National Aeronautics
and Space Administration

Getting SiC Power Devices Off the Ground: Design, Testing, and Overcoming Radiation Threats

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Acknowledgment:
This work was sponsored by:
NASA Office of Safety & Mission Assurance
in collaboration with:
NASA Space Technology Mission Directorate

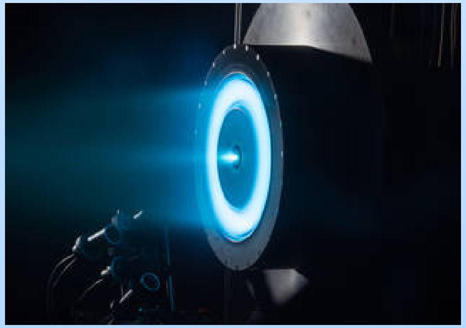
Abbreviations & Acronyms

Acronym	Definition
GCR	Galactic Cosmic Ray
I_D	Drain Current
I_G	Gate Current
I_R	Reverse-Bias Leakage Current
ICSCRM	International Conference on Silicon Carbide and Related Materials
JFET	Junction Field Effect Transistor
LBNL	Lawrence Berkeley National Laboratory cyclotron facility
MOSFET	Metal Oxide Semiconductor Field Effect Transistor
RHA	Radiation Hardness Assurance
RHBD	Radiation Hardened By Design
SEB	Single-Event Burnout

Acronym	Definition
SEE	Single-Event Effect
Si	Silicon
SiC	Silicon Carbide
SOA	Safe Operating Area
TAMU	Texas A&M University cyclotron facility
TID	Total Ionizing Dose
VDMOS	Vertical Double-diffused MOSFET
V_{DS}	Drain-Source Voltage
V_{GS}	Gate-Source Voltage
V_R	Blocking Voltage

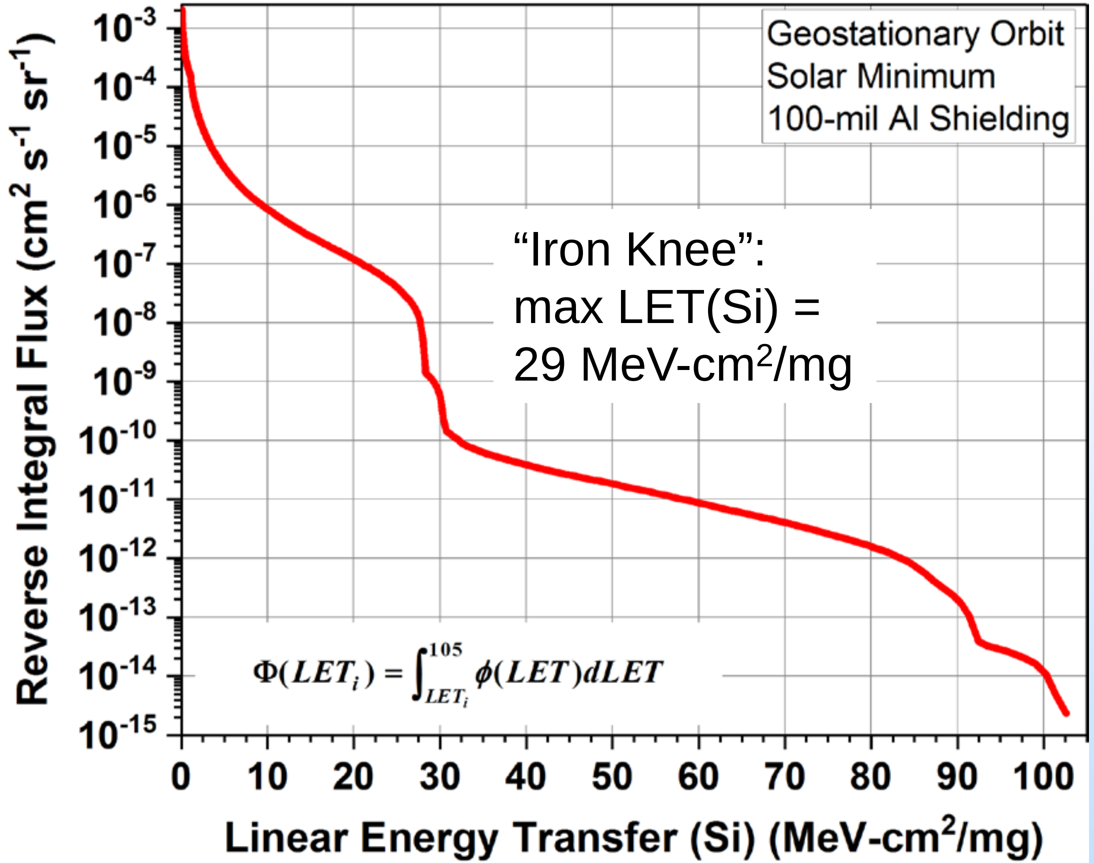
Outline

- **Part 1: Design**
  - Understanding single-event effects susceptibility of SiC power devices through heavy-ion test data on different device types
- **Part 2: Testing**
  - Additional findings from heavy-ion test conditions
- **Part 3: Overcoming Radiation Threats**
  - Putting design insights into action: radiation hardening of a 1200 V SiC MOSFET
  - Radiation Hardness Assurance conclusions



Solar Electric Propulsion
image courtesy of NASA

Heavy-Ion Environment



"Iron Knee":
max LET(Si) =
29 MeV-cm^2/mg

$$\Phi(LET_i) = \int_{LET_i}^{105} \phi(LET)\,dLET$$

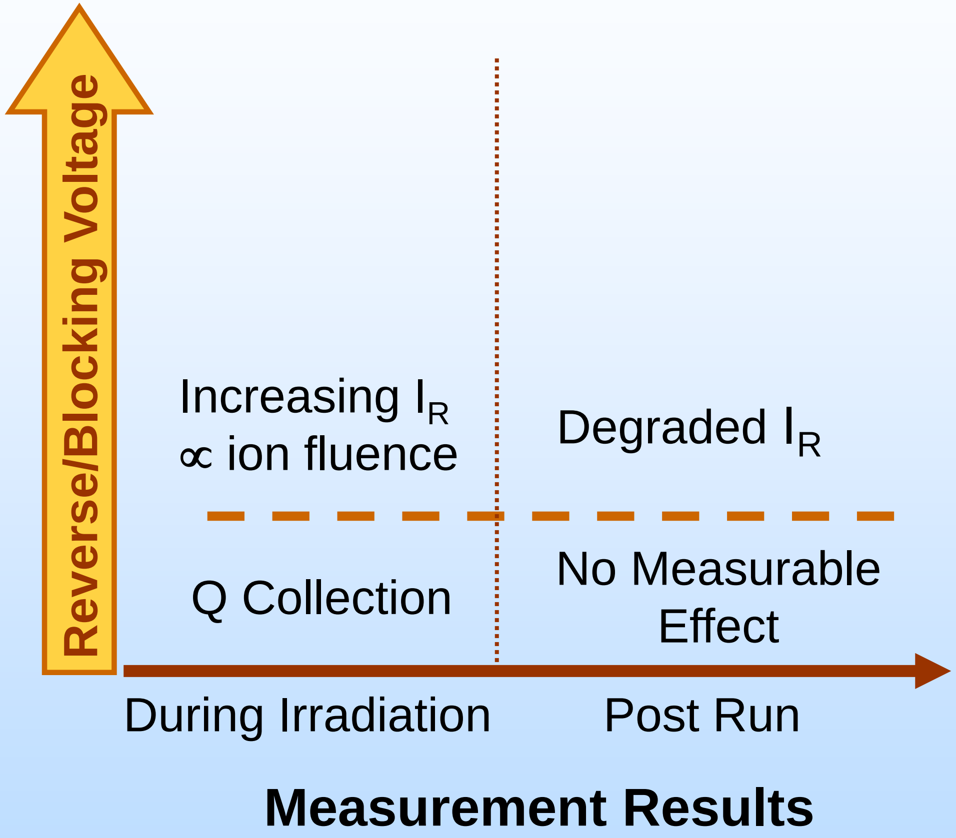
SEE radiation requirements are derived in part by the environment specified as a function of linear energy transfer (LET) in silicon;

SiC test results therefore are in LET(Si)

PART 1: DESIGN

SINGLE EVENT EFFECTS:
LEARNING FROM DIODE DESIGNS

Schottky Diode Effects: Degradation



Reverse/Blocking Voltage

Increasing I_R $\propto$ ion fluence

Degraded I_R

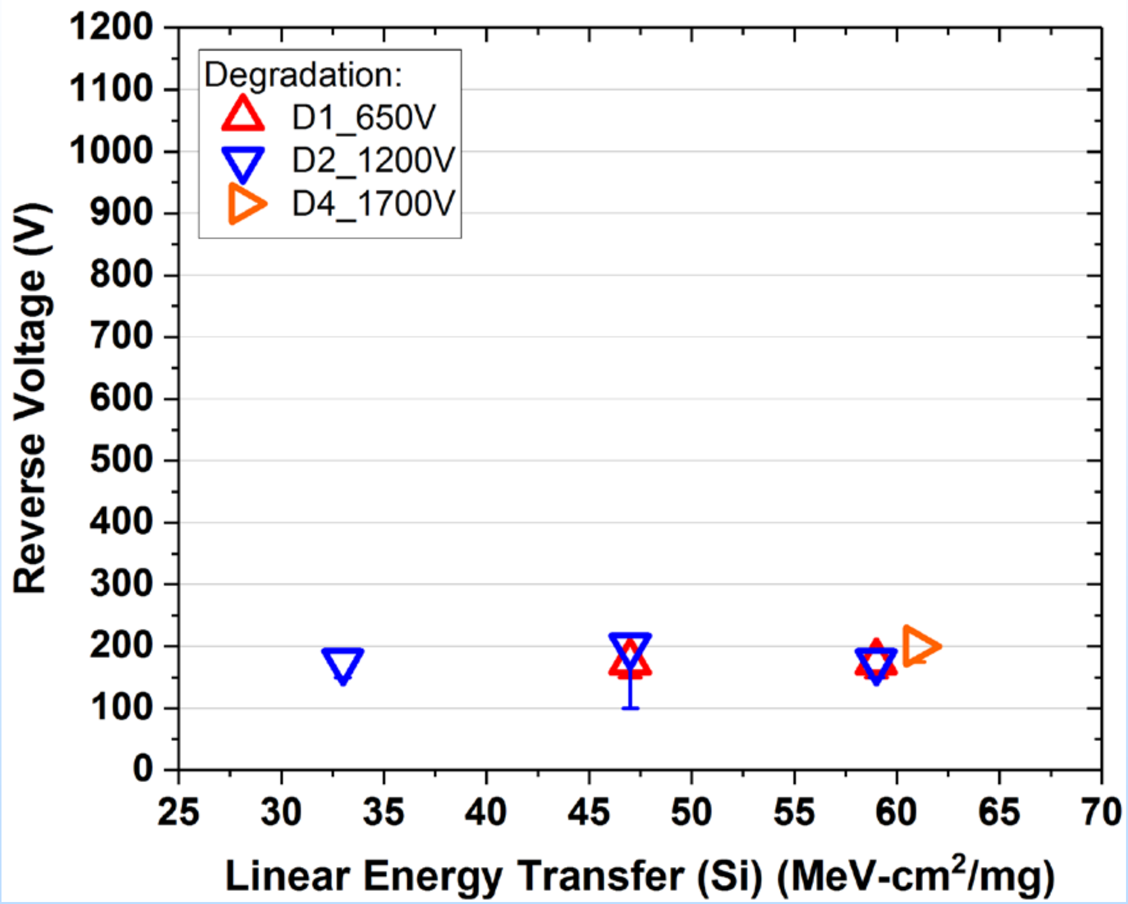
Q Collection

No Measurable Effect

During Irradiation

Post Run

Measurement Results



Onset V_R for degradation is similar for 650 V – 1700 V Schottky diodes: Electric field may not be a primary factor

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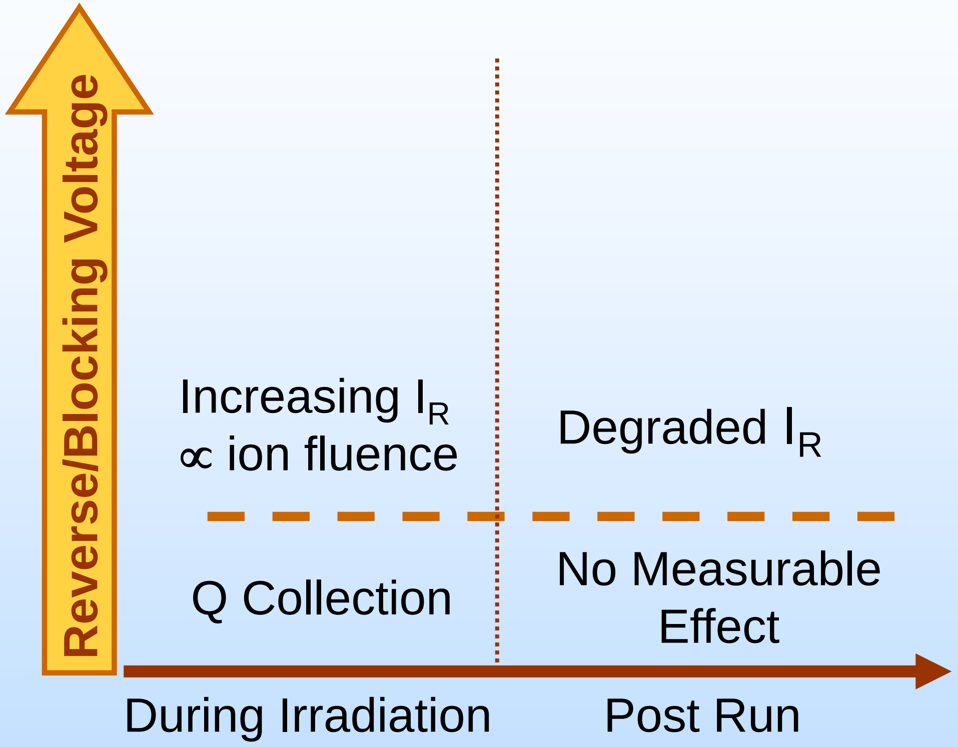
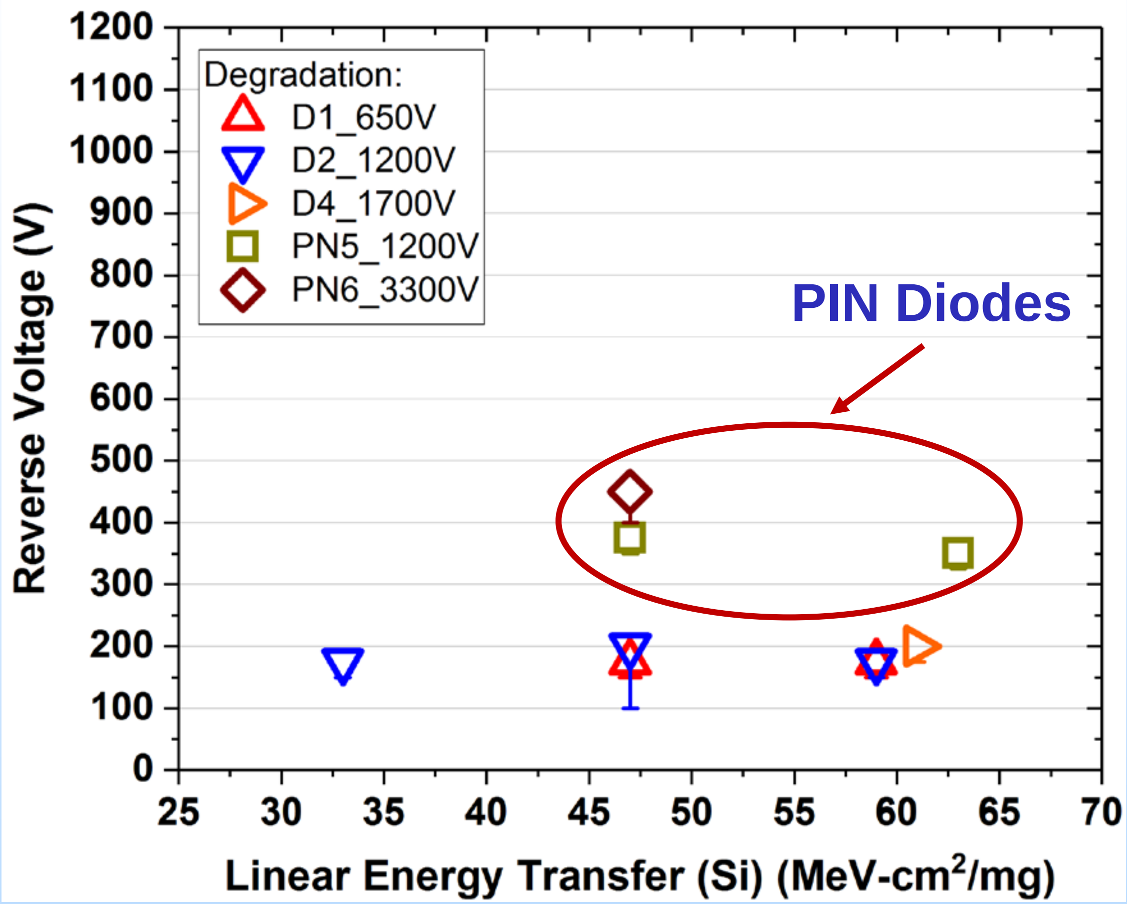
Schottky vs. PIN Diode Effects: Degradation



Measurement Results



Onset V_R for degradation is higher for PIN diodes:

The Schottky contact may contribute an additional mechanism

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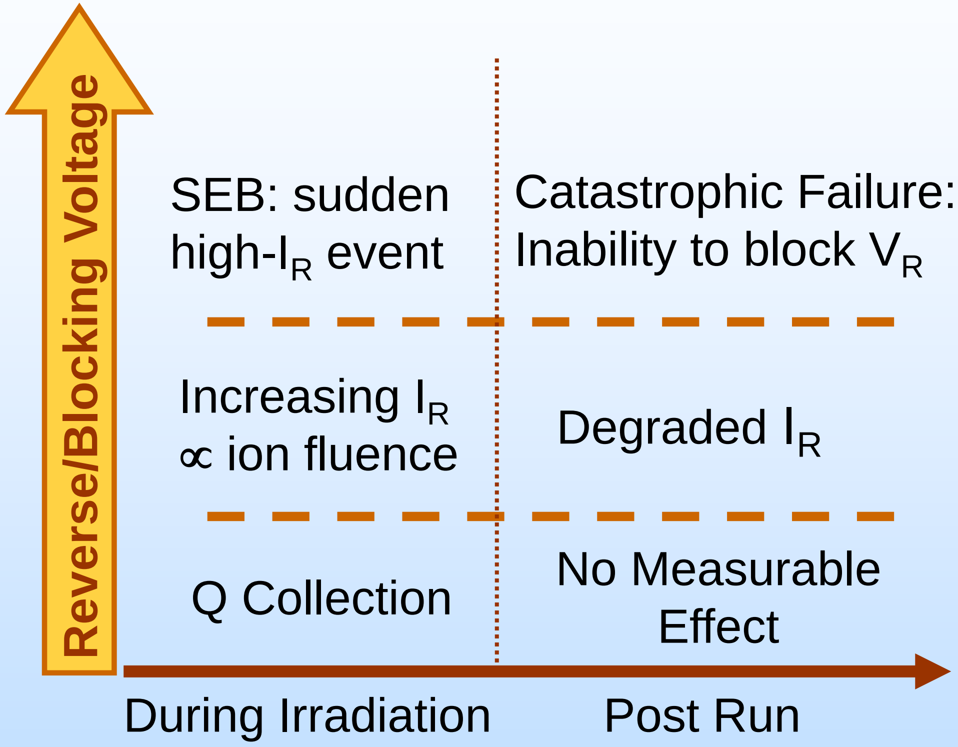
Schottky Diode Effects: SEB



SEB: sudden high-I_R event

Catastrophic Failure: Inability to block V_R

Increasing I_R ∝ ion fluence

Degraded I_R

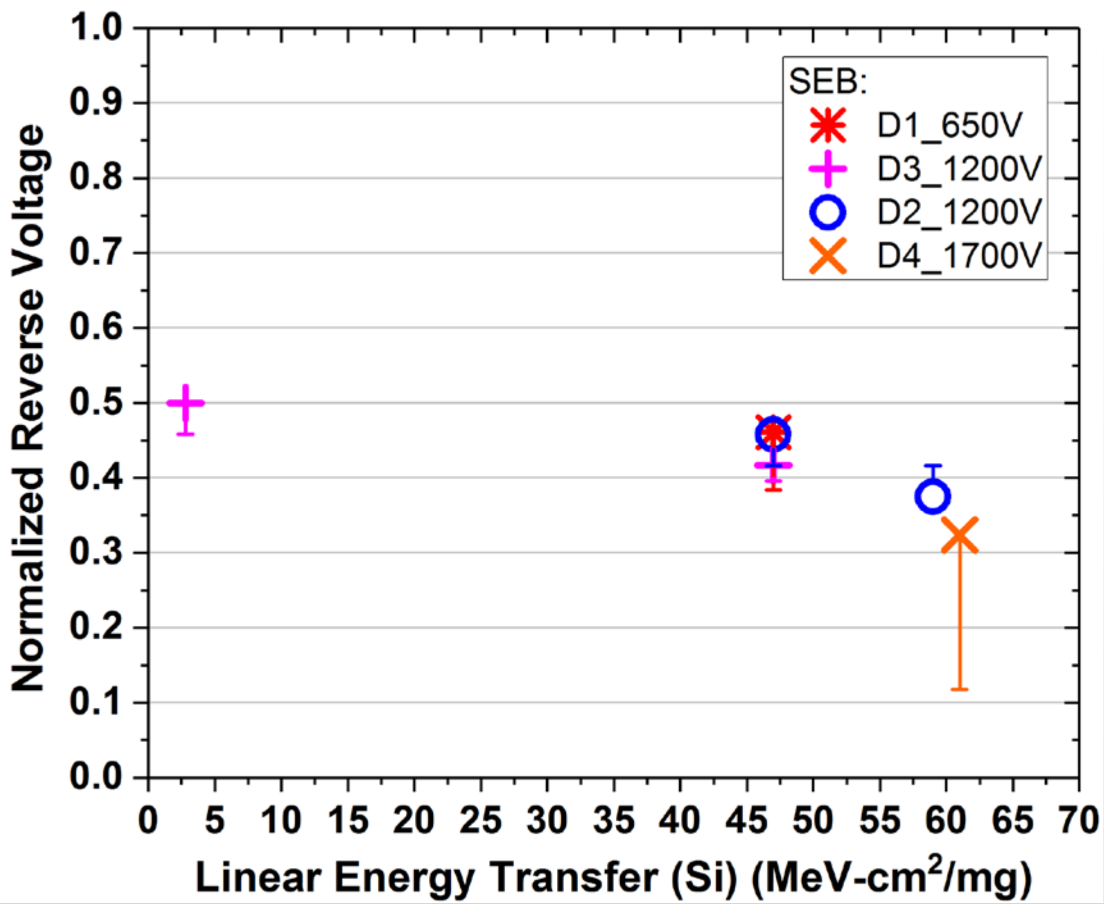
Q Collection

No Measurable Effect

During Irradiation

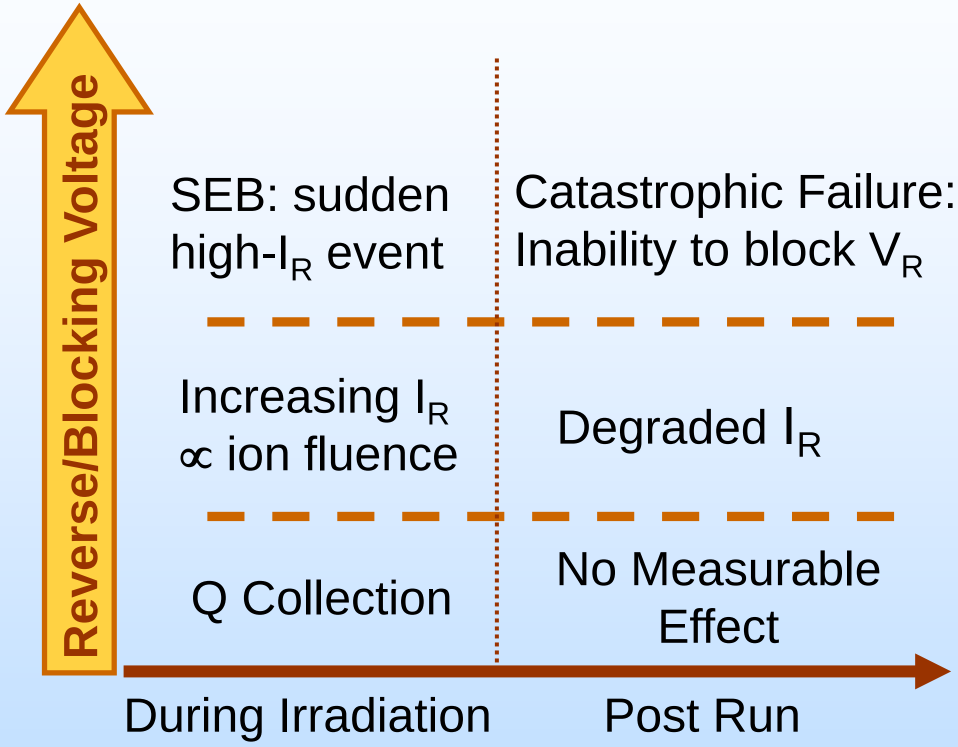
Post Run

Measurement Results

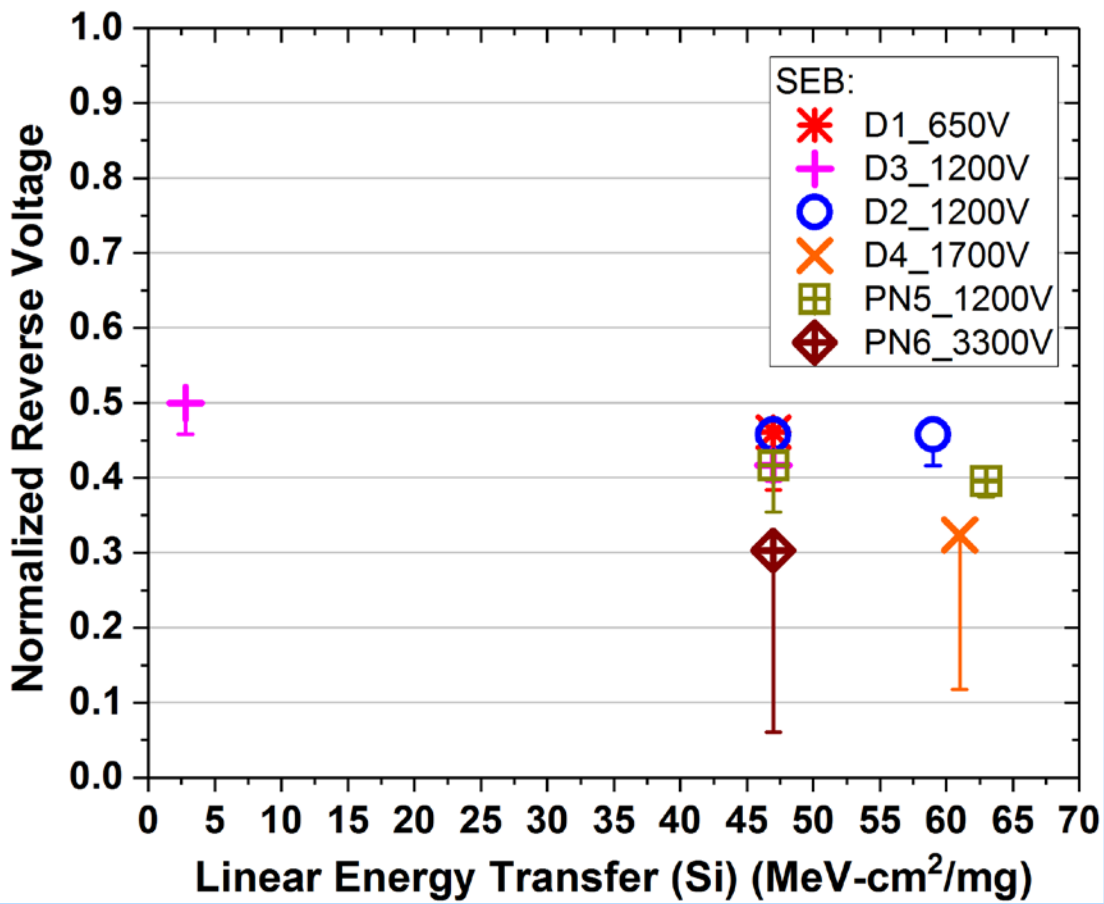


650 V – 1700 V Schottkys show SEB at similar fraction of rated V_R: Electric field dependent

Schottky vs. PIN Diode Effects: SEB



Measurement Results



No difference between Schottky and PiN diodes for normalized SEB onset voltage

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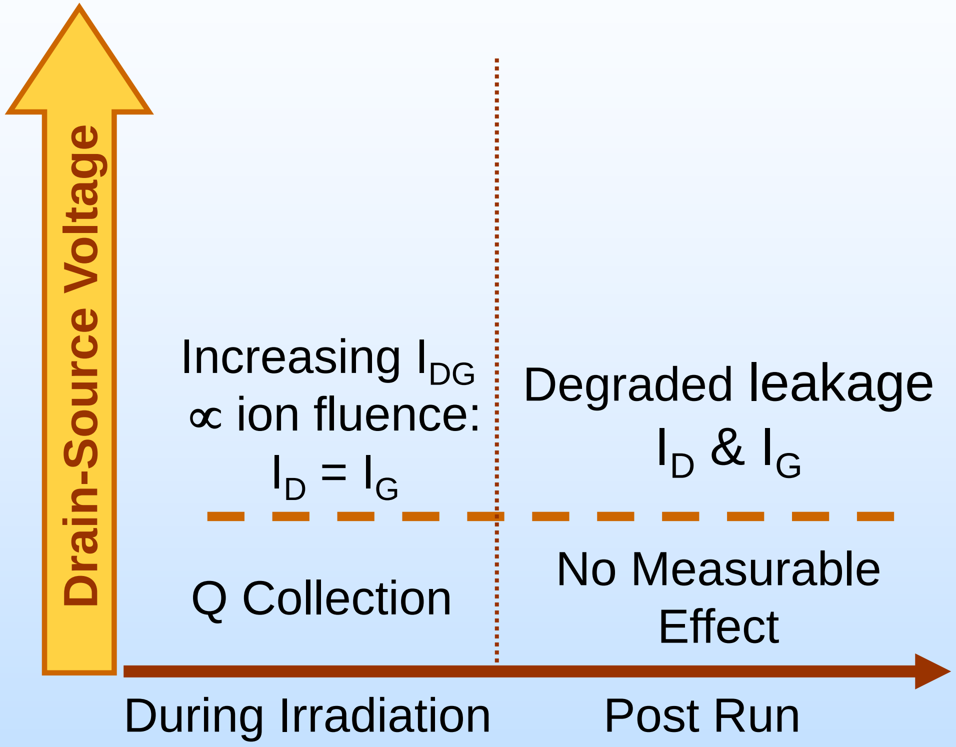
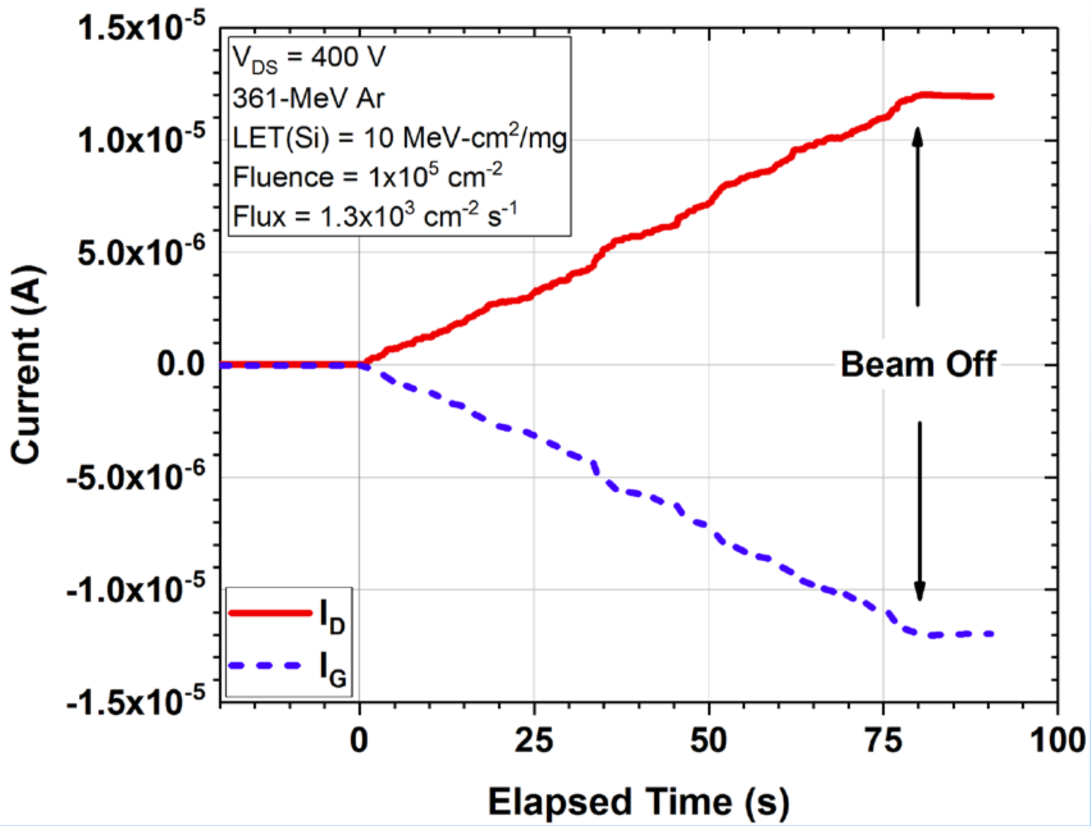
SINGLE EVENT EFFECTS: LEARNING FROM JFET DESIGNS

JFET Effects as a Function of V_{DS} at Fixed off V_{GS}: Degradation

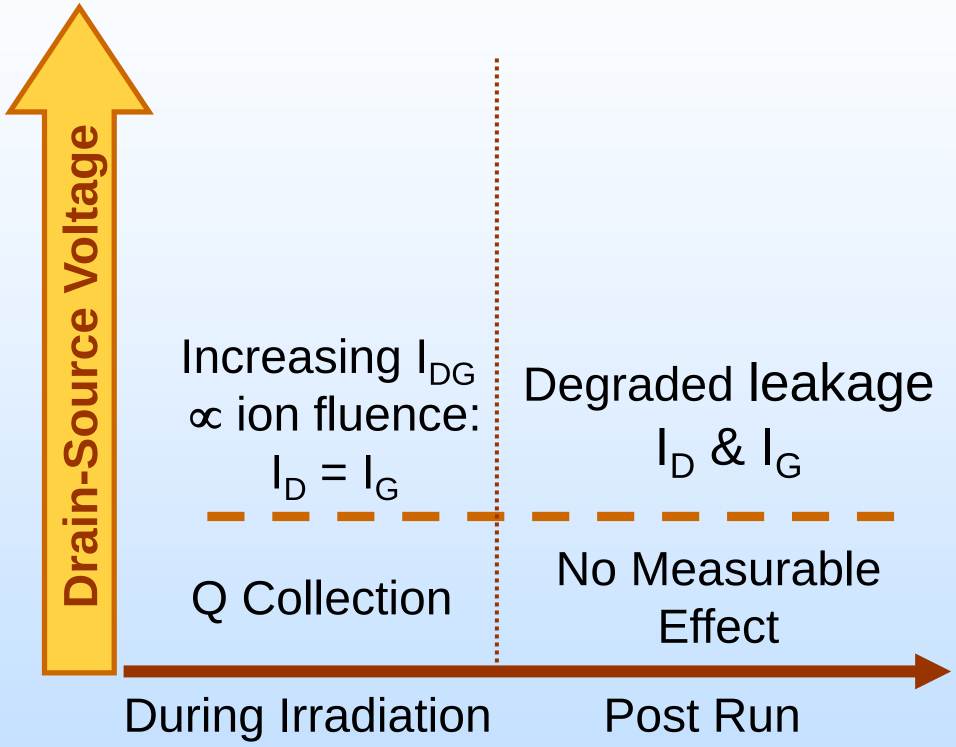


Measurement Results

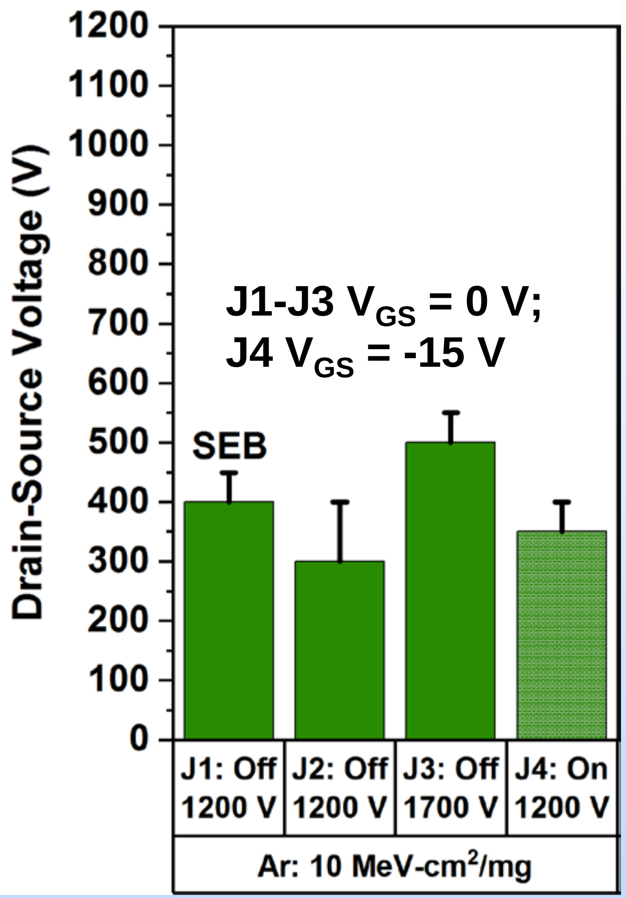


Degradation in normally-on and normally-off JFETs in this study is always drain-gate leakage, suggesting a trench design

JFET Effects as a Function of V_{DS} at Fixed off V_{GS}: Degradation



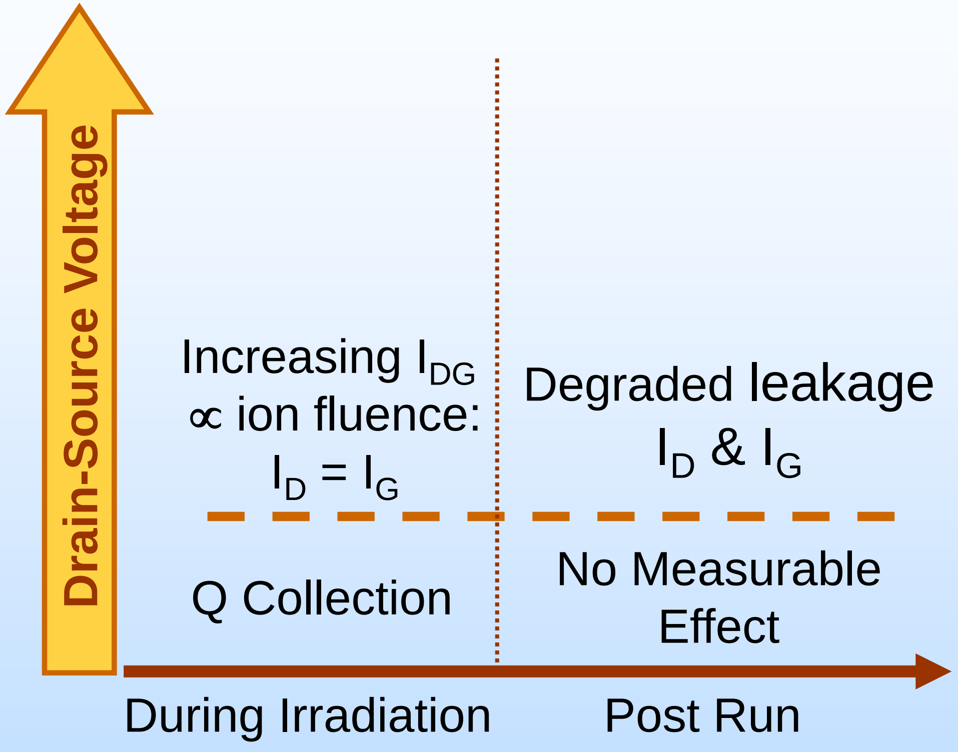
Measurement Results



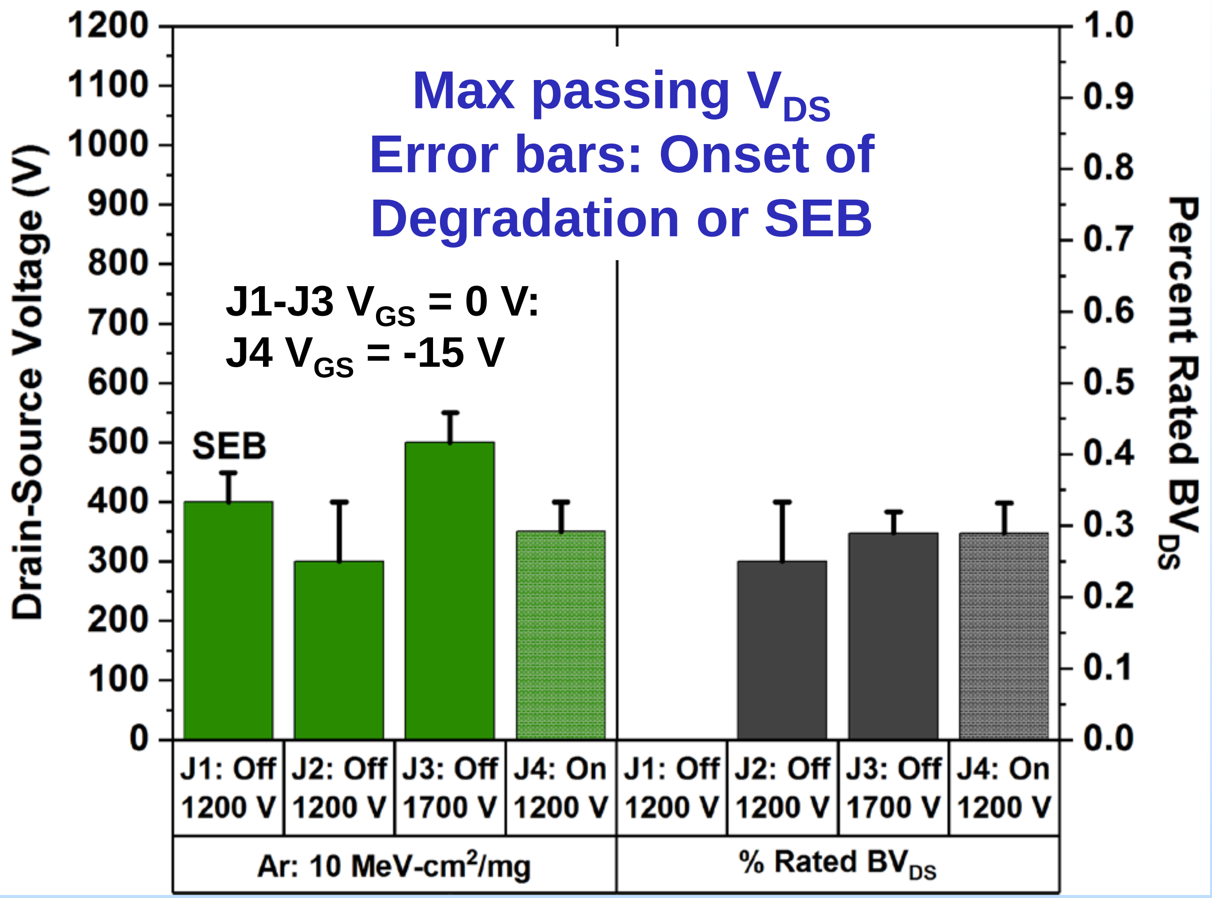
Columns: no effects
Error bars: Onset of degradation or SEB

Onset V_{DS} for degradation is similar for normally-on and (non-cascaded) normally–off JFETs

JFET Effects as a Function of V_{DS} at Fixed off V_{GS}: Degradation



Measurement Results



1200 V & 1700 V JFETs have similar normalized onset V_{DS}: Greater field dependence of degradation mechanism vs. diodes (due to gate involvement or to lower LET?)

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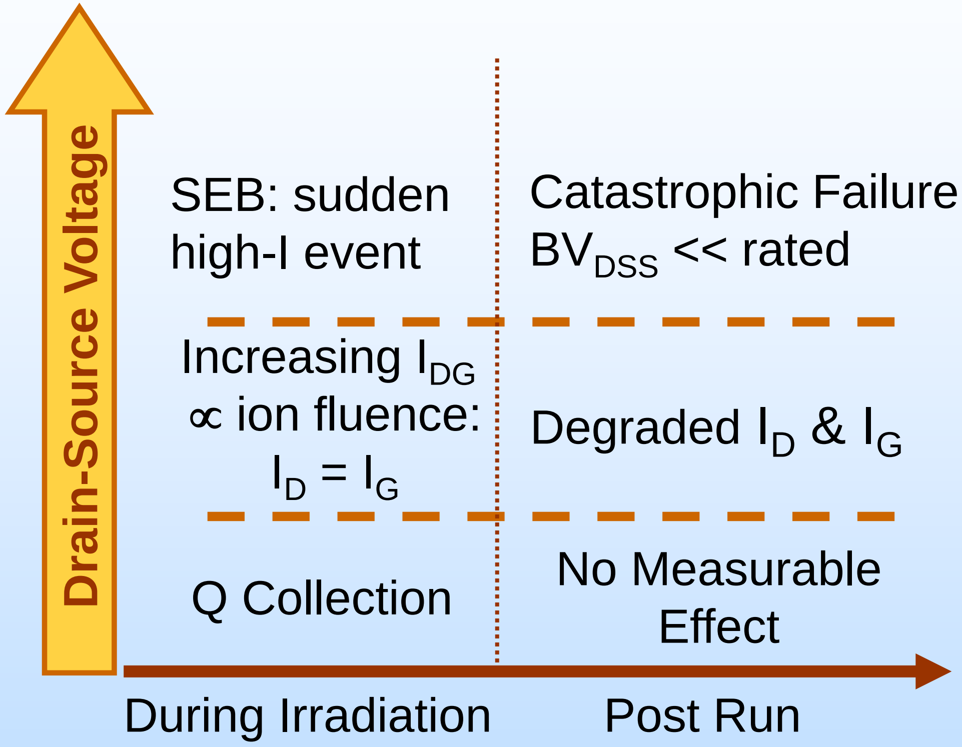
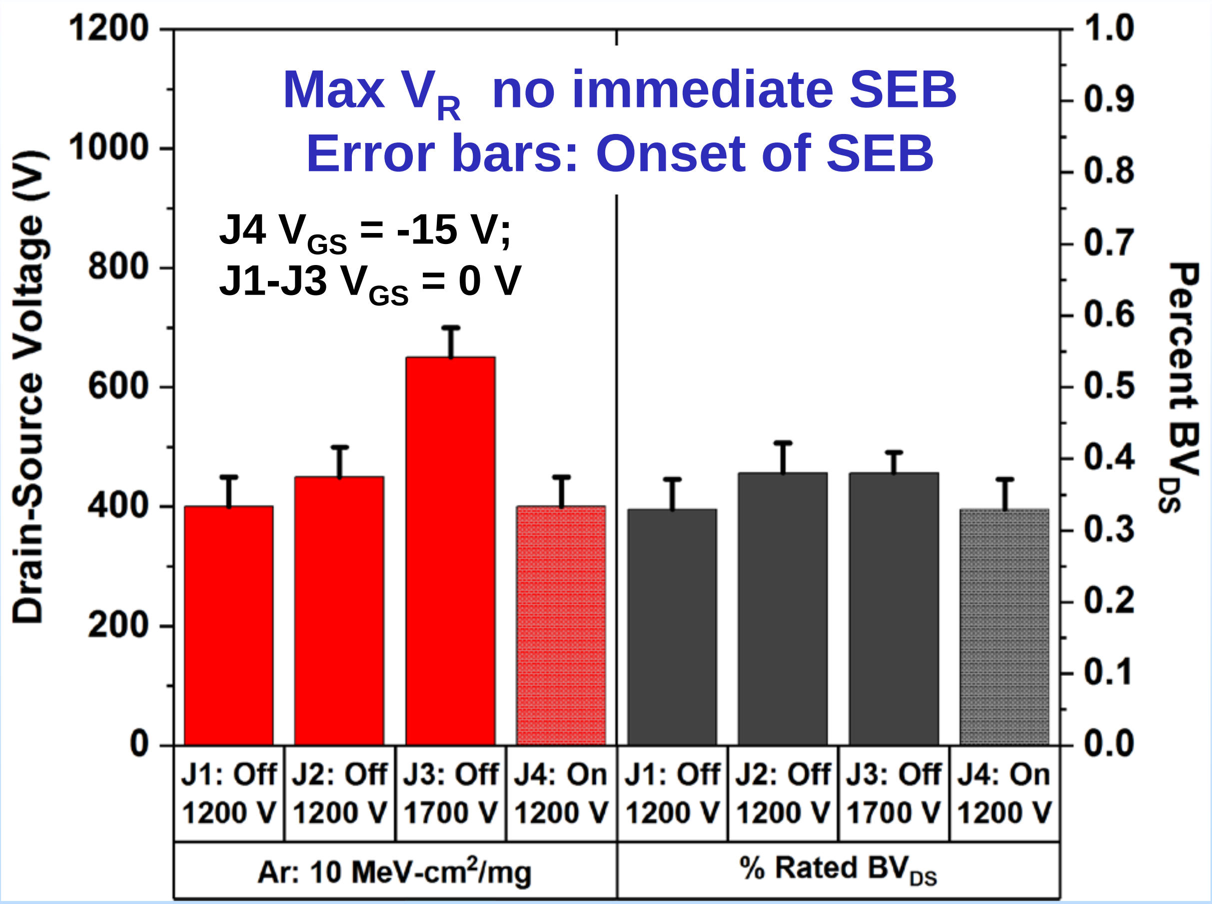
JFET Effects as a Function of V_{DS} at Fixed off V_{GS}: SEB



During Irradiation	Post Run
SEB: sudden high-I event	Catastrophic Failure: BV_{DSS} << rated
Increasing I_{DG} ∝ ion fluence: $I_D = I_G$	Degraded I_D & I_G
Q Collection	No Measurable Effect

Measurement Results

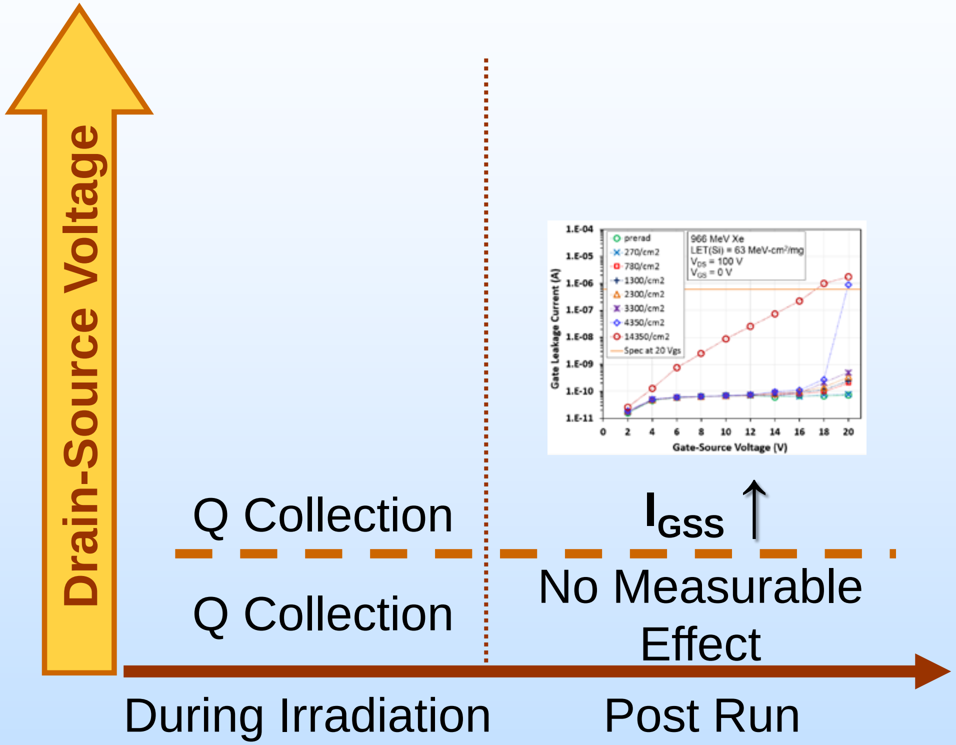


1200 V – 1700 V JFETs show SEB at similar fraction of rated V_{DS}

Normally-on similar to normally-off JFET susceptibility

SINGLE EVENT EFFECTS: LEARNING FROM MOSFET DESIGNS

MOSFET Effects as a Function of V_{DS} at V_{GS} = 0 V: Latent Gate Damage



Drain-Source Voltage

Q Collection

I_{GSS} ↑

Q Collection

No Measurable Effect

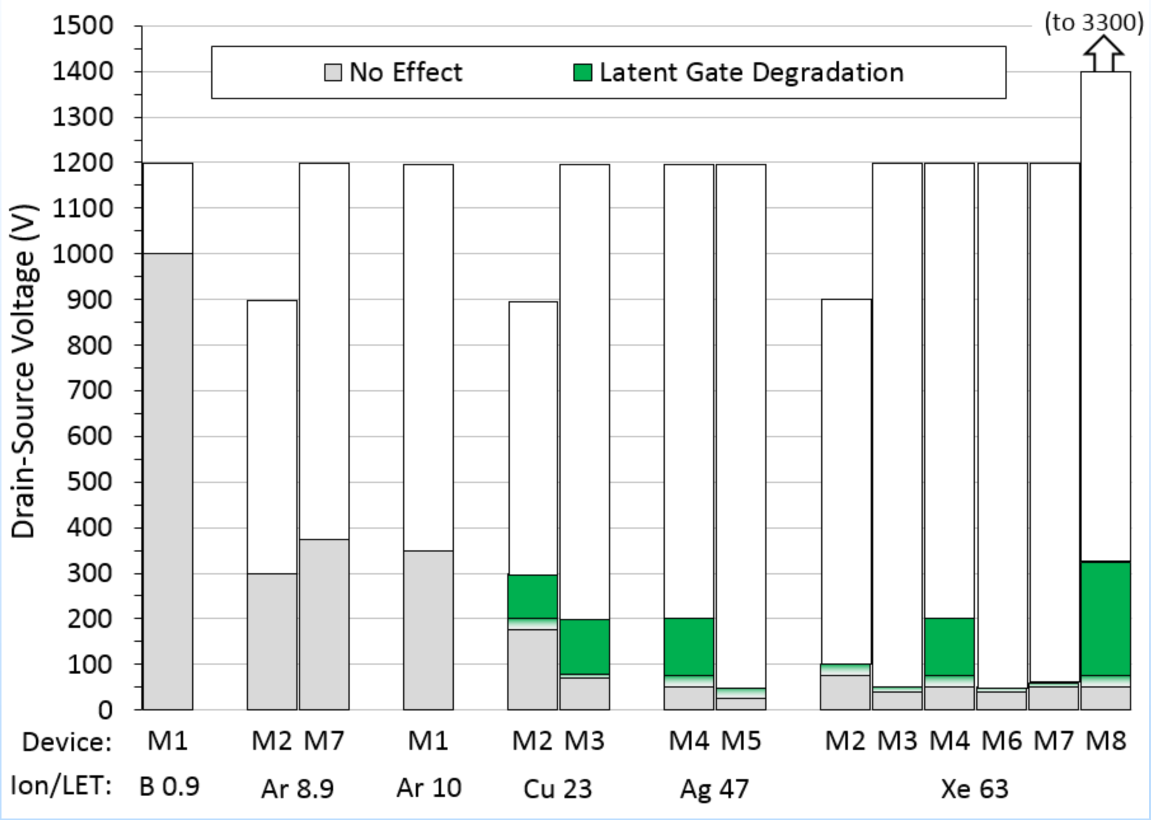
During Irradiation

Post Run

Measurement Results

Grey = no ion effects;

Green = V_{DS} range for which only latent damage occurs



No latent damage to gate from low LET/light ions;

Onset is independent of MOSFET voltage rating at higher LETs

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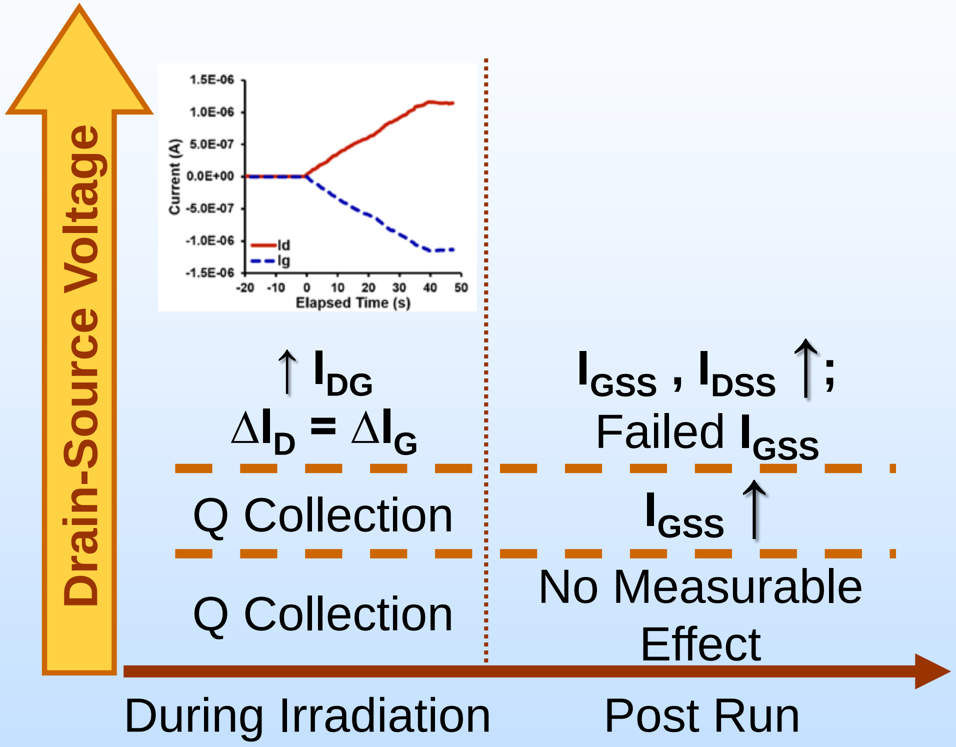
MOSFET Effects as a Function of V_{DS} at V_{GS} = 0 V: Degradation During Beam Run



↑ I_{DG}

$\Delta I_D = \Delta I_G$

I_{GSS} , I_{DSS} ↑;

Failed I_{GSS}

Q Collection

I_{GSS} ↑

Q Collection

No Measurable Effect

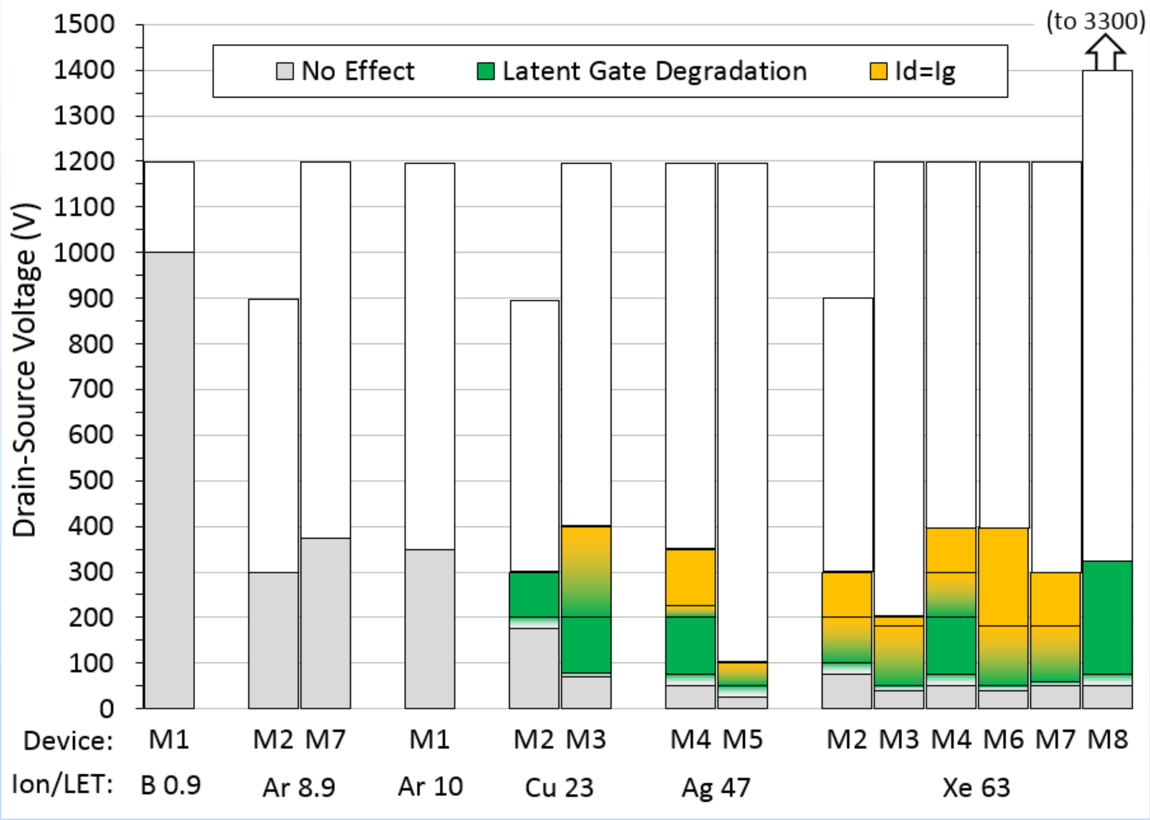
During Irradiation

Post Run

Measurement Results

Yellow = V_{DS} range for $\Delta I_D = \Delta I_G$ degradation

Green = V_{DS} range for which only latent damage occurs



Color gradients span between known V_{DS} for given response types

Not all MOSFETs exhibit drain-gate leakage current degradation: Design techniques may eliminate this vulnerability

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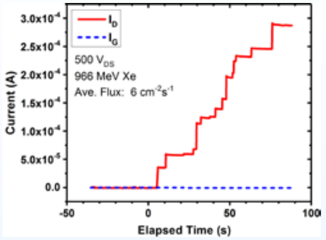
MOSFET Effects as a Function of V_{DS} at V_{GS} = 0 V: Degradation During Beam Run

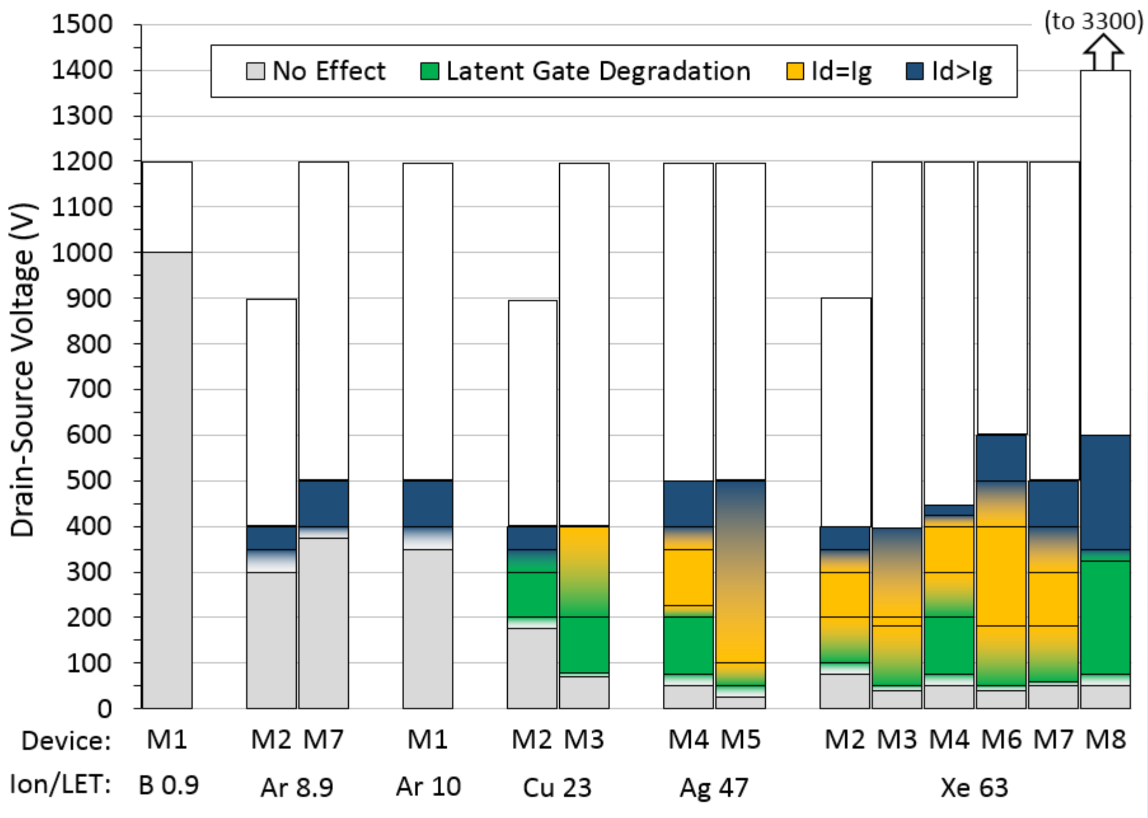


Drain-Source Voltage

During Irradiation	Post Run
↑ I_{DG}, I_{DS} $\Delta I_D >> \Delta I_G$	I_{DSS} ↑; ↑ or Failed I_{GSS}
↑ I_{DG} $\Delta I_D = \Delta I_G$	I_{GSS} , I_{DSS} ↑; Failed I_{GSS}
Q Collection	I_{GSS} ↑
Q Collection	No Measurable Effect

Measurement Results

Blue = V_{DS} range for $\Delta I_D >> \Delta I_G$ degradation
Yellow = V_{DS} range for $\Delta I_D = \Delta I_G$ degradation



Color gradients span between known V_{DS} for given response types

I_{DS} degradation least influenced by electric field and ion LET: linked to material properties??

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MOSFET Effects as a Function of V_{DS} at V_{GS} = 0 V: SEB

Drain-Source Voltage

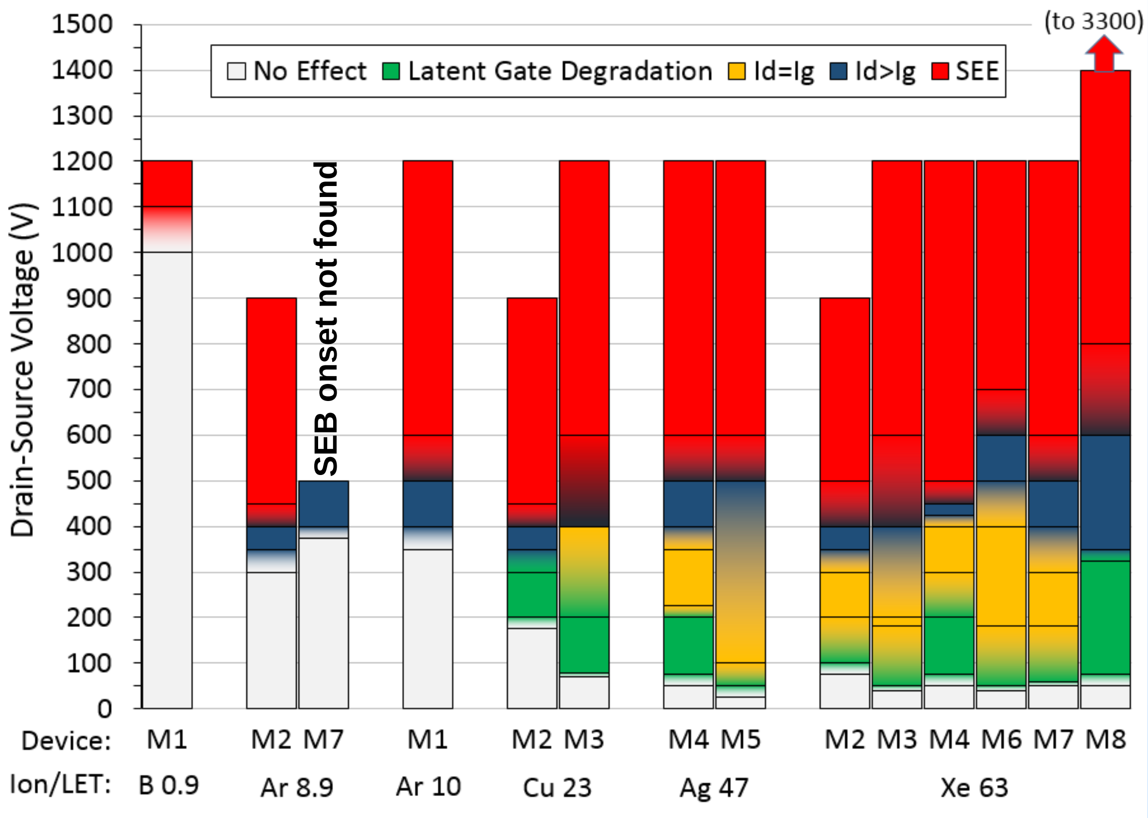
During Irradiation	Post Run
SEB: sudden high-I event	Catastrophic Failure: BV_{DSS} < 2 V
↑ I_{DG}, I_{DS} $\Delta I_D >> \Delta I_G$	**I_{DSS} ↑; ↑ or Failed I_{GSS}**
↑ I_{DG} $\Delta I_D = \Delta I_G$	**I_{GSS} , I_{DSS} ↑; Failed I_{GSS}**
Q Collection	**I_{GSS} ↑**
Q Collection	No Measurable Effect

Measurement Results

Red = V_{DS} range for SEB

Blue = V_{DS} range for $\Delta I_D >> \Delta I_G$ degradation

Yellow = V_{DS} range for $\Delta I_D = \Delta I_G$ degradation



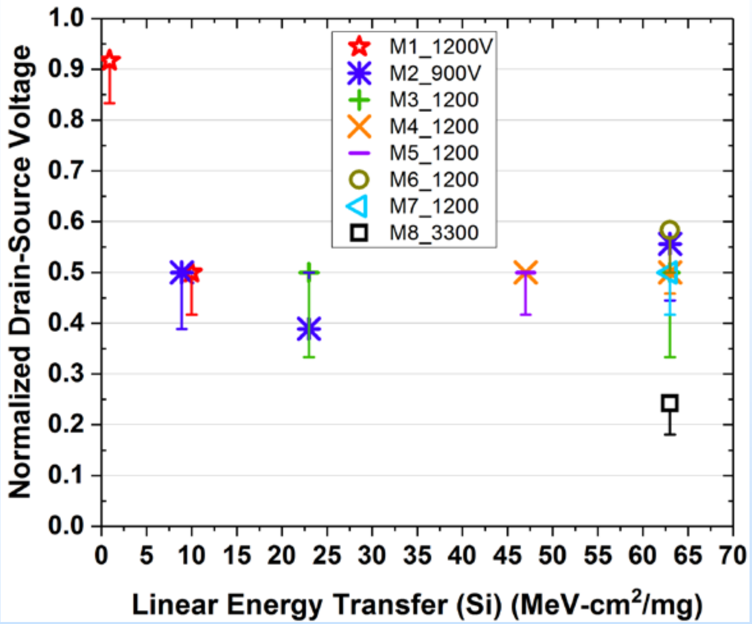
Color gradients span between known V_{DS} for given response types

SEB vulnerability at LET(Si) < 1 MeV-cm^2/mg

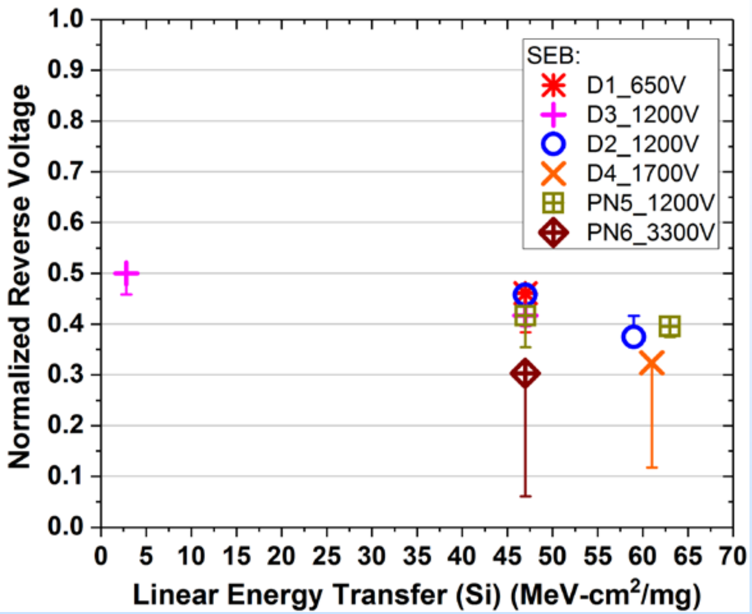
Vulnerability saturates before the GCR flux "iron knee"

Normalized Onset Voltage for Immediate SEB: Comparison of Device Types

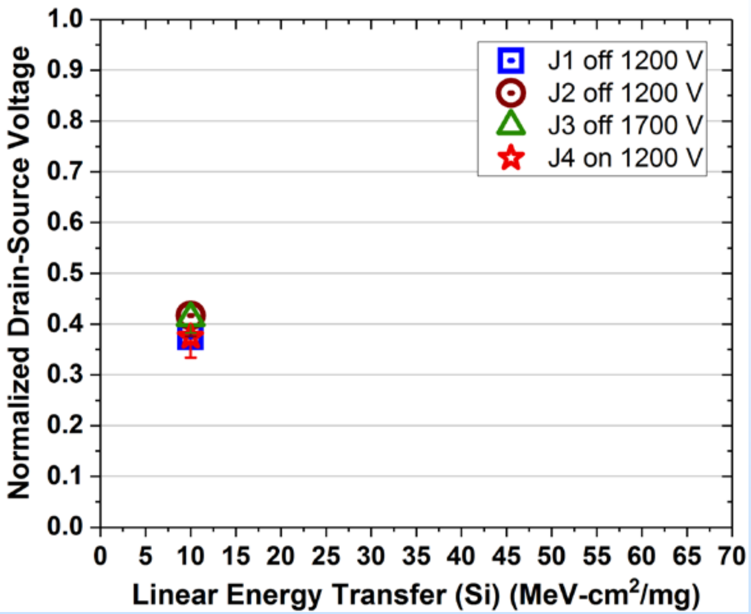
MOSFETs



Diodes



JFETs



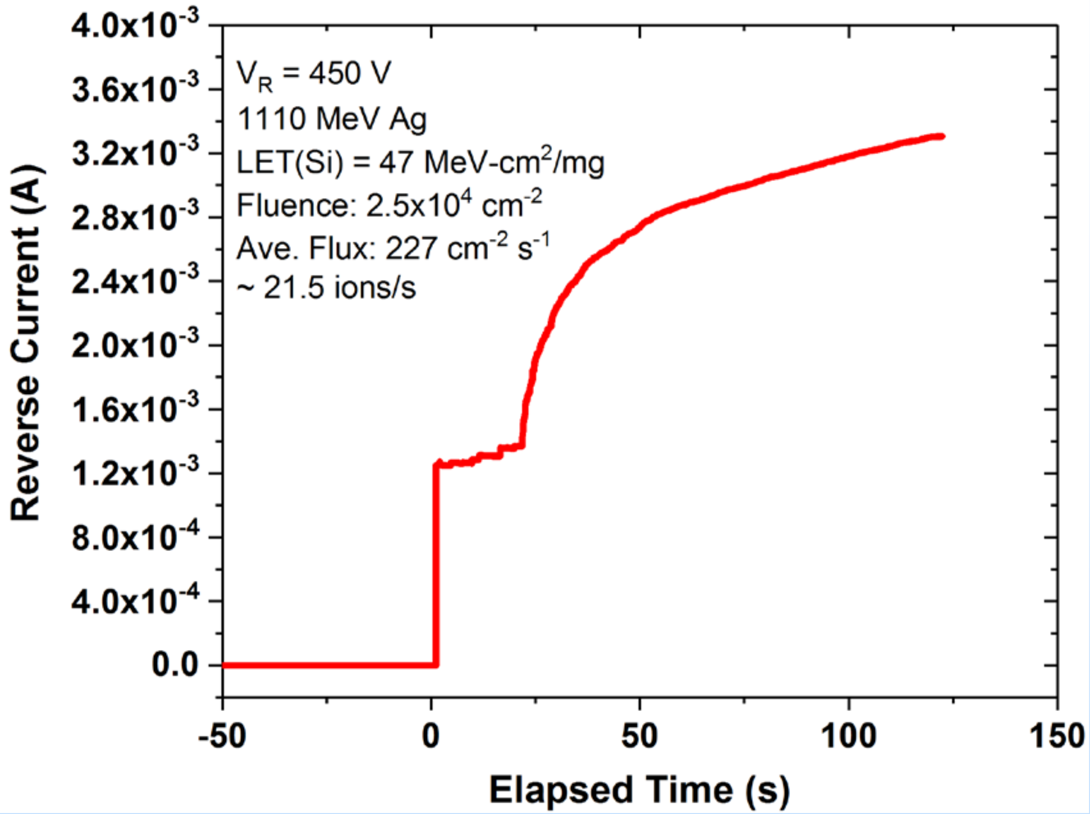
Onset for SEB similar across device types: ~40% to 50% of rated V;
Use of real breakdown voltage would strengthen
similarity across devices of different ratings

Summary of Design Insights

- **SEB susceptibility similar across all device types suggesting common mechanism**
  - E-field dependent
  - Saturated onset at ~40% – 50% of rated voltage
- **Schottky contact increases susceptibility of I_R degradation but not SEB**
- **I_R and I_{DS} degradation in diodes & MOSFETs may be most linked to material properties**
  - Minimal E-field dependence
  - Susceptibility saturates at low LETs (< 10 MeV-cm^2/mg)
- **JFET I_{DG} degradation, however, shows field dependence**
  - No difference between normally-on and normally-off designs
- **MOSFET I_{DG} degradation is design-dependent – expected to be easiest effect to eliminate**
  - Does not occur at low LETs / lighter ions
- **MOSFET latent gate damage susceptibility occurs in all designs at very low V_{DS}**
  - Onset by ~100 V_{DS}
  - Does not occur at low LETs / lighter ions
  - Expected to be the most difficult heavy-ion effect to eliminate

PART 2: TESTING

Test Challenge: Identification of SEB SOA



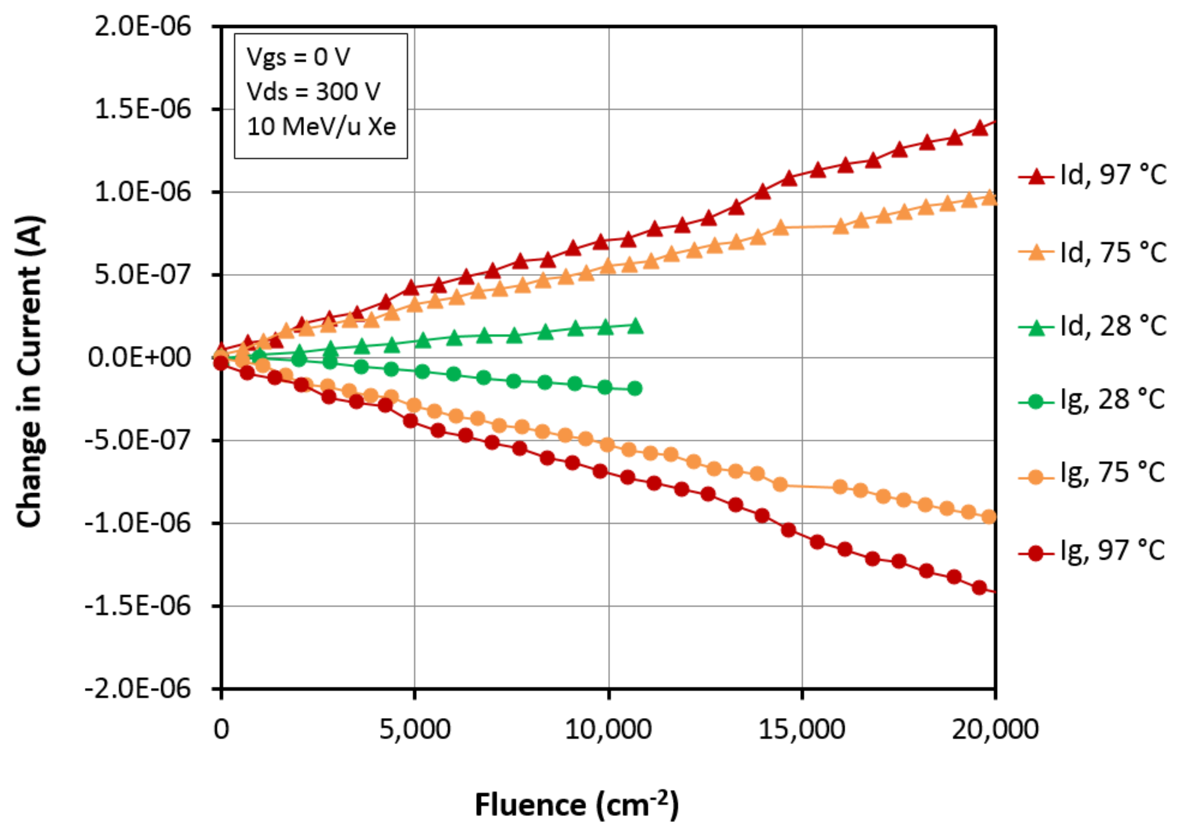
Saturation: Heat? or Degraded E-field?

Degradation is non-Poisson process: Prior damage can impact effect of next ions.

Threshold for SEB can be affected, preventing accurate identification of "SEB-safe" region of operation*.

***see Kuboyama, IEEE Trans. Nucl. Sci. 2006.**

Testing: Temperature Effects

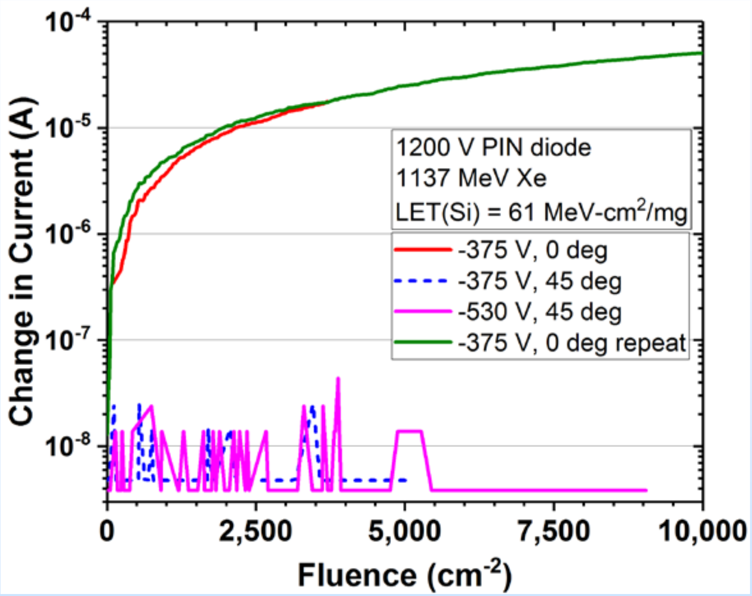


Rate of leakage current degradation in 1200-V power MOSFET increases with increasing temperature.

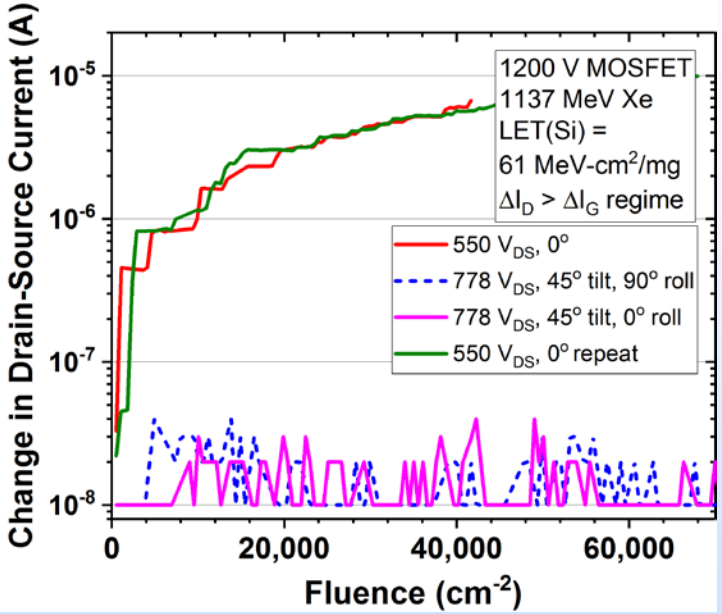
Because SiC dopants may not be fully ionized at room temperature, important to test at application temperature!

Testing: Angle Effects

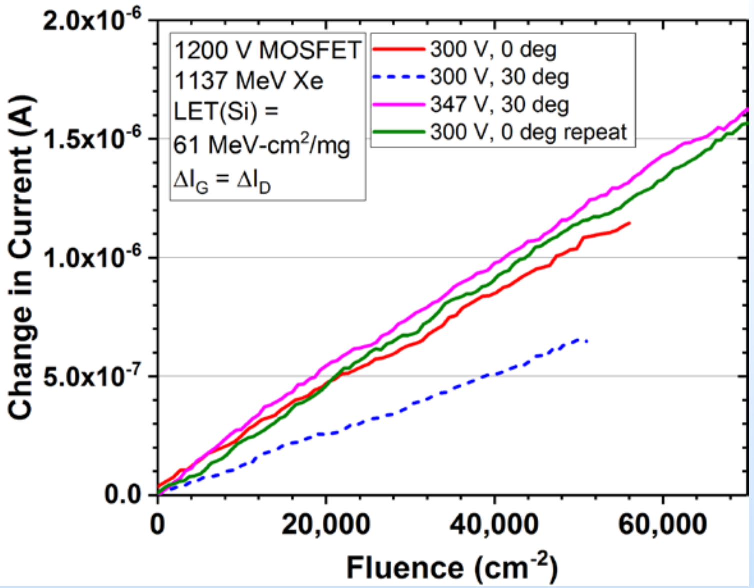
PIN Diode



MOSFET: $\Delta I_D >> \Delta I_G$



MOSFET: $\Delta I_D = \Delta I_G$



- **Diode & MOSFET (in $\Delta I_D >> \Delta I_G$ regime): Strong angle effect**
  - At given V_R / V_{DS}, no degradation at 45°
  - Matching vertical component of E-field has no impact: Cosine law not followed
- **MOSFET (in $\Delta I_D = \Delta I_G$ regime): Follows cosine law**
  - Path length through gate likely dominates angle effect (Vertical field reduced with angle)

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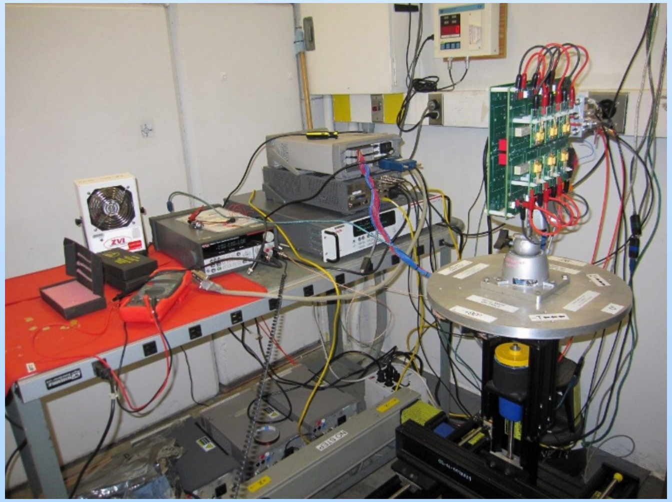
Summary of Testing Insights

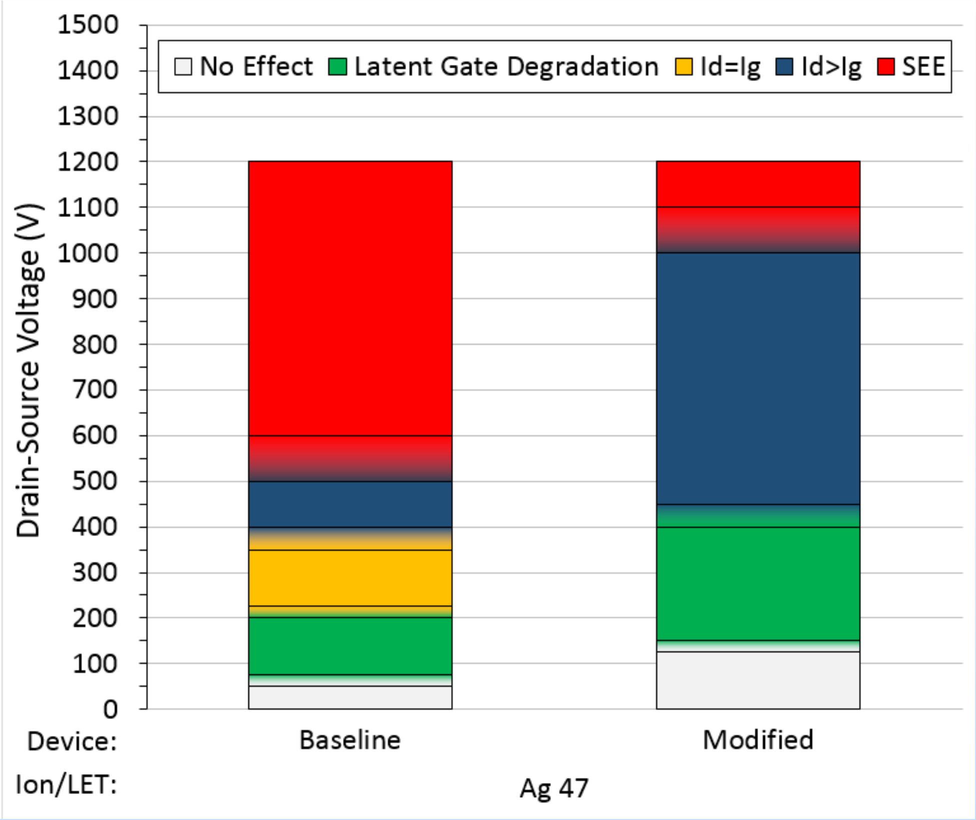
- **We may not be able to reliably define the SEB safe-operating area**
  - Appropriate test fluence may not be achievable before damage influences SEB susceptibility
  - No longer a true “single-event effect” due to effect of prior ion strikes
- **Temperature influences rate of current degradation**
  - Application temperature testing may be required
- **Strong angle responses will help reduce on-orbit susceptibility**
  - May also make rate calculations difficult
- **Lighter ions/lower LETs will reveal nuances between designs**
  - Responses saturate quickly



PART 3: OVERCOMING RADIATION THREATS

Radiation Hardness by Design: 1200 V MOSFET

Color gradients span between known V_{DS} for given response types



After Zhu, X., et al., 2017 ICSCRM

- **Reduced SEB susceptibility**
  - Thicker epilayer
- **Degradation of I_{DG} eliminated**
  - Drain neck width reduction
- **Minimal change in onset of other degradation effects:**
  - $\Delta I_D >> \Delta I_G$
  - latent gate damage

Continued research and development efforts are necessary to understand residual degradation mechanisms!

Summary & RHA Conclusions

- **SEB safe operating area is difficult to reliably define**
  - Susceptibility quickly saturates before the high-flux iron knee of the GCR spectrum
    - Mission orbit will have less influence on risk
- **Application-specific temperature testing may be necessary**
  - Dopants not fully ionized at room temperature
  - Effects of temperature on SEB susceptibility must be established
- **Some degradation mechanisms may persist despite RHBD efforts**
  - Impact on device long-term reliability must be established
- **Radiation hardening comes with a cost**
  - As with Si power MOSFETs, electrical performance will suffer from hardening techniques
- **Lighter ion/lower LET tests will reveal nuances between designs and aid on-orbit degradation predictions**
  - Responses are saturated at LETs dictated by typical mission destructive-SEE radiation requirements
  - LET should be specified in terms of LET(Si) but penetration range must be for SiC
- **Characterization data should include identification of voltage conditions at which different effects occur**
  - Richer dataset will include how susceptibility to these effects changes with ion species/LET