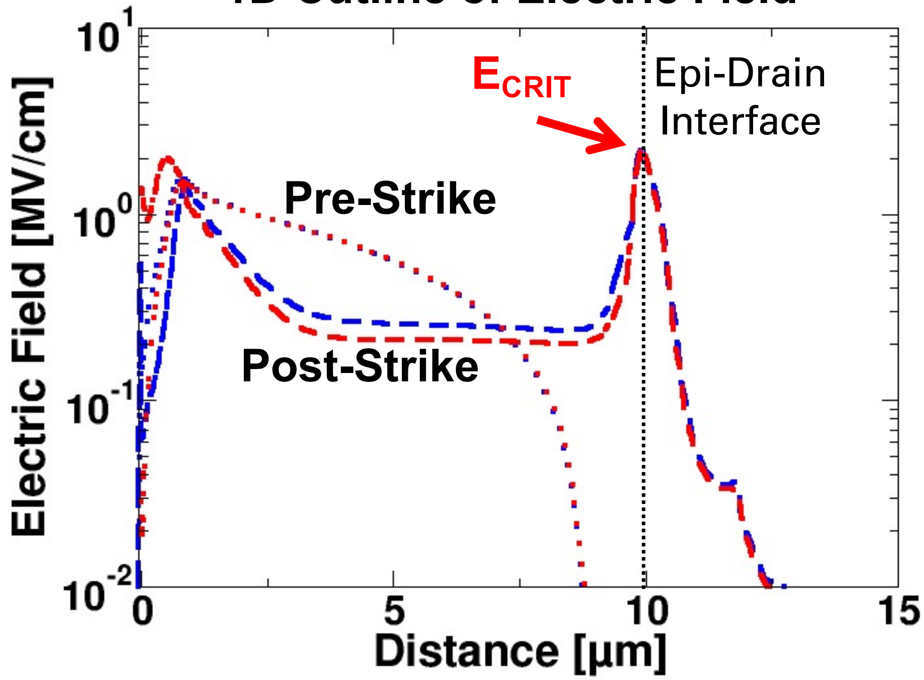
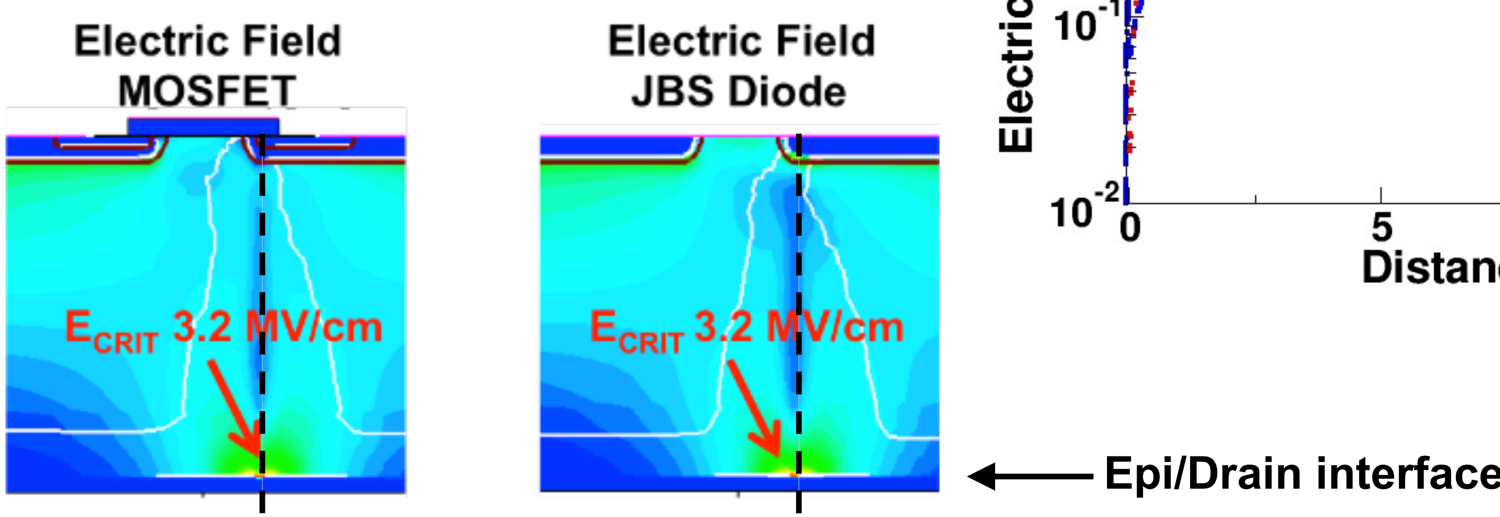
Ion strike at 500 V drain/cathode bias results in…

- **Short circuit from high carrier density**
- **Re-distribution of bias and electric field**
- **Local field exceeding electrical breakdown field (3.2 MV/cm which occurs at 1600 V DC)**

1D Cutline of Electric Field





Impact of Voltage Rating and Epitaxial Depth on SEB in SiC

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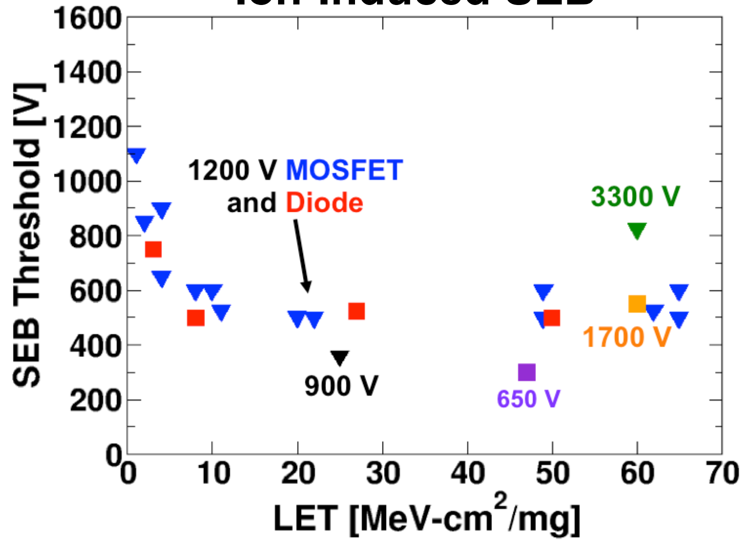
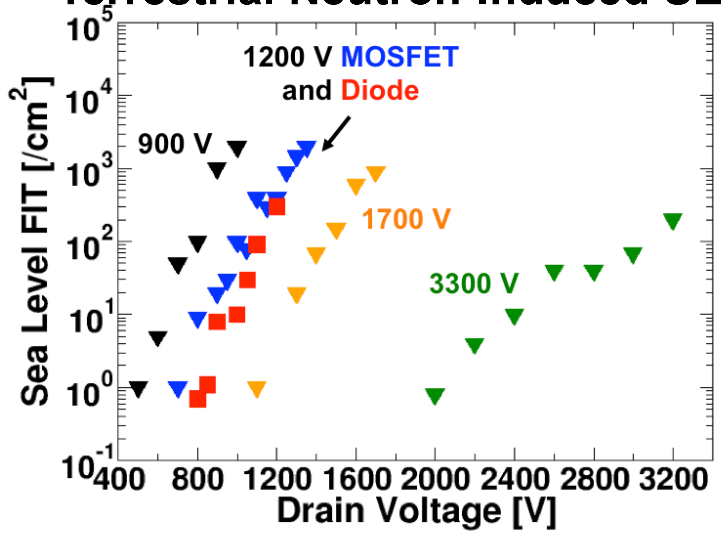
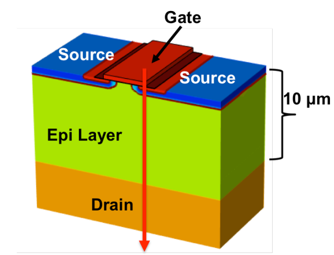
Data show increased SEB tolerance for thicker, more lightly-doped epitaxial regions

Ion-Induced SEB



Terrestrial Neutron-Induced SEB





D.R. Ball, et al, IEEE TNS 2021
Early Access on IEEE Xplore

Ion Data from Lauenstein 2017
Neutron Data from Lichtenwalner 2018, Wolfspeed Devices

VU and GE LuSTR Project: Silicon Carbide Power Components for NASA Lunar Surface Applications

Vanderbilt Engineering

TEAM MEMBERS AT VANDERBILT UNIVERSITY

- Prof. Arthur F. Witulski, Dr. Dennis R. Ball, Professor Ronald D. Schrimpf, Dr. Andrew Sternberg, Professor Kenneth F. Galloway, Professor Robert Reed, Professor Michael Alles, and Professor John Hutson

TEAM MEMBERS AT GE RESEARCH AND GE AVIATION

- Dr. Biju Jacob, Dr. Ljubisa Stevanovic, Mr. Edmund Hindle, Ms. Emily Potter

APPROACH

- Vanderbilt conducts SEE tests on existing GE 3300 V parts to establish baseline performance
- Vanderbilt analyses test results and does TCAD simulation to make recommendations to GE for hardened devices.
- GE designs 3300 V devices that will meet both the SEE-tolerance requirement and electrical specifications for a candidate diode and transistor.
- GE fabricates, tests, packages new MOSFET and diode with hardening strategy (~ 1 year)
- In parallel, Vanderbilt continues testing, simulation, materials analysis of existing devices
- Vanderbilt tests new devices to verify success in meeting program requirements.

Timeline for the LuSTR SiC Project

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Major Tasks for LuSTR Project

	Objectives	2021 Q1	2021 Q2	2021 Q3	2021 Q4	2022 Q1	2022 Q2	2022 Q3	2022 Q4	2023 Q1	2023 Q2	2023 Q3	2023 Q4
A	**R&D/Testing Specific Aims**												
	Months			1 2	3 4 5	6 7 8	9 10 11	12 13 14	15 16 17	18 19 20	21 22 23 24		
1	**GE Delivery of Existing Devices to VU**												
2	**VU Preparation for first ion test**												
3	**TCAD Model of SiC Diodes and MOSFETs**												
4	**1st heavy-ion test of GE devices at TAMU**												
5	**GE and VU spec., order wafer**												
6	**VU failure analysis on pristine and post-rad devices**												
7	**VU electrical testing in-situ of pre- and post-rad devices**												
8	**GE mask design**												
9	**GE fabricates RH diode and MOSFET in parallel**												
10	**GE tests, packages, and ships new RH Devices**												
11	**Vanderbilt conducts second heavy-ion test**												

Other tasks Fabrication

Summary for VU-GE LuSTR Program on SiC

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- Rad-Hard, high voltage, high current power devices required for lunar exploration
- Silicon carbide naturally suited to these applications (electric vehicles on earth)
- 1200 V SiC devices show vulnerability to SEB at ~40% rated voltage
- VU-GE LuSTR program aims to use 3300 V devices to push SiC SEB boundary to significantly higher voltage, without losing electrical advantages
- Tests on hardened 3300 V devices will take place in Spring 2023