# Terrestrial Neutron-Induced Single Event Burnout Cross-Sections and FIT Rates for High-Voltage SiC Power MOSFETs

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[3] NASA Goddard Space Flight Center

# THANKS to Our Sponsors …

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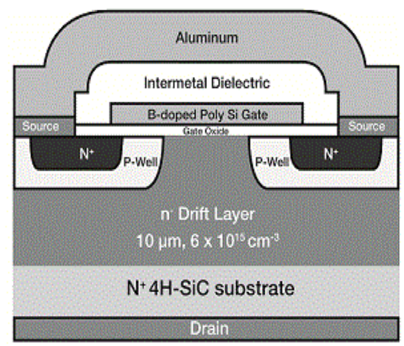
**At Vanderbilt University: NASA Early Stage Innovation Grant No: NNX17AD09G**

**At NASA Goddard: NEPP Program**

**At University of Jyväskylä: ESA/ESTEC Contract No. 4000111630/14/NL/PA and Academy of Finland Project No. 2513553**

## Outline

1. Vanderbilt's simulation framework
2. Why the interest in SiC power?
3. SEB in SiC power MOSFETs
4. Predicting neutron susceptibility




**1200 V SiC Power MOSFET**

# Vanderbilt's Simulation Framework

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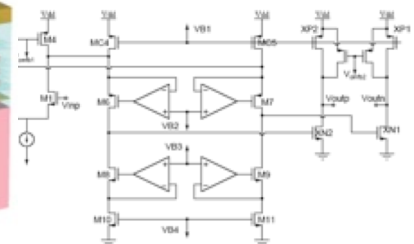
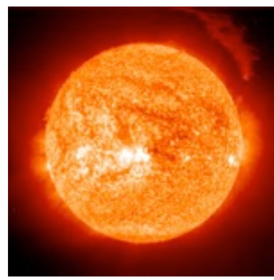
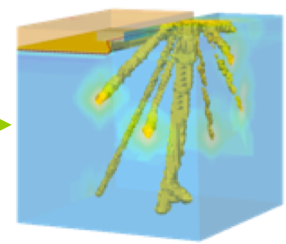
**Device/Circuit/System Virtualization**

OR



**Radiation Event Generation**





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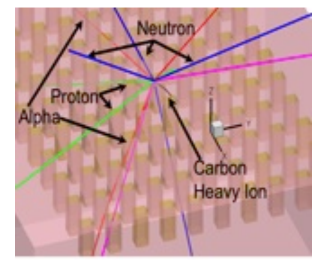
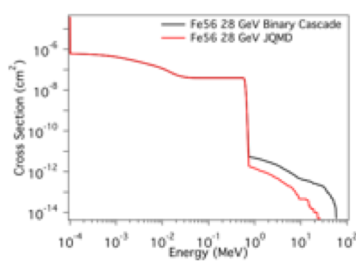
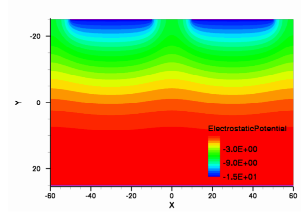
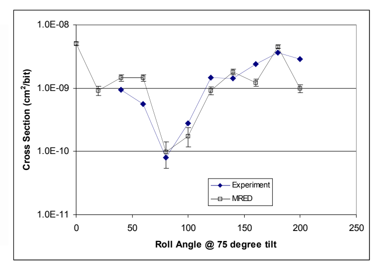



**Response Prediction**




Calorimetry TCAD Other…

# Key Technology:
# Monte Carlo Radiative Energy Deposition (MRED )

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- **A comprehensive analytical foundation of the full process of the simulation**
- **Geant4 plus unique Fortran components, CEM03, LAQGSM, and PENELOPE**
- **A sophisticated and rigorously based algorithm for cross section biasing**
- **Exact ion-ion scattering algorithm replaces Geant4's approximate multiple scattering classes**
- **Not a c++ program but rather a massive Python module written in c++ configurable at run time**
- **MRED code frozen at Geant4 version 9 to satisfy community need for traceability**


R. A. Weller, M. H. Mendenhall, R. A. Reed, et al, "Monte Carlo Simulation of Single Event Effects," IEEE Trans. Nucl. Sci., vol. 57, no. 4, pp. 1726-1746, Aug. 2010.

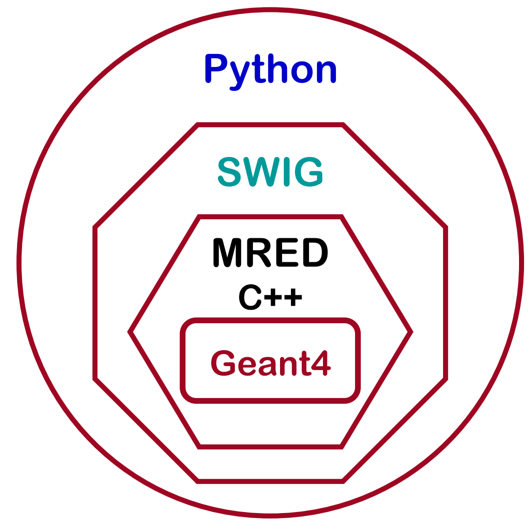
R. A. Reed, R. A. Weller, M. H. Mendenhall, et al, "Physical processes and applications of the Monte Carlo radiative energy deposition (MRED) code," IEEE Trans. Nucl. Sci., vol. 62, no. 4, pp. 1441-1461, Aug. 2015.

M. H. Mendenhall and R. A. Weller, "A probability-conserving cross-section biasing mechanism for variance reduction in Monte Carlo particle transport calculations," *Nucl. Instrum. Methods Phys. Res., Sect. A,* vol. A667, no. 1, pp. 38-43, 2012.

M. H. Mendenhall, and R. A. Weller, "Algorithms for the rapid computation of classical cross sections for screened Coulomb collisions," *Nucl. Instrum. Methods Phys. Res., Sect. B,* vol. B58, no. 1, pp. 11-17, 1991.

M. H. Mendenhall, and R. A. Weller, "An algorithm for ab initio computation of small-angle-multiple scattering angular distributions," *Nucl. Instrum. Methods Phys. Res., Sect. B,* vol. B93, no. 1, pp. 5-10, 1994.

R. A. Reed, et al, "Anthology of the development of radiation transport tools as applied to single event effects," IEEE Trans. Nucl. Sci., vol. 60, no. 3, pp. 1876-1911, 2013.

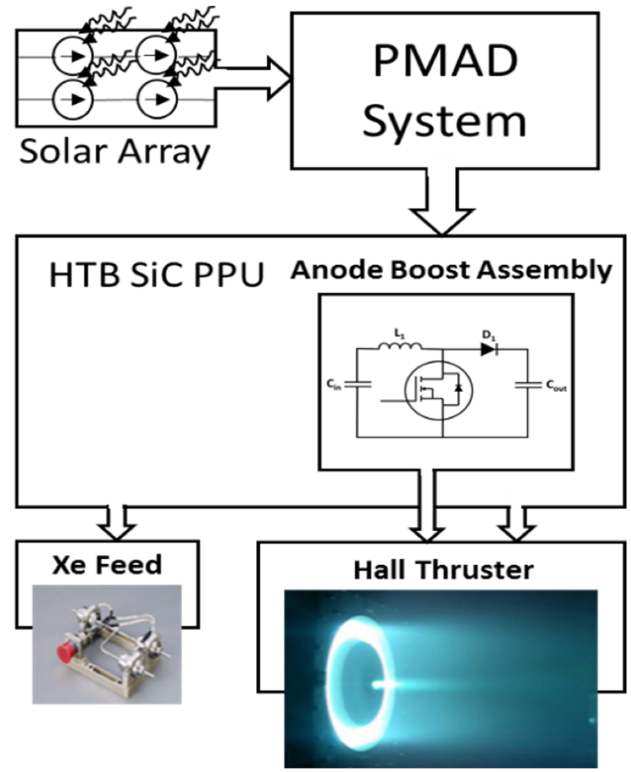



# Why Silicon Carbide Power Devices for Space?

**SiC vs Silicon Power Devices:**

- **Higher Breakdown Voltage (~ 10x vs. Si)**
- **Lower On-State Resistance (~1/100 vs. Si)**
- **Higher Temperature Operation (~3x vs. Si)**
- **High Thermal Conductivity (~10x vs. Si)**
- **Mass, cost, power savings**

**After: A. Elasser and T.P. Chow, Proc. IEEE, vol. 90, 2002.**




**Example: Concept Design of High Power Solar Electric Propulsion (SEP) for Human Exploration**

- **Desired power levels ~400 kW**
- **Change from 120 V bus voltage to 300 V**

**After: D.J. Hoffman, *et al.*, NASA/TM—2011-217281**

# Accelerated Testing – High-Temperature Reverse Bias

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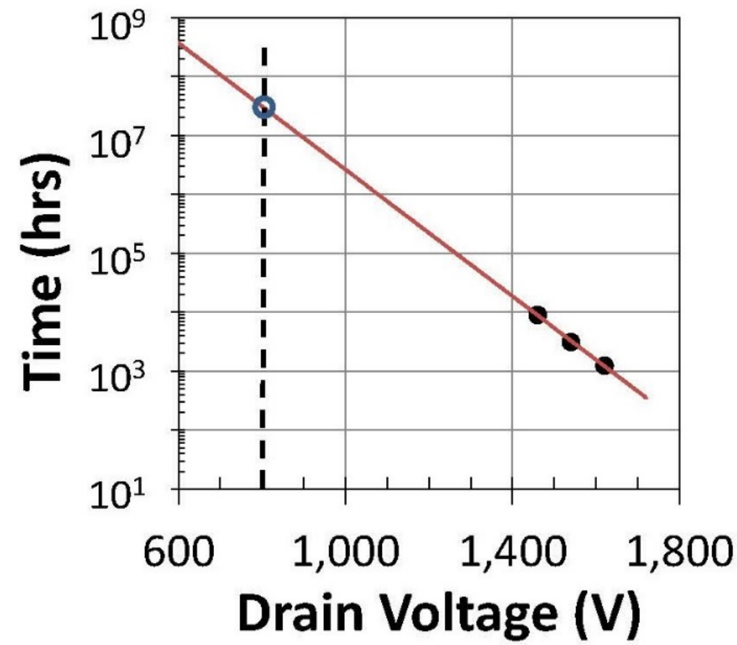
- **High-Temperature Reverse Bias (HTRB)**
- **Wolfspeed 1200 V 20A G2 MOSFETs**
- **$V_{GS}$ = 0V, $V_{DS}$ = 1460V, 1540V, 1620V**
- **Mean failure time at a given VDS predicted by extrapolation**
- **At 800 $V_{DS}$, extrapolated failure time is ~ 3 x $10^7$ hours (~ 3400 years)**




**After: D.J. Lichtenwalner, B. Hull, J. Richmond, J. Casady, D. Grider, S. Allen, and J.W. Palmour, Wolfspeed – A CREE Company, presented at NASA Space Technology Mission Directorate Early Stage Innovation Technical Exchange, NASA GSFC, September 2017.**

**See: D.J. Lichtenwalner, et al., MRS Advances, vol.1, no. 2, pp. 81-89, 2016.**

# What is the Problem ?

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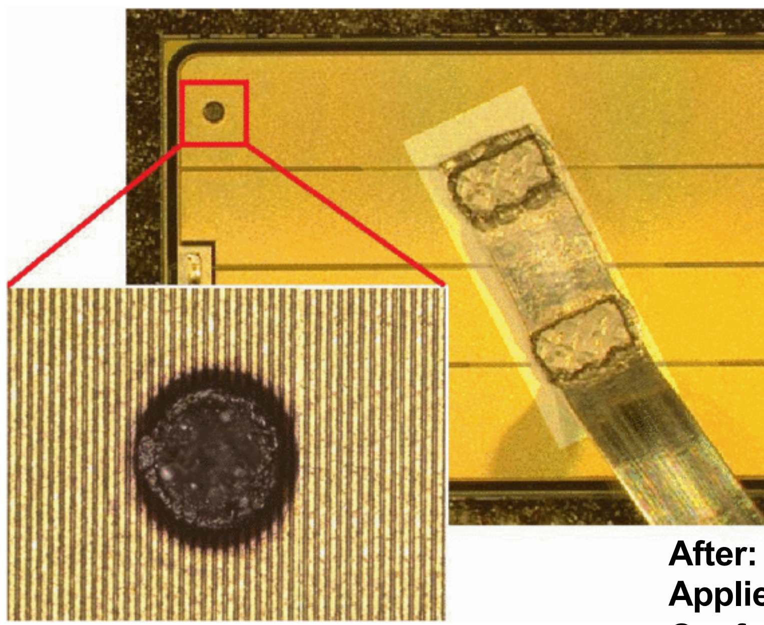
**Single Event Burnout (SEB):**

**SiC power devices – both diodes and MOSFETs – are susceptible to catastrophic failure in the swift, energetic heavy ion environment encountered in space or neutron environments**



**After: G. Consentino et. al, 2014 IEEE Applied Power Electronics Conference and Exposition, Fort Worth, TX**

# Measurement of Ion-Induced SEB in SiC Power MOSFET

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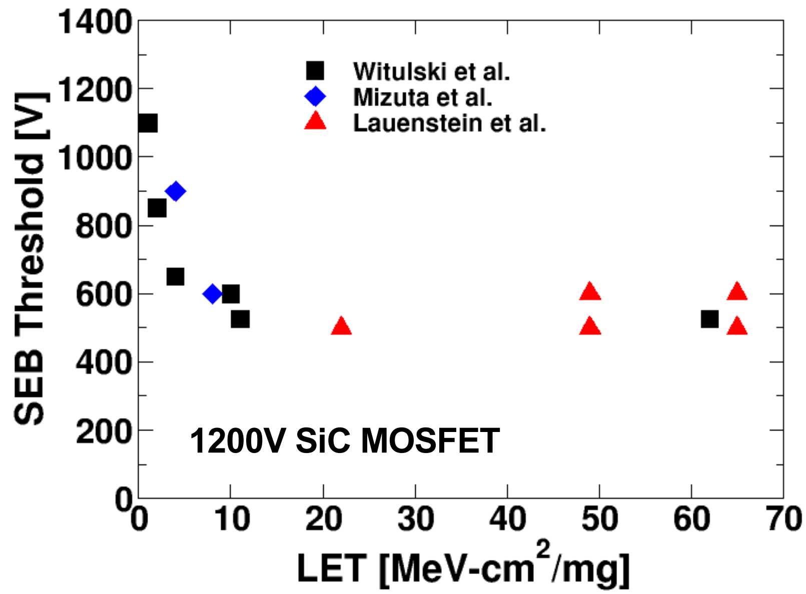
- Heavy ion tests performed on SiC power devices rated 650 V to 3300 V by NASA, ESA, JAXA, and others
- Single-event burnout (SEB) occurs at typically ½ rated $V_{DS}$
- Ion-induced degradation observed in gate, drain leakage currents prior to SEB




Witulski, *et al.,* RADECS 2017 and IEEE Trans. Nucl. Sci. (tbp).
Mizuta, *et al.,* IEEE Trans. Nucl. Sci., vol. 61, 2014.
Lauenstein, *et al.,* NASA Report GSFC-E-DAA-TN25023 (2015).

# No Methods Available for Estimating Neutron or Proton-Induced SEB in SiC Power MOSFETs

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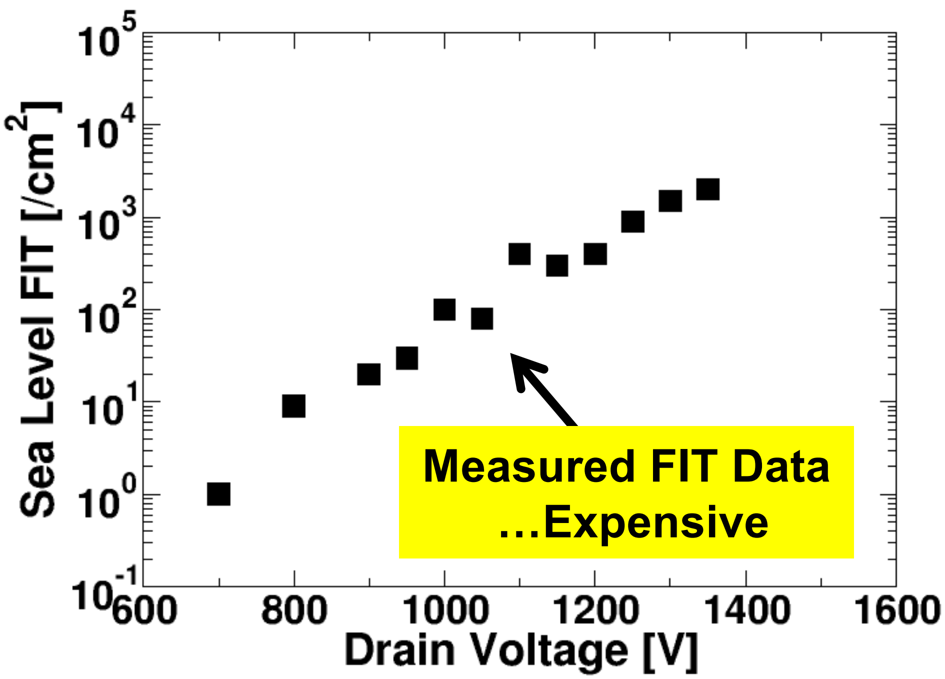
***Currently no method available for estimating SEB cross-section or FIT***




**Data: Lichtenwalner *et al.*, IRPS 2018**

# Identify Mechanisms Contributing to Neutron-Induced SEB in SiC Power MOSFETs

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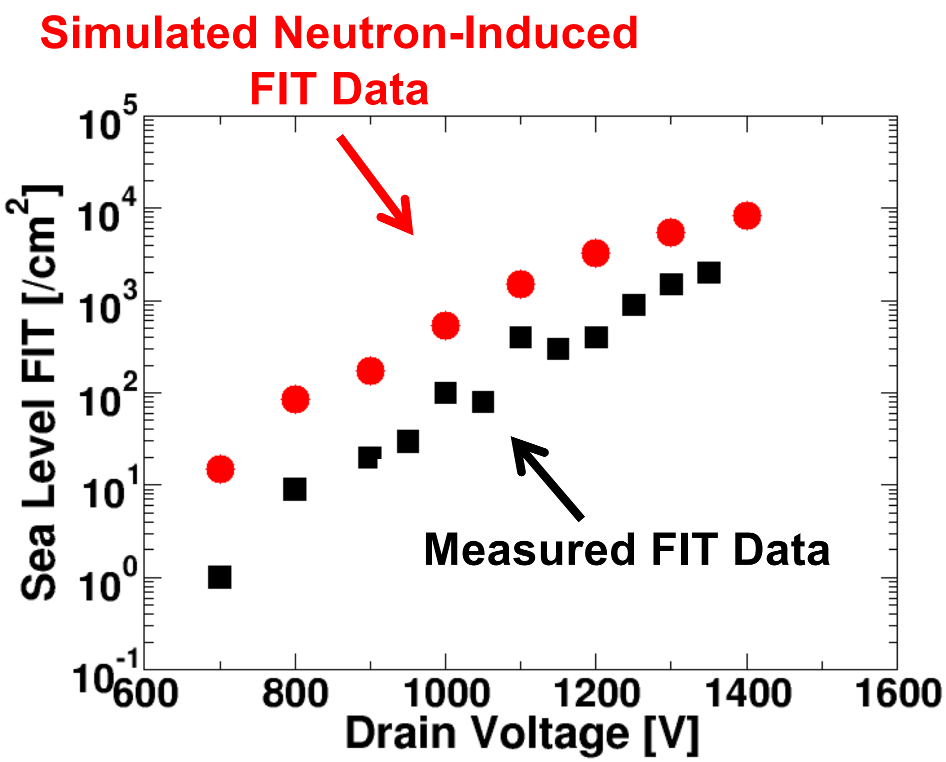
***In this work, a method has been developed for estimating neutron-induced SEB cross-section and FIT in SiC power MOSFETs***




***Approach:***

***3D TCAD for identifying mechanisms***
**+**
***Monte Carlo-based simulations for energy deposition***
**+**
***Heavy ion data for SEB threshold***

**Data: Lichtenwalner *et al.*, IRPS 2018**

# 3D TCAD Model SiC Power MOSFET

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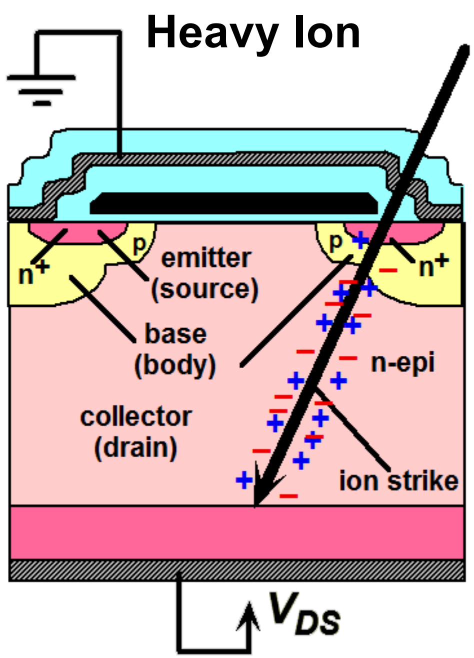
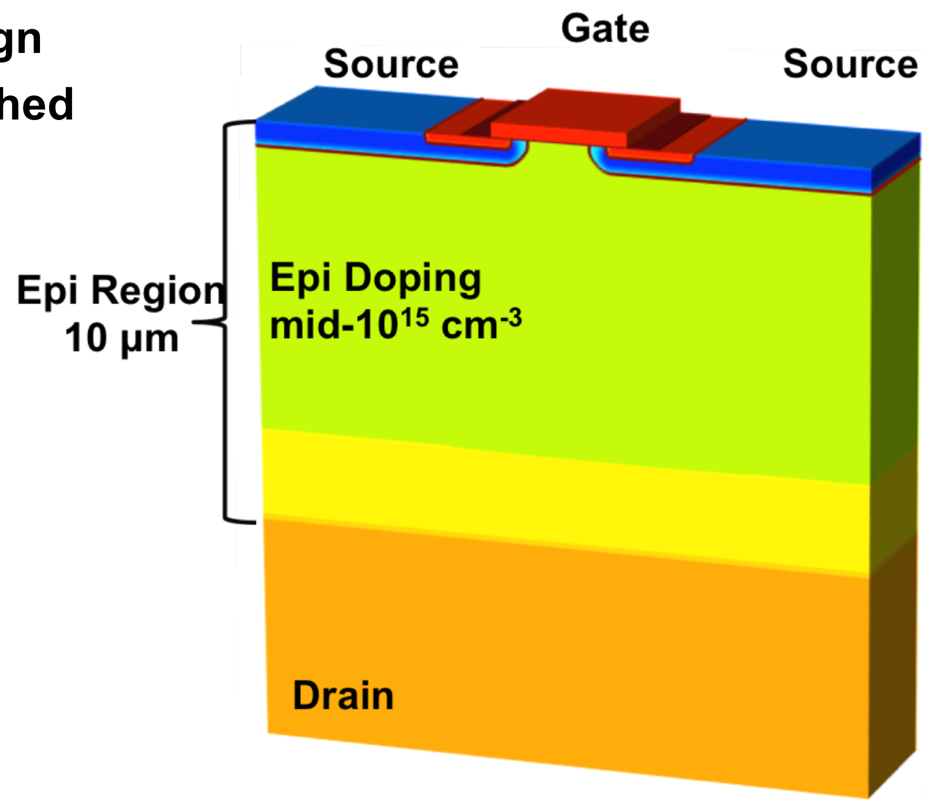
- Synopsys 3D TCAD model developed
  - 1200 V vertical MOSFET, striped design
  - Dimensions/dopings based on published literature from Wolfspeed




Witulski et al., IEEE TNS 2018

SYNOPSYS

# Heavy Ion SEB Threshold Comparing Data and TCAD

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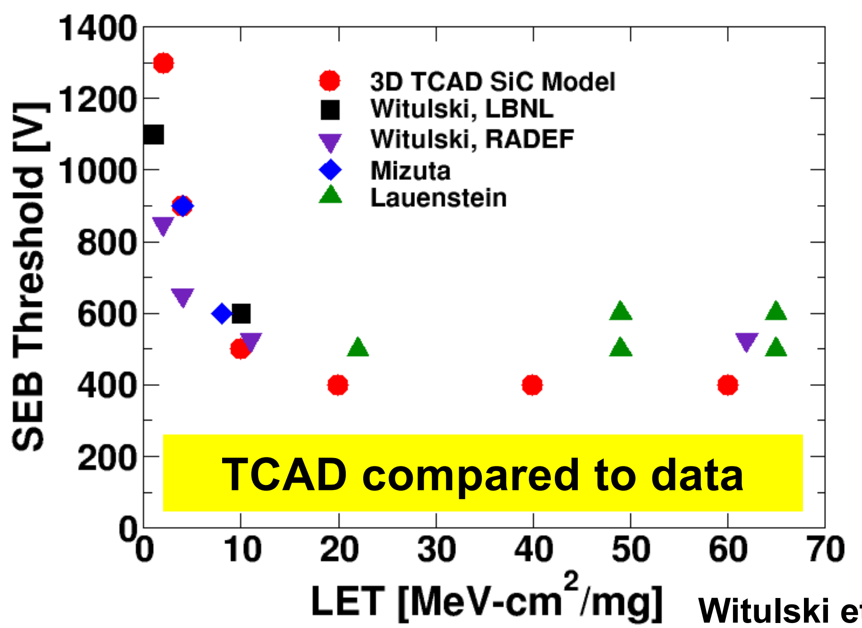
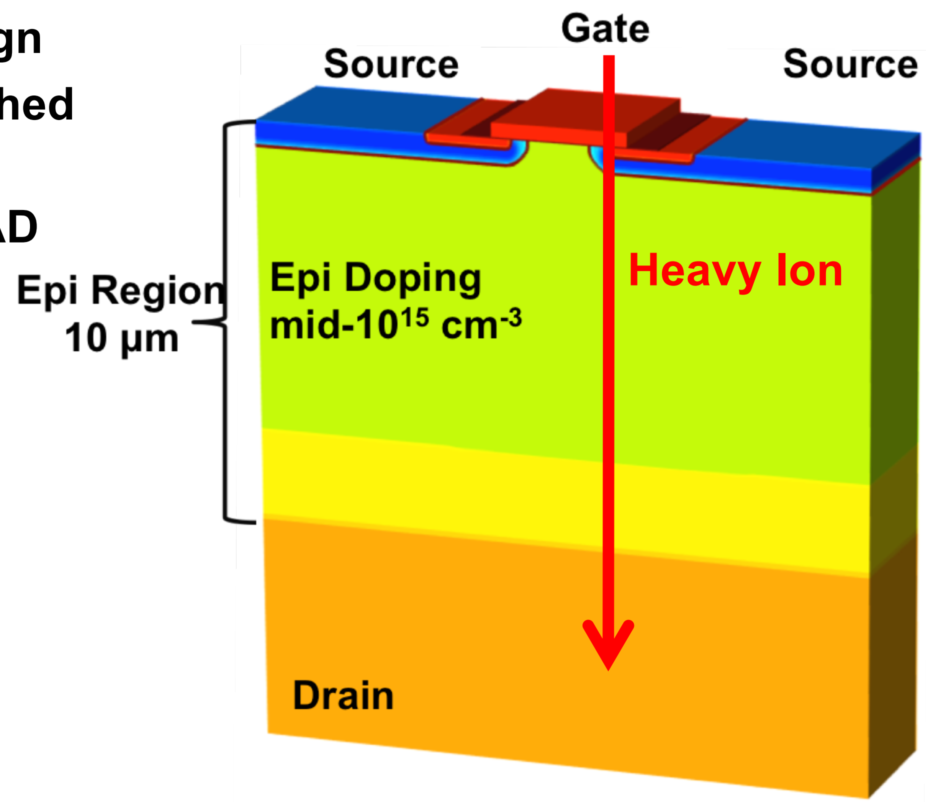
- **Synopsys 3D TCAD model developed**
  - **1200 V vertical MOSFET, striped design**
  - **Dimensions/dopings based on published literature from Wolfspeed**
  - **Heavy ion SEB data compared to TCAD simulations**




Witulski et al., IEEE TNS 2018




SYNOPSYS

# Heavy Ion SEB Threshold Sensitive Volume

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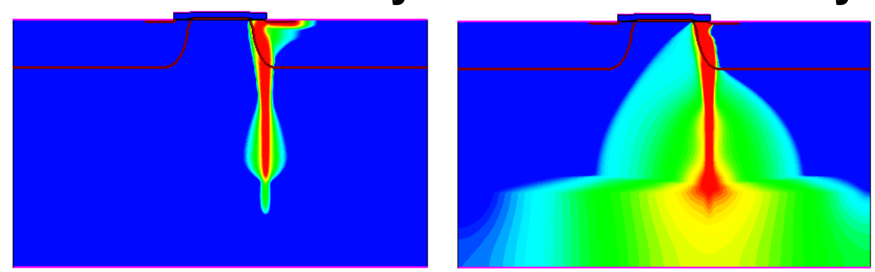
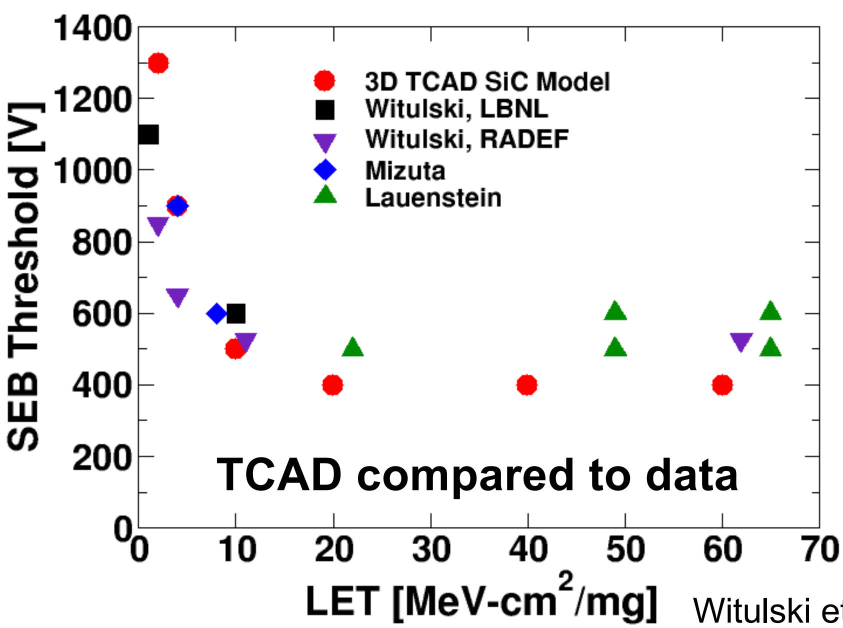
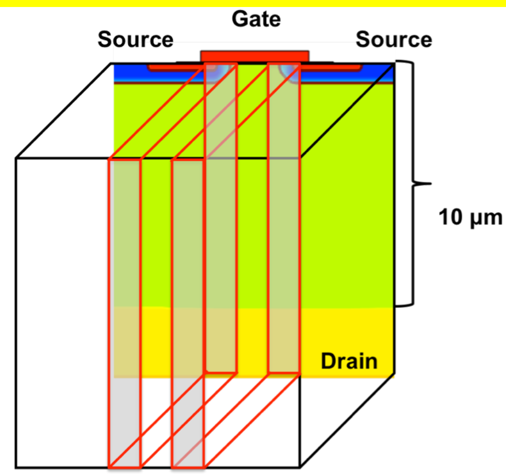
- TCAD simulation for heavy ion-induced SEB
  - Parasitic BJT turn-on
  - Avalanche multiplication dominates
  - Current runs away indicating SEB
  - Vary strike location




Witulski et al., IEEE TNS 2018

**Heavy ion SEB TCAD simulations suggest the SV is approximately the depth of the epi and the width of the channel**



# Comparing Heavy Ion SEB SV to Neutron-Induced SEB SV

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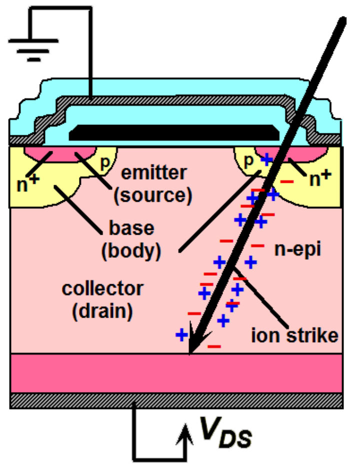
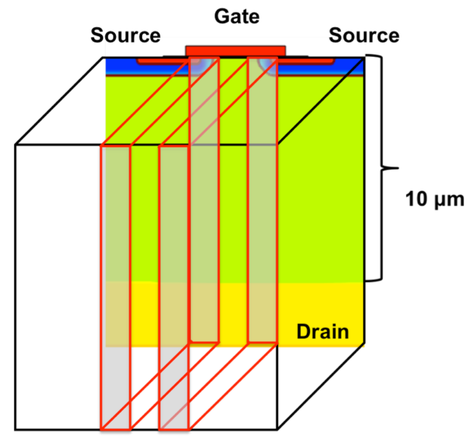
**Heavy Ion**

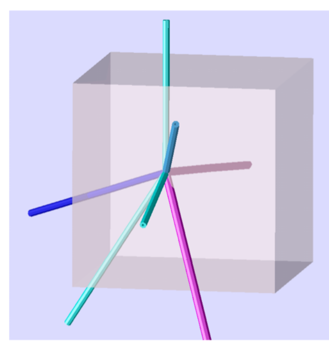
**SV ≈ Channel Width x Epi Depth**




**Neutron-induced Secondary Reactions**

**SV ≈ ?**



**Does Heavy Ion SV Apply to Neutrons ?**

# MRED Simulations of Neutron-Induced Secondary Reactions

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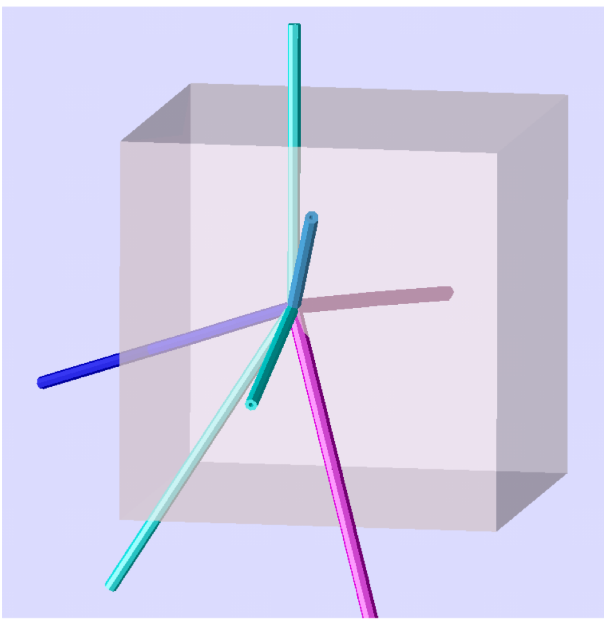
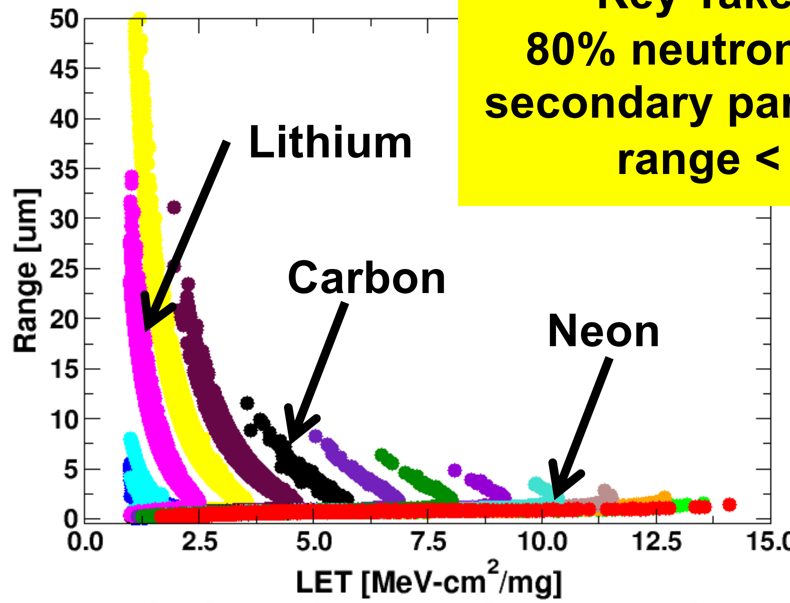
- Monte-Carlo Radiative Energy Deposition (MRED) simulations
  - Monte-Carlo radiation transport computing energy deposition in volumes
  - 2 mm x 3 mm (die area) x 30 μm SiC target
  - Terrestrial neutron spectra from LANL, JESD89A
  - Simulate neutron-induced secondary reactions



**Key Takeaway:**
**80% neutron-induced secondary particles have range < 5 μm**




Neutron-induced secondary reaction products

# Neutron-Induced SEB Threshold Sensitive Volume

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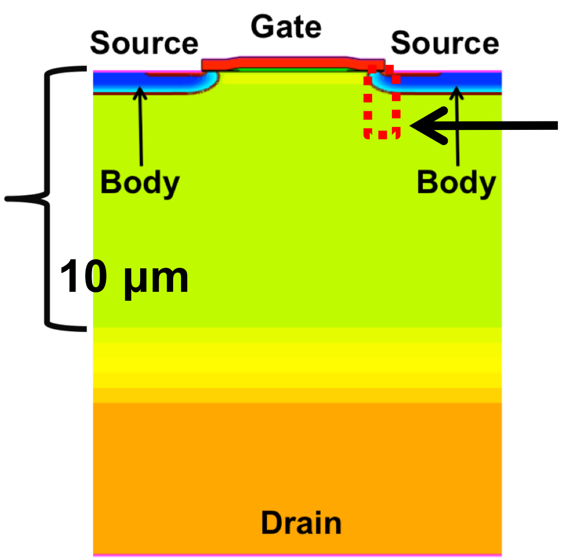
- **3D TCAD heavy ion simulations indicate SV width equivalent to the channel width, and height is 10 µm through the epi**
- **3D TCAD neutron-induced SEB simulations limit SV height < 5µm based on MRED simulations**
- **Deposited charge must be able to turn on parasitic BJT to cause SEB**




***No SEB*** **when charge is deposited in the top of the epi region**

# Neutron-Induced SEB Threshold Sensitive Volume

Vanderbilt Engineering

- **3D TCAD heavy ion simulations indicate SV width equivalent to the channel width**
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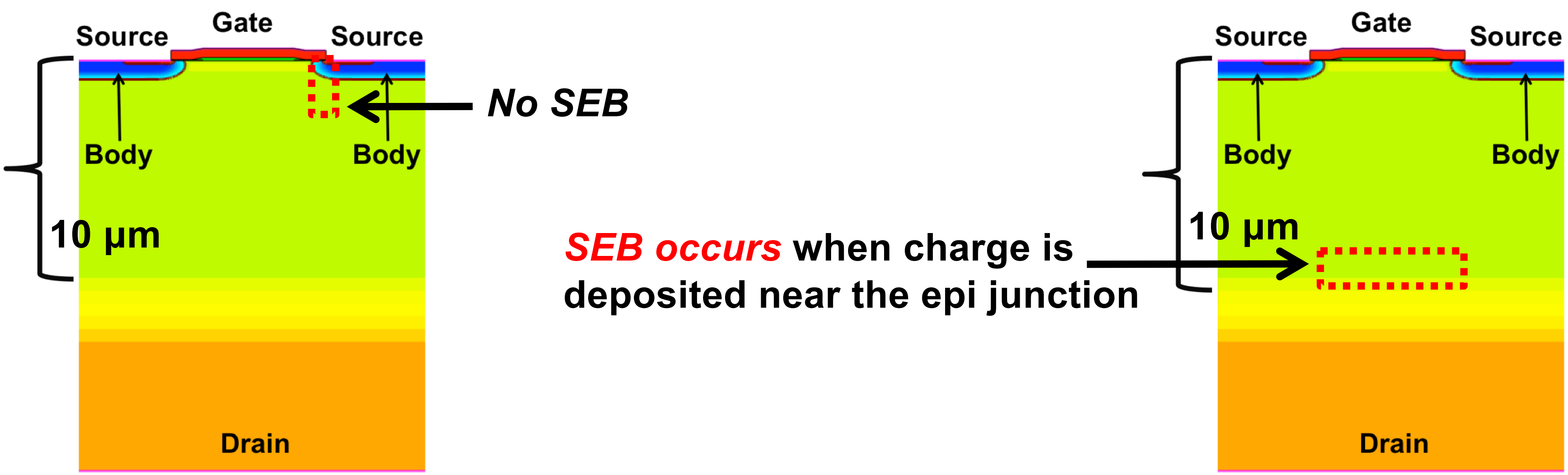

# Neutron-Induced SEB Threshold Sensitive Volume

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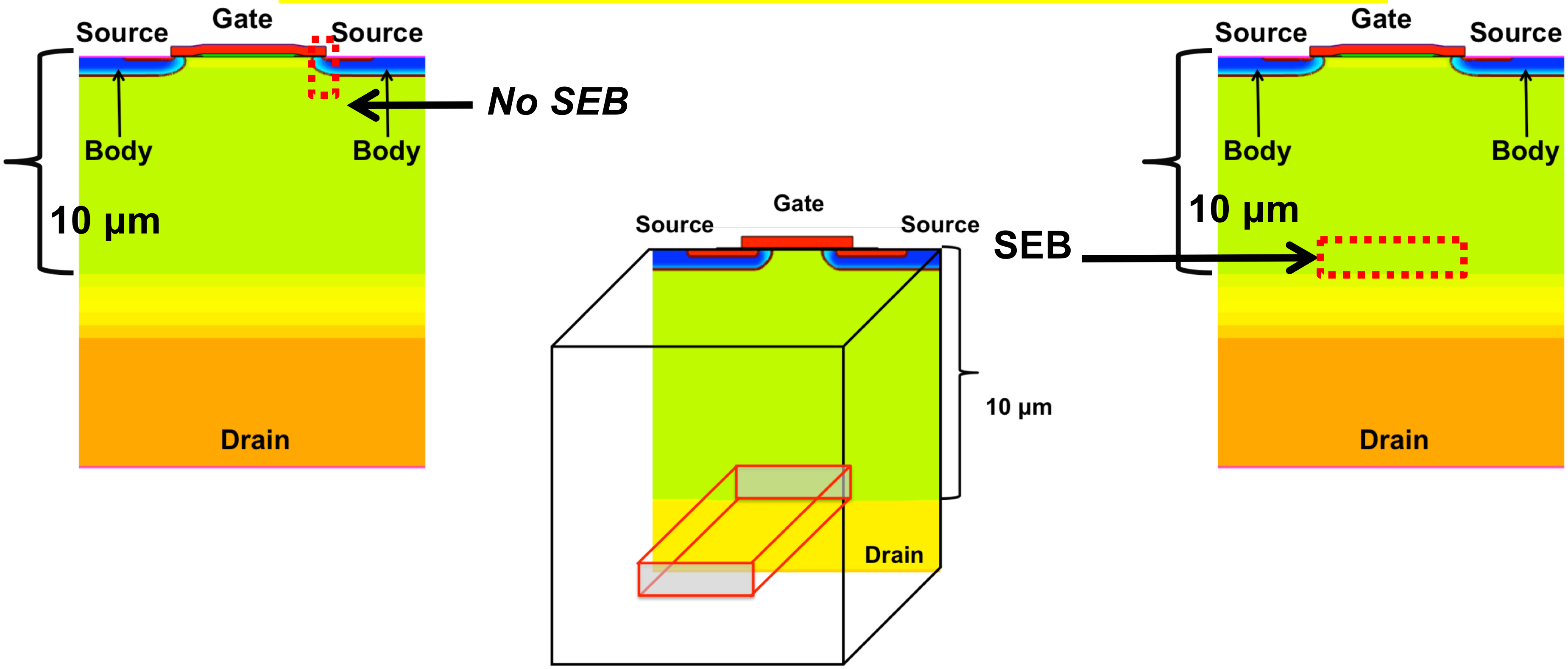
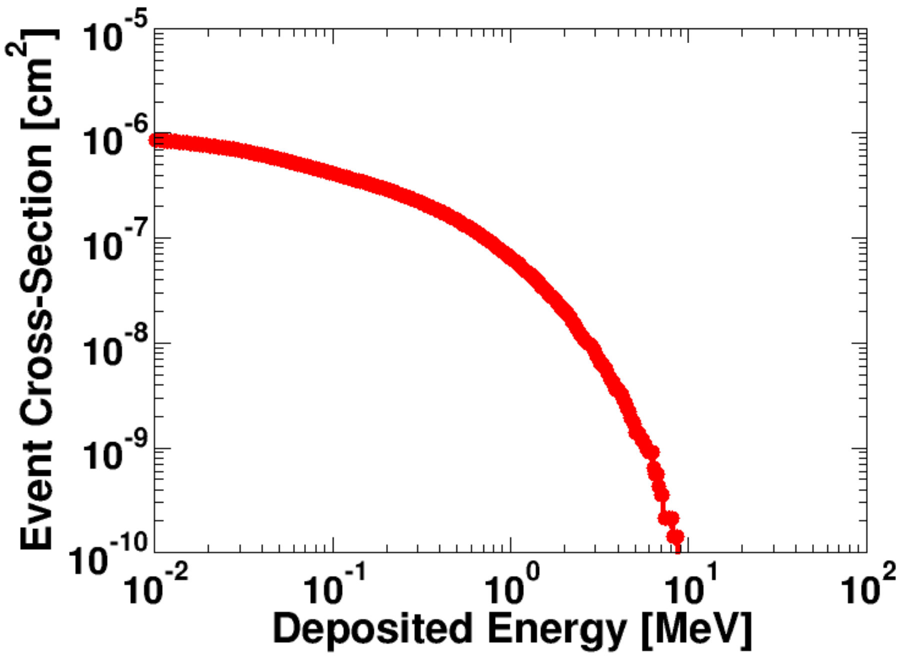
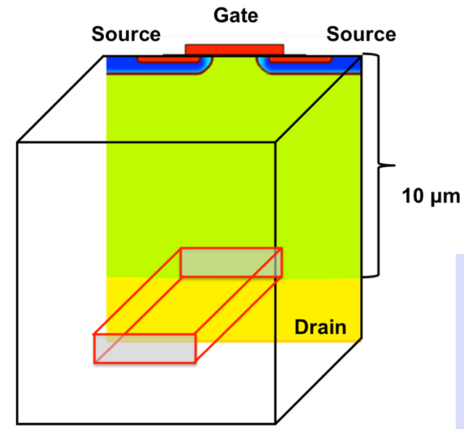
**Neutron-induced SEB TCAD simulations suggest that charge must be deposited near the epi/drain interface and under the channel/neck region**



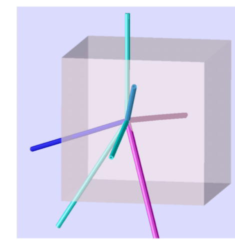
# MRED Simulations of Neutron-Induced Secondary Reaction Cross-Section

- **MRED simulations capture energy deposited in SV resulting from neutron-induced secondary reactions**
- **Event cross-section (σ) is computed as a function of deposited energy**




**TCAD-estimated SV**

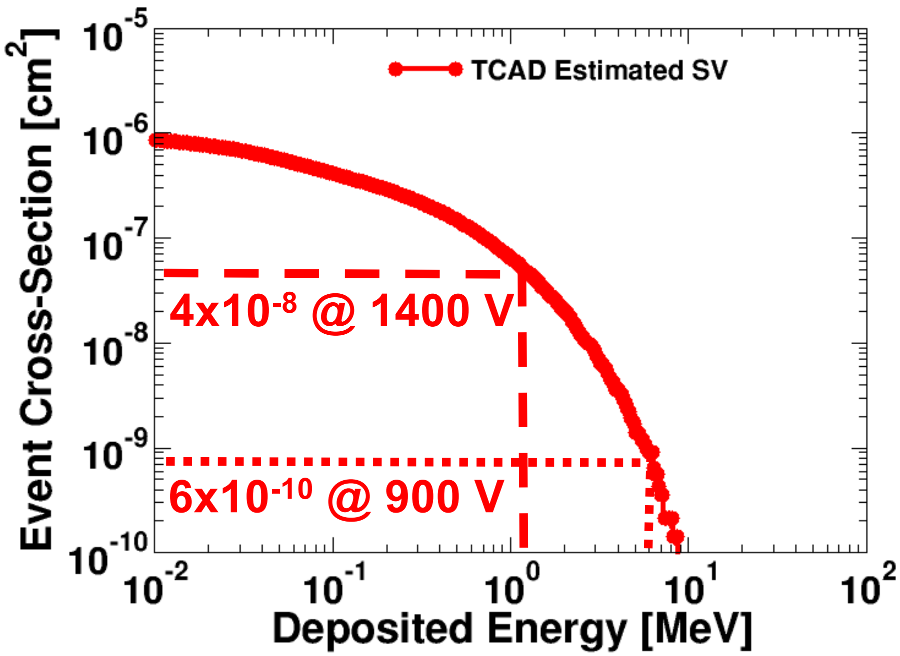


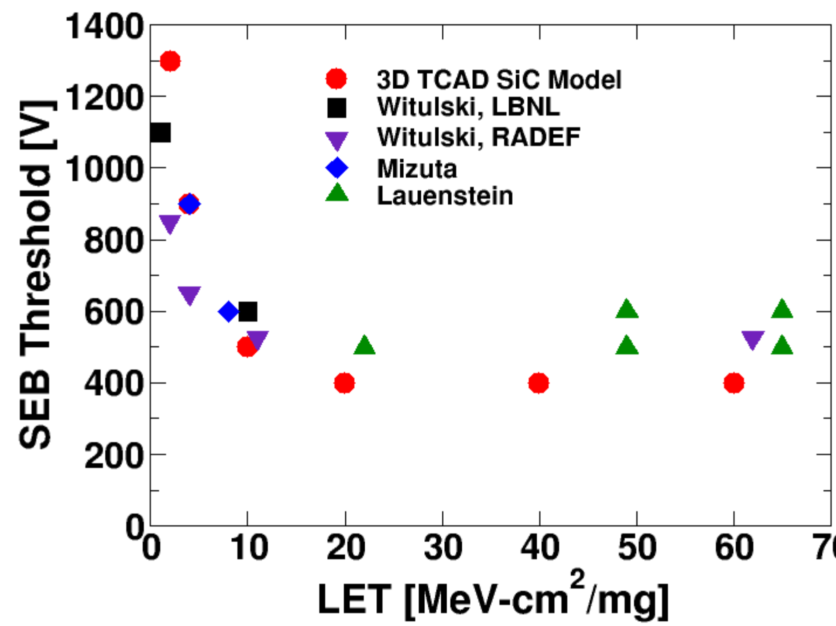
**MRED simulations generate cross-section for depositing at least an energy (E) in sensitive volume**

# Mapping Neutron-Induced Secondary Reaction Cross-Section to $SEB_{TH}$



- **Particle LET can be converted to energy deposited in a sensitive volume**
- **Event cross-section (σ) is simulated as a function of deposited energy**
- **Cross-section mapped to $SEB_{TH}$**




**Event cross-section mapped to SEB bias threshold via deposited energy**

# Calculating Neutron-Induced Secondary Reaction FIT

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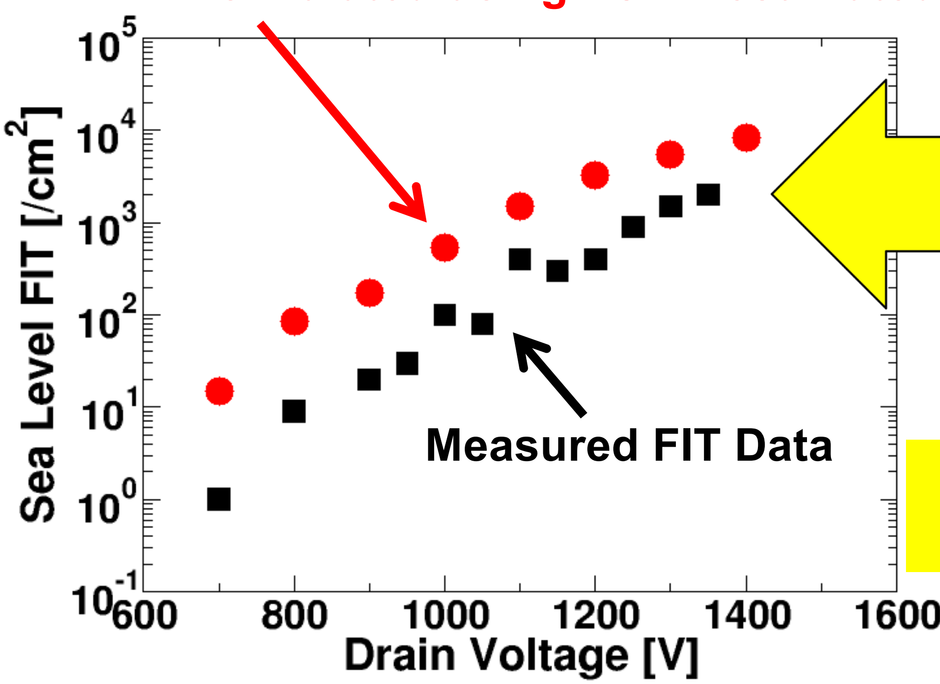
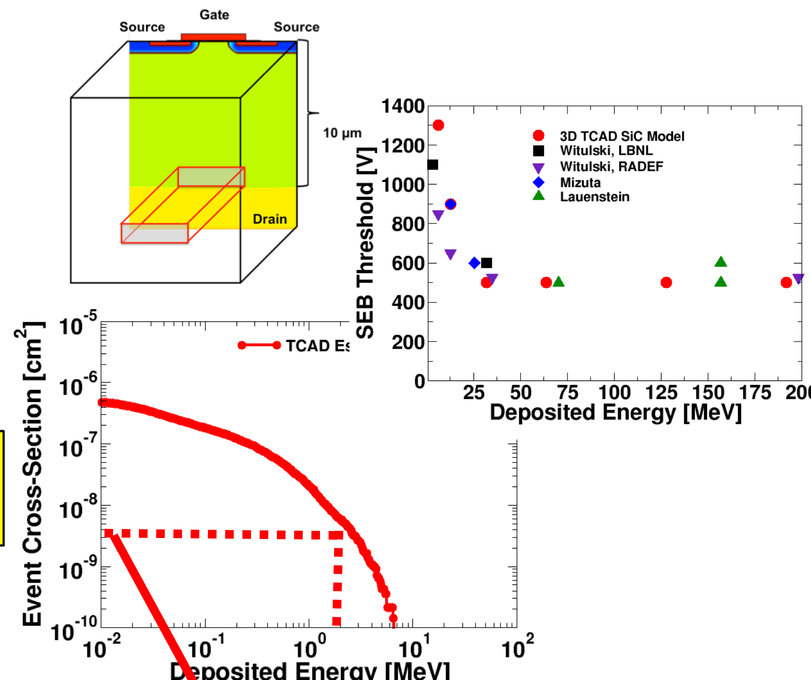
- **Terrestrial FIT rate calculated from event cross-section (σ)**
  - **TCAD SV + MRED + Heavy Ion Data**

**FIT simulated using TCAD-estimated SV**




$$\text{FIT [/cm}^2\text{]} = \frac{\sigma * \text{Neutron Flux} * 10^9 \text{ hours}}{\text{Die Area}}$$

Data: Lichtenwalner *et al.*, IRPS 2018

# Conclusions

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- **Heavy ion data used to estimate critical charge for SEB**
- **Simulations explore where charge must be deposited for SEB**
- **Sensitive volume constructed based on spatial sensitivity**
- **Charge generated by neutron-induce secondary production in a sensitive volume near the epi/drain interface and beneath the channel results in SEB**
- **Method used to estimate neutron-induced SEB cross-sections and FIT rates**