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Ion irradiation and analysis of SiC Schottky diodes

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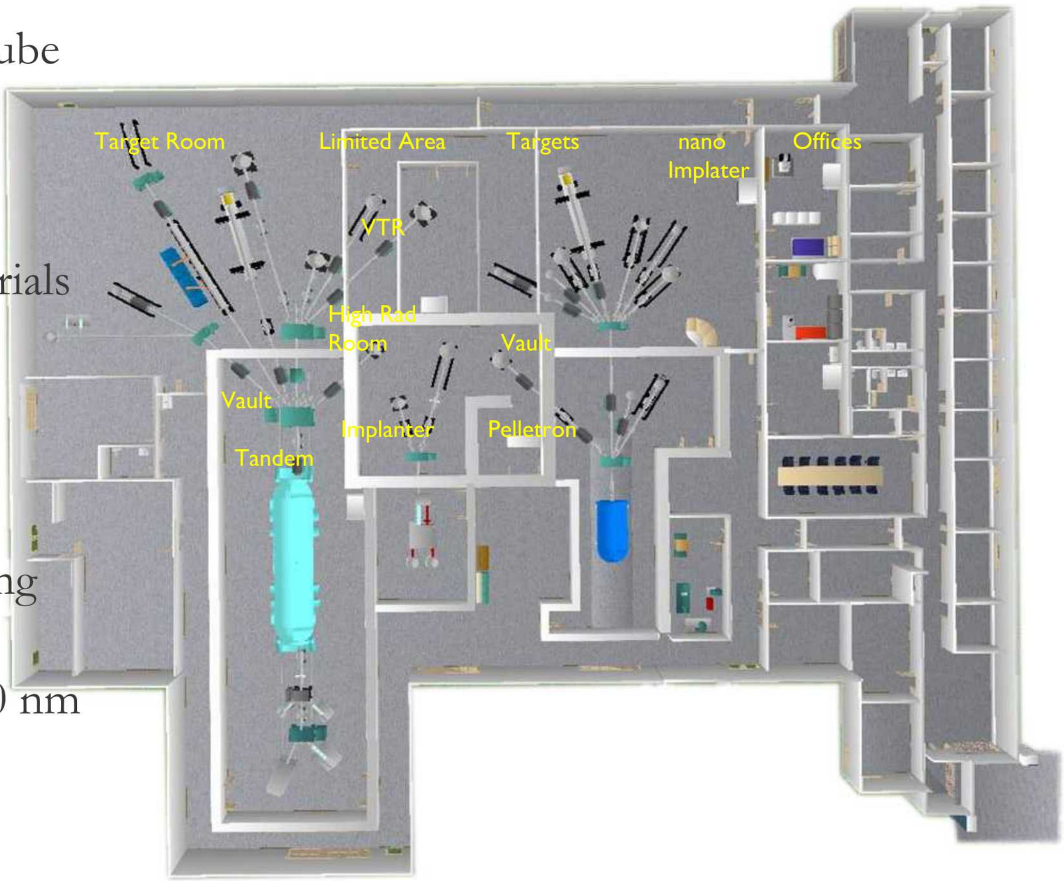
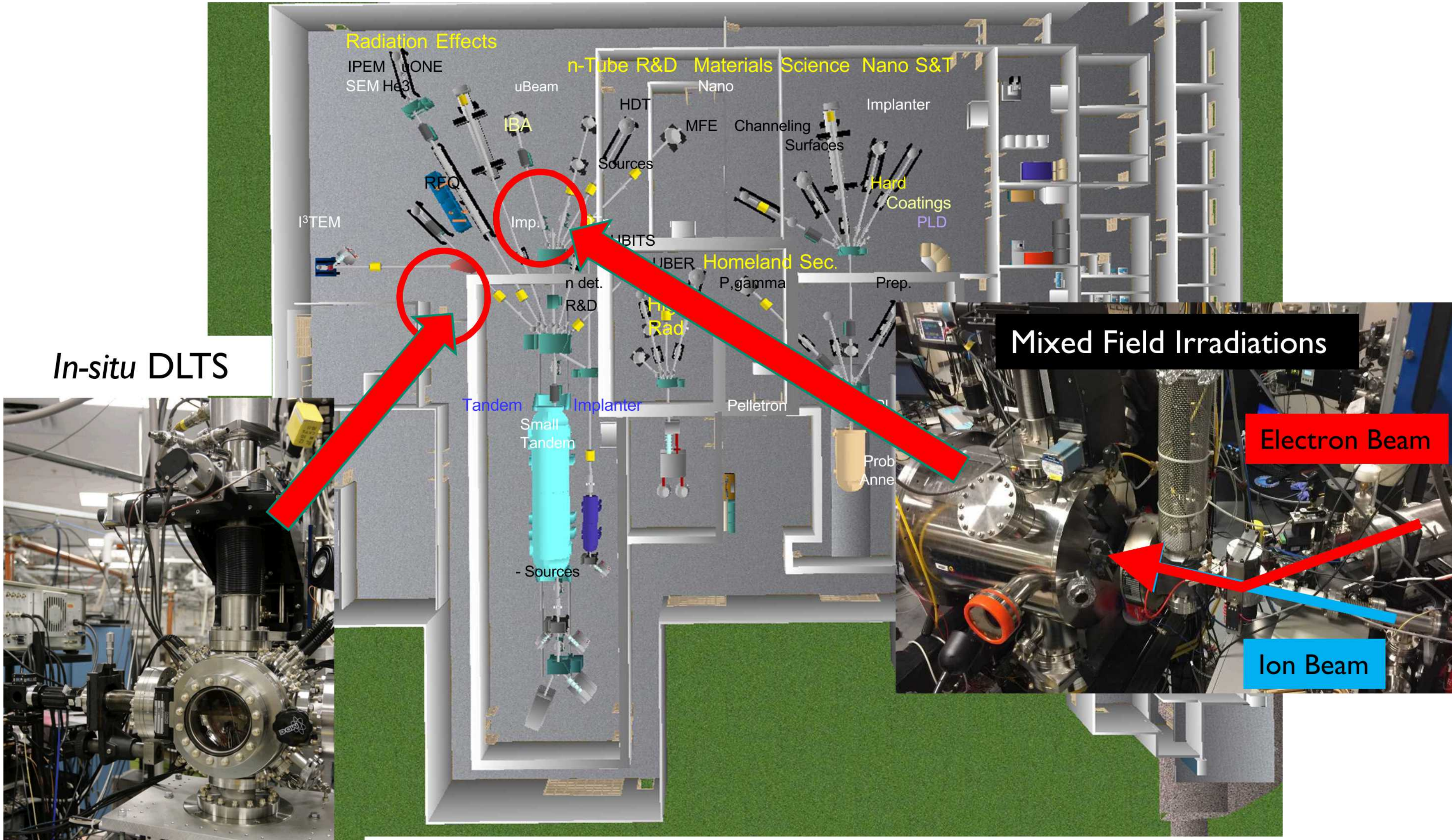
Accelerators in the Ion beam Laboratory (IBL)

- **6 MV Tandem**
  - Radiation effects testing
  - Ion Beam Analysis (IBA) of neutron tube materials
- **3 MV Pelletron**
  - Ion Beam Analysis
  - Microbeam IBA of neutron tube materials
- **1 MV "Baby Tandem"**
  - Installation nearly complete
- **350 kV Implanter**
  - DT neutrons for detector calibration
  - DT neutrons for radiation effects testing
- **100 kV Nano-Implanter**
  - Focused ion beam lithography (sub -20 nm area)
  - Single atom device fabrication
- **30 kV He ion microscope**
  - 0.5 nm spot size



Radiation Effects Testing



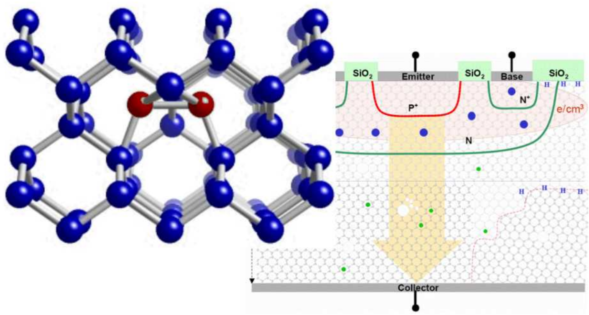
Probing basic mechanism of radiation effects from displacement damage through ionizing dose rates effects

Ions Simulate Neutron Effects

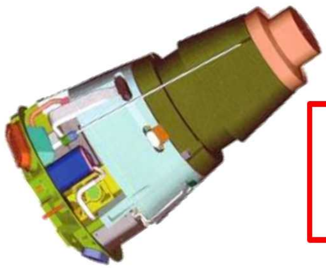
Substituting the primary knock-on atom of a neutron collision with MeV ions

Defect Study Motivation – Displacement Damage

Radiation Effects



Fundamental Radiation Induced Defects



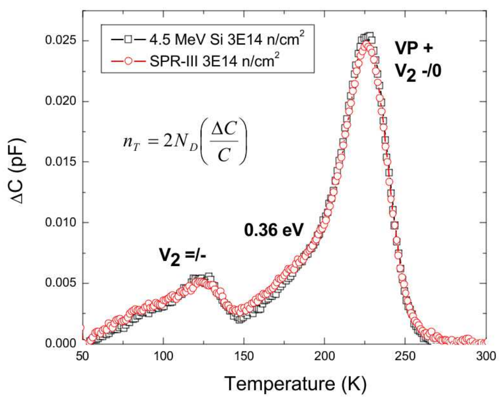
Of particular interest is early-time (<1s) gain degradation

Degradation of Device/Circuit Performance

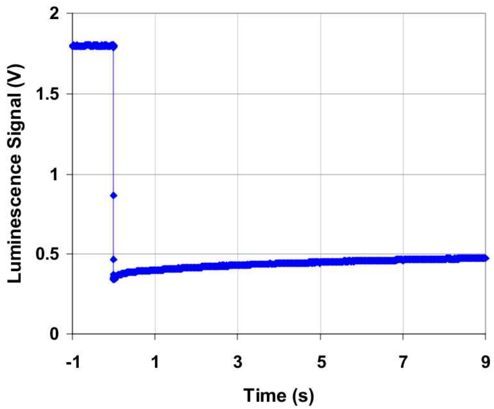
Experimental Techniques at the Ion Beam Laboratory (IBL)

We use a series of *in-situ* techniques to explore the defect creation and annealing

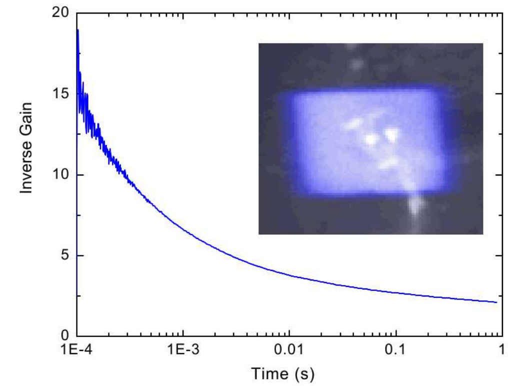
Deep-level Transient Spectroscopy (DLTS)



Photoluminescence

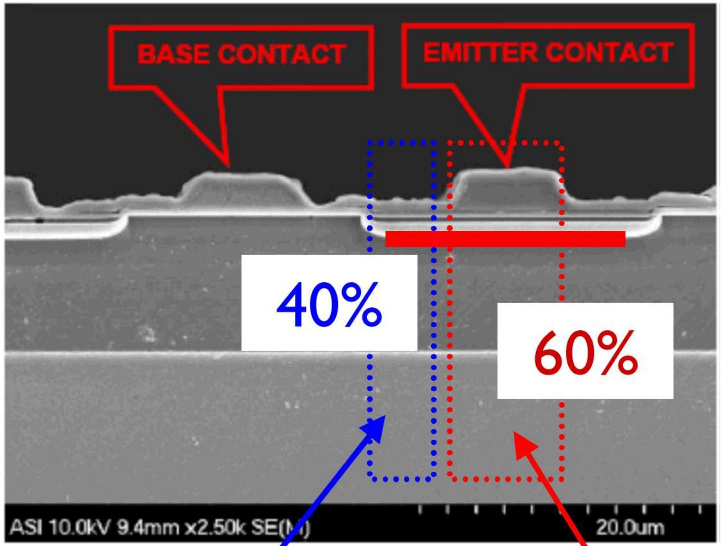


Active Gain



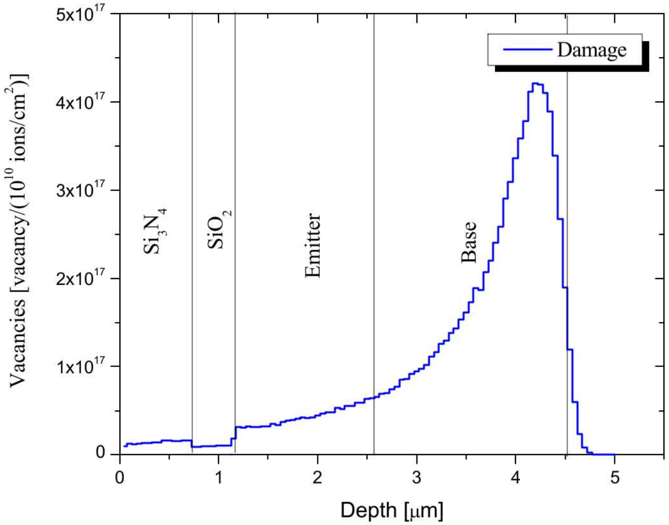
SRIM-2003 Calculations for 10 MeV Si 3+

Critical Region: Base-Emitter Junction for low emitter currents

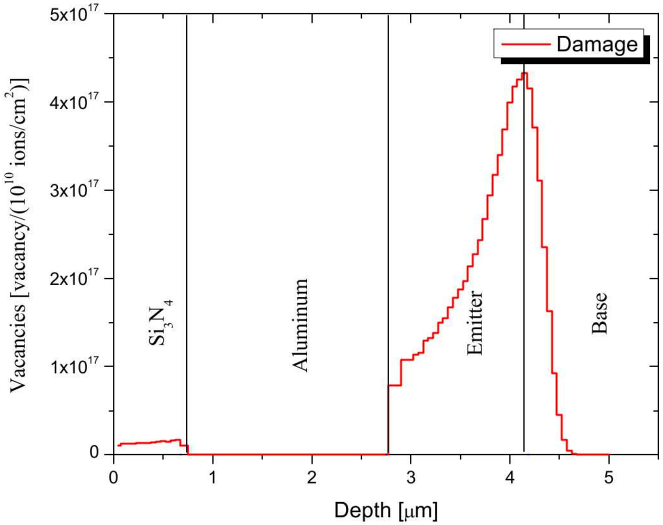


- Ions lose energy as they travel through the device
- Ion/energy combinations need to be tailored to specific device geometry

Ions through field oxide



Ions through emitter contact



Ion-to-Neutron Damage Equivalence

Messenger-Spratt damage constant

- The ***damage constant*** as determined from late-time gain degradation (Messenger-Spratt) is the same for all neutron irradiation facilities and we can scale the ion fluence to relate ion-to-neutron irradiation conditions.

DLTS trap identification

- The ***spectra of defects*** as measured by DLTS in the base of pnp transistors that are responsible for the gain degradation are the same after neutron (including SPR-III and ACRR) and ion irradiations.

DLTS trap quantification

- A given ***number of defects***, as measured by DLTS in the base of a pnp transistor, produces the same late-time gain reduction for neutron (SPR-III) and ion irradiations.

Annealing factor

- The SPR-III early-time ***annealing factor*** can be matched using ion irradiations (simulating a wide range of SPR-III fluence values).

Messenger–Spratt Relation

Messenger and Spratt have shown that irradiation induced degradation of gain in BJTs is due to the reduced carrier lifetime through the base.

MS relation given by,

$$\frac{1}{\tau_f} - \frac{1}{\tau_i} \sim \frac{1}{G_f} - \frac{1}{G_i} \sim N_t \sim \varphi$$

$$DIG = \frac{1}{G_f} - \frac{1}{G_i} = k\varphi$$

G_f and G_i are gain after and before irradiation

τ_f and τ_i are minority carrier lifetimes through the base after and before irradiation

N_t is the number of traps introduced to the device

k is damage factor which quantifies damage per ion as a function of energy

φ is ion fluence

G.C. Messenger, M.S. Ash, The Effects of Radiation on Electronic Systems, 2nd ed., Van Nostrand Reinhold, New York, 1992.

Late-Time Gain Comparison

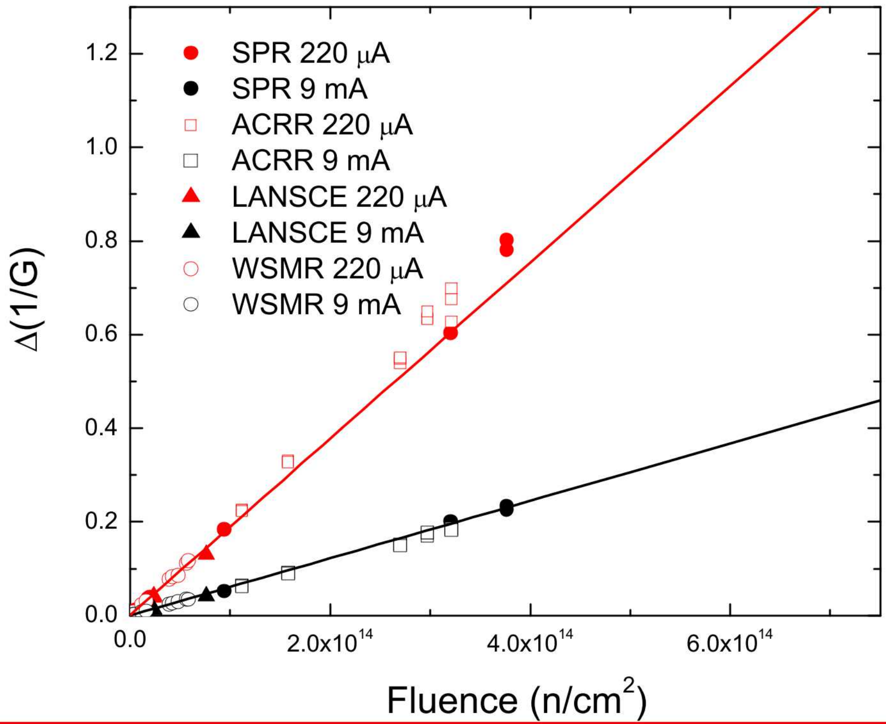
- Displacement damage follows the Messenger-Spratt equation:

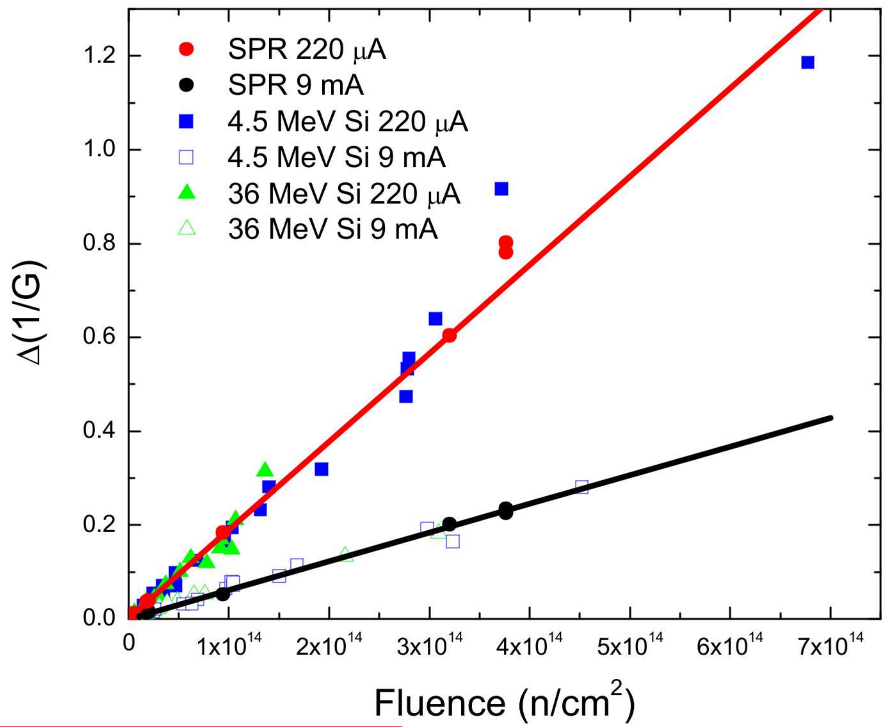
$$\frac{1}{G_\infty} - \frac{1}{G_0} = k \cdot \Phi$$

Damage Constant

- Scale ion fluence to 1 MeV Neutron Equivalent Fluence using:

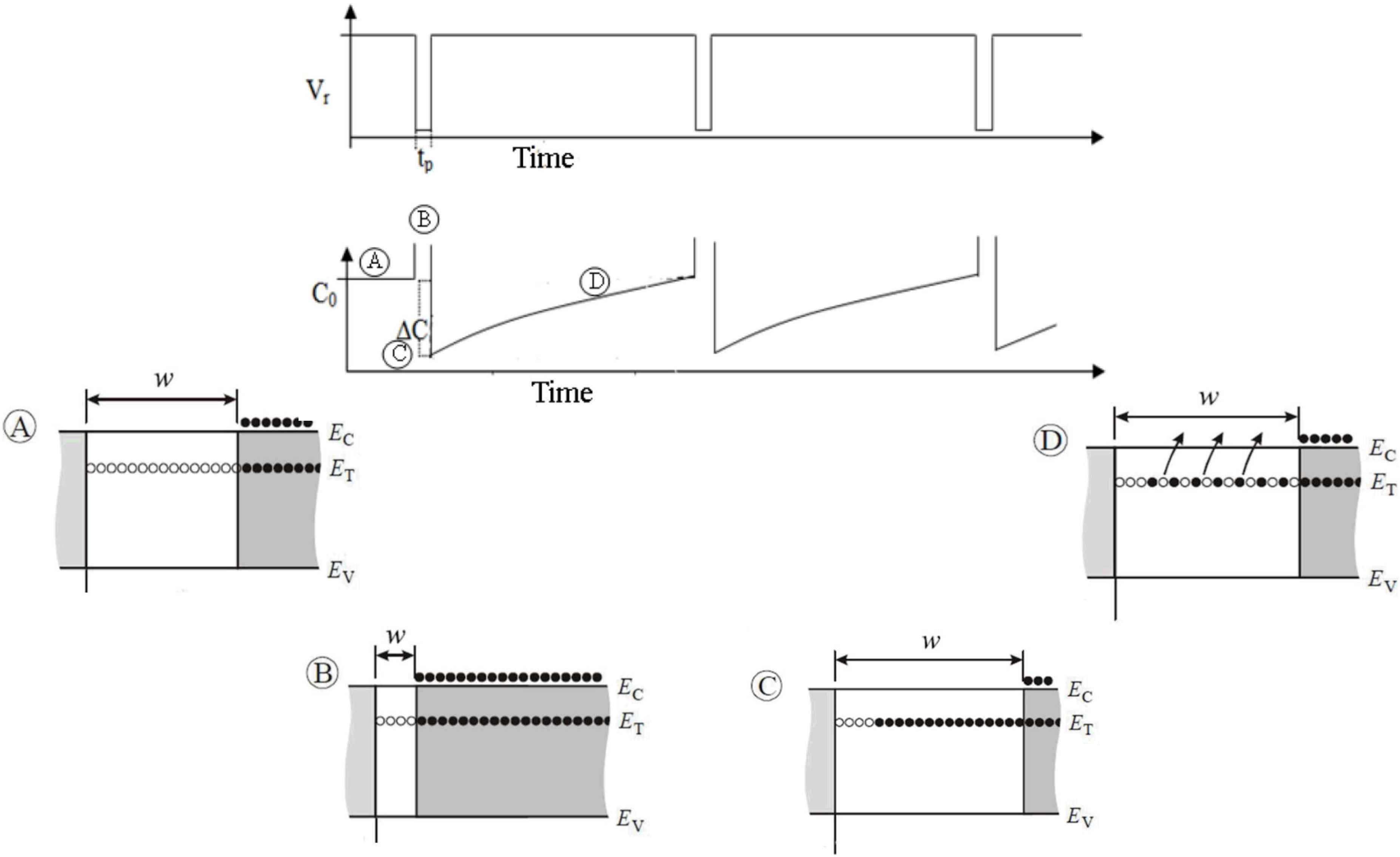
$$\Phi_{neutron} = \frac{k}{k_n} \cdot \Phi_{ion}$$





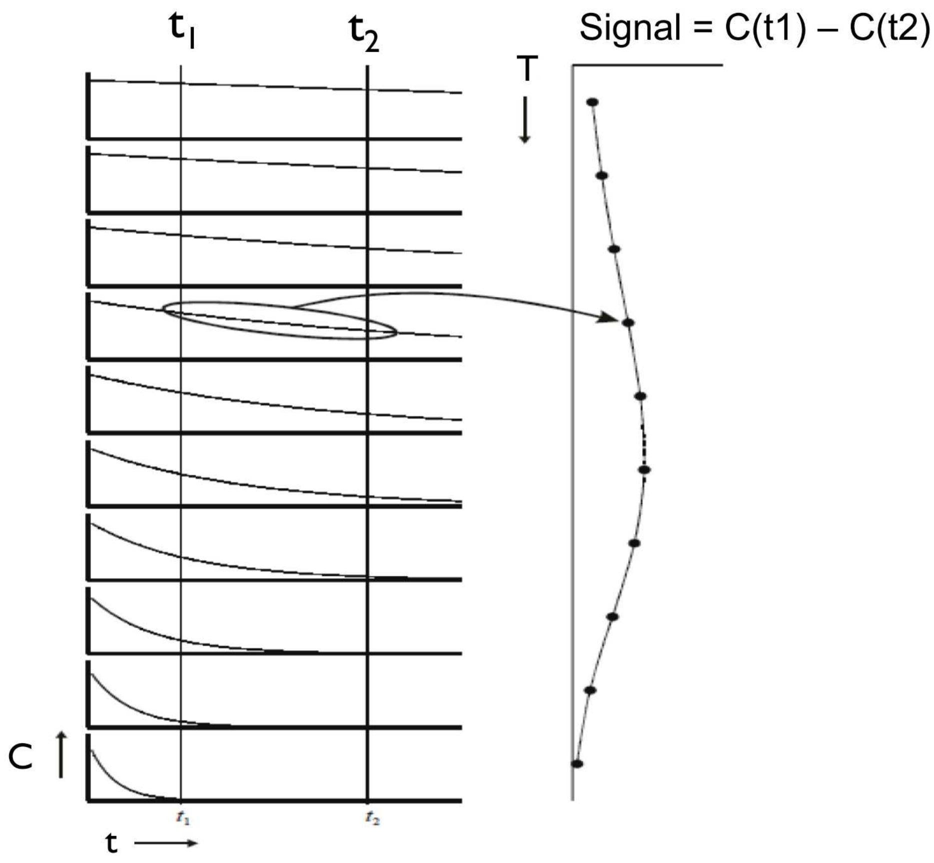
The ***damage constant*** as determined from late-time gain degradation (Messenger-Spratt) is the same for all neutron facilities. We can scale ion fluence to relate ion-to-neutron irradiation conditions.

DLTS Overview (Part 1)



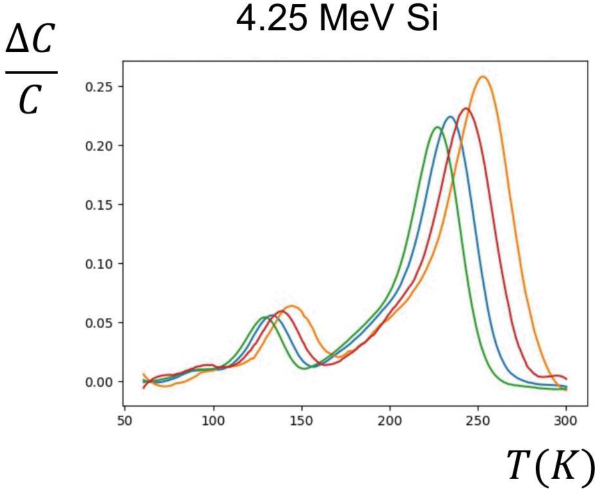
Mannan, M. A.(2015). *Defect Characterization of 4H-SIC by Deep Level Transient Spectroscopy (DLTS) and Influence of Defects on Device Performance.* (Doctoral dissertation).

DLTS overview (Part 2)



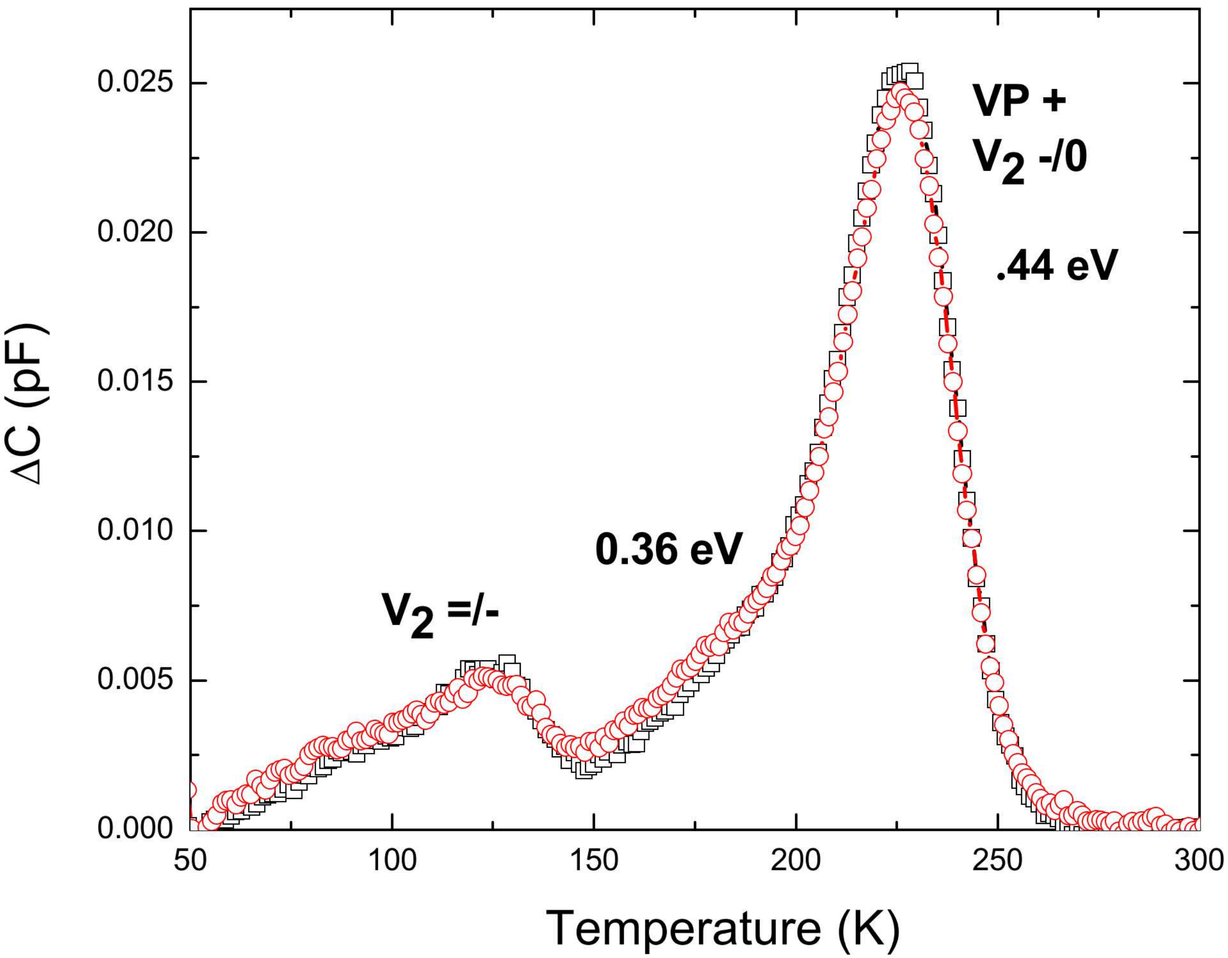
Rate of trapped carrier emission depends on temperature.

PNP BJTs
5E9 ions / cm^2
4.25 MeV Si



Multiple (4) boxcar averagers set to different "rate windows" record spectra.

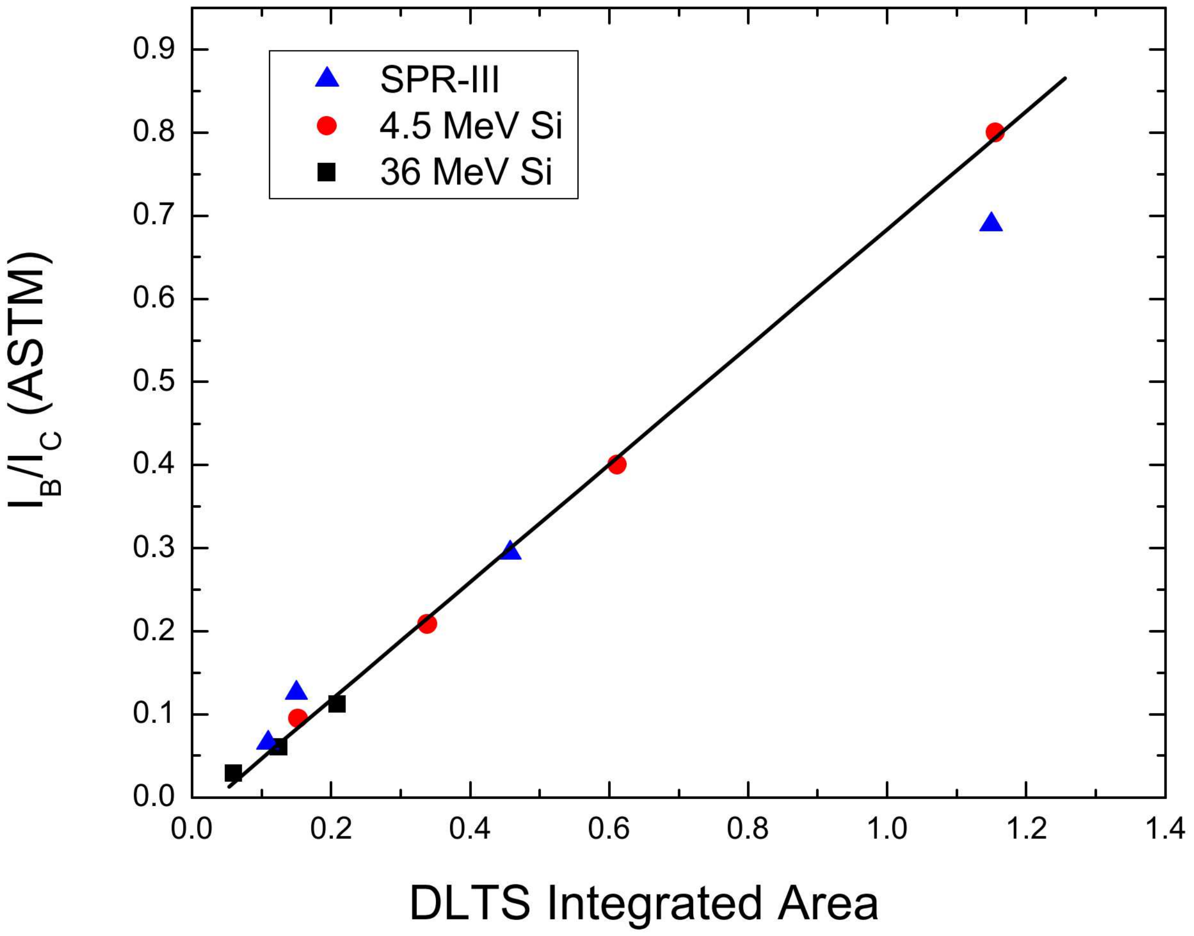
Spectra of Defects: Ions and Neutrons



- DLTS peak amplitude proportional to number of traps
- Temperature scale provides a means to determine emission energy of the defect
- DLTS spectra of the base region of a PNP device.
- Probes the N-type area of the devices most closely associated with the BE junction.

The ***spectra of defects*** in the base of pnp transistors are the same after neutron and ion irradiations.

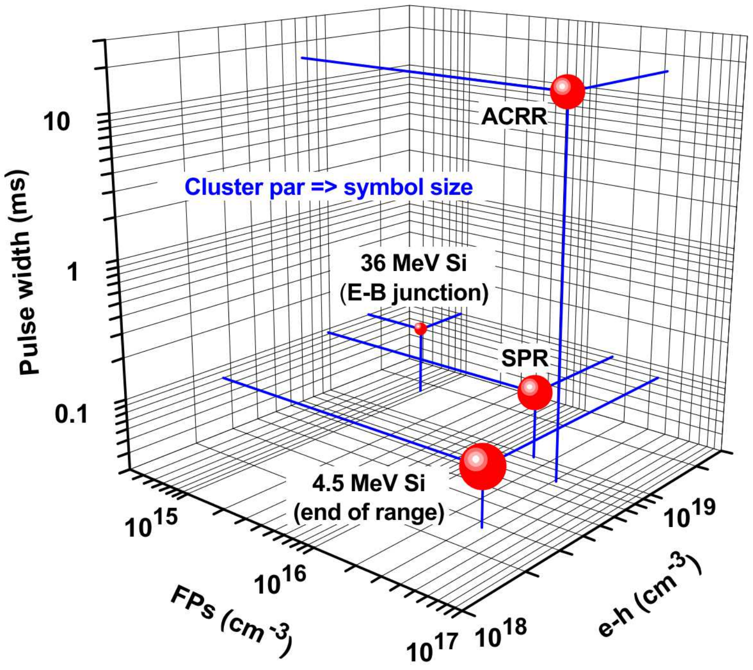
Defect to Gain Comparison: Ions and Neutrons



- Integrated area of deep DLTS peaks
- Direct relationship between the DLTS area and the inverse gain degradation for ion neutron irradiations

A given ***number of defects***, as measured by DLTS in the base of a pnp transistor, produces the same late-time gain reduction for neutron (SPR-III) and ion irradiations.

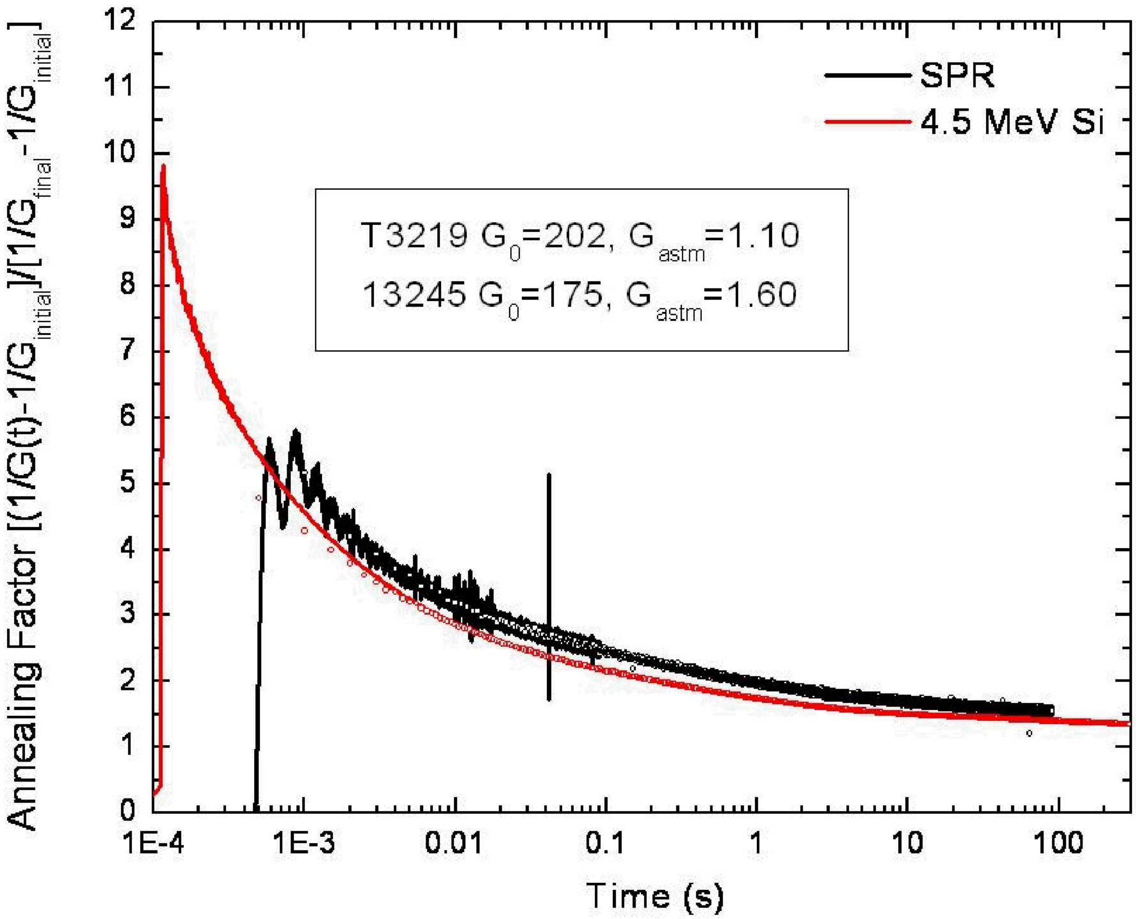
Fast Neutron and Ion Facilities are used for early-time device response



- SPR Shutdown September 30, 2006
- SPR Alternative Facilities
  - **Ion Beam Laboratory** (IBL)
    - Short pulse ion environment, High flux
  - **White Sands Missile Range FBR** (WSMR)
    - Short pulse Neutron Environment, Low flux
  - **Annular Core Research Reactor** (ACRR)
    - Late time neutron environment
  - **Little Mountain Test Facility** (LMTF)
    - Photocurrent, 2 – 30 MeV electron

We need the ion beam facility for high flux early time neutron simulations – we need to understand the ***ion-to-neutron damage equivalence***

Early-Time Annealing Factor Comparison



$$AF(t) = \frac{\frac{1}{G(t)} - \frac{1}{G_0}}{\frac{1}{G_\infty} - \frac{1}{G_0}} = \frac{N_t(t)}{N_t(\infty)}$$

The SPR-III early-time ***annealing factor*** can be matched using ion irradiations (simulating a wide range of SPR-III fluence values).

SiC Schottky Diode Experiment

Measurements of early-time radiation effects

SiC Schottky Diode Experiments - Motivation

Wide band gap materials provide high electric field strength, switching speed, and efficiency in radiation environments

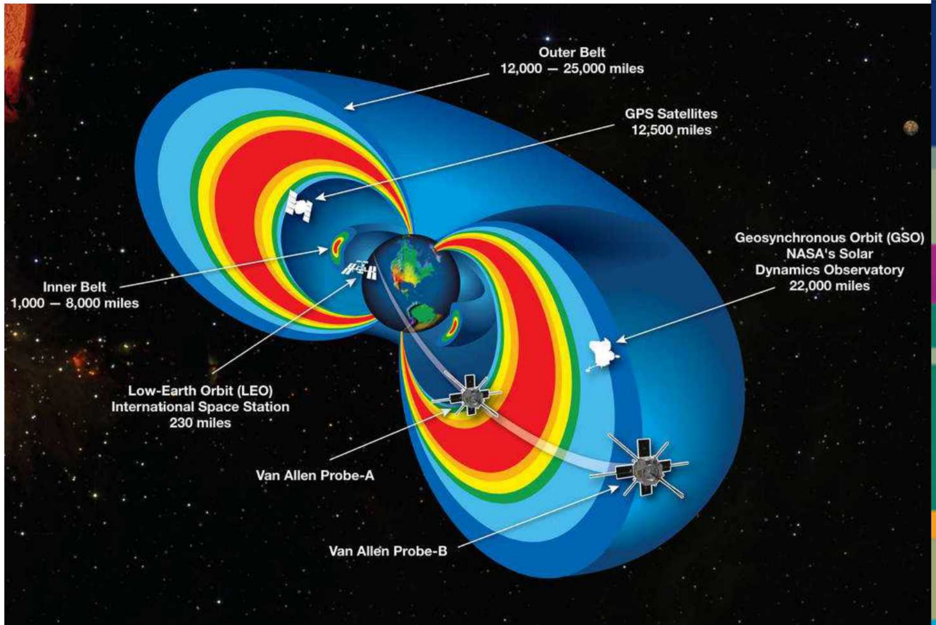
- Satellites and spacecraft
- Detectors for hadron colliders, fission and fusion reactors

Radiation Effects of Interest:

- Leakage current vs fluence from displacement damage
- Understanding mechanisms of room temperature annealing
- Early time effects (<1 s)

We will use ion irradiation to simulate the neutron environment

- Allows access to early-time effects as ion irradiations lack the gamma environment of nuclear reactors



https://www.nasa.gov/mission_pages/sunearth/news/gallery/20130228-radiationbelts.html

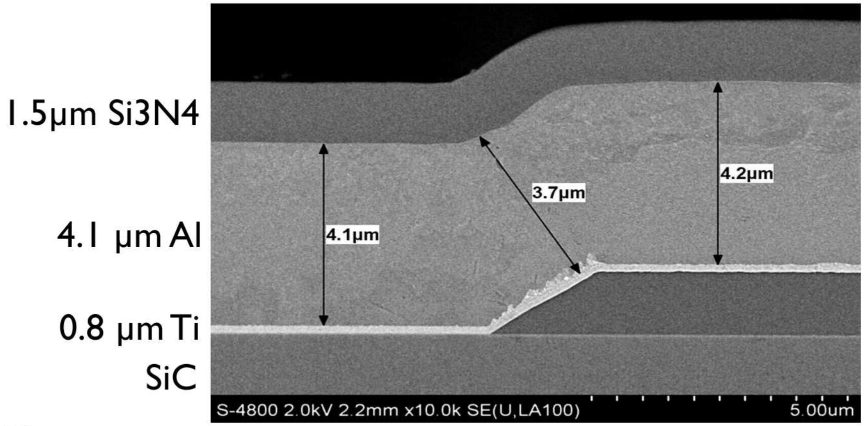
Overview of Device

Cree/Wolfspeed SiC Schottky diode (C3D02060F)

4H-SiC bandgap = 3.23 eV

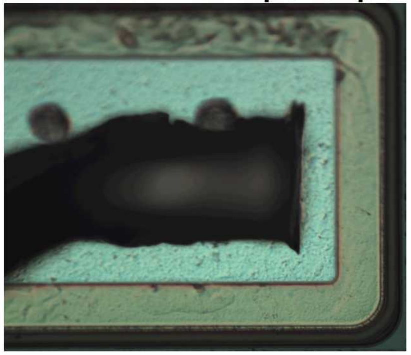
4A, 600V COTS decaped to expose die

SEM Cross-section of the die



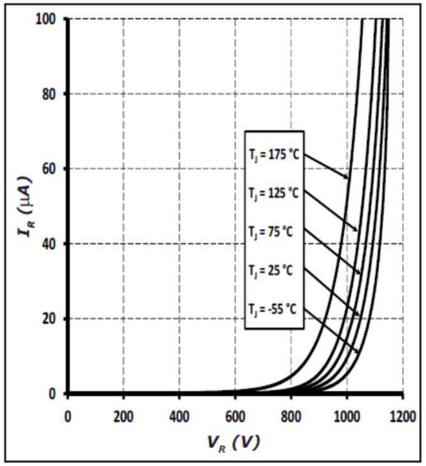
TO-220

Jet etched to expose part



(To allow ion access)

Typical DC IV from spec sheet

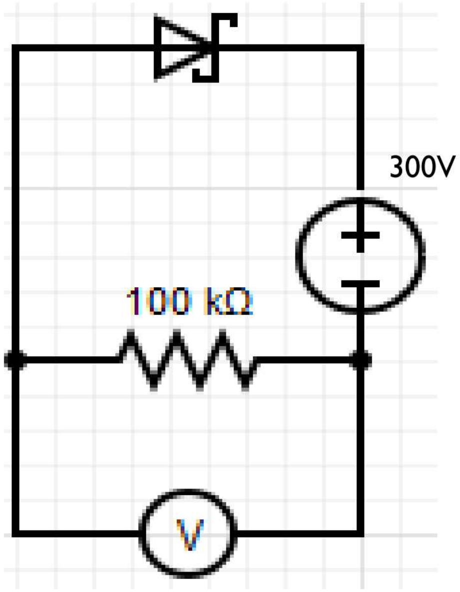


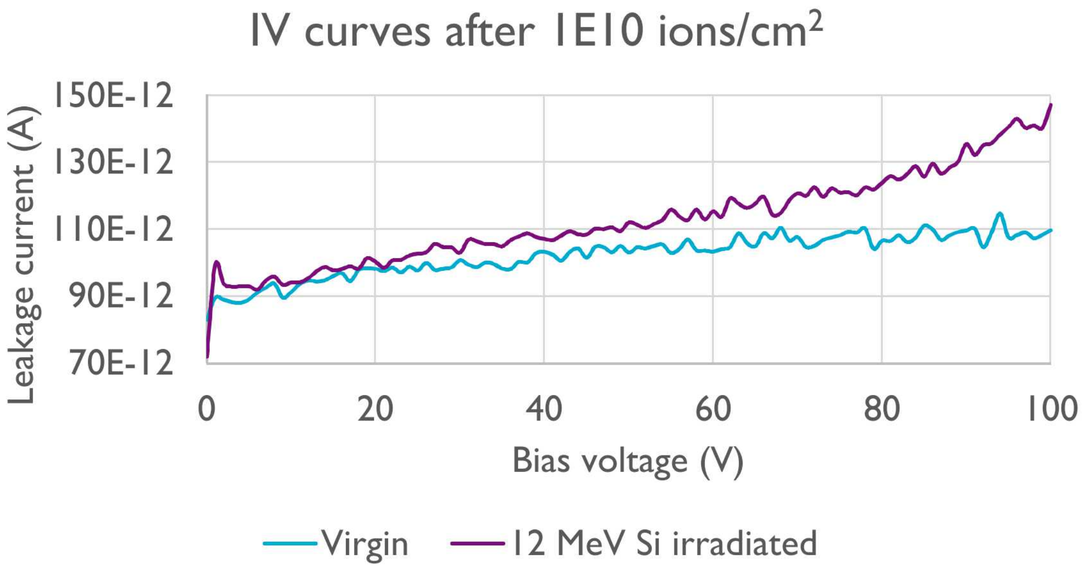
Vbreakdown > 600V

Ileakage (600V) << µA

Leakage Current Measurement

- Diodes were reversed biased to 300 V in series with a 100 kΩ resistor
- Diodes were shot with 10 – 1000 μs pulses of Si ions.





Quantifying Ion Irradiation Damage (Displacement Damage)

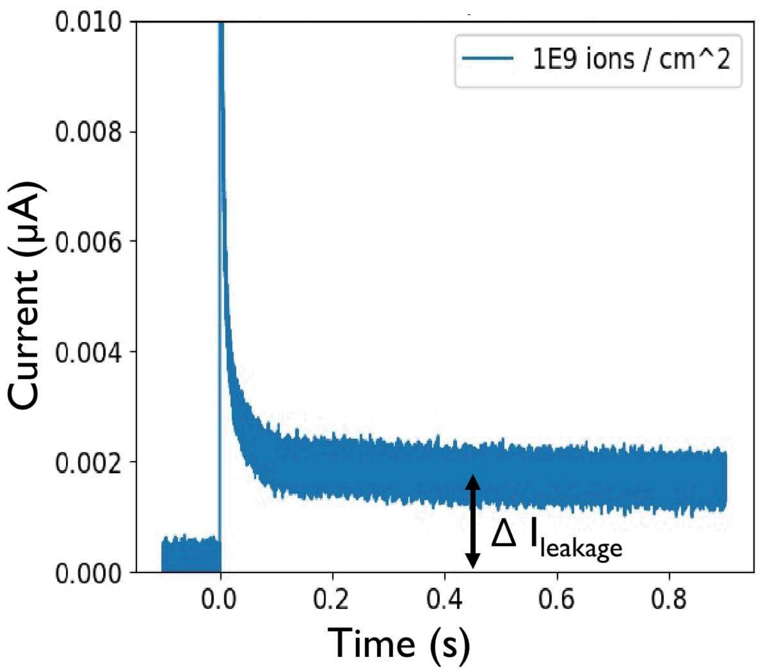
Schottky diode reverse bias leakage current is proportional to depletion region defects.

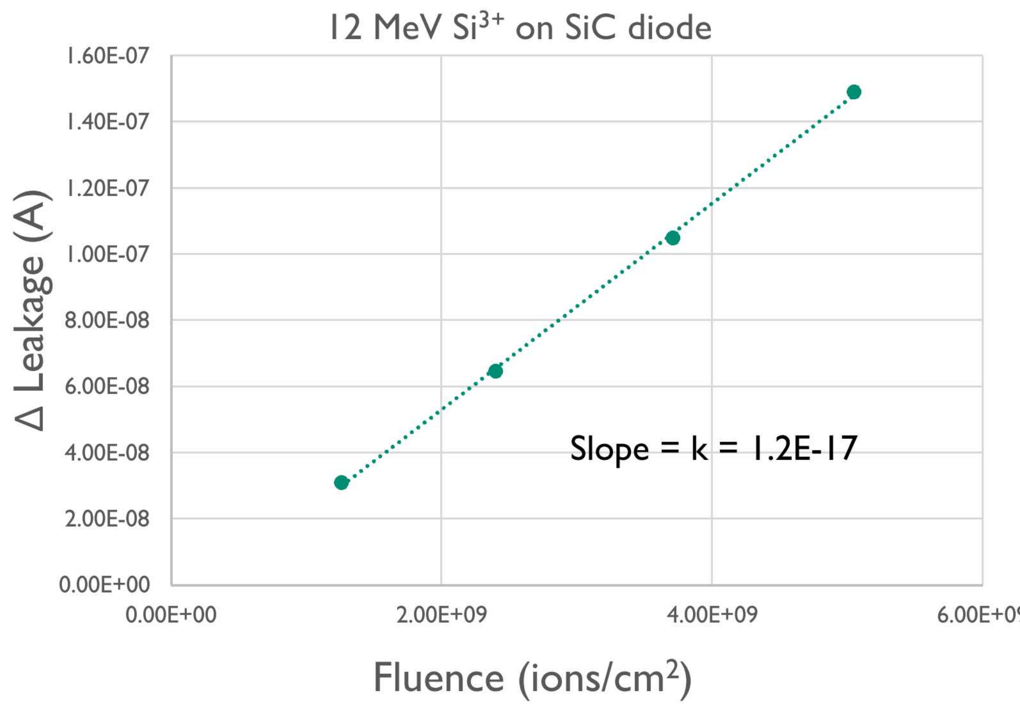
We use a k-factor relationship to quantify damage to the device under test.

- Analogous to Messenger–Spratt k-factor describing carrier lifetime

$$\Delta I_{leakage} \sim \frac{1}{\tau} - \frac{1}{\tau_0} \sim N_t \sim \varphi$$

$$\Delta I_{leakage} = k\varphi$$

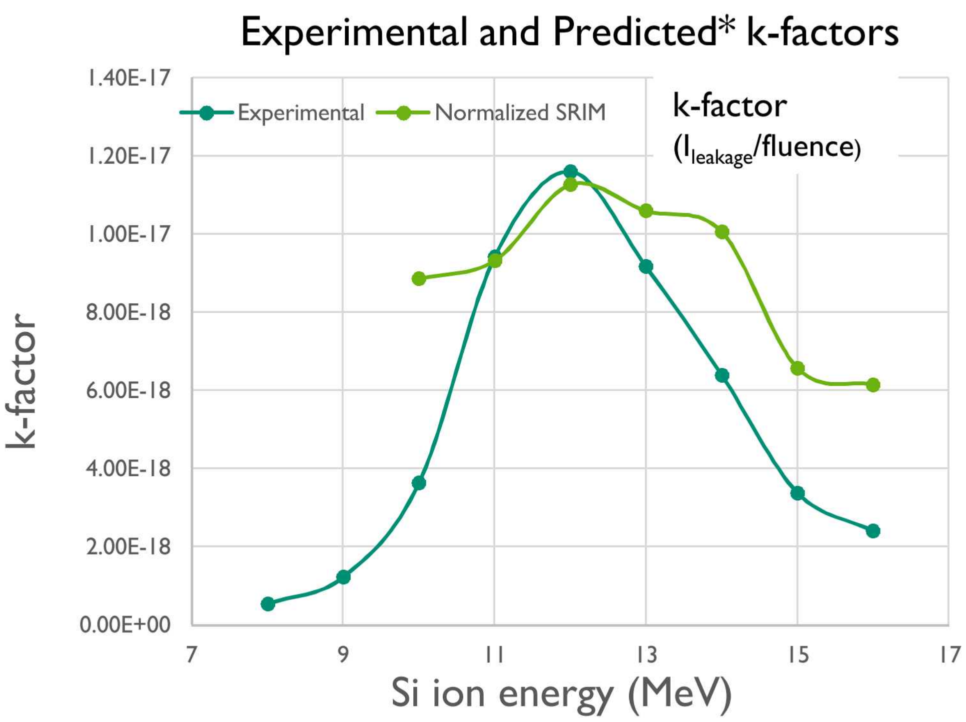


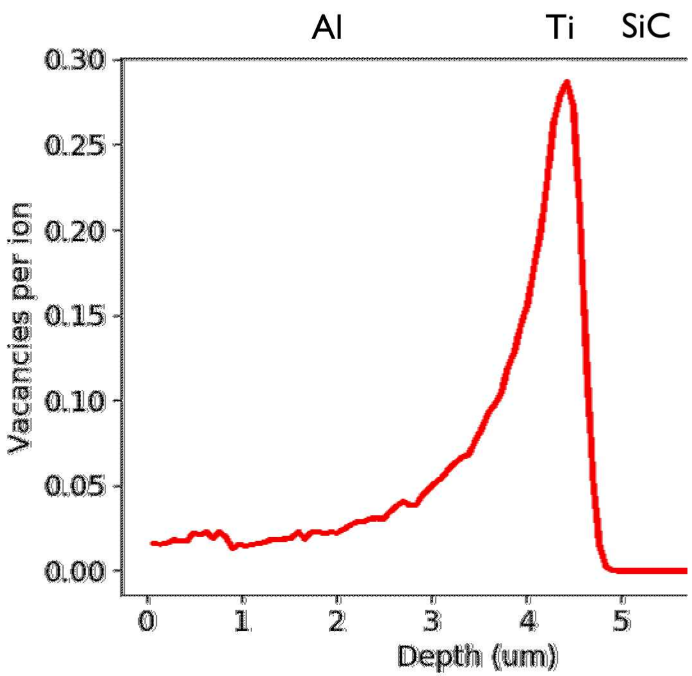


Ion Energy to Simulate Neutron Irradiation

Si Ion energy varied at constant fluence

- Largest damage effect at 12 MeV → this is our End-of-Range condition which maximizes the damage
- Determined at a fixed time of 0.1 s after shots



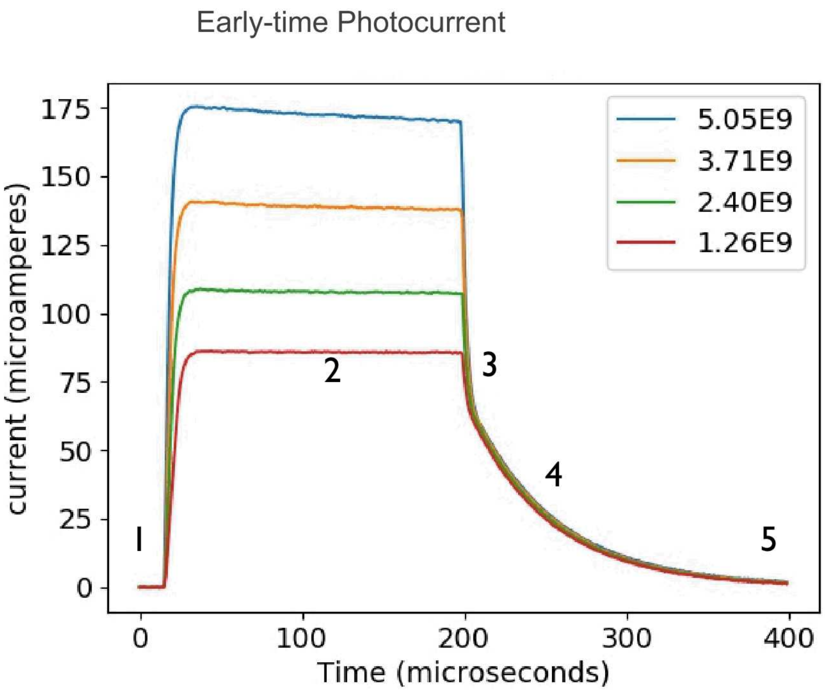


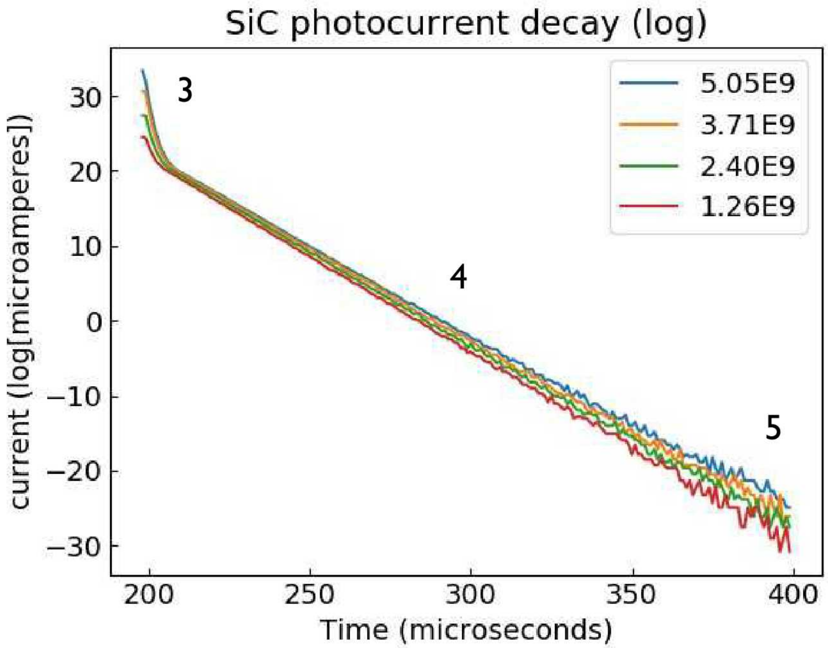
* Accounting only for vacancies produced within 100 nm of junction

Early-time ion response

Device Response Characteristics

1) Pre-shot leakage
2) Photocurrent during irradiation (proportional to flux)
3) Super –exponential, plasma enhanced recombination
4) Recombination, de-trapping
5) Late-time Annealing and leakage current



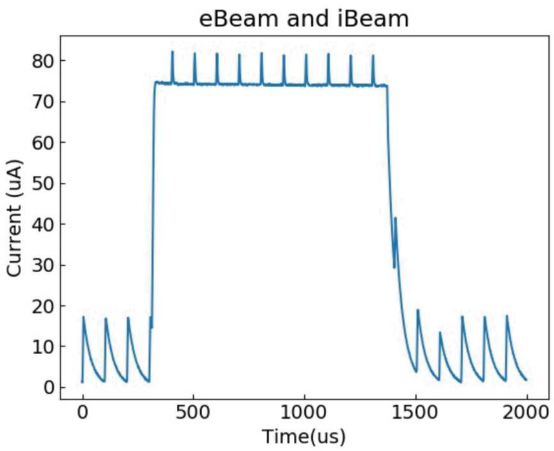


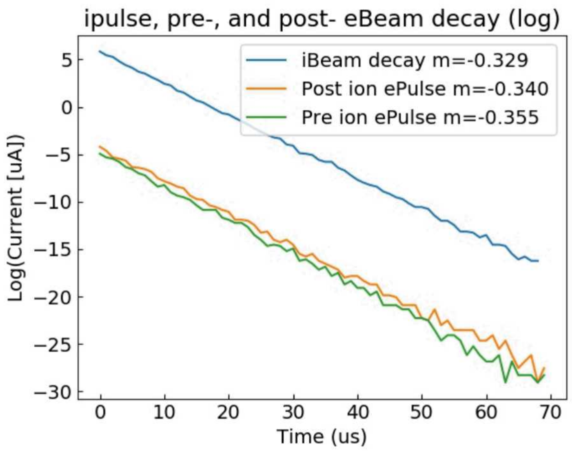
Probing Early-Time Response With Electron Pulses

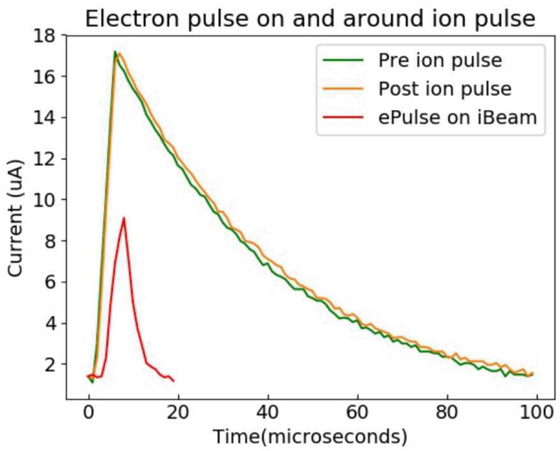
Use a short pulse electron gun to create e-h pairs (photocurrent without displacement damage)

Electron gun probes early-time effects of annealing and recombination by observing decay features

- We observe the same exponential fit for both the pre and post ion beam irradiation decay
  - $\tau = \frac{1}{m}$
  - Charge collection efficiency (CCE) degrades after multiple ion pulses
- During the ion irradiation we observe a super-exponential fit
  - Enhanced recombination and reduced amplitude due to plasma recombination





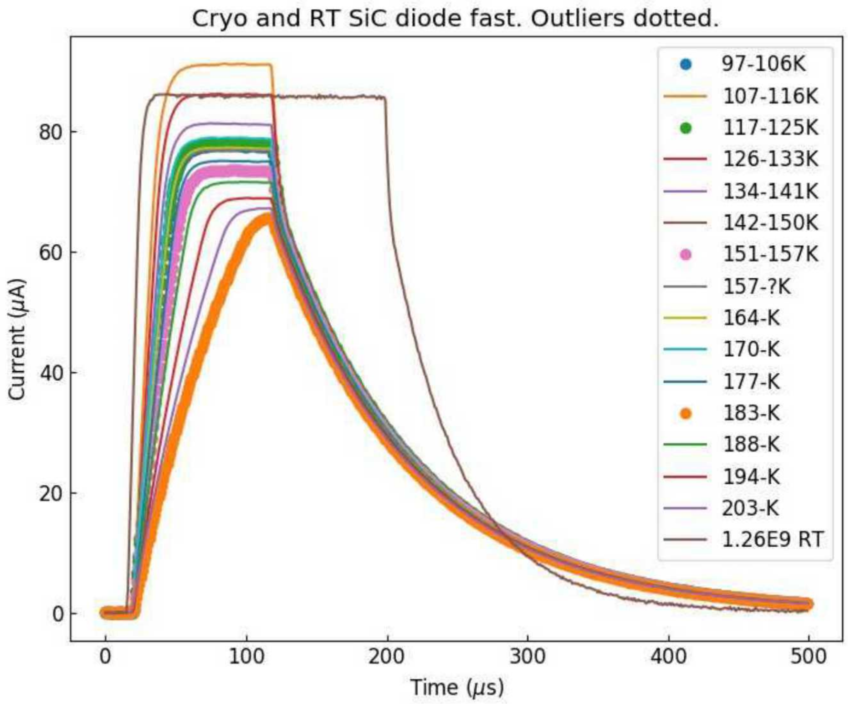


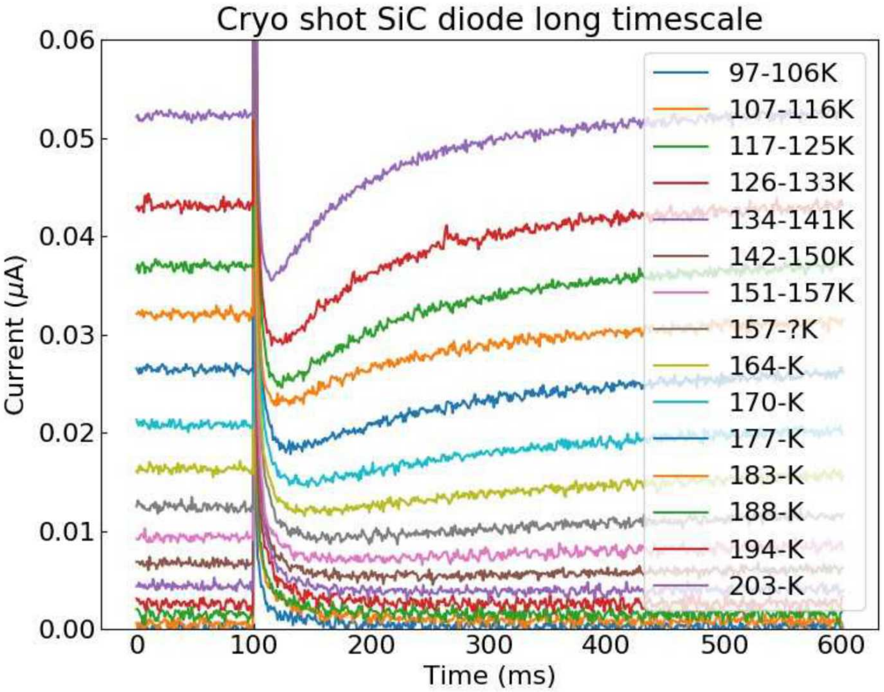
Cryogenic shot

Intended to suppress thermal effects of carrier de-trapping

Expected to slow down processes to better understand early-time effects

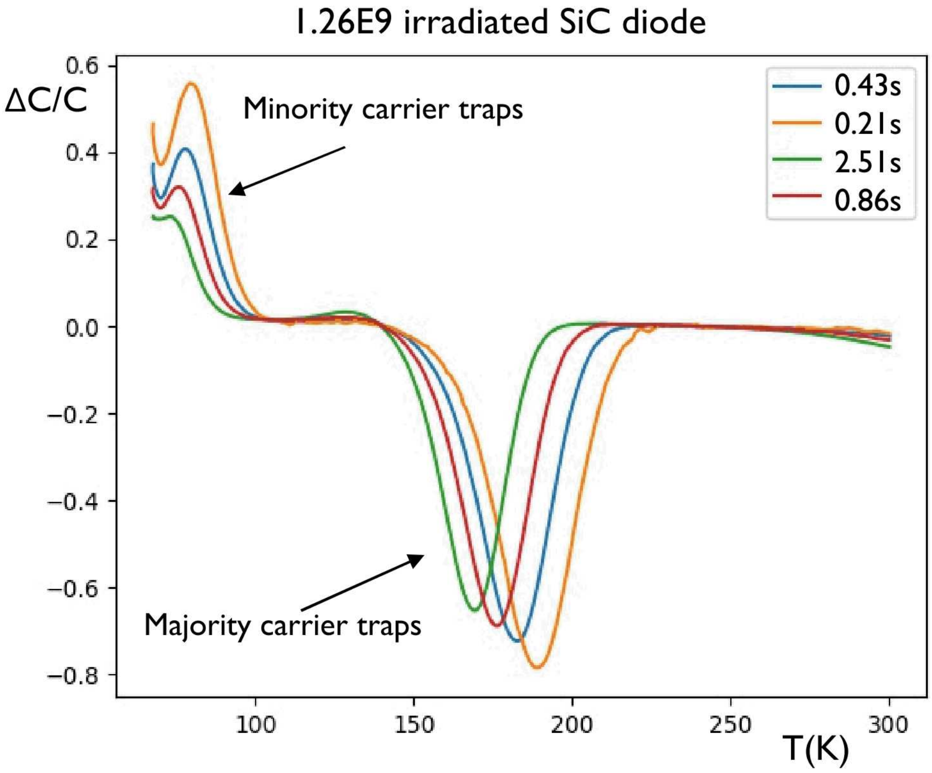
Experiment provided more questions than answers





DLTS measurements

Initial DLTS studies are underway



- Observe both minority and majority carrier traps

- We observe a decrease in trap concentrates with increasing fluence

  Why? Likely charge compensation, more work on-going!

Conclusions

The IBL at SNL is equipment rich

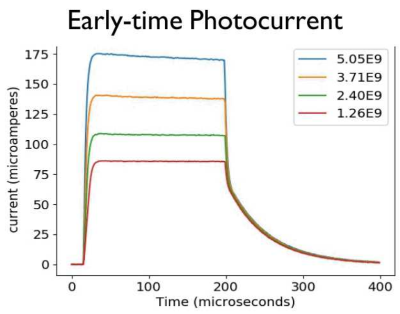
- But people poor

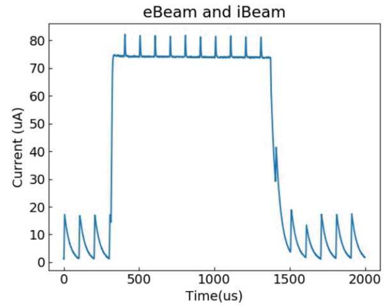
We can simulate neutron damage with ions

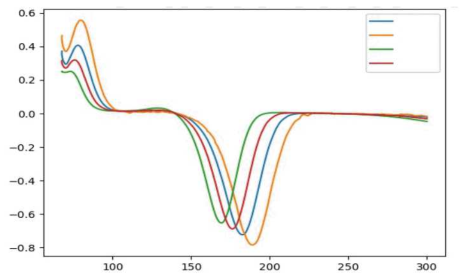
- Large equivalent flux
- Greater cross section than neutrons

On-going SiC SD study

- Three distinct post-irradiation features
- Experiments, analysis, modeling on-going







Advertisement

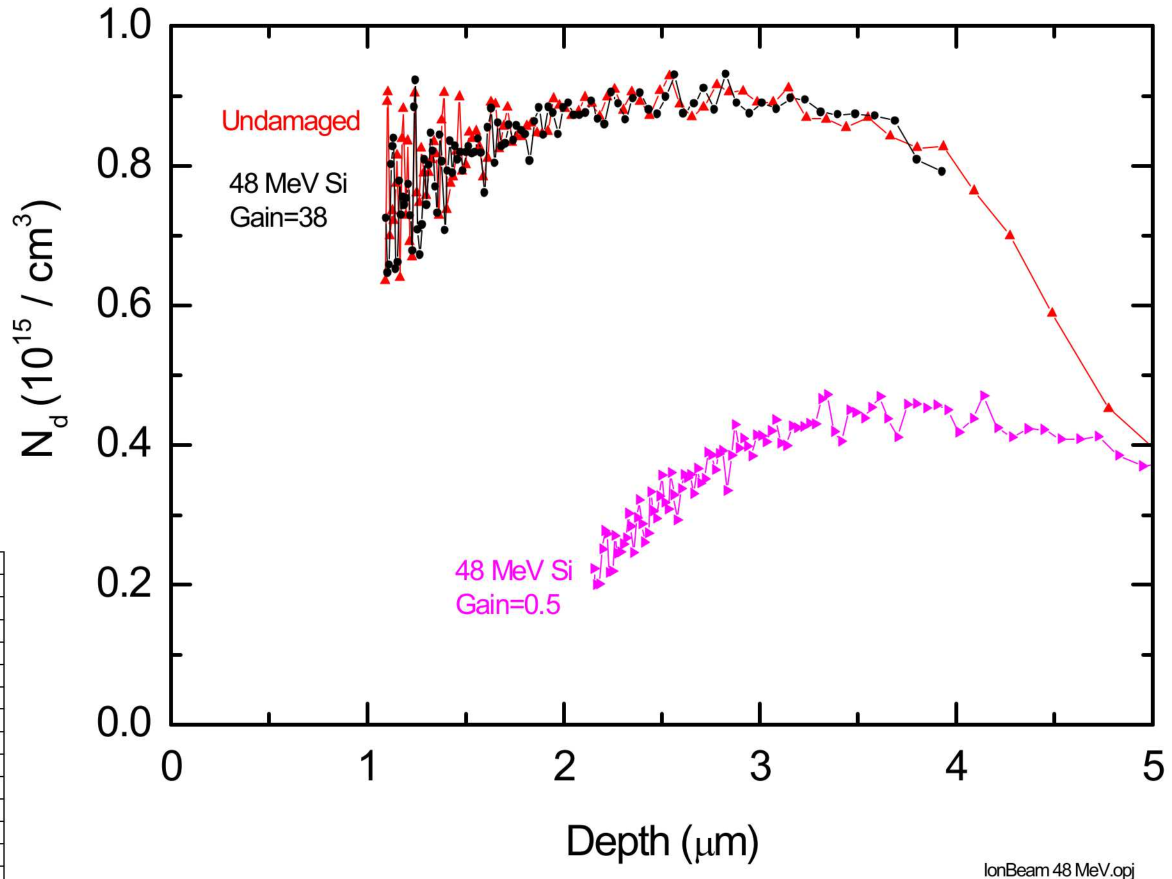
SNL IBL is opening positions for 2 more postdocs

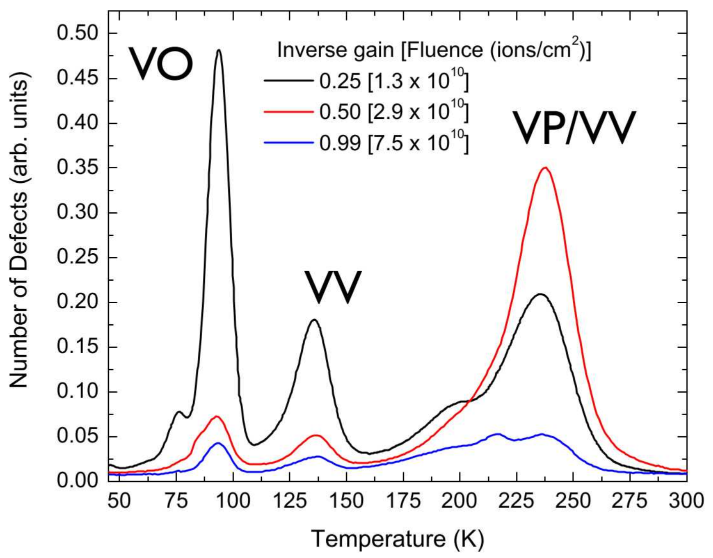
- Mixed field irradiations
- D-T neutron experimentation and modeling

Extra slides

Heavy Ion to Neutron Equivalence: SPR

Heavy ions: linear behavior at high fluence values



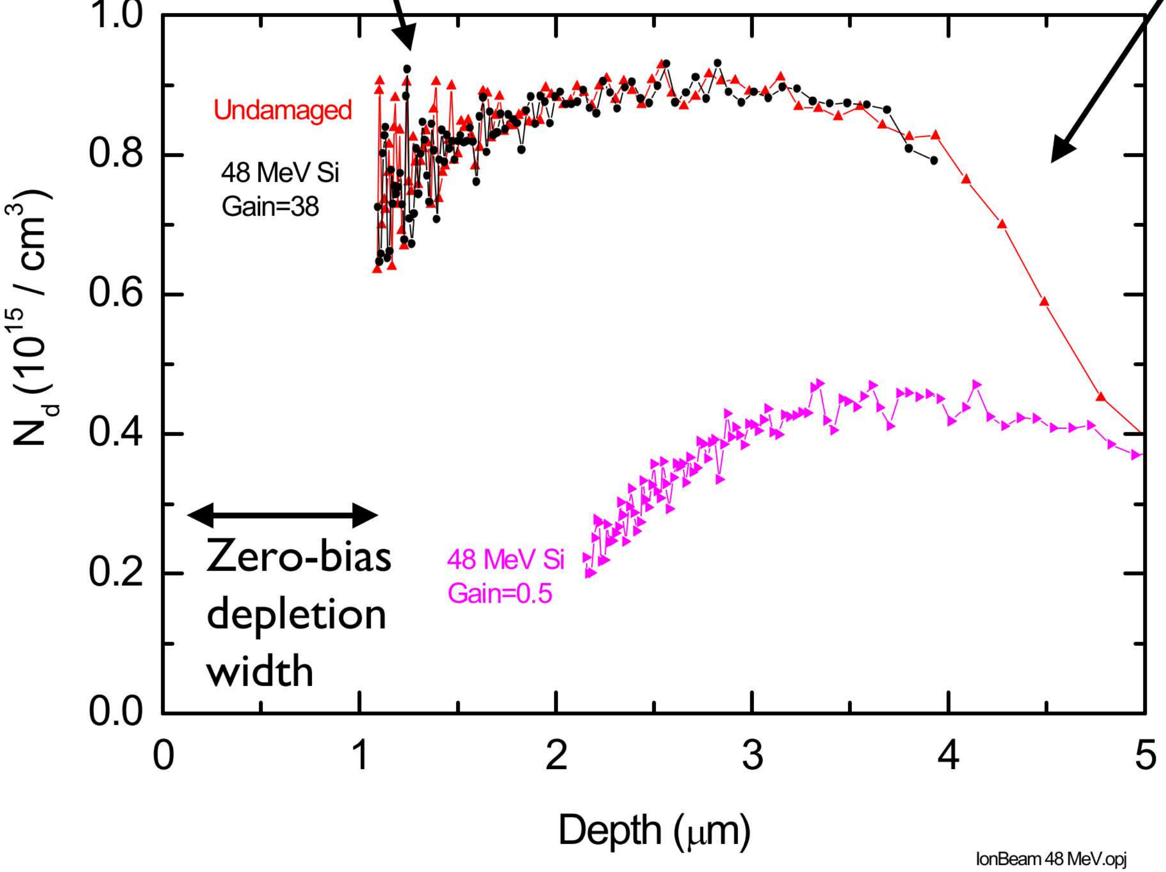


For high fluence we observe a change in the doping profile of the collector, and in the zero-bias depletion width.

Base-Collector Junction Capacitance

Frequency roll-off

Parasitic MOS capacitance roll-off



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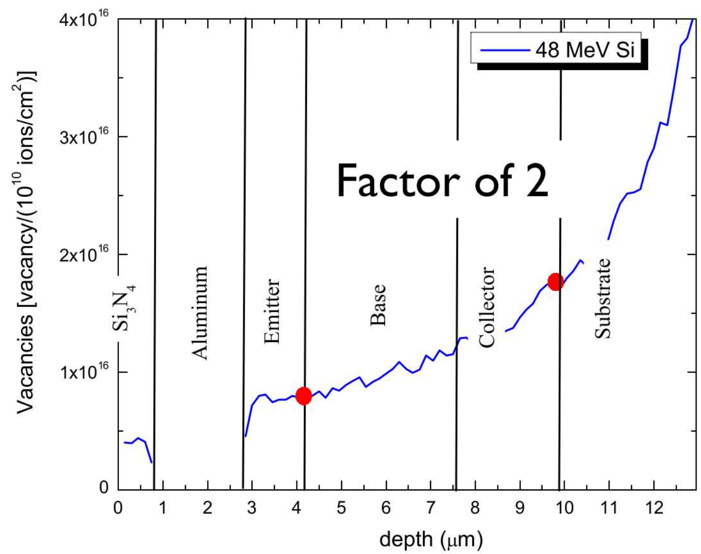
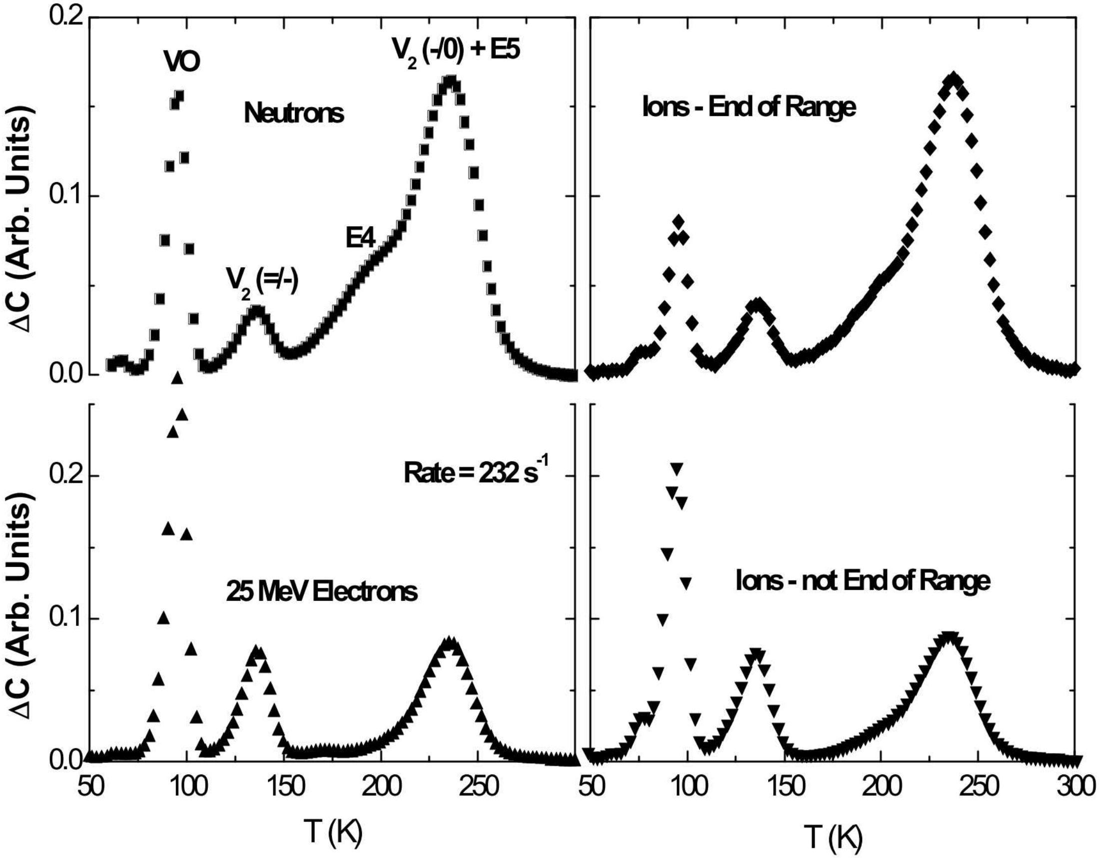


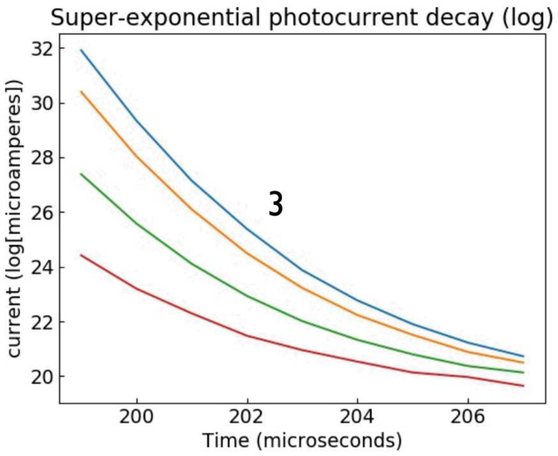
DLTS - Basic science technique to explore defect properties

Clustered damage produces larger single-acceptor V_2



- Extended from diodes to actual devices (BJT's)
- Enabled study of clustered defects (neutrons and ions) - **R. M. Fleming, et al, JAP, 102, 043711 (2007)**
- This has led to discoveries of new Si defects - Strained and bistable V_2 defects in damage clusters
- Bistable V_2-like defect can be used as a tool to de-convolve VP and V_2 in the BJT base - **R. M. Fleming, et al, JAP, 108, 063716 (2010)**

Uniquely identify and count the type and number of fundamental defects caused by irradiation


Super-exponential photocurrent decay (log)
current (log[microamperes])
32
30
28
26
24
22
20
200
202
204
206
Time (microseconds)
3