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Challenges for Radiation Hardness Assurance (RHA) on Power MOSFETs

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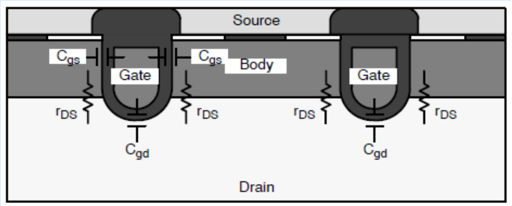
Introduction

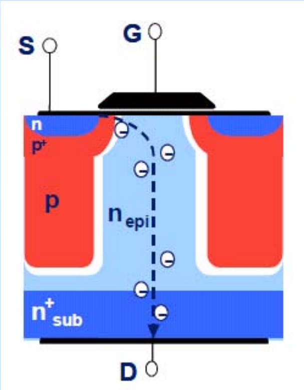
- **Definition of RHA on power MOSFETs:**
  - All activities undertaken to ensure that the MOSFET will perform to its design specifications after exposure to the space radiation environment
- **RHA involves:**
  - Mission/system/subsystem requirements
    - Power, voltages, current, switching speed, size, quantity, etc.
  - Radiation environment definition
    - Low Earth orbit (LEO)? Geosynchronous orbit (GEO)? ...
    - Heavy ion fluence, total ionizing dose (TID) accumulation
  - **Part selection**
    - Availability, cost, reliability, electrical performance
    - and for RHA, single-event effect (SEE) & TID performance
  - **Part testing**
    - Radiation source parameters, bias conditions, test setup
  - **Failure rate prediction**: method (?)

NEPP RHA Focus

- **Support test method revision/guideline development**
- **Evaluate alternative power devices for space applications**
  - New technologies
  - New suppliers
- **Develop reliable single event gate rupture (SEGR)/ single-event burnout (SEB) rate prediction capability**
  - Enhance understanding of failure mechanisms
  - Develop a SEE rate prediction tool



Trench topologies



Superjunction structures

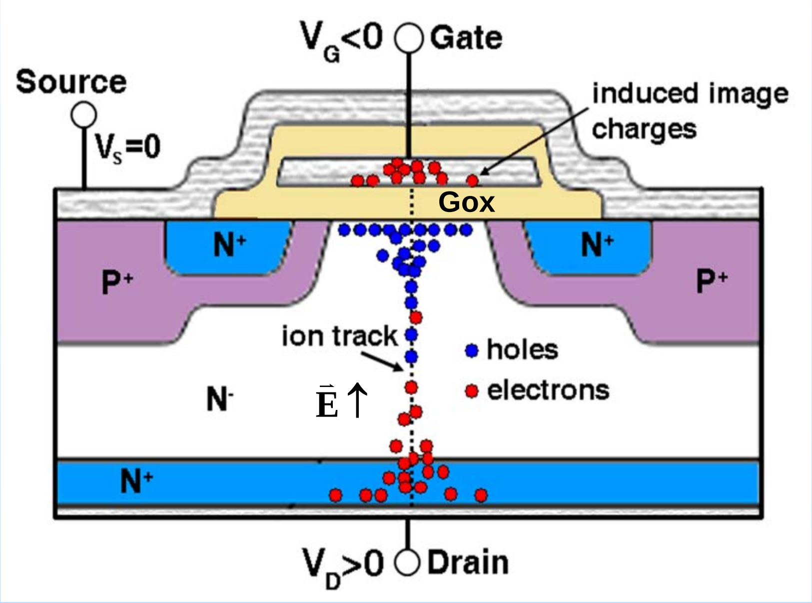
Expected Impact to Community

- **Minimize power MOSFET derating penalty (maximize performance) through better failure rate prediction**
  - Benefit to designers AND suppliers
- **Strengthen existing and foster new relationships with industry**
  - Expansion of power device options available for insertion into space applications
  - Development of products that meet the needs of spacecraft and instrument designers
- **Streamline test and qualification methods**
  - Foster agreement through collaborative efforts
  - Produce meaningful radiation test data

Some Background

- **Single-event gate rupture (SEGR) continues to be a key failure mode in power MOSFETs**
- **SEGR is complex, making rate prediction difficult**

- **SEGR mechanism has two main components:**
  - Gate oxide (G_{ox}) damage
    - Reduces field required for rupture
  - Epilayer response
    - Creates transient high field across the oxide

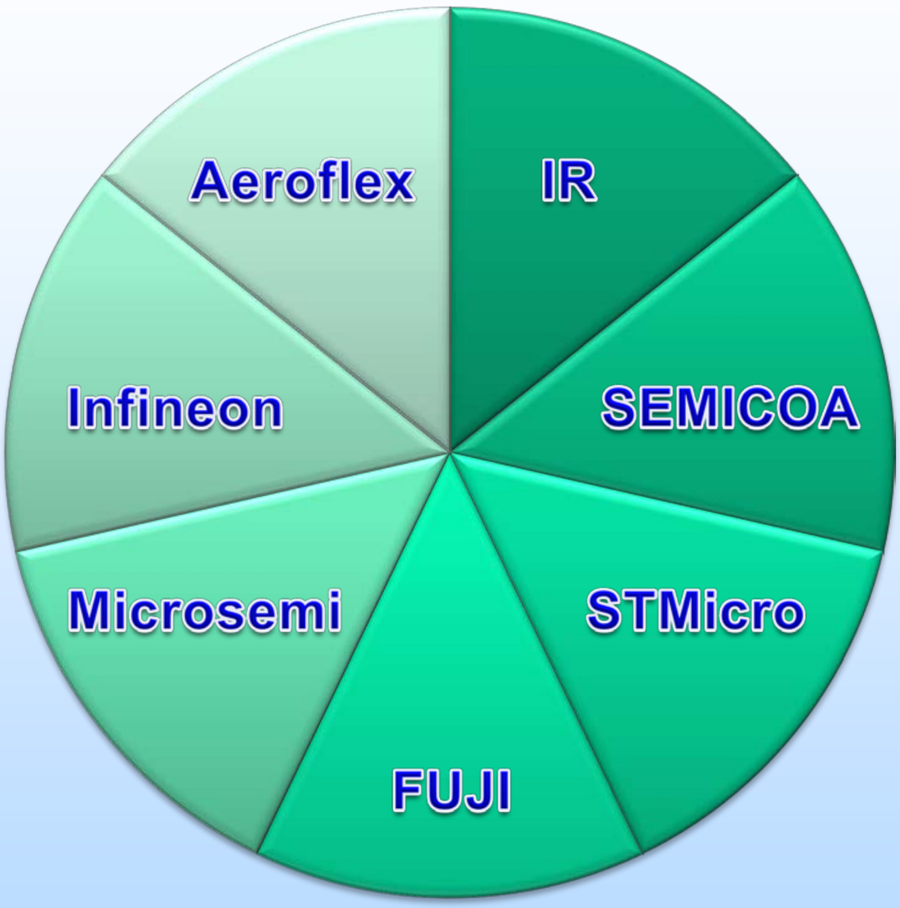


SEGR in a typical planar vertical power MOSFET (VDMOS)

We know our mission requirements and our radiation environment. We are ready for:

PART SELECTION

Vendors



The number of manufacturers of radiation-hardened silicon power MOSFETs is growing

Vendor Datasheets

PD-91224D

International
IOR Rectifier

RADIATION HARDENED
POWER MOSFET
THRU-HOLE (TO-254AA)

IRHM7360SE
JANSR2N7391
400V, N-CHANNEL
REF:MIL-PRF-19500/661
RAD Hard™ HEXFET® TECHNOLOGY

Product Summary

Part Number	Radiation Level	$R_{DS(on)}$	I_D	QPL Part Number
IRHM7360SE	100K Rads (Si)	0.20Ω	22A	JANSR2N7391

TO-254AA

International Rectifier's RADHard™ HEXFET® MOSFET technology provides high performance power MOSFETs for space applications. This technology has over a decade of proven performance and reliability in satellite applications. These devices have been characterized

Features:

- Single Event Effect (SEE) Hardened
- Ultra Low $R_{DS(on)}$

Table 2. Single Event Effect Safe Operating Area

Ion	LET MeV/(mg/cm²))	Energy (MeV)	Range (µm)	V_{DS} (V) @V_{GS}=0V	@V_{GS}=-5V	@V_{GS}=-10V	@V_{GS}=-15V	@V_{GS}=-20V	@V_{GS}=-25V
Cu	28	285	43	325	325	325	325	325	325
Br	36.8	305	39	325	325	325	325	320	—

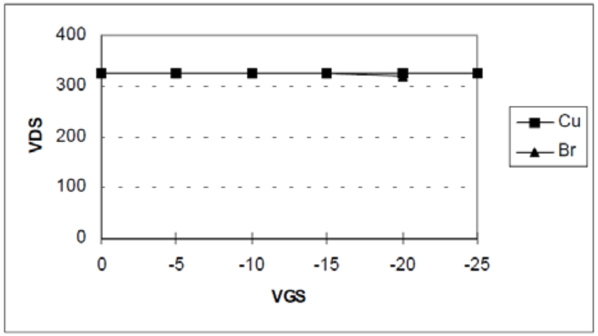


Fig a. Single Event Effect, Safe Operating Area

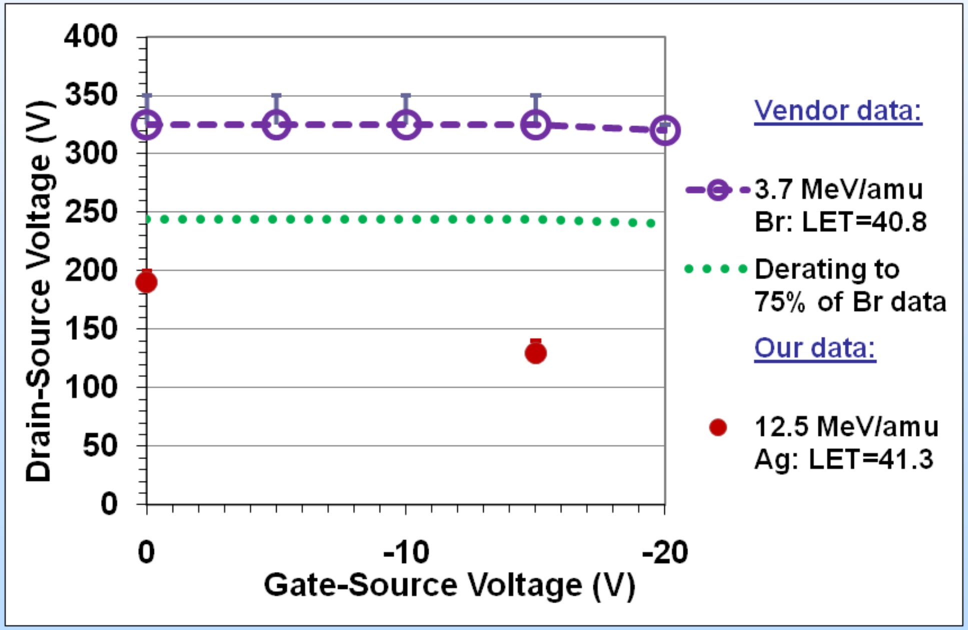
EEE-INST-002: Instructions for EEE Parts Selection, Screening, Qualification, and Derating

Type	Stress Parameter	Derating Factor
All (Note 2)	Power	0.60
	Current	0.75
	Voltage (Note 1)	0.75
	Junction Temperature 2/	0.80
Power MOSFETs	Gate to Source Voltage	0.60
	Source to Drain Voltage	0.75
	Junction Temperature 2/	0.80

- Ex/ operation bias needed: gate-source off bias (V_{GS}) = 0 V with peak drain-source voltage (V_{DS}) = 180 V
  – Per NASA EEE-INST-002, V_{DS} derating factor = 0.75; 180 V→ 240 V for "overhead"
- Circuit designer locates part that seems to fit all electrical needs, noting also:
  – JANS-qualified, appears to meet both TID and SEE requirements per Mission Radiation Requirements document prepared by radiation engineer

If Only RHA Were That Easy...

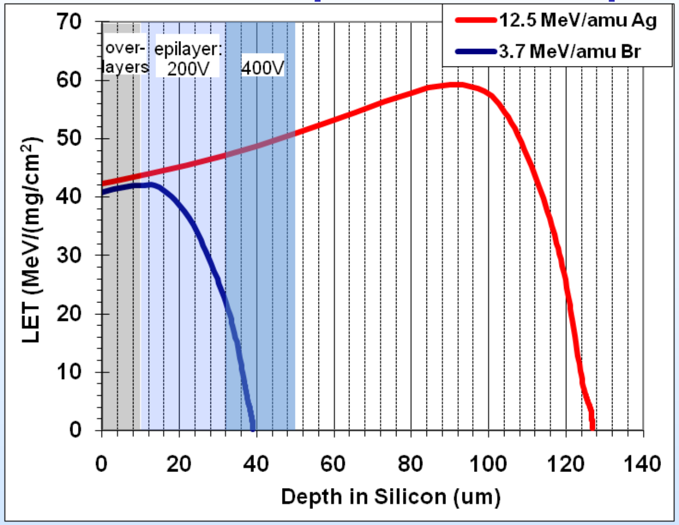
- **Power MOSFET SEE data are complex –**
  - Because the failure mechanisms are complex.
- **Linear energy transfer (LET) alone is not the appropriate metric for power MOSFET SEE RHA**



For the same incident LET, irradiation with a different ion yielded SEE failure at a much lower bias for this part

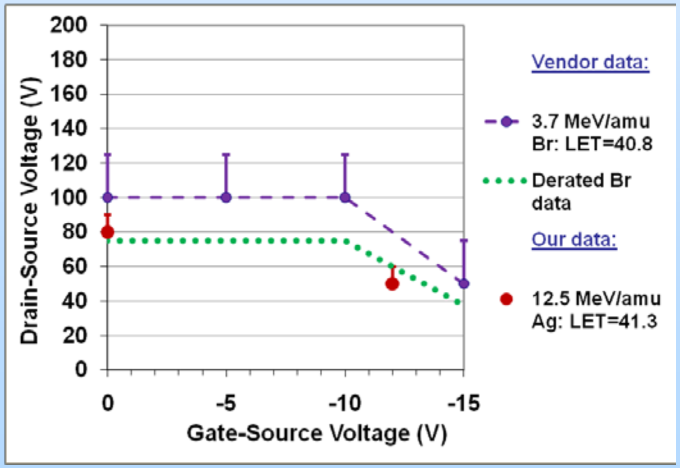
Ion LET vs. Energy

Ion range effects: Energy deposition versus ion penetration depth

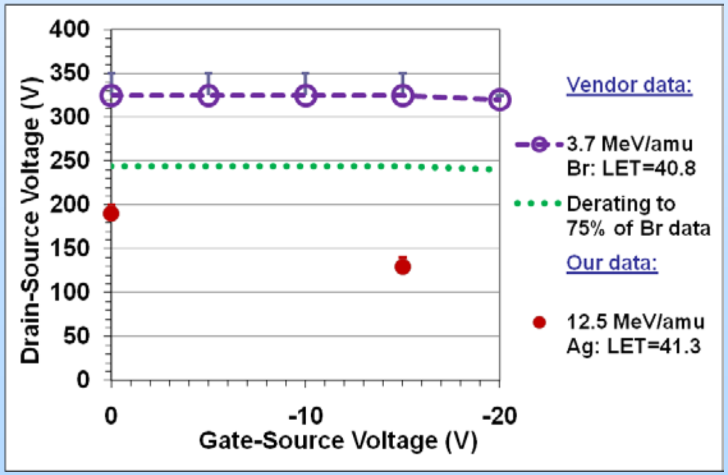


For the same incident LET, ions with different energies will deposit different total energy into the sensitive epilayer, yielding different SEGR test results. ***(see Titus, et al., 1996)***

– Example of this ion range effect is shown in a 200V and a 400V vertical power MOSFET (VDMOS):



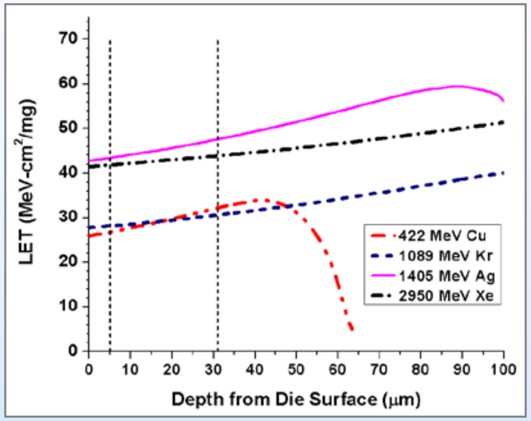
200V VDMOS

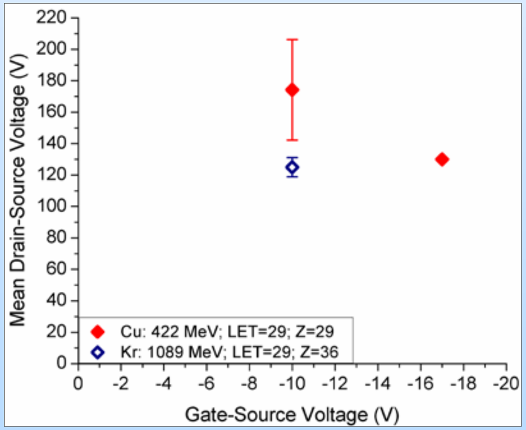


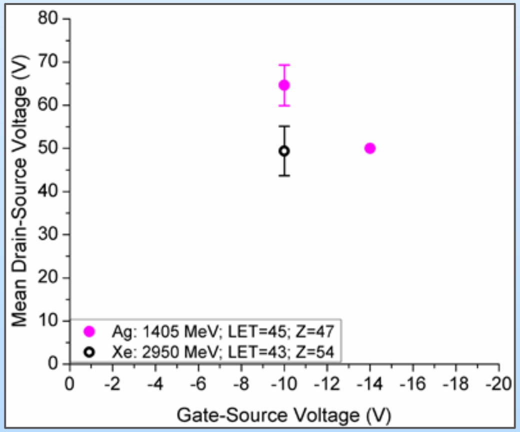
400V VDMOS

Ion Species vs. Energy Deposition

- **Tests controlling for charge ionized in epilayer expose effects of ion atomic number on SEGR failure threshold bias**





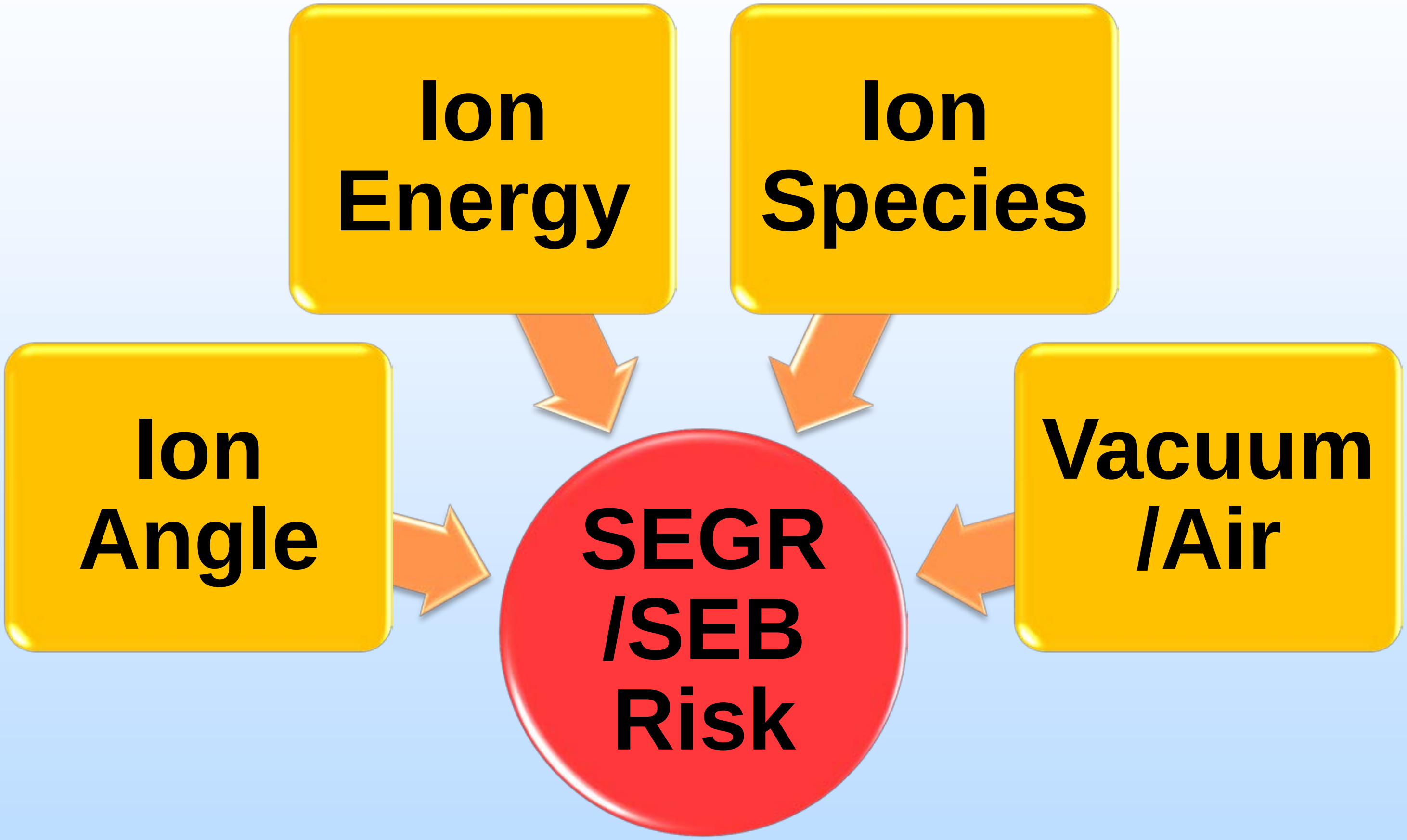


Ion species effects need to be included in efforts to bound the on-orbit risk of SEGR

Better RHA through improved standards for:

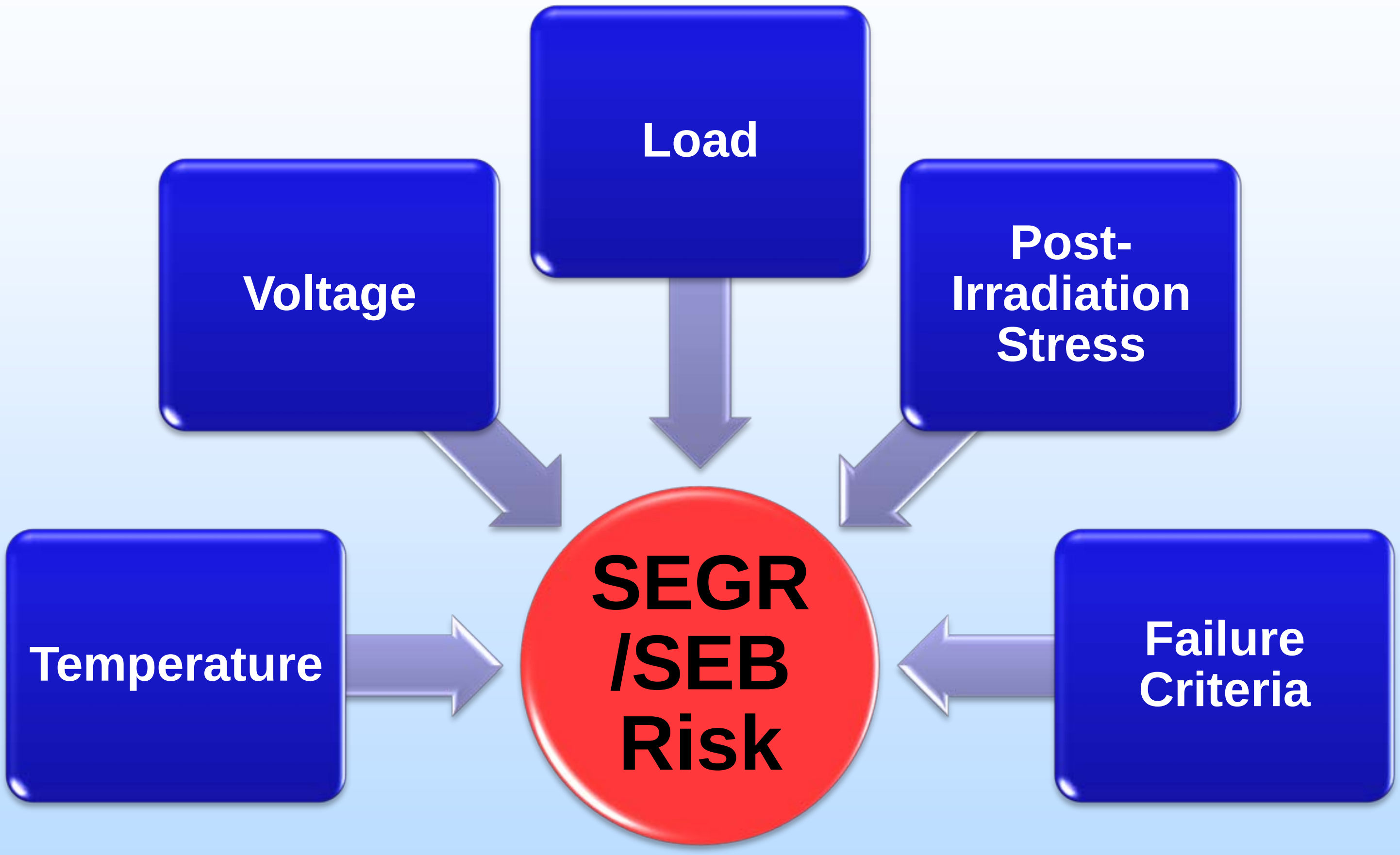
PART TESTING

The Risk Puzzle: Beam Conditions



LET is not a piece for bounding on-orbit risk: it can mask other key pieces

The Risk Puzzle: Test Conditions



Test conditions must be specified to enable data comparison

The Risk Puzzle: Device Properties

Structure:
VDMOS, LDMOS, HEMT, Trench, Super Junction, ...

Material:
Si, SiC, GaN, ...

SEGR /SEB Risk

VDMOS: vertical double-diffused MOSFET;
LDMOS: lateral double-diffused MOSFET;
HEMT: high electron mobility transistor

Appropriate beam and test conditions may vary based upon device properties

MIL-STD-750-1 TM1080

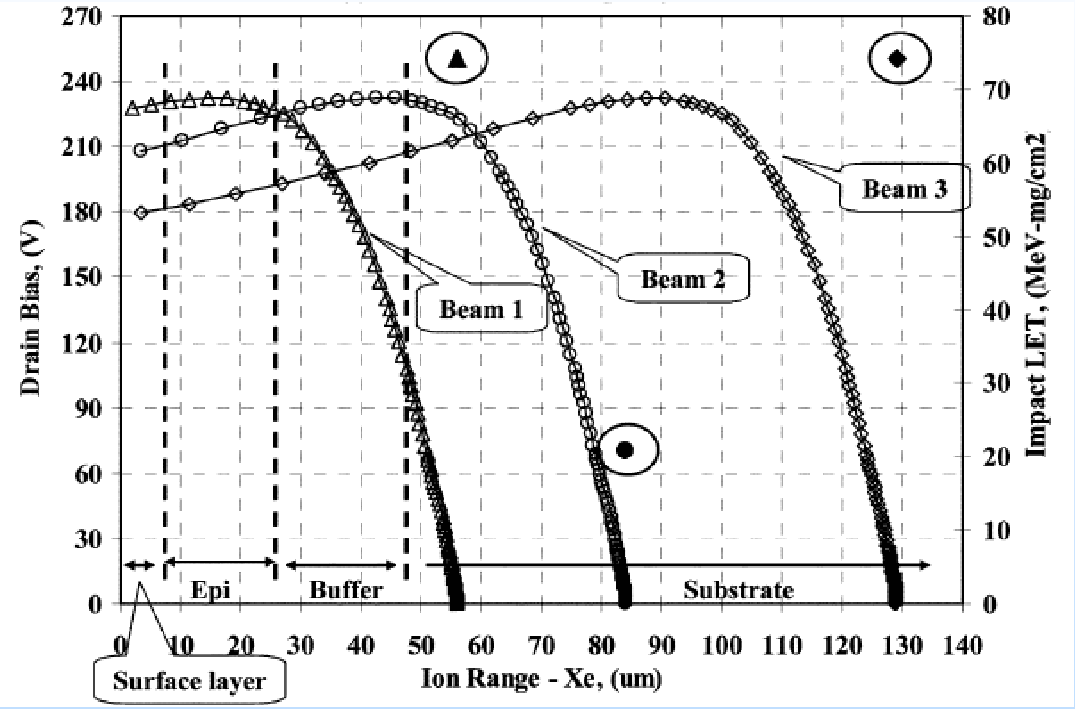
Environmental Test Methods for Semiconductor Devices: SEB and SEGR

- **Revision released this year addresses ion energy/species effects**
  - Device "characterization tests are typically conducted to define the worst-case operating conditions"
  - "Ion energy should be considered when determining/defining worst-case test conditions"
- **Worst-case (for SEGR) test condition for an ion species:**
  - "occurs when the ion fully penetrates the epitaxial layer(s) with maximum energy deposition through the entire epitaxial layer(s)"

TM1080 now specifies an ion range that places the Bragg peak at the epilayer/substrate interface

Worst-Case Ion Range

Failure Vds and Incident LET vs. Xe Range in 500V nVDMOS with Dual Epilayer, at -15 Vgs



Note: Encircled points = Failure Vds per left vertical axis.

Fig. from: Liu, et al., IEEE TNS, 2010.

- **Titus, *et al.*, 2001 first reported on the worst-case ion penetration range and in 2003, suggested a test method based upon this range.**

Empirically-Defined Worst-Case Ion Energy: Example

- **Worst-case ion range will be the sum of overlayer and epilayer thicknesses, PLUS <u>the ion range at its Bragg peak.</u>**

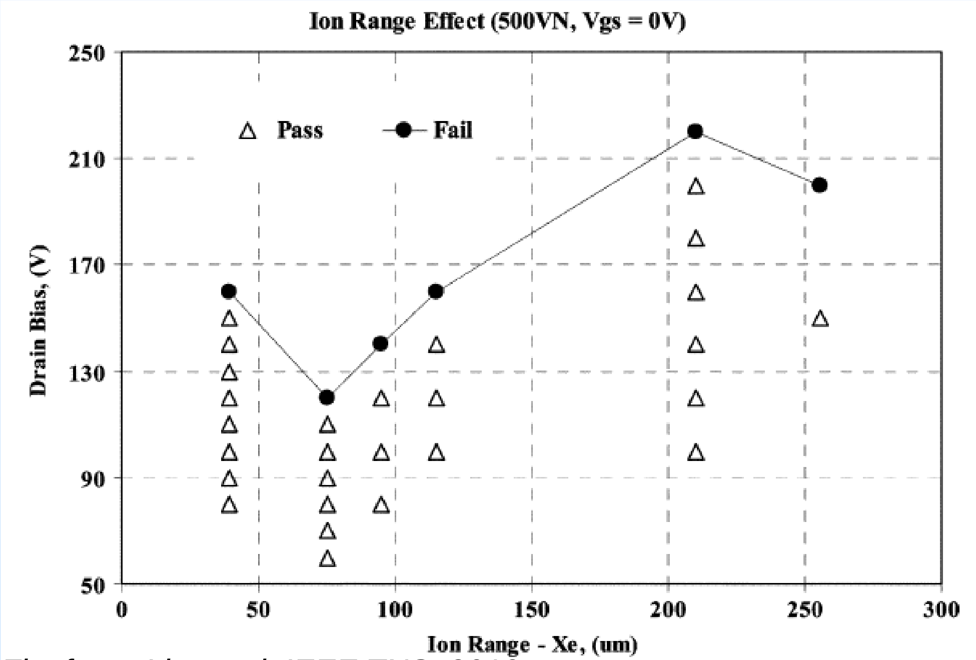


Fig. from: Liu, et al.,IEEE TNS, 2010.

Overlayers: ~ 7 μm

Epilayers: ~ 40 μm

Xe range at Bragg peak: 31μm

Total: 78 μm

NEPP is involved in developing an ASTM International guideline for power MOSFET testing

Existing Slash Sheet SEE Conditions

- **What about those older lower-energy data?**

Ex/ MIL-STD-19500/744

OLD:

LET = 39.4 MeV-cm^2/mg, range = 36.5 microns, energy = 292 MeV
In situ bias conditions: V_{DS} = 60 V and V_{GS} = -6 V

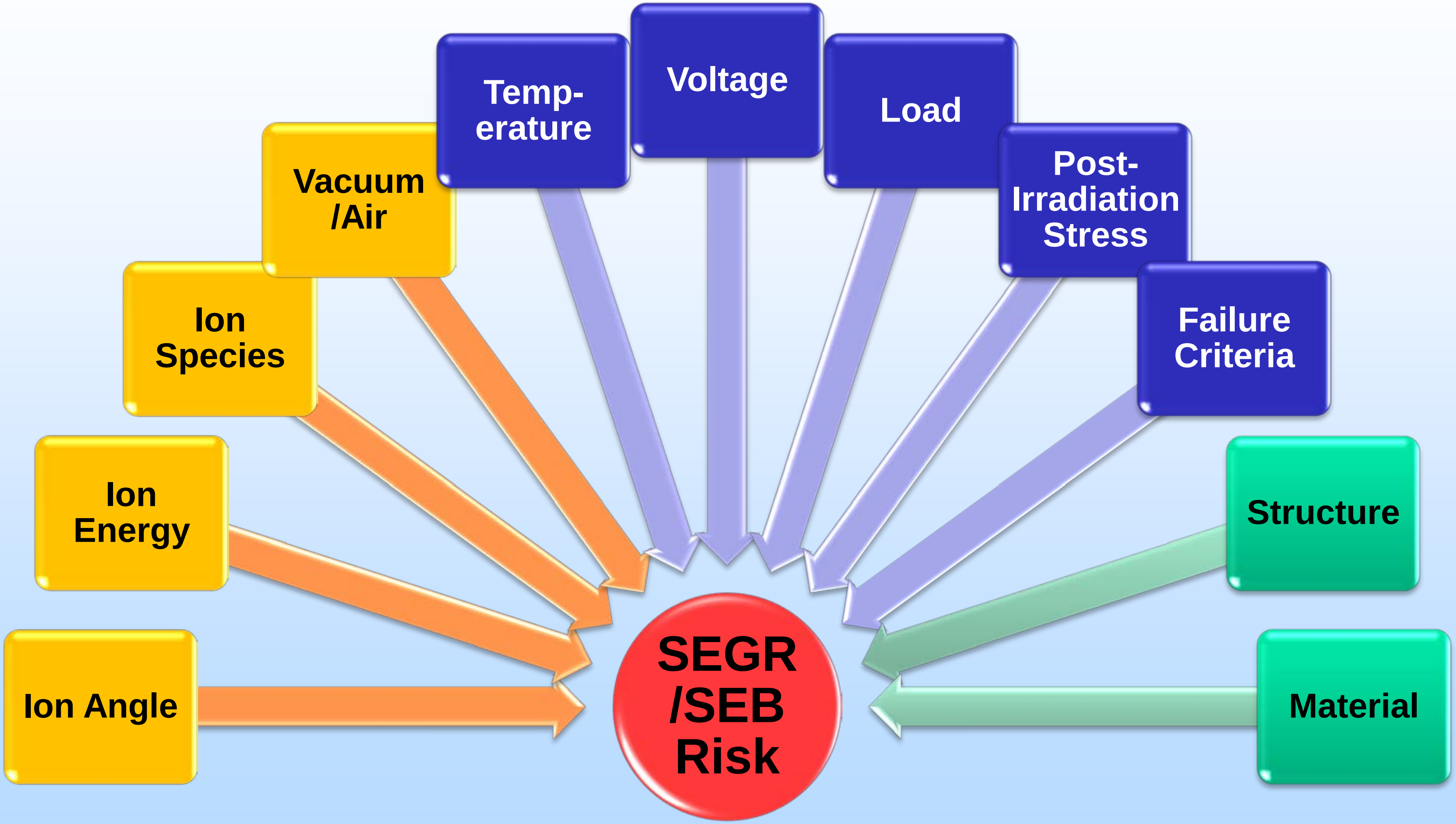
NEWER (2009):

Surface LET = 38 MeV-cm^2/mg ±5.0 %, range = 38 μm ±7.5%, energy = 300 MeV ±7.5%
(Nominal 3.86 MeV/Nucleon at Brookhaven National Lab Accelerator)
In situ bias conditions: V_{DS} = 60 V and V_{GS} = -6 V
V_{DS} = 35 V and V_{GS} = -7 V

FUTURE: ?

How do we add new vendors to existing slash sheets?

Which Factors Belong in a Slash Sheet?



An active topic at JEDEC Solid State Technology Association JC13.4 ...

Presented by Jean-Marie Lauenstein at the NASA Electronic Parts and Packaging Program (NEPP) Electronics Technology Workshop (ETW), NASA Goddard Space Flight Center in Greenbelt, MD, June 11-13, 2012 and published on nepp.nasa.gov.

How can we use the test data (worst-case or not)?

FAILURE RATE PREDICTION

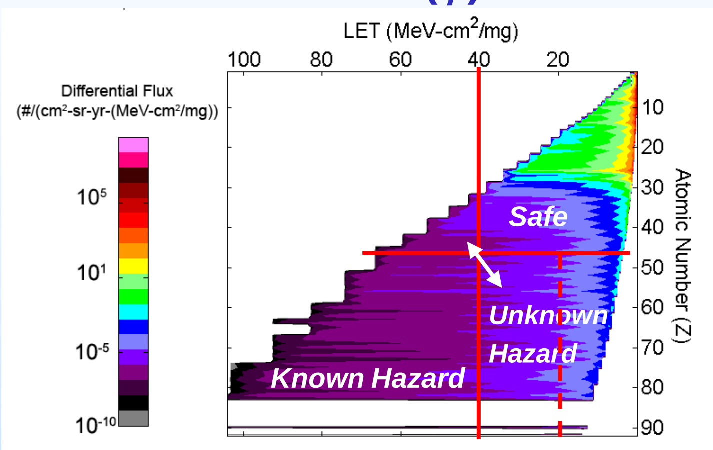
History of Rate Prediction

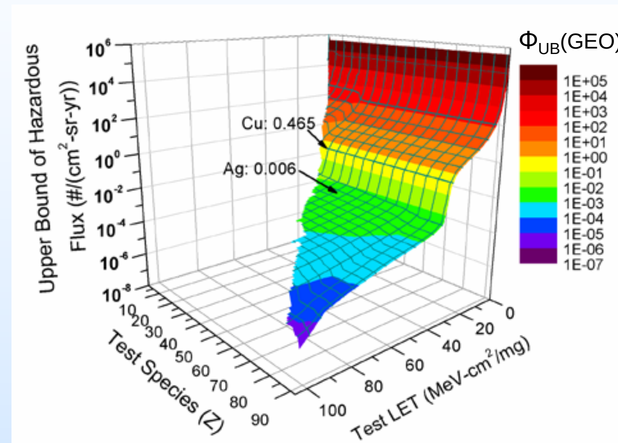
- **There is no accepted or verified power MOSFET failure rate prediction method.**
- **There are several proposed methods for estimating the failure rate:**
  - Titus, *et al*. (1999) prediction of “Early Lethal SEGR Failures” in VDMOS, via Monte Carlo and threshold LET
  - Thales Alenia (Marec, 2009) concept of equivalent LET with use of failure cross section vs. equivalent LET data
  - Edmonds & Scheick (2010) method for including contribution of failures by low-energy ions
  - Lauenstein, *et al.* (2011) definition of an upper bound on the failure rate considering both ion species and energy

Upper Bound on SEGR Failure Rate

Defining the upper bound (UB) of hazardous flux at a given orbit for a given SEGR response curve: examples for geostationary orbit (GEO)

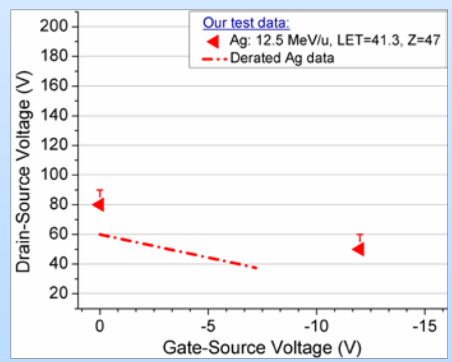
Differential Flux (ϕ) at GEO

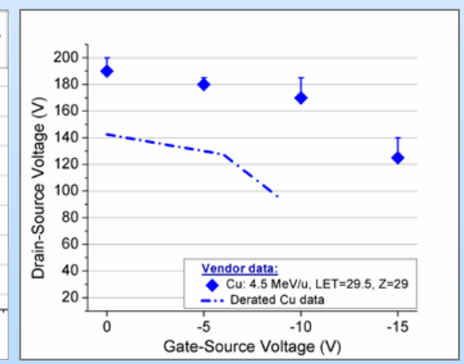




Ex/ Ag test ions: Hazardous integral flux (Φ):

$$\Phi_{UB}(Z_{47}, LET_{41.3}) = \int_{1}^{92}\int_{41.3+\Delta}^{105} \varphi(Z,LET)\,dLET\,dZ + \int_{48}^{92}\int_{20.7}^{41.3} \varphi(Z,LET)\,dLET\,dZ = 0.006\ \text{ions}/(\text{cm}^2 \cdot \text{sr} \cdot \text{yr})$$





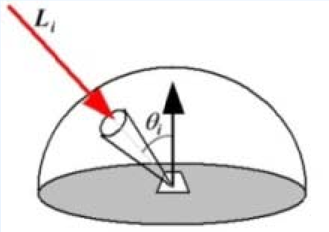
$$\Phi_{UB}(Z_i, LET_i) = \int_{1}^{92}\int_{LET_{i+\Delta}}^{105} \phi(Z,LET)\,dLET\,dZ + \int_{Z_{i+1}}^{92}\int_{(LET_i/2)}^{LET_i} \phi(Z,LET)\,dLET\,dZ$$

Upper Bound on SEGR Failure Rate (cont'd)

Upper Bound on SEGR Failure Rate Defined From Φ_{UB} :

$$\mathrm{Rate}_{\mathrm{UB}} = \Phi_{\mathrm{UB}} \cdot \mathrm{N} \cdot \mathrm{A} \cdot 4\pi(1-\cos(\theta)) \cdot f$$

- N = # devices to be flown
- A = SEGR cross-section
  - Gate area of die
- θ = max off-normal angle of incidence of SEGR vulnerability
- f = off-state duty cycle

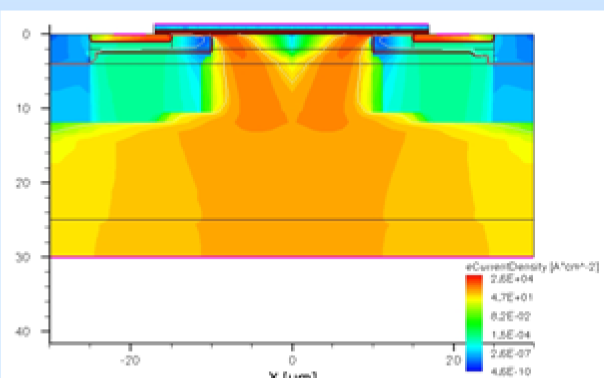


Current form is overly-conservative.

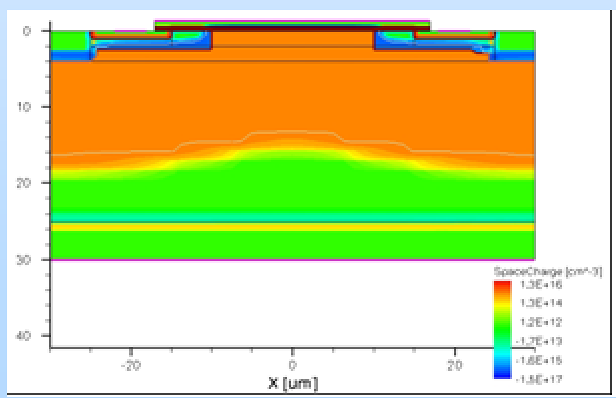
Next step: Refine inclusion of angular effects

Mechanisms of Ion Species Effects on SEB & SEGR

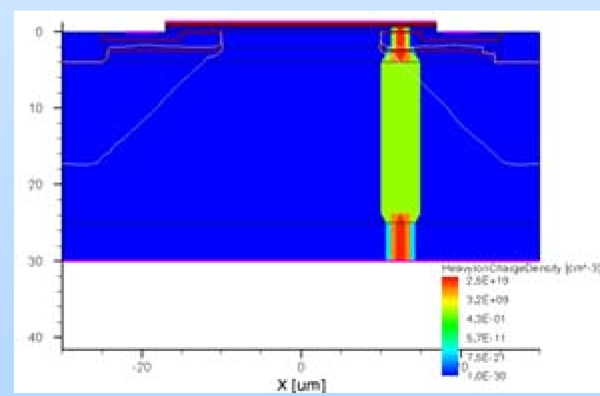
- **NEPP is involved in enhancing our understanding of power MOSFET failure mechanisms to:**
  - Permit failure rate prediction
  - Identify appropriate test methods
- **Vanderbilt University graduate student research**
  - Explain recent trending of SEB failure thresholds with ion atomic number through detailed modeling of test data
  - Identify mechanisms of oxide damage in SEGR



On-state electron current density



Off-state depletion regions



Striking ion's initial charge density

Presented by Jean-Marie Lauenstein at the NASA Electronic Parts and Packaging Program (NEPP) Electronics Technology Workshop (ETW), NASA Goddard Space Flight Center in Greenbelt, MD, June 11-13, 2012 and published on nepp.nasa.gov.

Conclusions: Power MOSFET RHA

- Good diversification of radiation hardened silicon power MOSFET suppliers
- Test method standards better reflect current research and understanding
- Work still to be done to develop meaningful slash sheets that permit multiple vendors marketing a given part number
- Despite SEGR/SEB discovery in power MOSFETs over 25 years ago, we still don’t fully understand the failure mechanisms
  - Many groups actively pursuing power MOSFET SEE research