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Taking SiC Power Devices to the Final Frontier: Addressing Challenges of the Space Radiation Environment

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Abbreviations & Acronyms

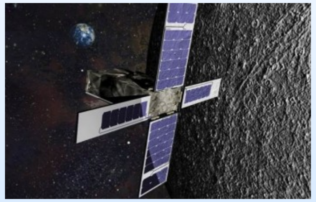
Acronym	Definition
BJT	Bipolar Junction Transistor
BV_{DSS}	Drain-Source Breakdown Voltage
COR	Contracting Officer Representative
COTS	Commercial Off The Shelf
ESA	European Space Agency
ETW	Electronics Technology Workshop
FY	Fiscal Year
GCR	Galactic Cosmic Ray
I_D	Drain Current
I_{DSS}	Drain-Source Leakage Current
I_G	Gate Current
I_R	Reverse-Bias Leakage Current
IC	Integrated Circuit
ICSCRM	International Conference on SiC and Related Materials
JAXA	Japan Aerospace Exploration Agency
JBS	Junction Barrier Schottky
JFET	Junction Field Effect Transistor
LBNL	Lawrence Berkeley National Laboratory cyclotron facility

Acronym	Definition
MOSFET	Metal Oxide Semiconductor Field Effect Transistor
Q	Charge
RADECS	Radiation and its Effects on Components and Systems
RHA	Radiation Hardness Assurance
SBD	Schottky Barrier Diode
SEB	Single-Event Burnout
Si	Silicon
SiC	Silicon Carbide
SMU	Source Measurement Unit
SOA	State Of the Art
STMD	Space Technology Mission Directorate
SWAP	Size, Weight, And Power
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
V_{TH}	Gate Threshold Voltage

Motivational Factors

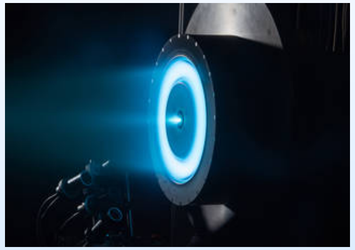
Images courtesy of NASA

Orion



SmallSats

High Voltage Instruments



Solar Electric Propulsion

Commercial Space

- Game-changing NASA approaches are demanding higher-performance power electronics
  - *SEE rad-hardened high-current MOSFETs > 250 V do not exist*
  - *High-voltage transistors with fast switching speeds are also needed*
- SWAP benefits for existing technologies
  - *SiC power devices are flying now (Orion, MMS)*

Conclusions: We must understand the risk of damaged parts

We must support industry/government/academic partnerships to expand SEE hardening efforts

Radiation Effects in SiC Power Technology

- **Wide-bandgap power electronics are frequently referred to as "inherently radiation hard" – but to what type of radiation?**
  - Total ionizing dose (TID)
  - Displacement damage dose (DDD)
  - Heavy-ion induced single-event effects (SEE)
- **Prior work by NASA and other researchers has shown that serendipitously SEE-hard commercial SiC power devices are rare or non-existent**

TID hardness came for "free"; SEE hardness will not!

SiC parts included in this talk:

Device Type	# COTS or Engineering Parts/ # Manufacturers
Diode	6/4
MOSFET	8/4
JFET	4/2
BJT	1/1

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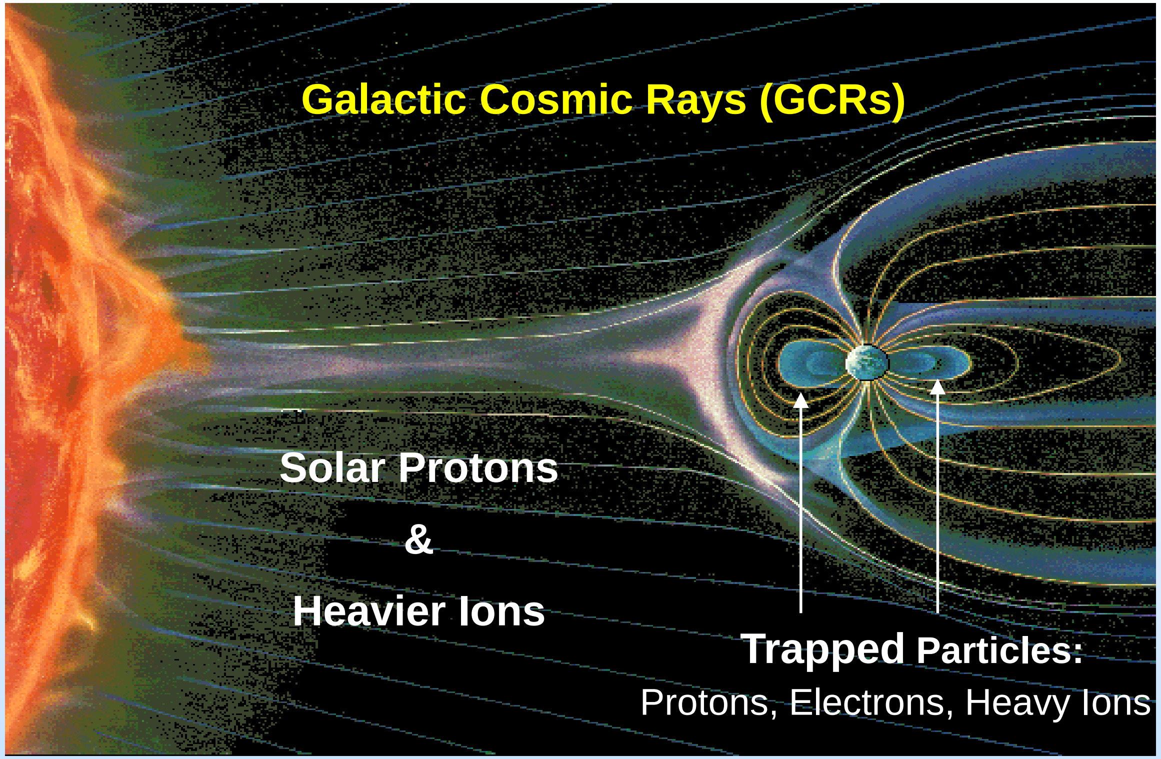
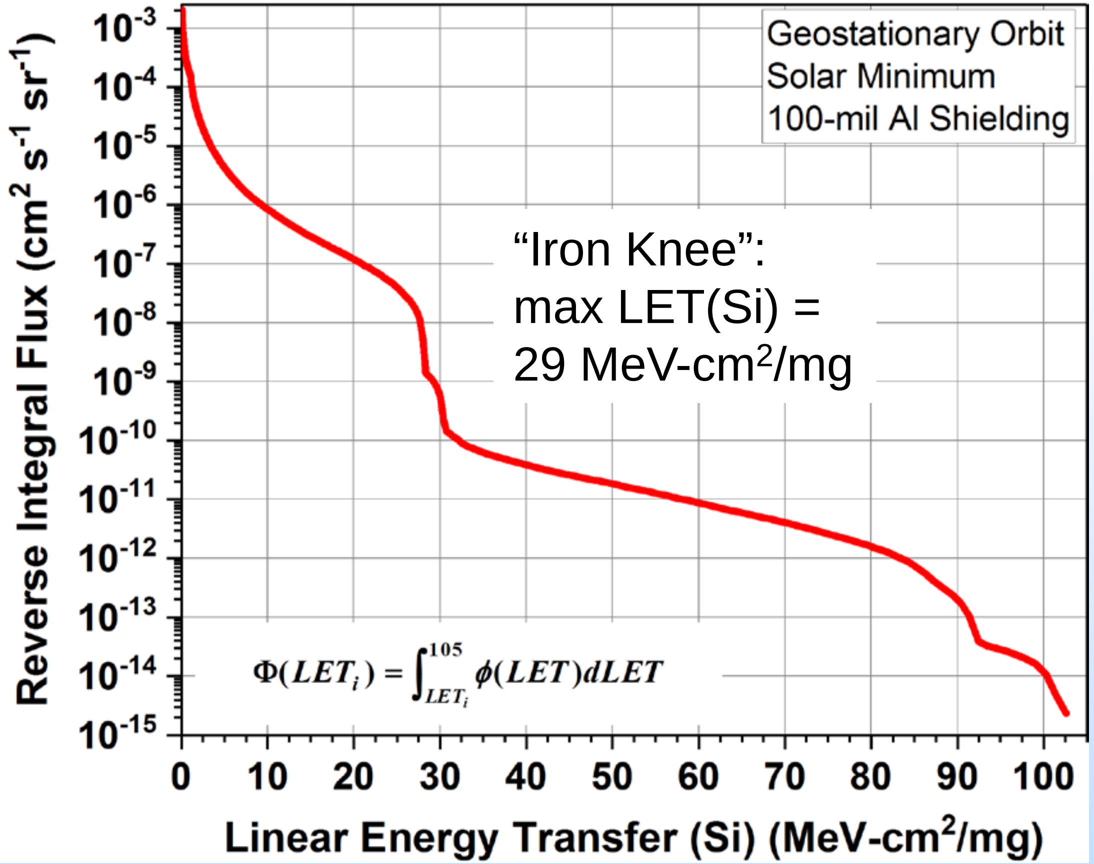
Space Radiation Environment



After K. Endo, Nikkei Science Inc. of Japan

- **Cumulative effects**
  - TID—Total Ionizing Dose (degradation due to charge trapped in device oxides)
  - DDD—Displacement Damage Dose (degradation from damage to semiconductor)
- **Single-particle effects**
  - SEE—Single-Event Effect (change in performance of device resulting from passage of a single energetic particle)

Heavy-Ion Environment



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)

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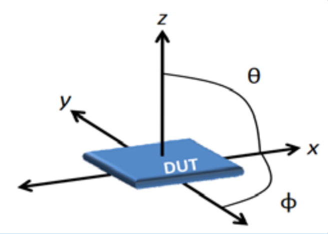
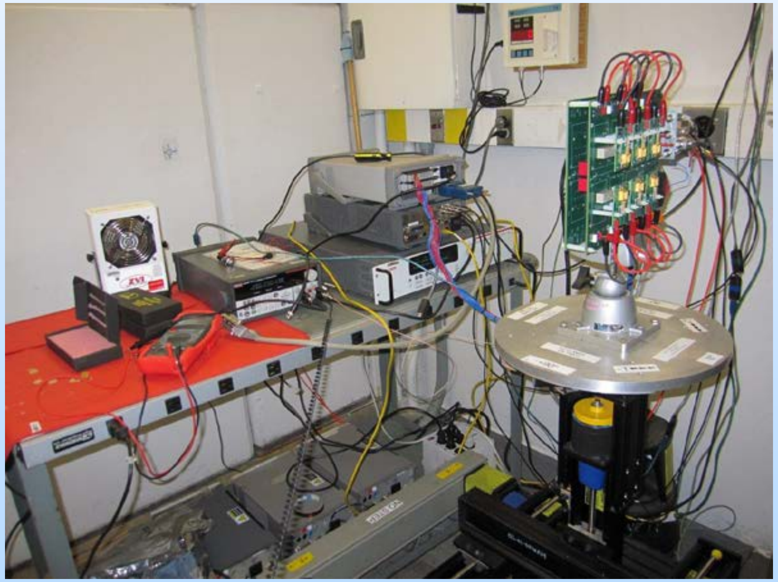
SiC Power Device Response to Heavy Ion Irradiation

- **Heavy-ion radiation effects in SiC power devices are a function of:**
  - **Applied voltage**
    - Reverse voltage (V_R) or drain-source voltage (V_{DS}) when in the “off” or blocking state
  - **Incident ion energy and species**
    - Linear energy transfer (LET)
  - **Angle of ion strike**
    - Tilt/roll angle
  - **Device temperature**

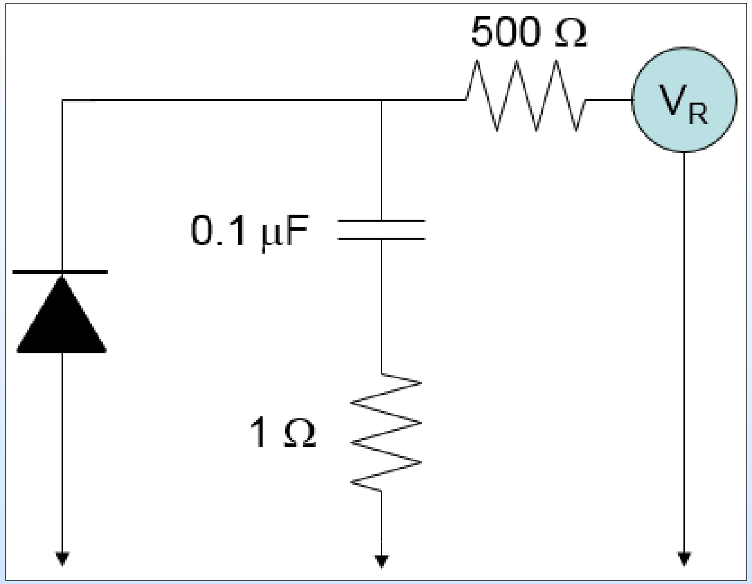


Θ = tilt angle

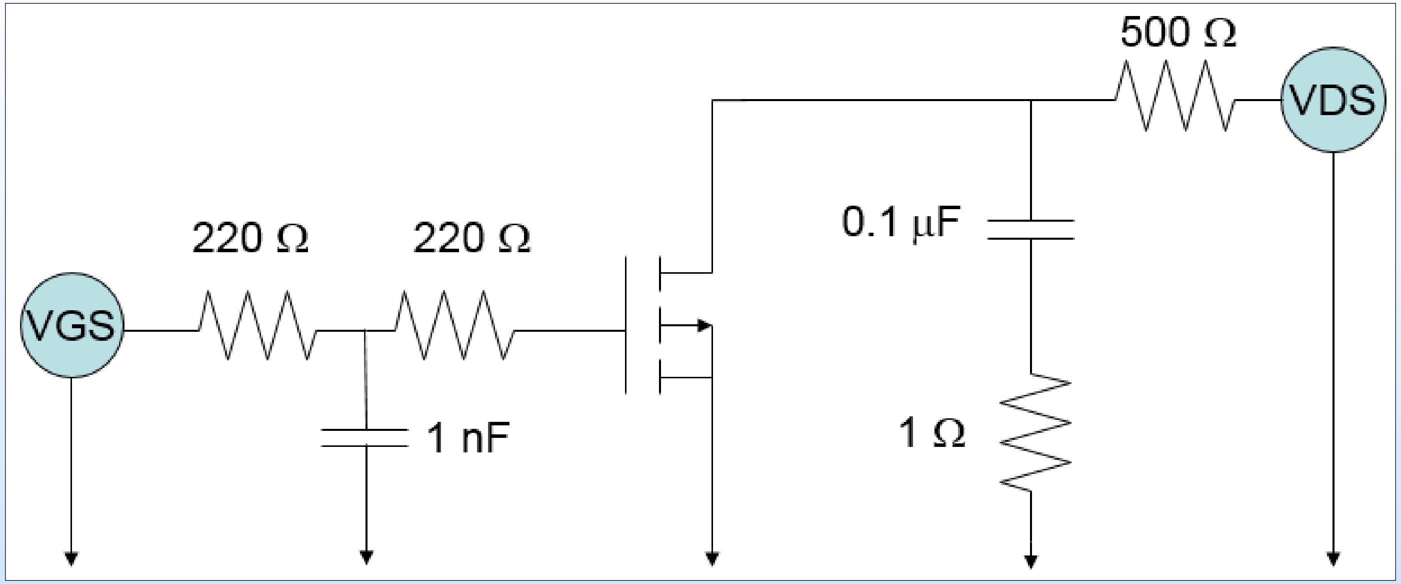
Φ = roll angle



Test Circuits



Diode Test Circuit



MOSFET/JFET Test Circuit

- **Per MIL-STD 750, TM1080**
  - **Stiffening capacitor prevents voltage sagging upon sudden increase in current**
  - **Gate filter to protect MOSFET oxide from electrically induced transients**
    - **Filter removed for BJT tests**

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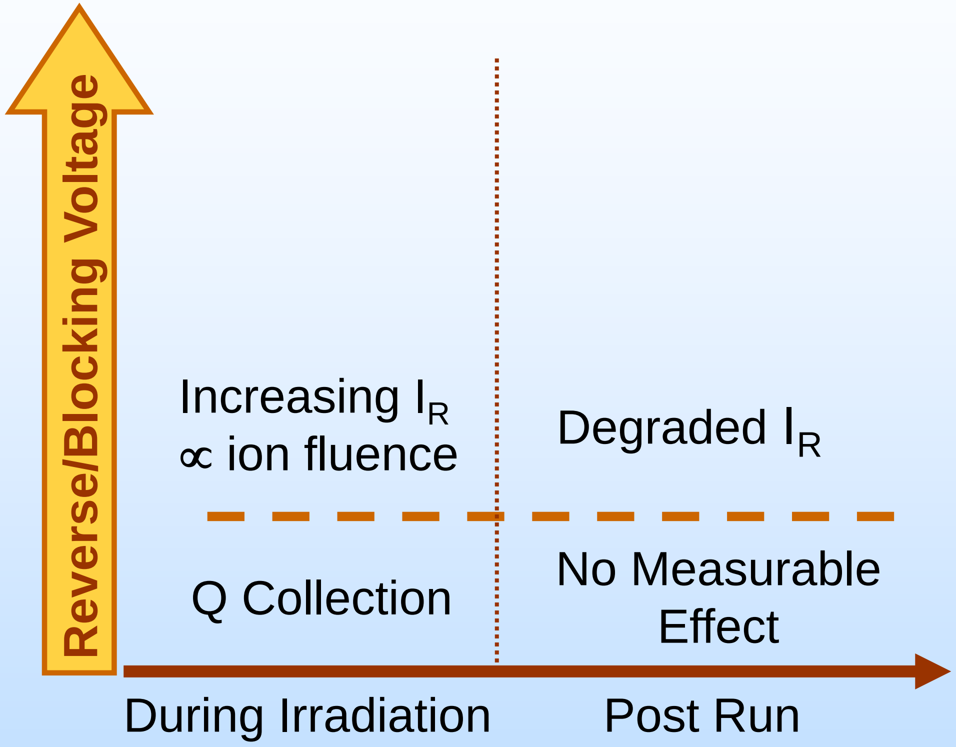
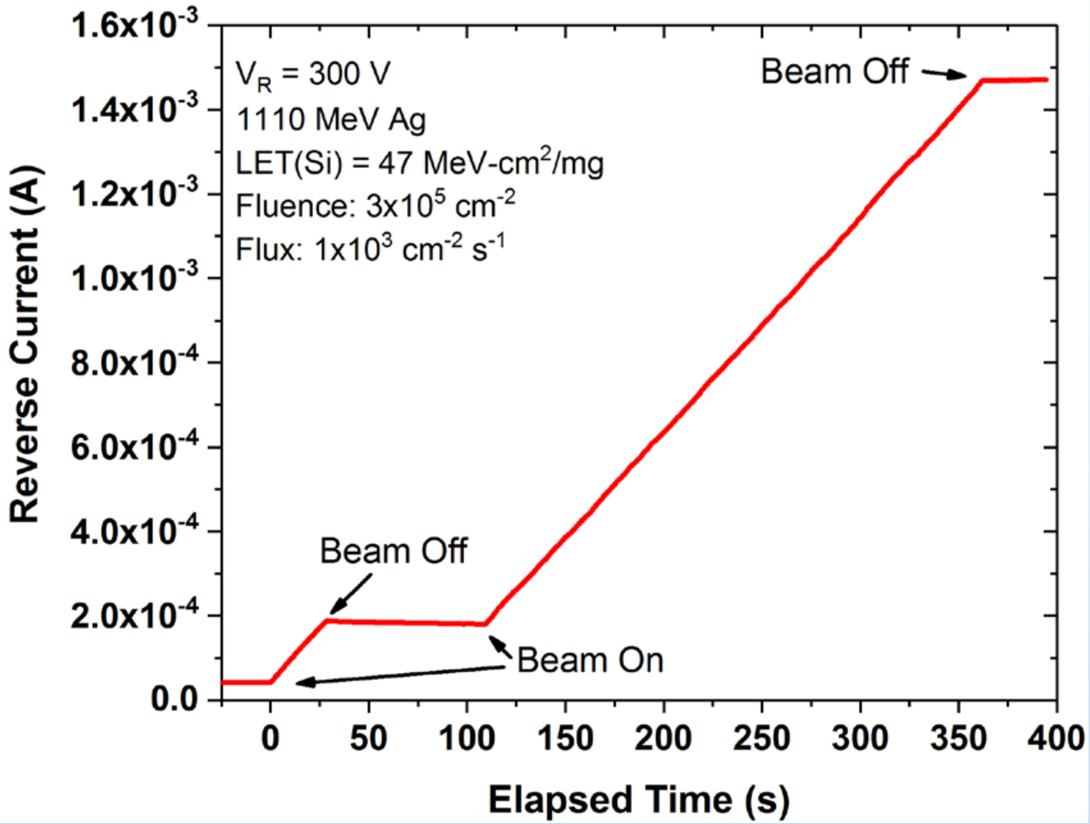
Applied Voltage and Ion LET:

SCHOTTKY DIODES

Diode Effects as a Function of V_R: Degradation



Measurement Results



Leakage current increases linearly with ion fluence;
Slope increases with increasing V_R

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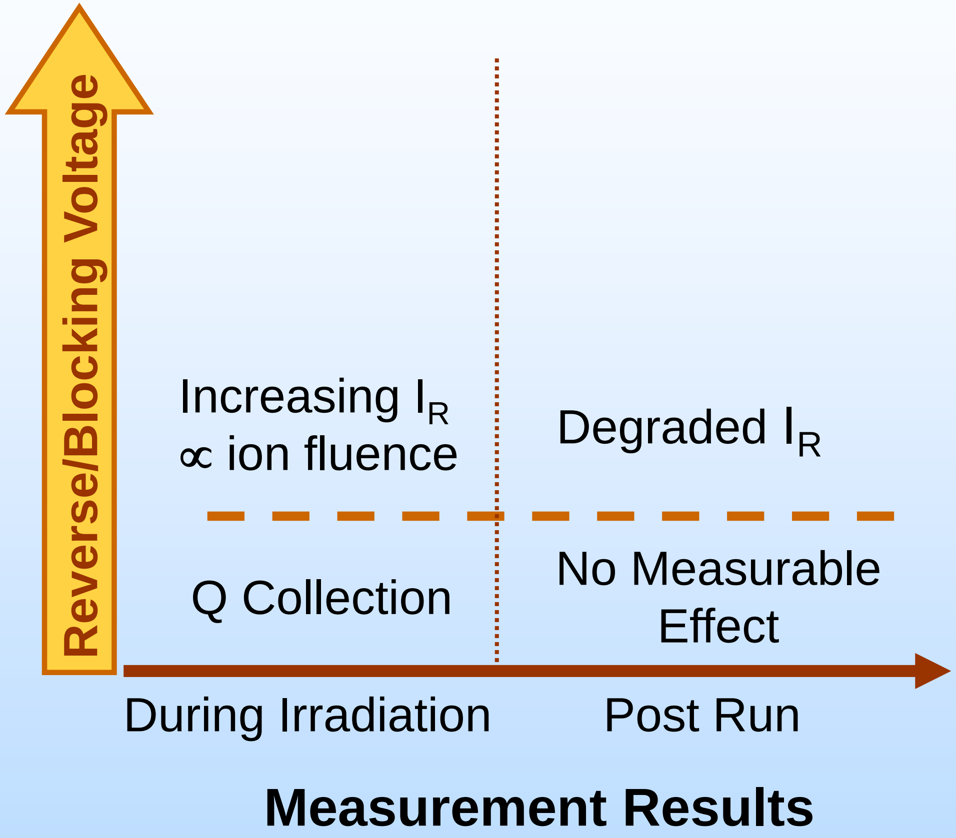
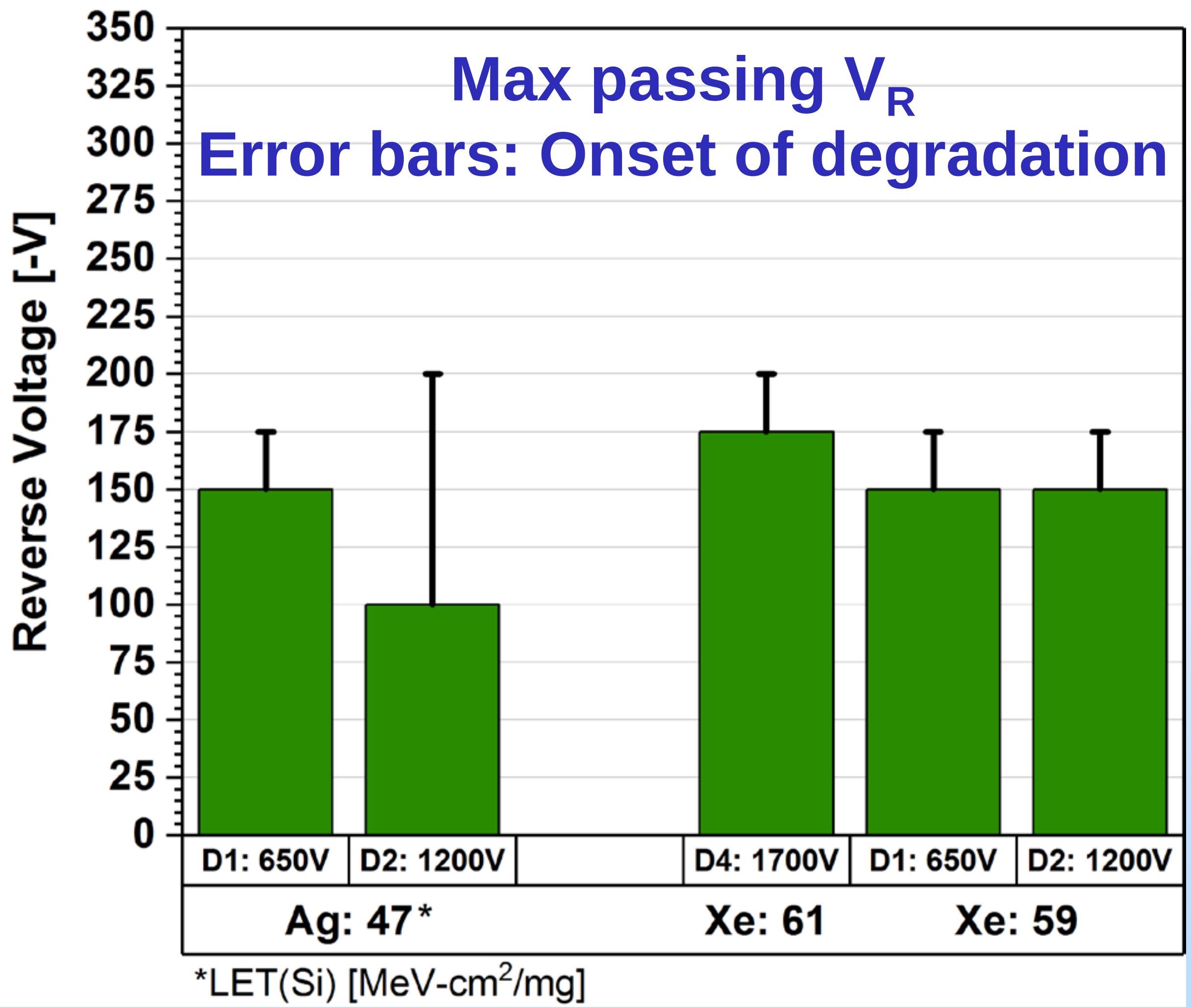
Diode Effects as a Function of V_R: Degradation





*LET(Si) [MeV-cm^2/mg]

Onset V_R for degradation is similar for 650 V – 1700 V SBD or JBS diodes: Once minimum conditions met, electric field may not matter

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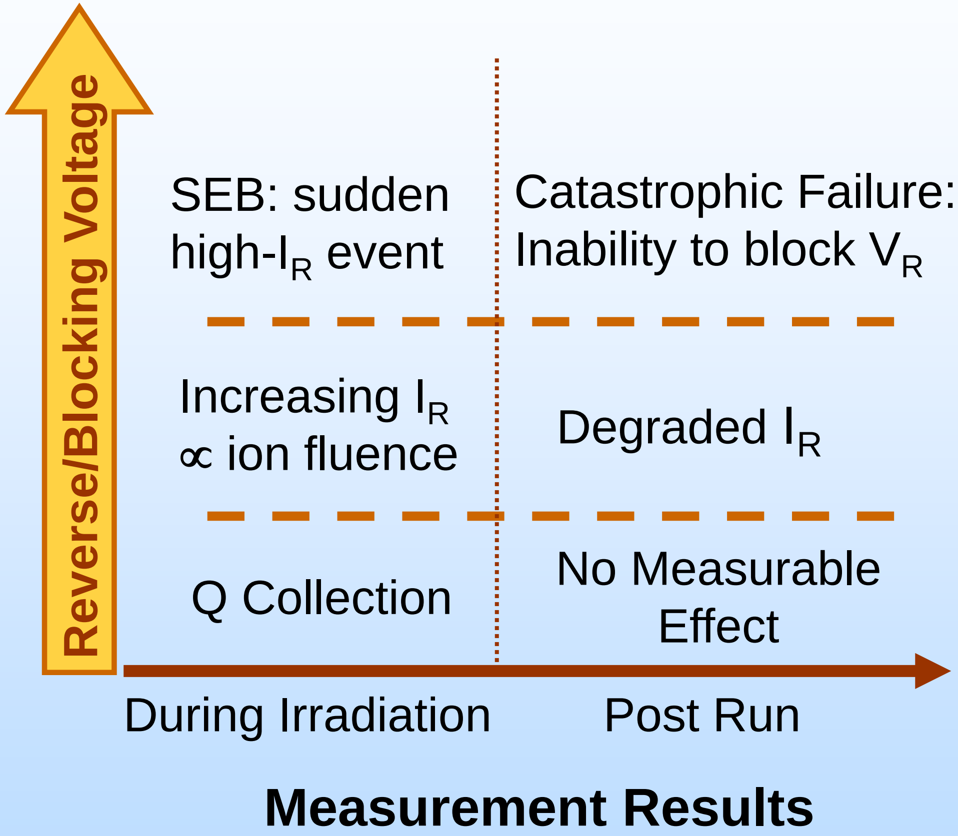
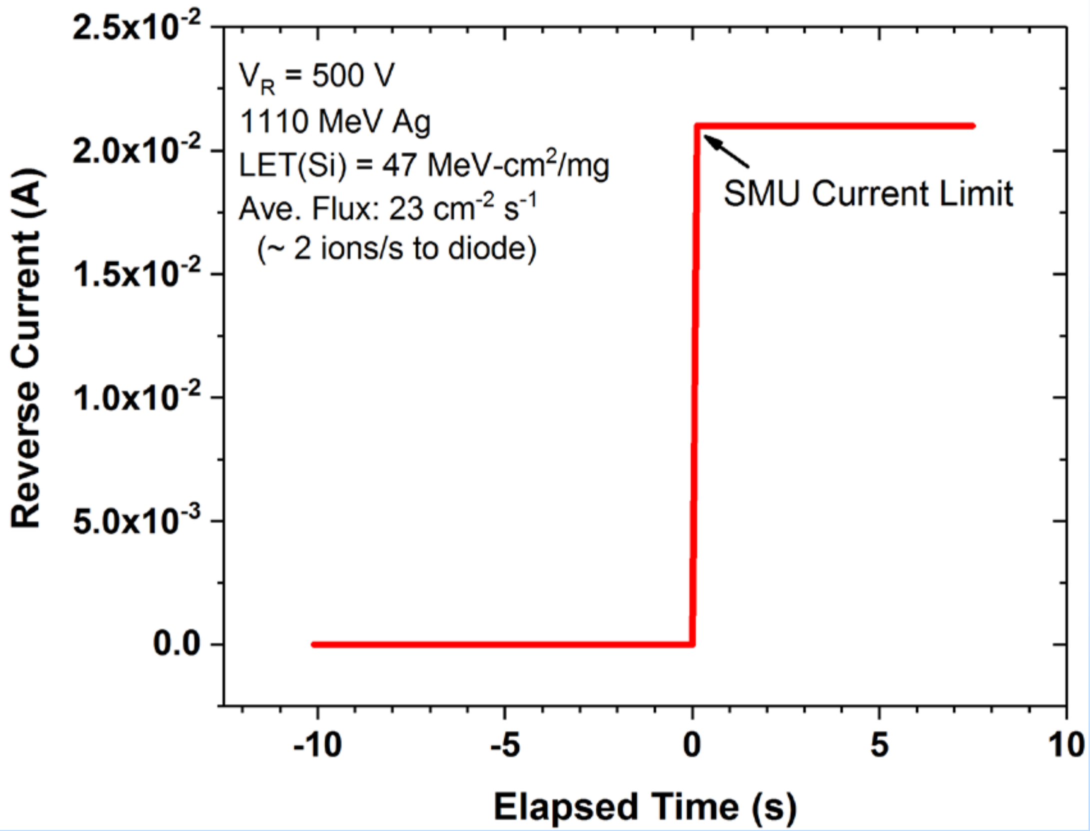
Diode Effects as a Function of V_R: SEB



Reverse/Blocking Voltage

	During Irradiation	Post Run
	SEB: sudden high-I_R event	Catastrophic Failure: Inability to block V_R
	Increasing I_R $\propto$ ion fluence	Degraded I_R
	Q Collection	No Measurable Effect

Measurement Results



After catastrophic single-event burnout (SEB), the diode can no longer block voltage

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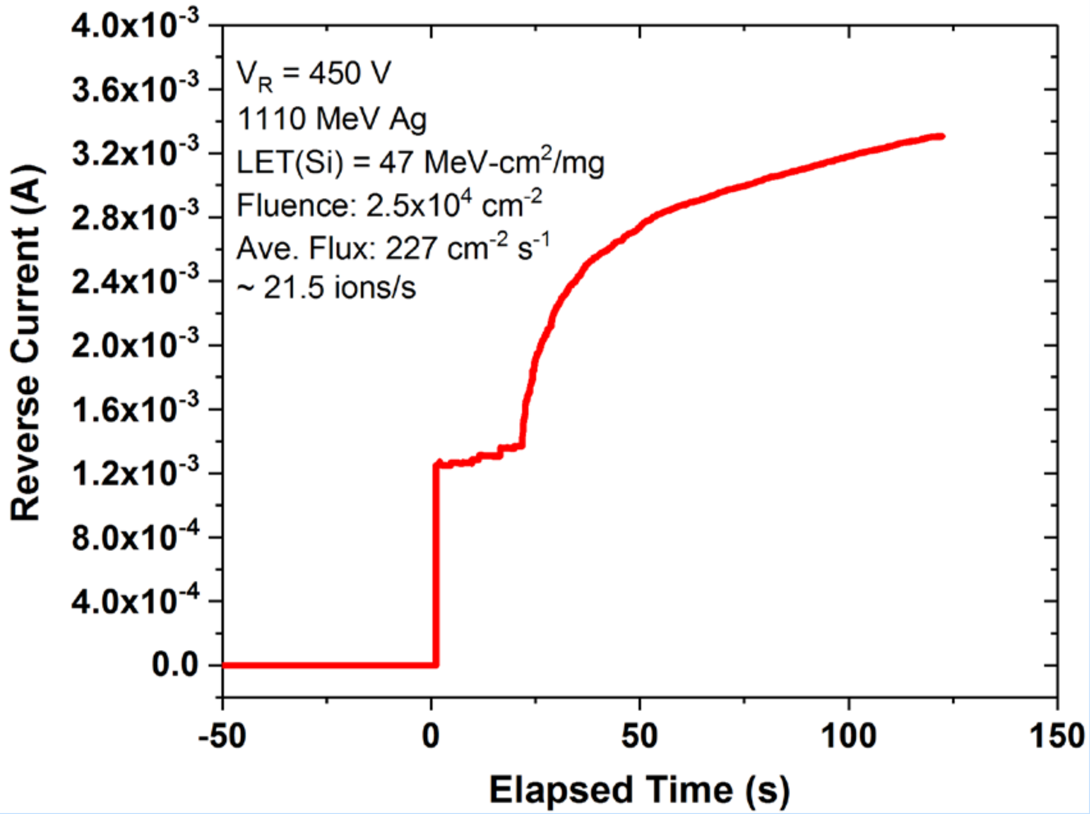
Diode Effects as a Function of V_R: Test Challenge



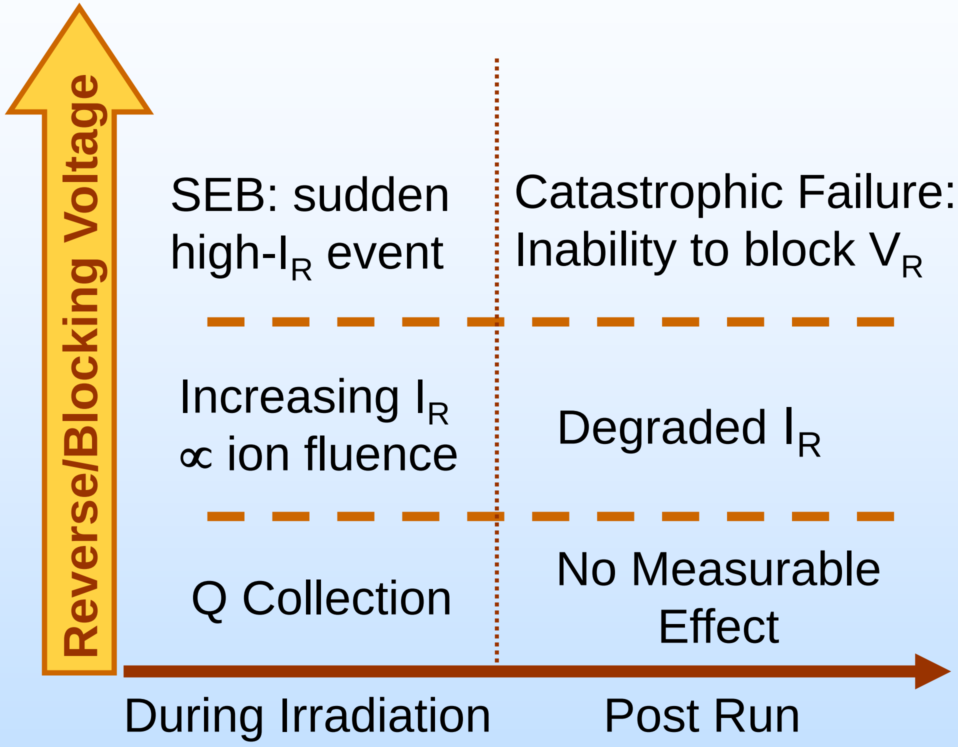
Saturation: Heat? or Degraded E-field?

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.**

Diode Effects as a Function of V_R: SEB



Reverse/Blocking Voltage

SEB: sudden high-I_R event

Catastrophic Failure: Inability to block V_R

Increasing I_R $\propto$ ion fluence

Degraded I_R

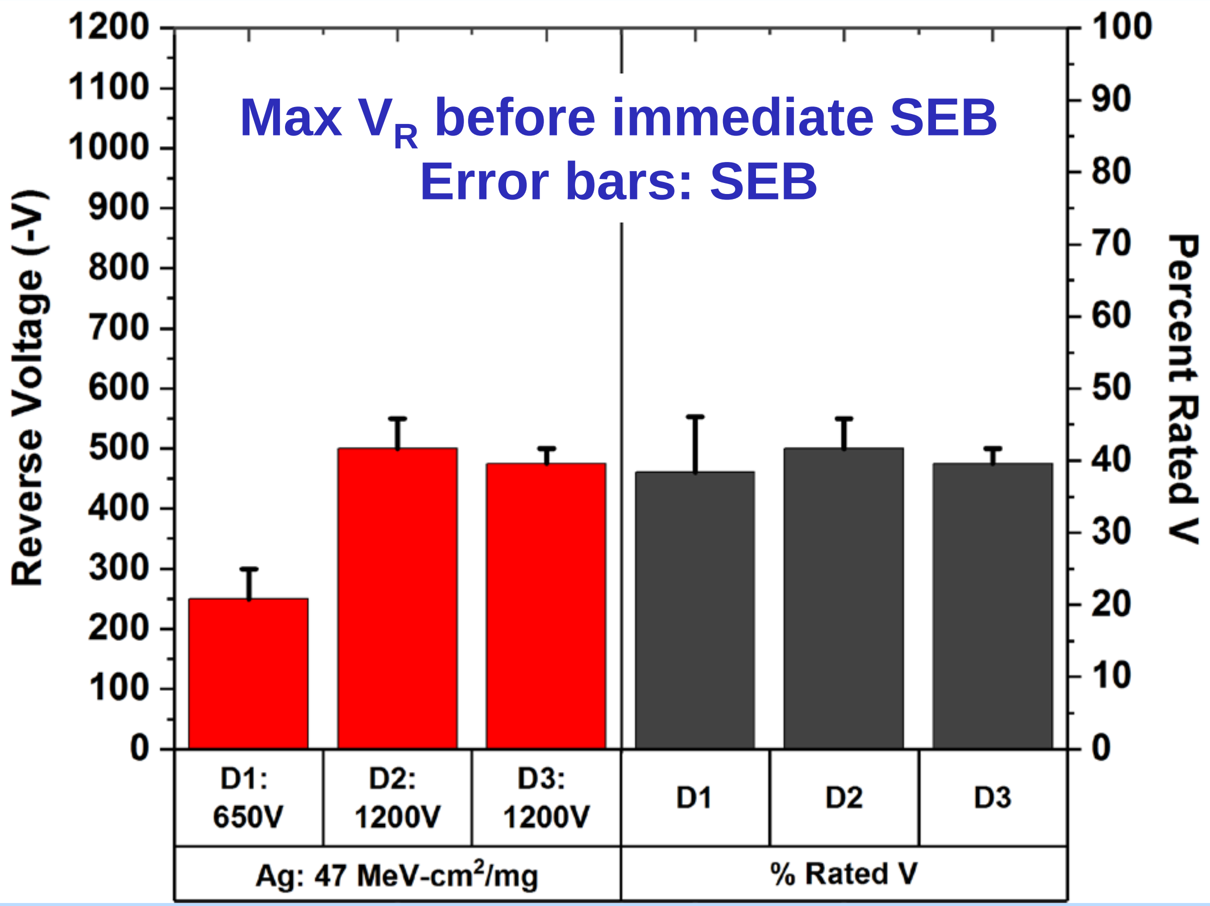
Q Collection

No Measurable Effect

During Irradiation

Post Run

Measurement Results



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

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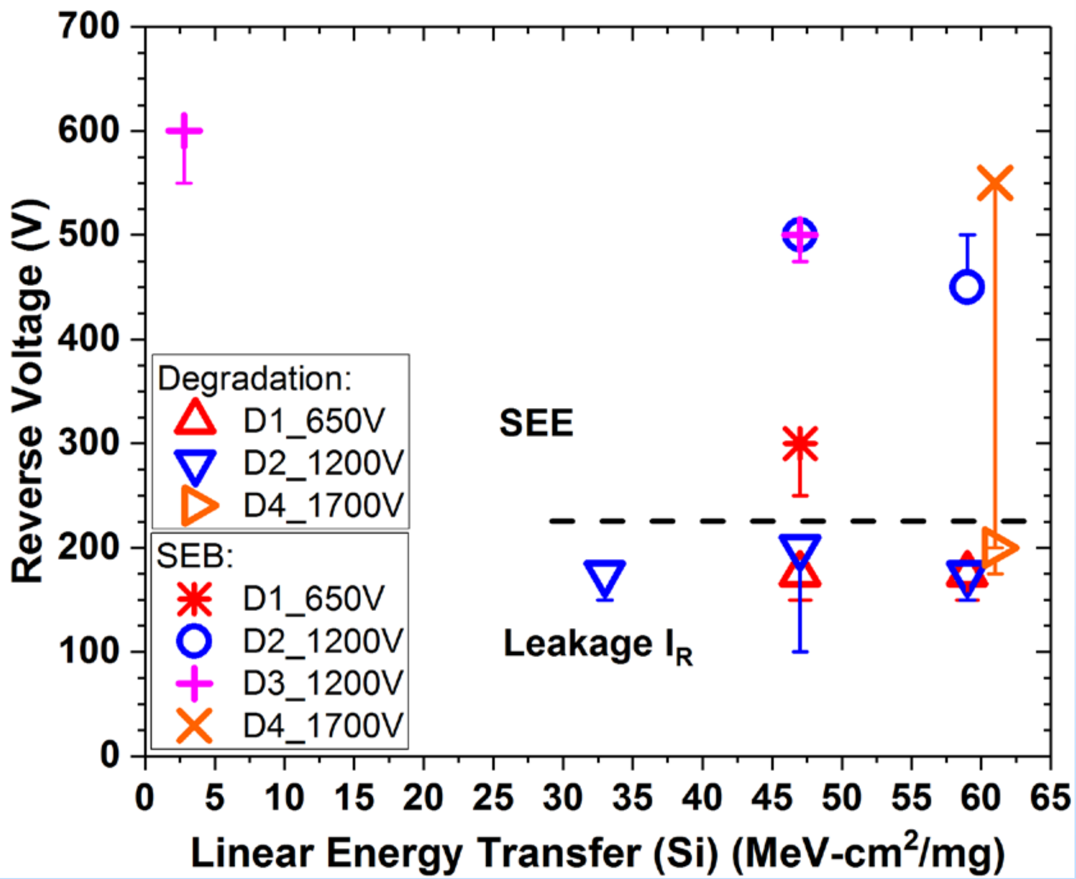
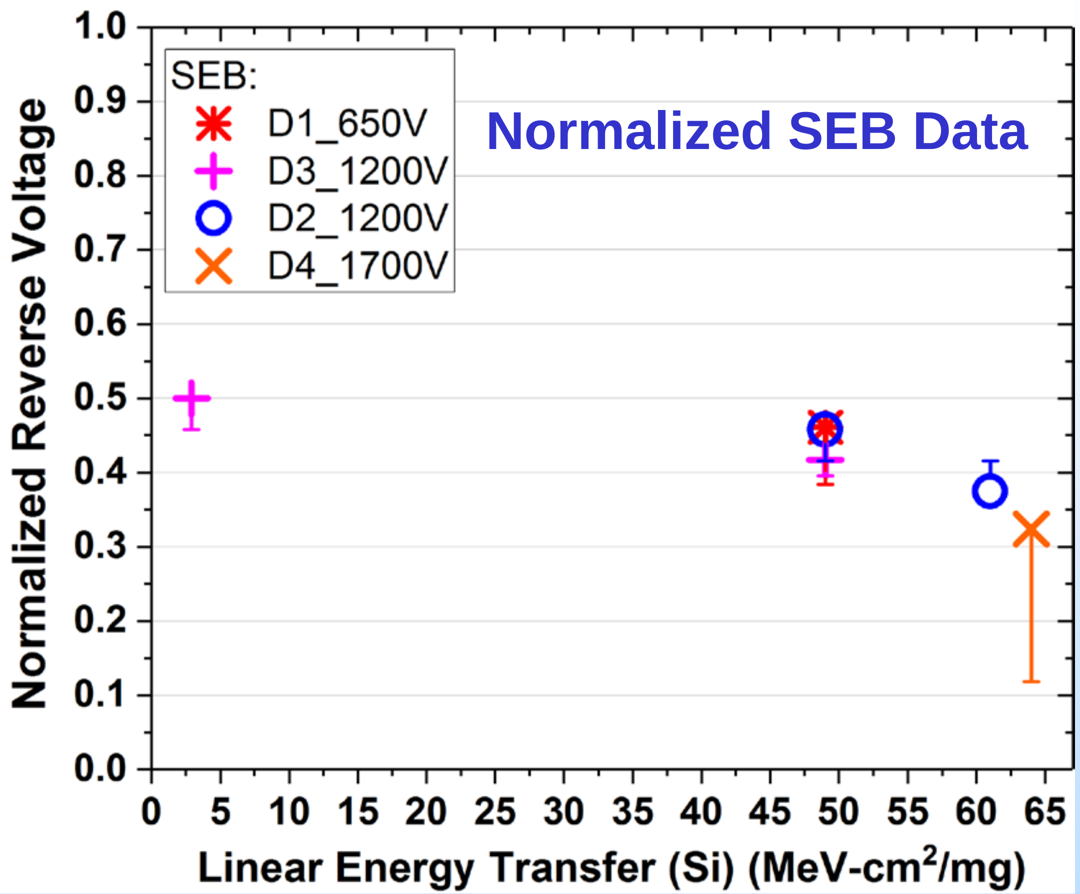
Schottky Diode Effects as a Function of LET





No degradation with neon at LET = 2.8 MeV-cm^2/mg but

SEB still occurs at 50% of rated V_R despite very low LET

Suggests high-energy protons will cause SEB

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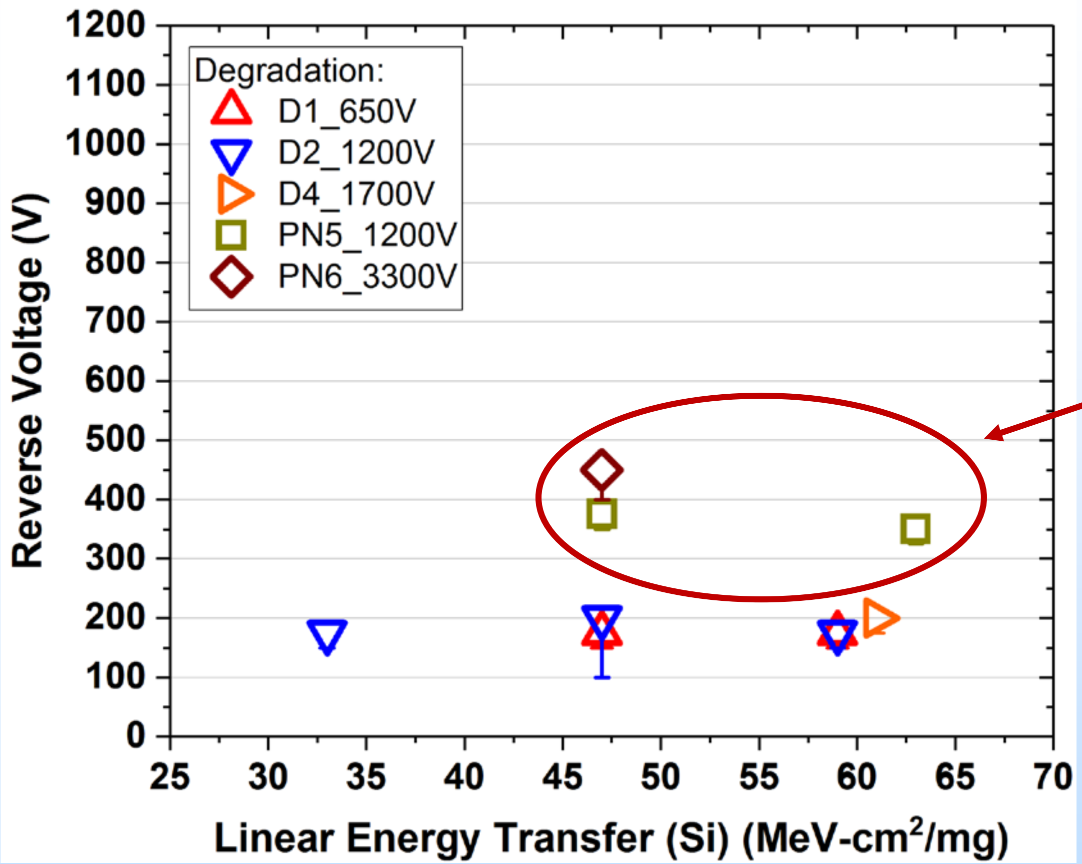
Applied Voltage and Ion LET:

PIN DIODES

PIN vs. Schottky Diode Effects: Degradation



PIN Diodes

PIN diode onset V_R for degradation is higher than that for Schottkys.

Similar degradation onset V_R for 1200 V and 3300 V PINs

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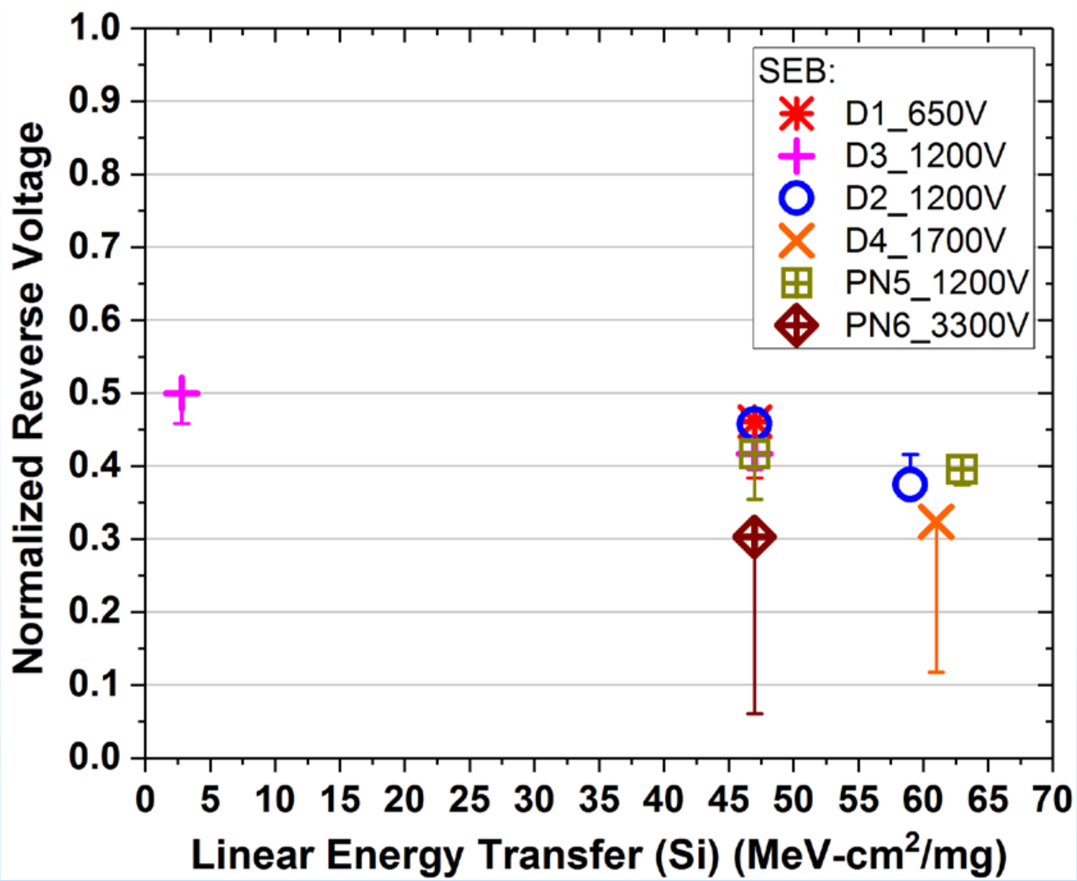
PIN vs. Schottky Diode Effects: SEB



PIN and Schottky diode SEB occurs at similar normalized V_R – Again suggests different mechanisms for SEB vs. degradation

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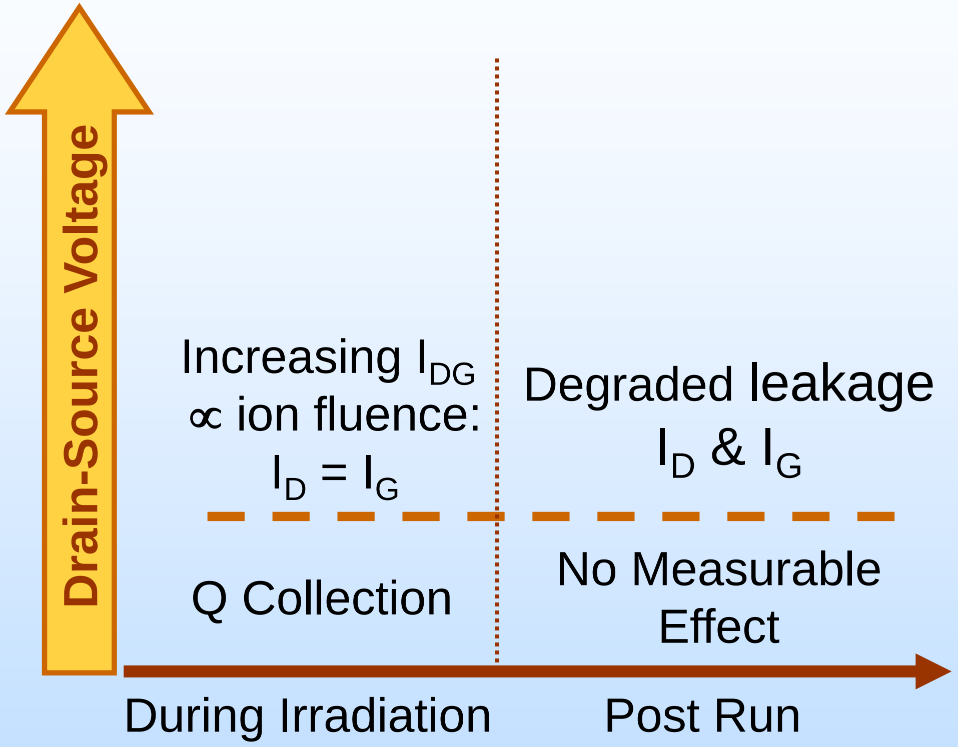
Applied Voltage:

JFETS

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



Drain-Source Voltage

Increasing I_{DG} $\propto$ ion fluence: $I_D = I_G$

Degraded leakage I_D & I_G

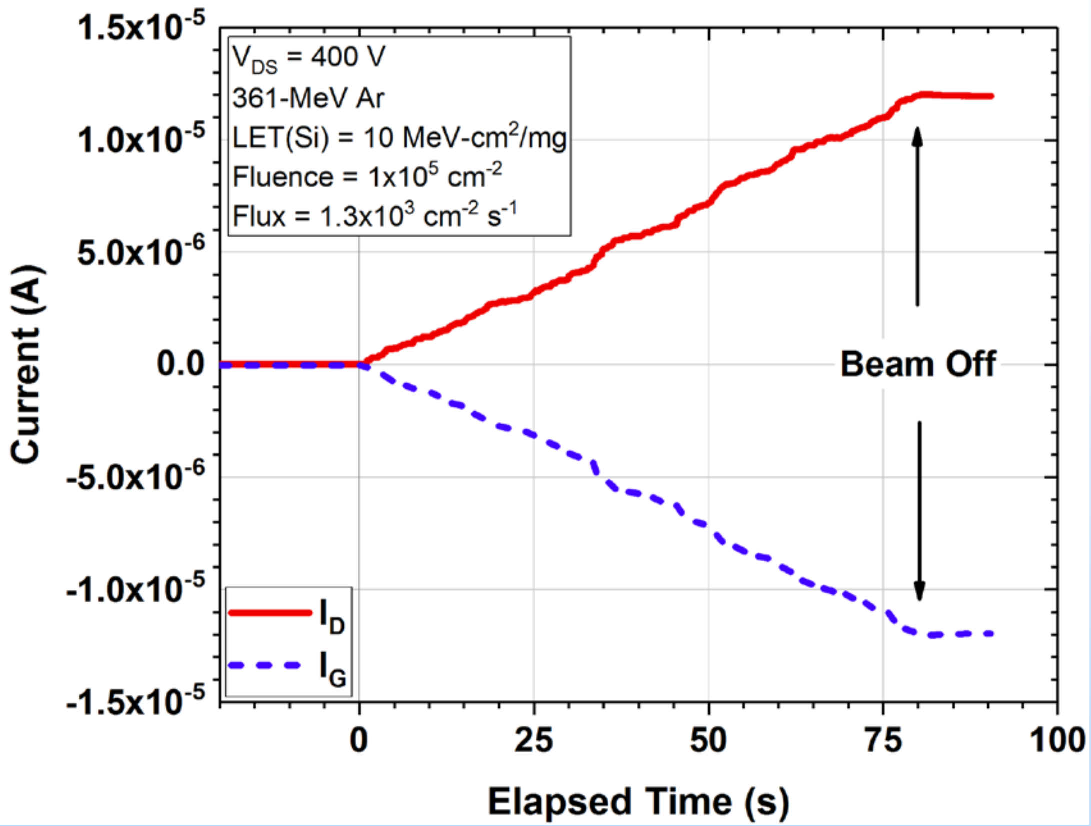
Q Collection

No Measurable Effect

During Irradiation

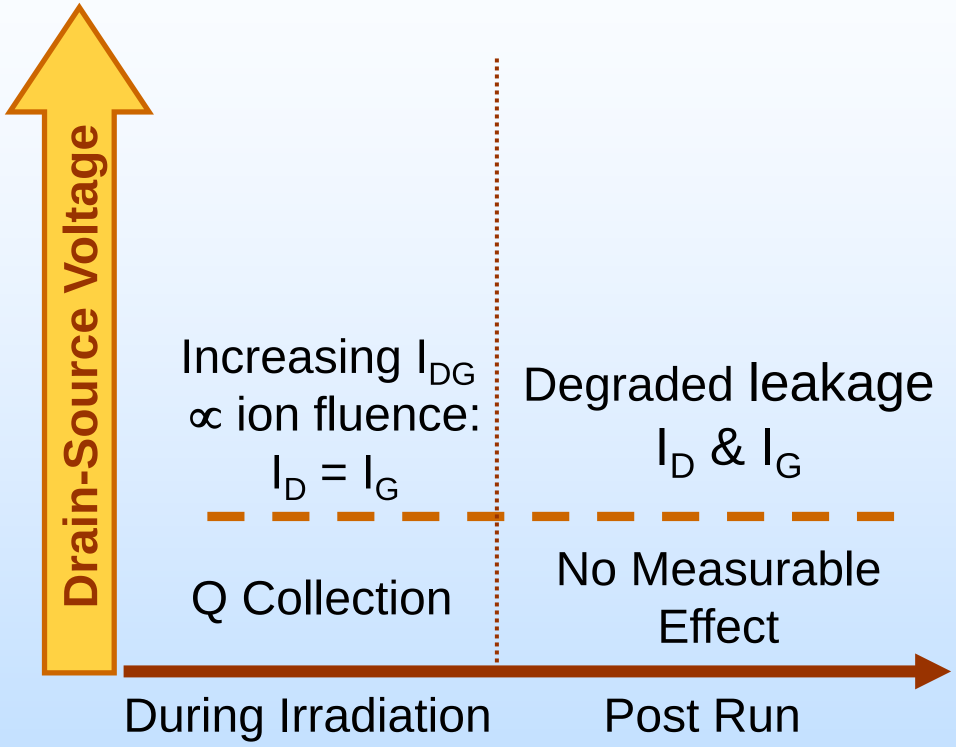
Post Run

Measurement Results

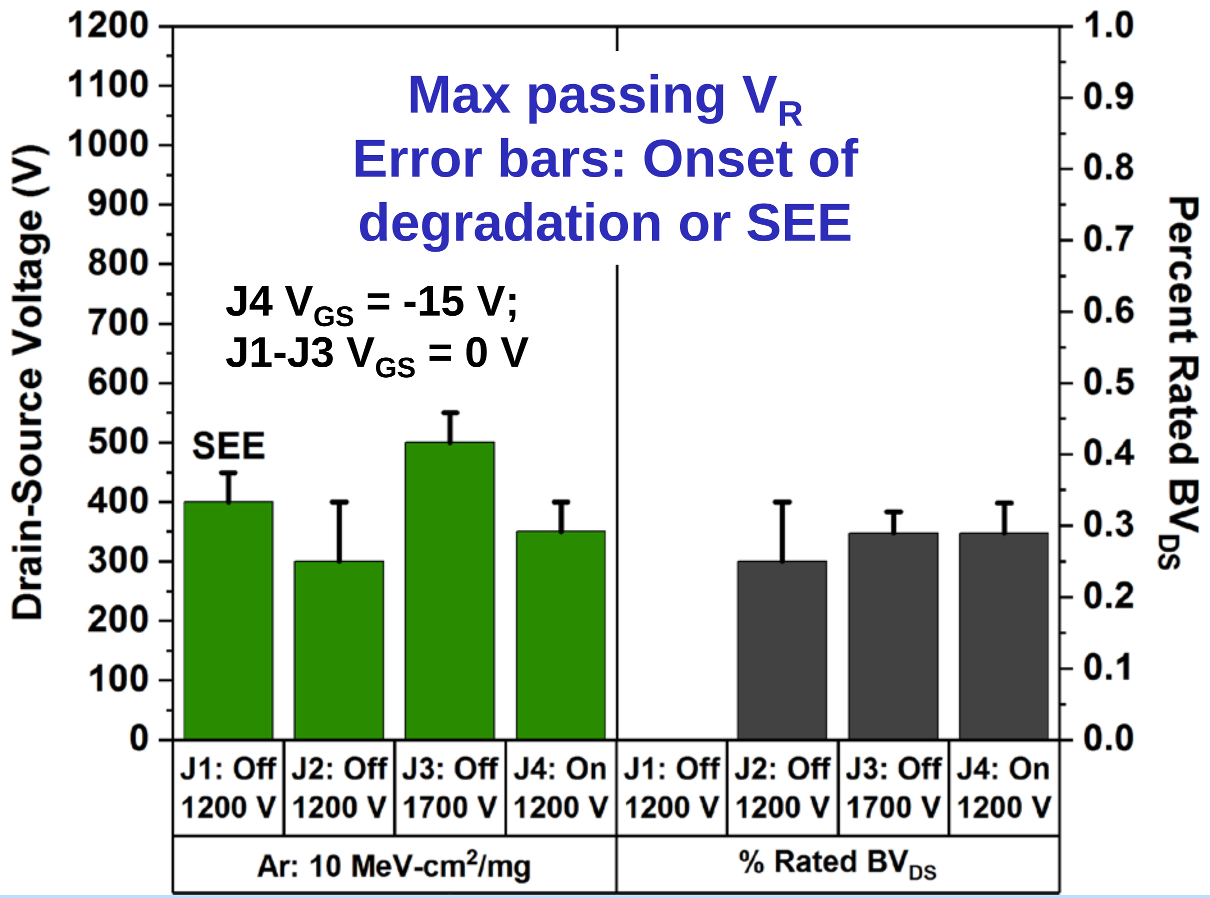


Degradation in tested normally-on and normally-off JFETs is always drain-gate leakage, likely due to trench design

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



Measurement Results



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

Possibly greater field dependence of degradation mechanism vs. diodes (or due to lower test LET?)

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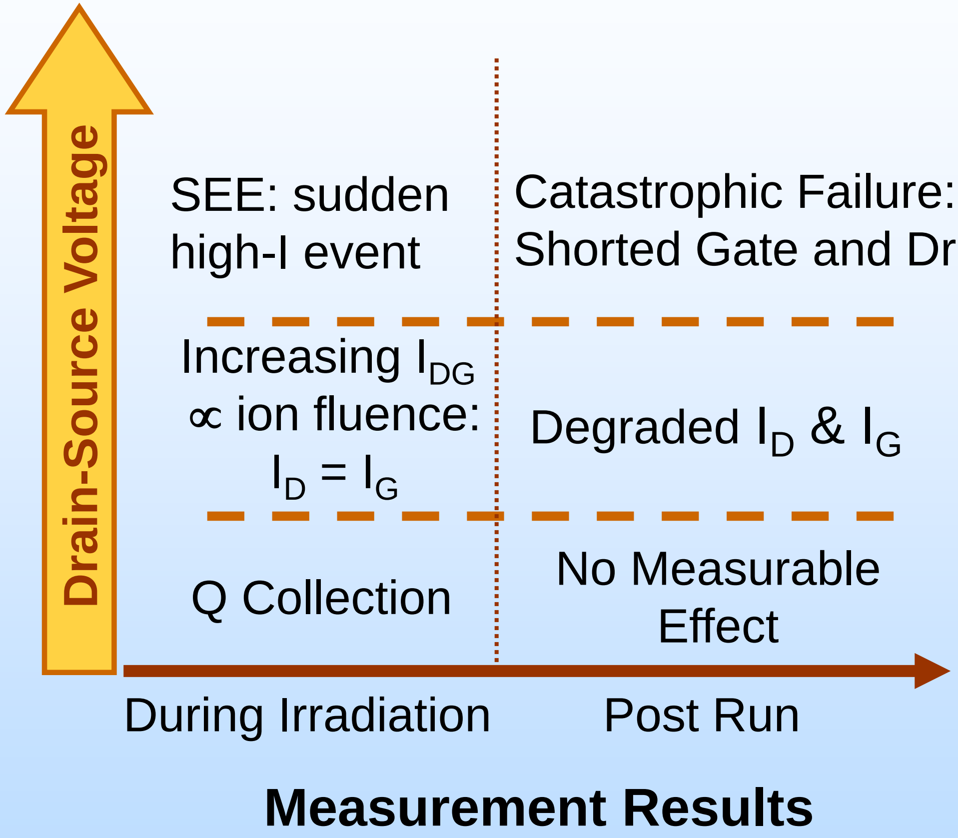
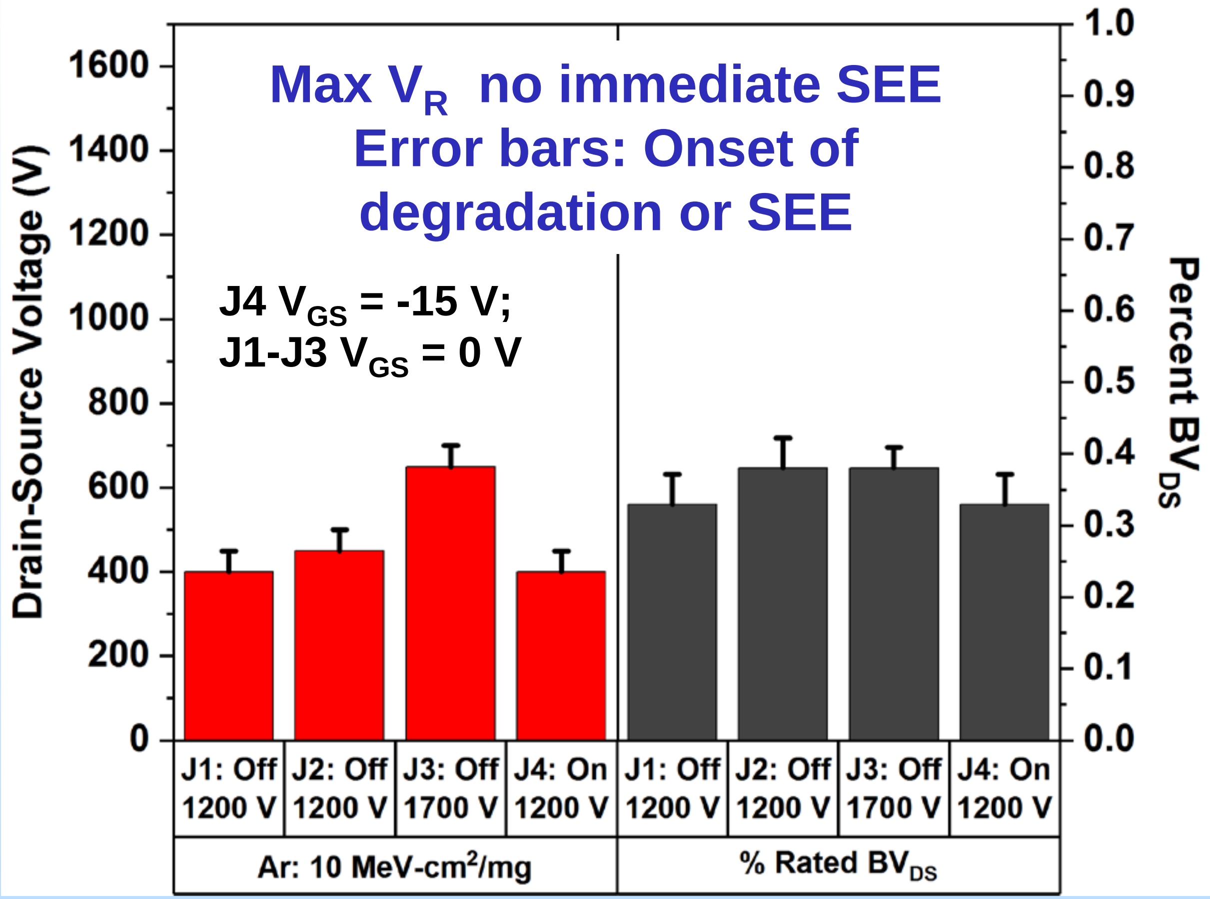
Effects as a Function of V_{DS} at Fixed off V_{GS}: SEE



Drawn by Drain-Source Voltage against time of measurement, from lowest to highest voltage:

- Q Collection (during irradiation); No Measurable Effect (post run)
- Increasing I_{DG} ∝ ion fluence: $I_D = I_G$ (during irradiation); Degraded I_D & I_G (post run)
- SEE: sudden high-I event (during irradiation); Catastrophic Failure: Shorted Gate and Drain (post run)

Measurement Results



Max V_R no immediate SEE
Error bars: Onset of degradation or SEE

J4 V_{GS} = -15 V;
J1-J3 V_{GS} = 0 V

1200 V – 1700 V JFETs show SEE at similar % of rated V_{DS}
Normally-on similar to normally-off JFET susceptibility

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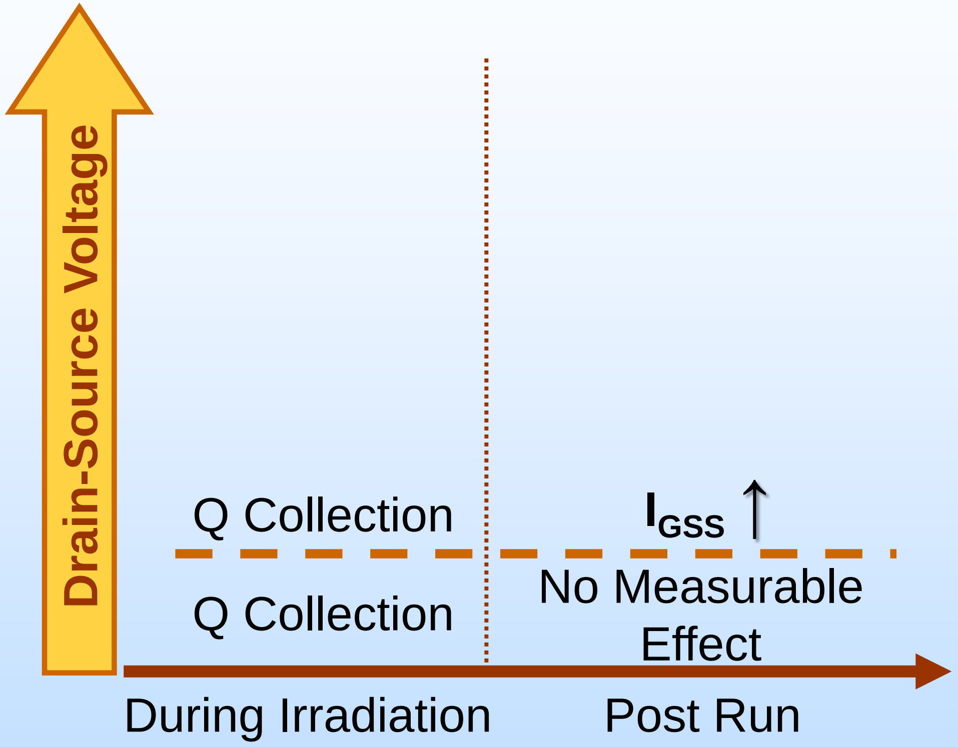
Applied Voltage and LET:

MOSFETS

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


Drain-Source Voltage

Q Collection

I_{GSS} ↑

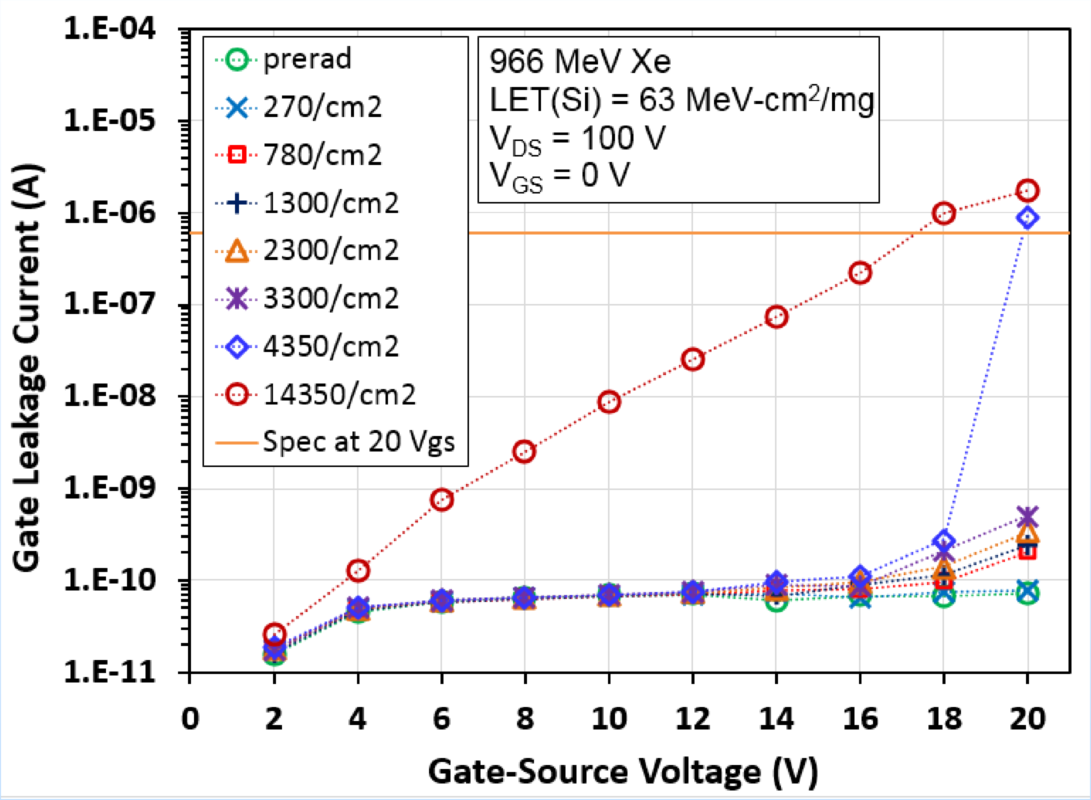
Q Collection

No Measurable Effect

During Irradiation

Post Run

Measurement Results



Presence of gate oxide introduces a latent-damage mechanism revealed only on post-irradiation gate stress (PIGS) test

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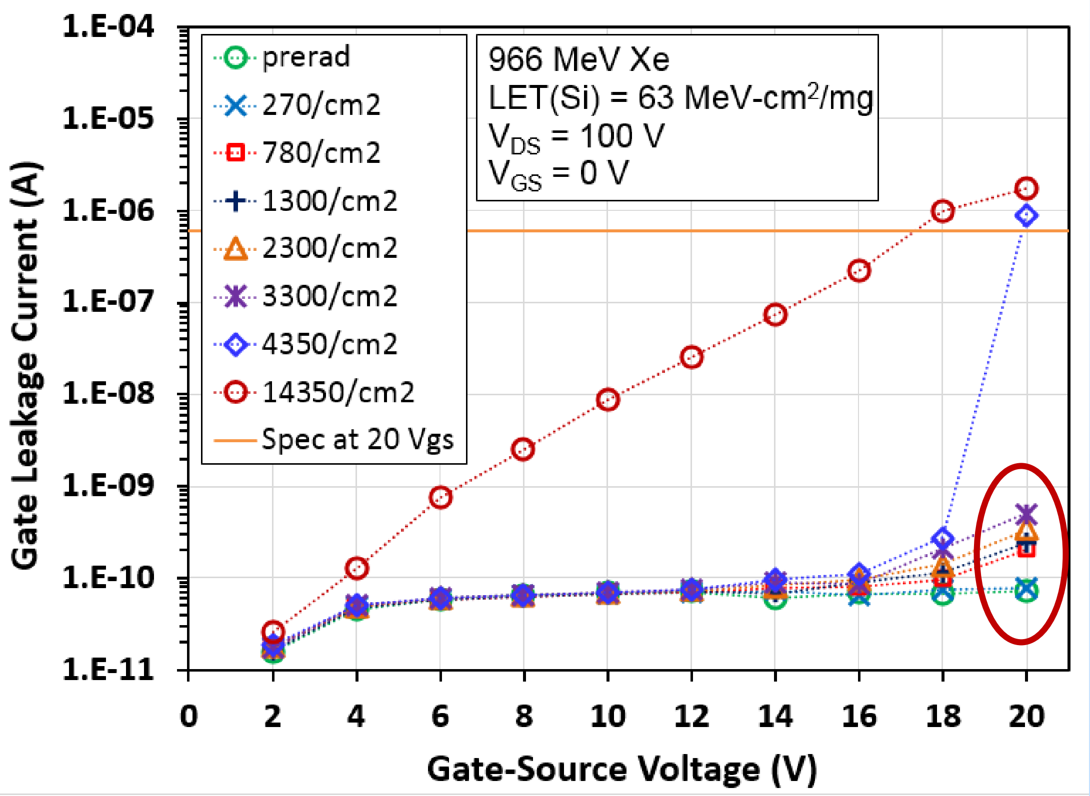
Effects as a Function of V_{DS} at V_{GS} = 0 V: Latent Gate Damage



Linear increase

Gate Leakage Current (I_{GSS}) initially increases linearly with fluence but then thermal damage likely occurs

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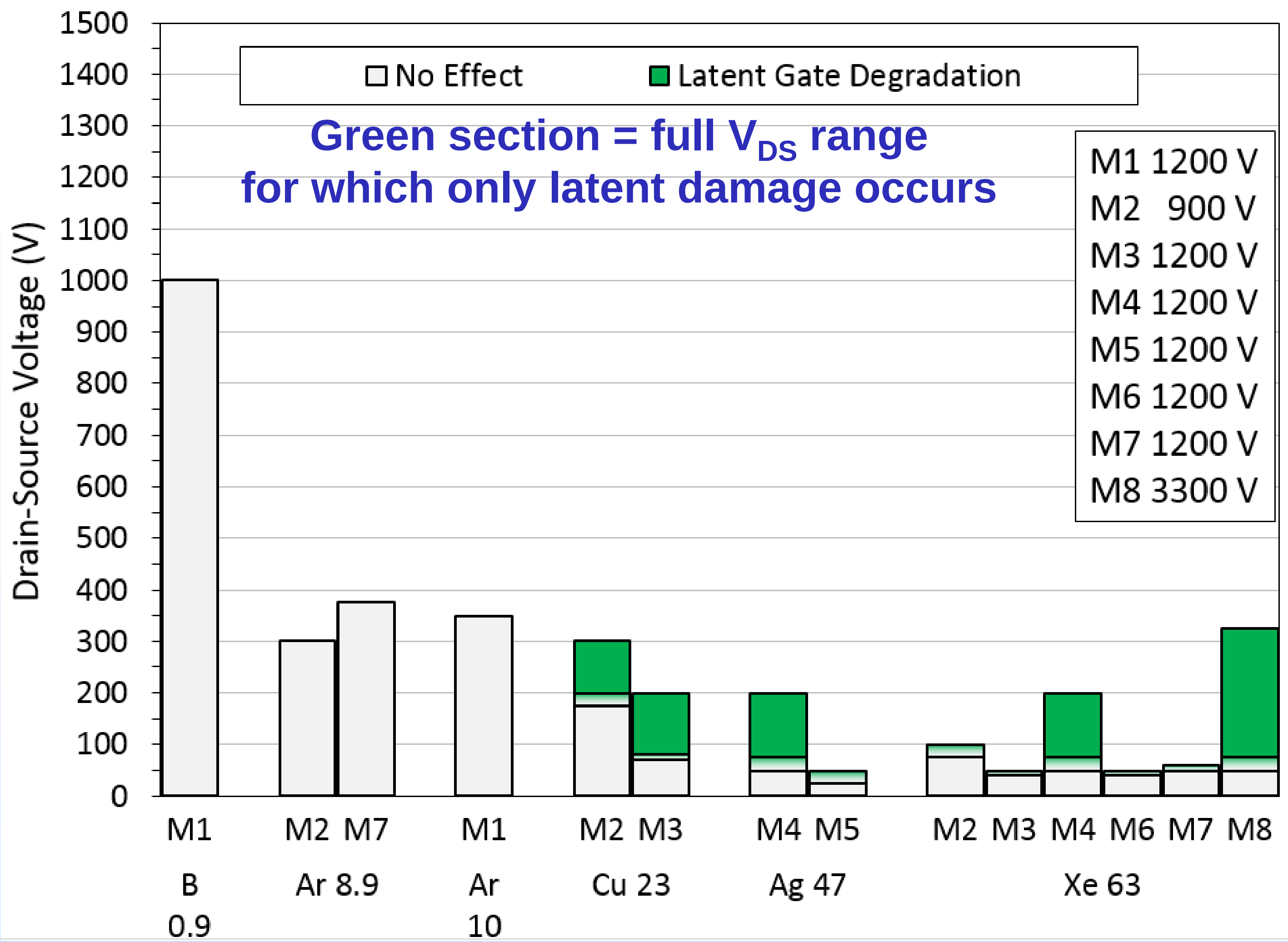
Effects as a Function of V_{DS} at V_{GS} = 0 V: Latent Gate Damage



Latent gate damage is LET/ion species-dependent; Onset is independent of voltage rating at higher LETs

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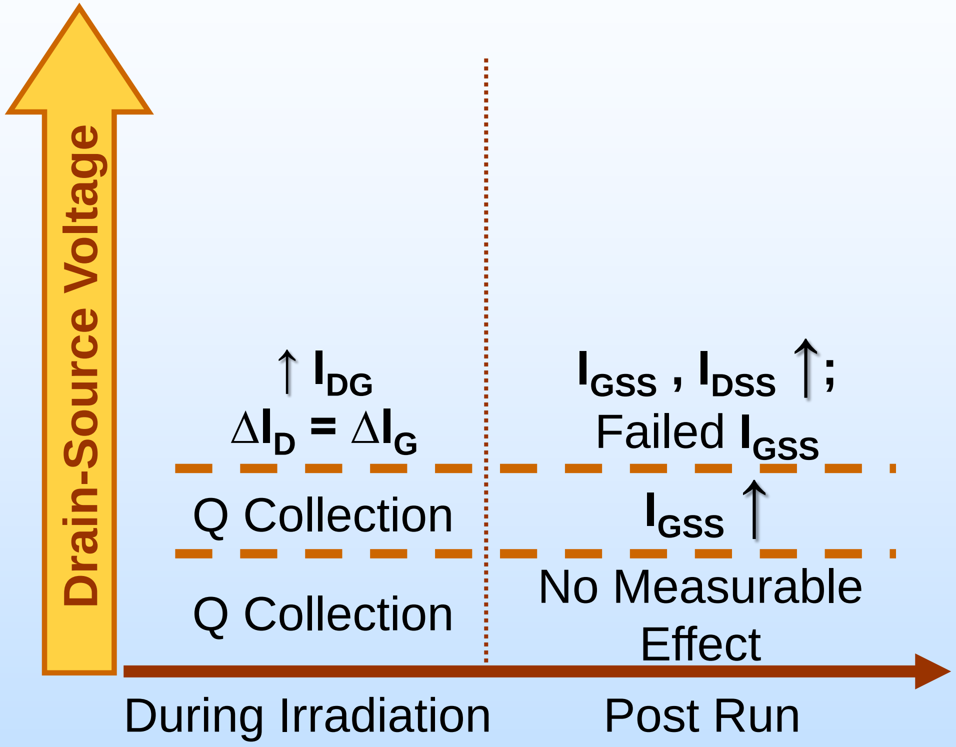
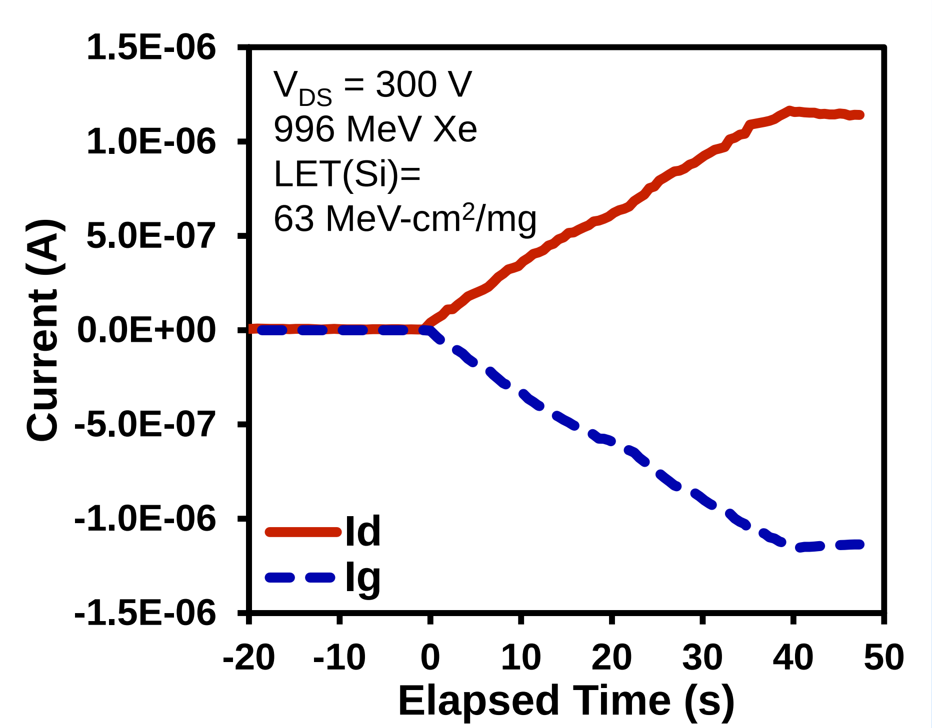
Effects as a Function of V_{DS} at V_{GS} = 0 V: Degradation During Beam Run



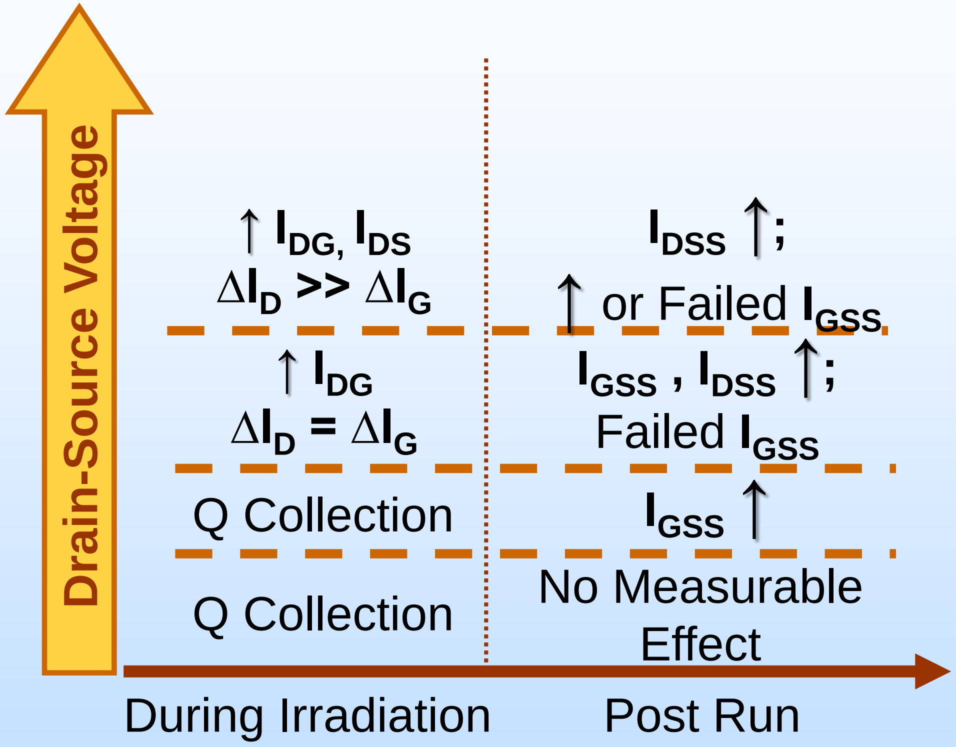
Measurement Results



Gate oxide degradation is linear with ion fluence

Slope is a function of V_{DS} and ion LET/species

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



Drain-Source Voltage

↑ 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} ↑

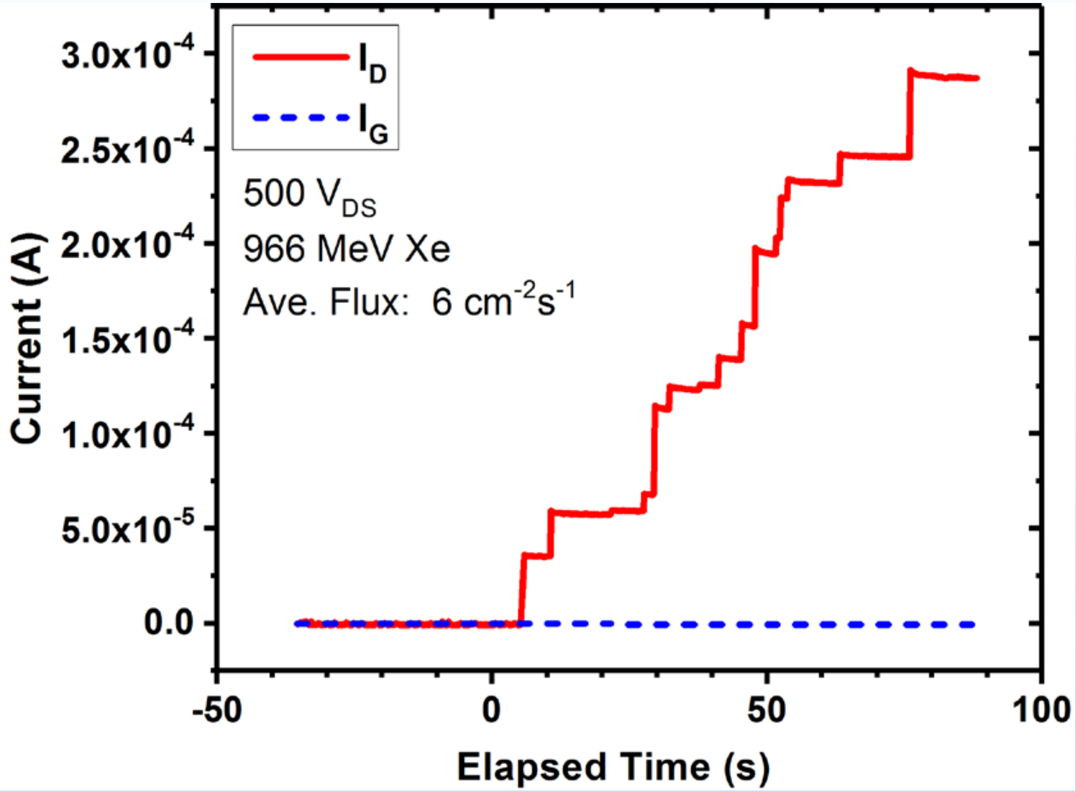
Q Collection

No Measurable Effect

During Irradiation

Post Run

Measurement Results



Unlike vertical JFET topology, planar-gate MOSFETs show drain-source leakage current.

Very low flux reveals damage from individual ion strikes.

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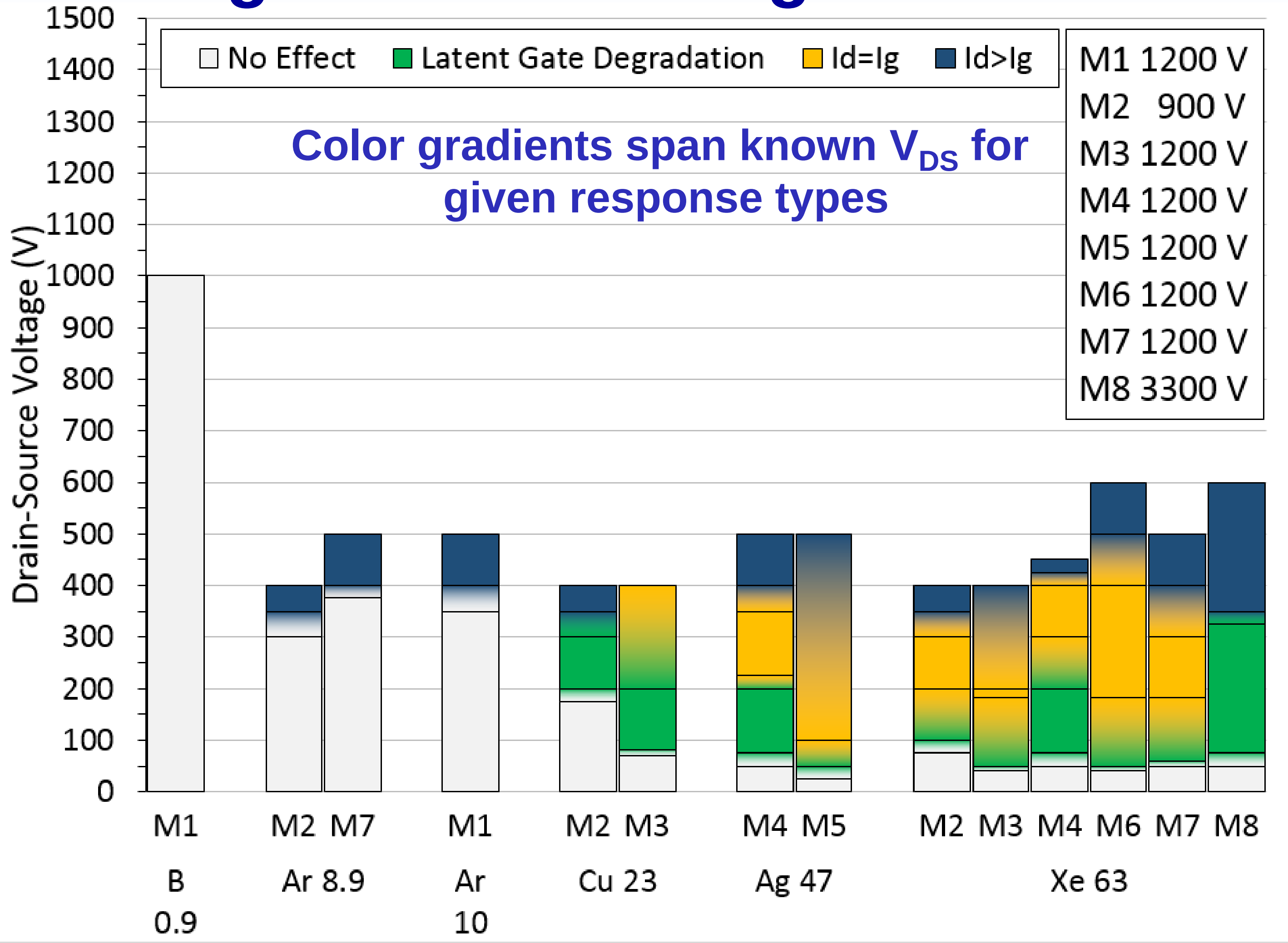
Effects as a Function of V_{DS} at V_{GS} = 0 V: Degradation During Beam Run



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

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

Not all MOSFETs suffer drain-gate leakage current degradation: Per ICSCRM MO.DP.14 (Zhu, et al.), likely a "JFET" drain neck width factor

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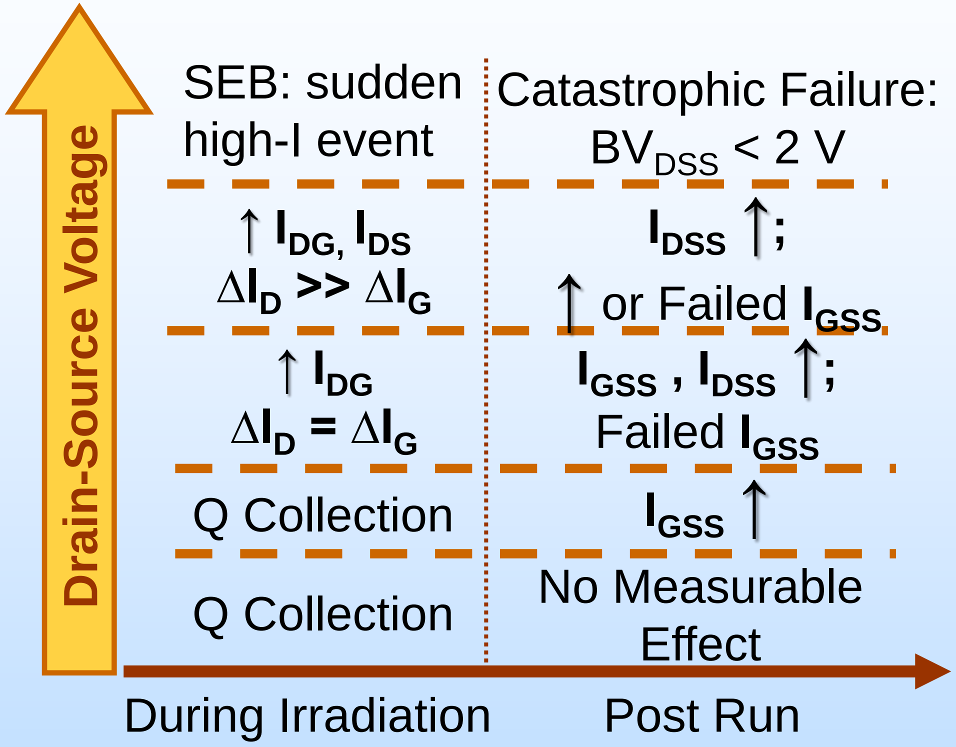
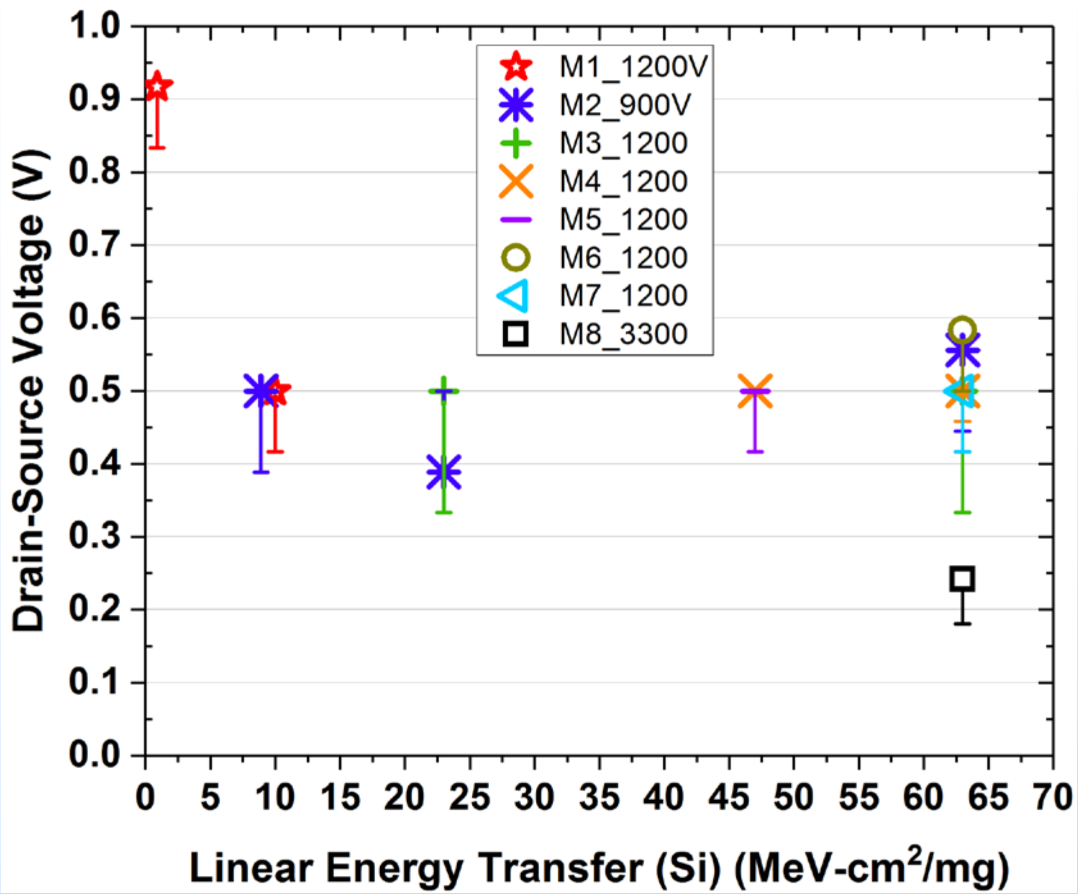
Effects as a Function of V_{DS} at V_{GS} = 0 V: SEB



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

Measurement Results

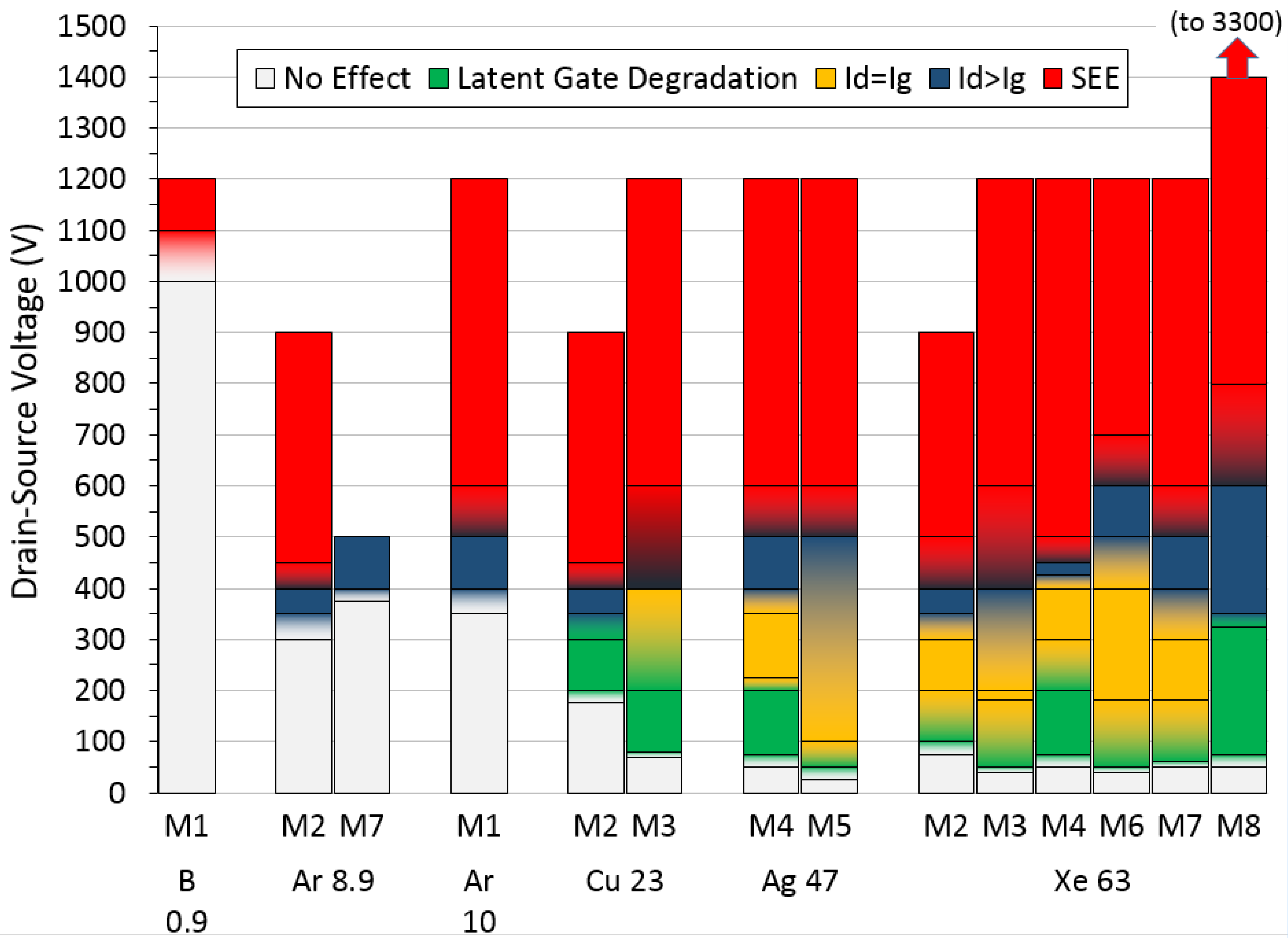


Use of real BV_{DS} will likely strengthen similarity across MOSFETs of different ratings.

SEB vulnerability saturates before the GCR flux "iron knee".

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

M1 1200 V
M2 900 V
M3 1200 V
M4 1200 V
M5 1200 V
M6 1200 V
M7 1200 V
M8 3300 V



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

Drain-source leakage current degradation is least influenced by electric field and ion LET; it may be more closely linked to material properties

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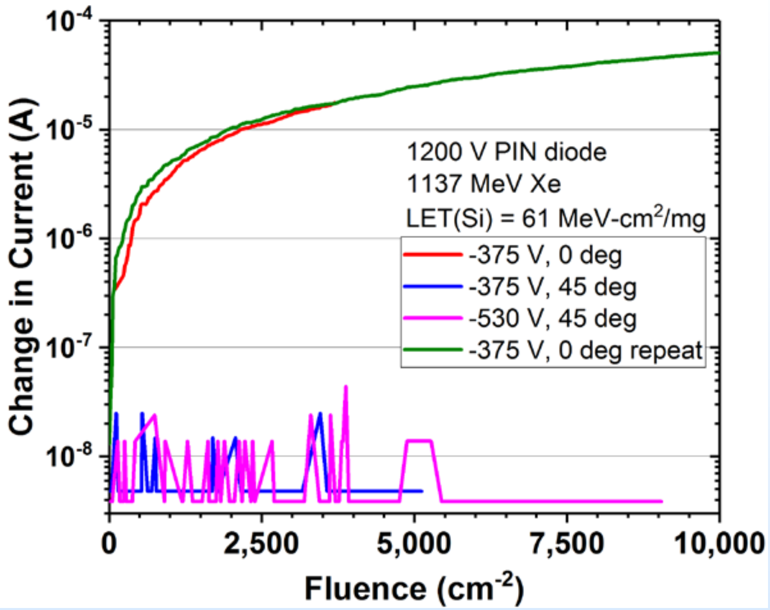
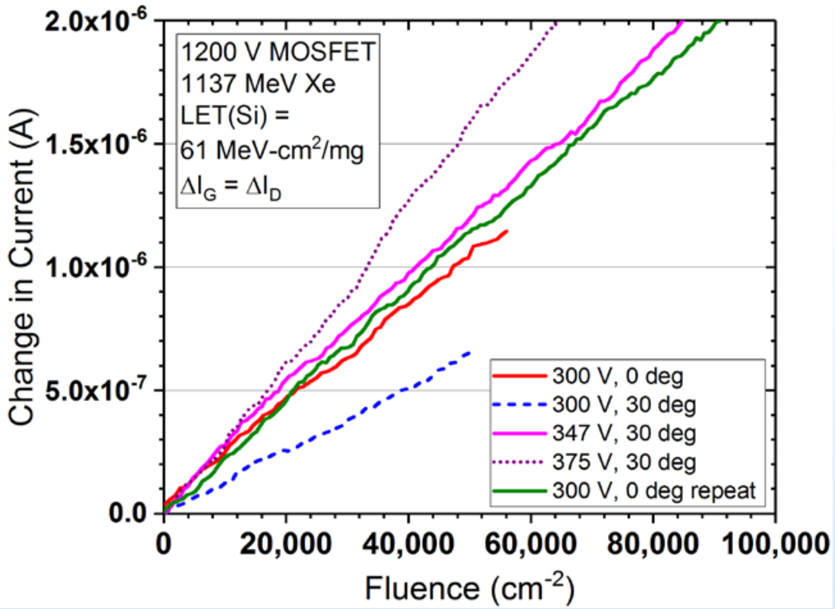
Angle of Ion Incidence

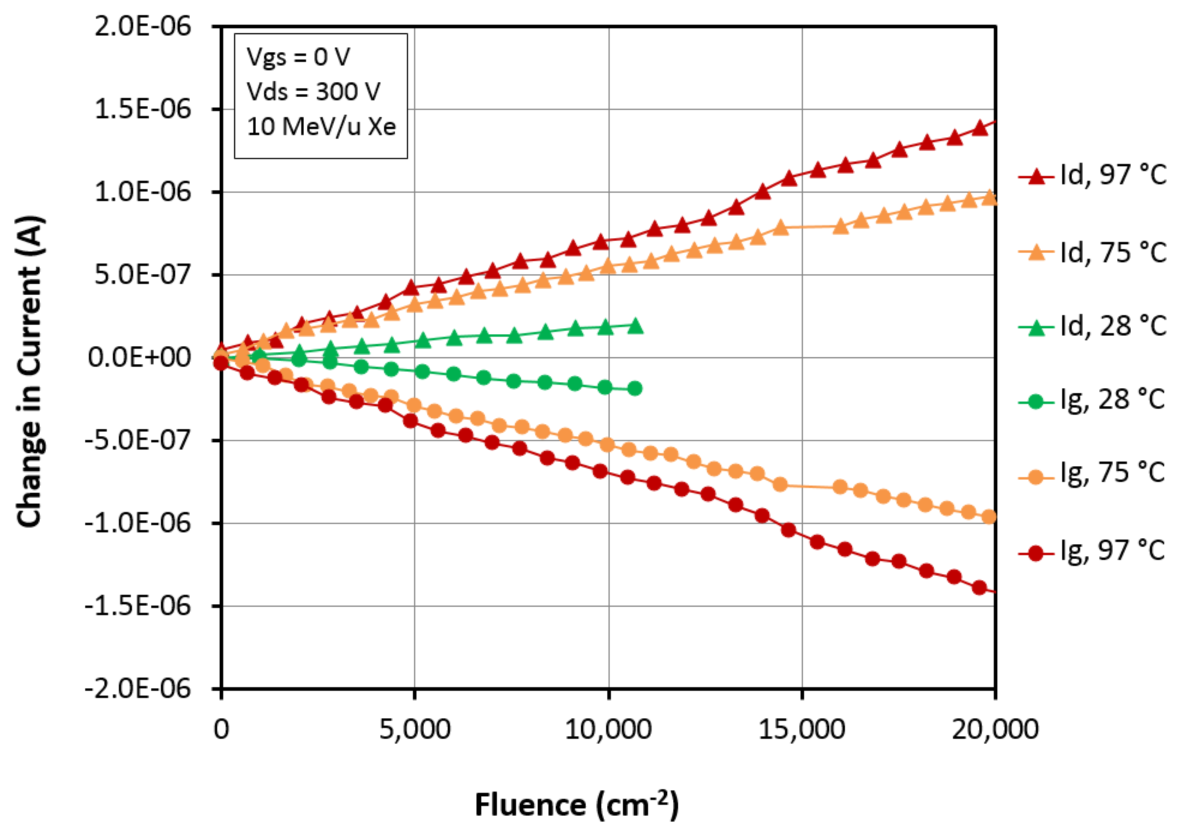




- **Diode: Strong angle effect**
  - At given V_R, no degradation at 45°
  - Matching vertical component of electric field has no impact
    - Cosine law not followed

- **MOSFET: Follows cosine law when gate-leakage dominated**
  - For $I_G = I_D$ degradation signature, path length through gate likely dominates angle effect
  - For drain-source current degradation dominant region/device, expect behavior similar to diode response

Temperature Effects: Power MOSFET



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

To be published on nepp.nasa.gov.

Summary & Conclusions

- **All discrete, unhardened SiC power devices in this work exhibit catastrophic failure at 50% of rated voltage or below**
  - Electric field and ion LET/species are shown to impact this threshold.
  - LET/species effects are quickly saturated below the high-flux iron knee of the GCR spectrum
    - Mission orbit will have a weaker influence on risk
- **Non-catastrophic damage occurs at voltages as low as 10% of rated values (gate oxide latent damage effects), and 30% for non-oxide degradation effects.**
  - Degradation within the SiC material is not correlated significantly with electric field strength and thus may require other methods than doping or geometry changes.
  - Reliability studies will be important to understand the impact of degradation mechanisms on long-term mission reliability
- **Due to saturation effects at high LETs, performance discrimination may best be achieved by testing at LETs below those dictated by typical space mission radiation requirements.**

Summary & Conclusions

Angle effects – Diodes and MOSFETs:

- **Both Schottky and PIN diodes exhibit faster roll-off of degradation effects with angle of incidence than would be expected if the vertical component of the electric field were the critical component of the mechanism.**
  - This lack of strong field dependence is also seen at normal angle of incidence when comparing effects in diodes of different voltage ratings.
- **Additional angle studies are needed in transistor devices.**
  - Gate oxide leakage effects follow the cosine relationship of the vertical field as expected from historic silicon studies.

Temperature - MOSFETs:

- **For case temperatures up to 100 °C, rate of I_{DG} degradation increases.**
  - More studies are needed for non-oxide leakage pathways.