Radiation Hardening of Silicon Carbide Power Devices for Lunar Applications

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Abstract: Silicon carbide (SiC) has excellent properties for use in power device applications. In comparison to silicon, it has higher breakdown field and thermal conductivity. SiC devices are ideally suited to high voltage, high-power-density power converter applications in space and offer significant advantages in size, weight, and power (SWAP). However, SiC power MOSFETs have been found to be susceptible to single-event effects (SEE) from heavy-ion irradiation found in the space radiation environment. This project, based on an earlier NASA ESI Grant, will develop SEE tolerant SiC power diodes rated at 1200V, 40A and SEE tolerant SiC power MOSFETs with minimum rating of 600V, 40 A, RDS_{on} < 24 mΩ. This paper will briefly discuss the state of the art and the way forward to reach these goals.

Problem Description

Next Generation Power Systems for Lunar applications require ~10x Power compared to present generation space power systems.

- Current generation,: ~0.2 to 1 kW
- Artemis applications: 10 kW or greater

Conduction Loss $P_L=I^2R$ requires high bus voltage

- If conductor resistance is R_C=0.01 and I=100 A, P_{LOSS}=100 W just in conductors
- Target a bus voltage 1000 V, dramatically lowers current

High-voltage power semiconductors are needed for power conversion from the 1kV bus

- Operational margin requires electrical breakdown 25% greater than rated voltage
- Single-Event Burnout (SEB) 25% greater than rated voltage.

Current 1.2 kV Silicon Carbide (SiC) transistors have SEB of ~40% of rated voltage.

- Permanent damage, device not survivable in space radiation environment.
- Need to modify SiC power diodes and transistors to make the SEB voltage >1 kV for a wide range of ion energies.

Approach to SiC Hardening Problem

Based on extensive experimental measurements and TCAD simulations of SiC device physics, we have identified key device physical parameters that govern device single event burnout in SiC power devices. Working with General Electric Research for device fabrication, we jointly design and GE will fabricate devices and extensively test these devices in heavy ion beams. This should provide information necessary to reach a final design that will meet the LuSTR radiation tolerant device specifications given in the Abstract.

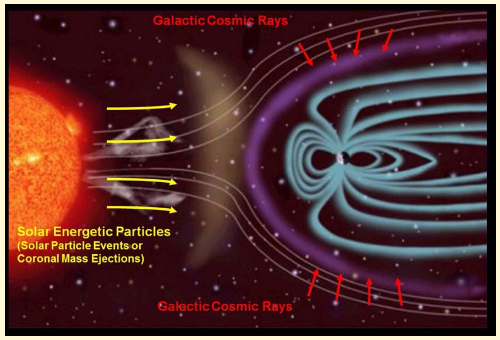


Image credit: NASA/JPL-Caltech/SwRI

Space Particle Radiation Environment

Galactic Cosmic Rays (GCR)

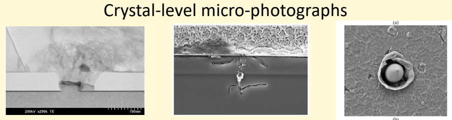
- Energetic ions (atomic nuclei) traveling at nearly the speed of light
- Originate in Super Nova
- All the elements in the periodic table
- Can penetrate through solid materials

Solar Energetic Particles (SEP)

- Charged particles generated in nuclear reactions and accelerated by magnetic fields in the sun
- Primarily electrons and protons, but other elements present as well

What happens when GCRs or SEPs go through a power transistor biased with a high voltage?

Crystal-level micro-photographs



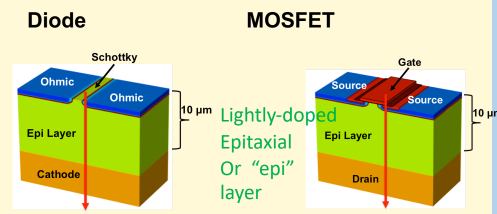
Kuboyama, et. al, RADECS 2018

Casey, et. al, IEEE TNS Jan. 2018

The semiconductor in the transistor is normally crystalline. The combination of the charge liberated by the ion and the electric field in the device creates permanent damage to the device, called Single Event Breakdown (SEB)

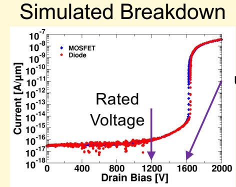
Structure of Silicon Carbide Transistors and Diodes

- Devices shown are 1200 V rated vertical JBS diode
- 1200 V rated vertical MOSFET
- Dimensions/dopings based on published literature
- Synopsys Sentaurus TCAD device simulation suite



Red arrow represents energetic ion transiting through the semiconductor device: "Single-Event"

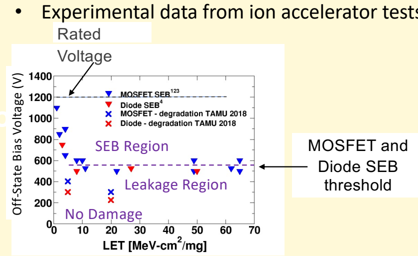
Simulated Breakdown



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

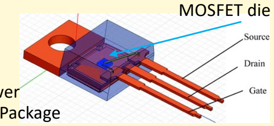
The SEB Boundary for SiC Diodes and MOSFETs

- LET=linear energy Transfer=Stopping power of ion
- 1200 V rated vertical MOSFET
- Experimental data from ion accelerator tests



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

Silicon Carbide Power Devices



Y. Liu: Discrete Power MOSFET Design and Analysis, Springer

Ion Beam Accelerator Testing

Low-energy ion beam at Vanderbilt University

Terrestrial Ion Radiation Testing

- Ion-beam testing can produce many of the ions encountered in space
- LuSTR SiC project is organized around two major ion beam tests and one fabrication cycle
- First ion test: Existing General Electric SiC power MOSFETs and diodes tested at high-energy ion beam facility
- GE fabricates new SiC MOSFETs and diodes that have good electrical charateristics AND are modified to reduce or eliminate SEB
- Second ion test: New GE MOSFETs and diodes will be tested at the same ion beam facility to characterize improvements in SEB hardness

Conclusions and Discussion

Single-event burnout in SiC is a challenging problem that when solved will increase power management capability on the Lunar surface and other space systems. An initial design has been agreed upon and the preliminary steps (material acquisition, etc.) are underway. Measurements that are expected to be informative as to validity of overall plan will be made on available SiC devices in the next twelve months. We expect this LuSTR program to advance the state of the art in understanding the SEB tolerance of higher voltage SiC power devices, further the understanding of the magnitude and frequency of ion-induced degradation, and explore fundamental material changes due to radiation.