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Test simulation of neutron damage to electronic components using accelerator facilities

D. B. King, R. M. Fleming, E. S. Bielejec, J. K. McDonald, G. Vizkelethy,
Sandia National Laboratories, Albuquerque, New Mexico

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U.S. DEPARTMENT OF ENERGY

NNSA National Nuclear Security Administration

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Overview and Motivation

- **Motivation**
- Historically, reactors have been used to test the transient response of electronic systems to displacement damage and ionization
- Reactor availability is decreasing
- Can ion facilities be used to replace neutrons for research activities?
- Can we demonstrate ion and neutron equivalent displacement damage in electronics?

- **Electronics of interest for this presentation**
  - Silicon bipolar junction transistors (BJTs)
  - III-V material heterojunction bipolar transistors (HBTs) and diodes

- **Metrics to demonstrate equivalent displacement damage**
  - Late time gain, early time gain
  - Deep Level Transient Spectroscopy (DLTS)

Facilities used in this study

WSMR Fast Burst Reactor
- Pulse width – 50 μs FWHM
- Neutron fluence: 5E13 n/cm^2 1 MeV Si Eqv
- Dose: 10 krad(Si)

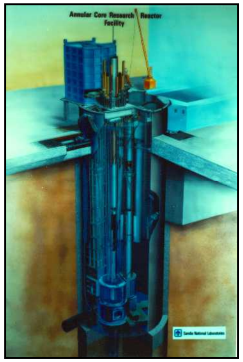
SNL ACRR
- Pulse width: 7 – 30 ms
- Neutron Fluence: 5E13 – 1E15 n/cm^2 1 MeV Si Eqv
- Dose: 10 – 100 krad(Si)

Ion Beam Laboratory
- Ions: H, C, Si (3, 4.5, 10, 36 MeV), O, Au, Ge
- Focused beam (μm – mm)
- Currents: fA (submicron beam) - 100s nA (large beam)
- Pulse length: 200 ns (90 ns rise and fall time) - ms

Little Mountain LINAC operated in electron beam mode
- Electron energy tuned from 2 to 30 MeV
- Pulse widths: 50 nsec to 50 μsec
- Beam currents: 0.1 to 2 Amps
- 1 Hz repetition rate

SPHINX
- 2.5MeV electrons
- Pulse width - 3.5 to 10 ns
- 1 Hz repetition rate

ACRR



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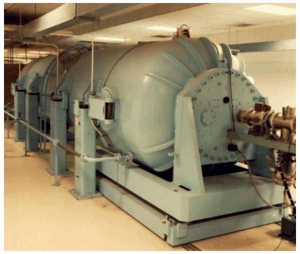
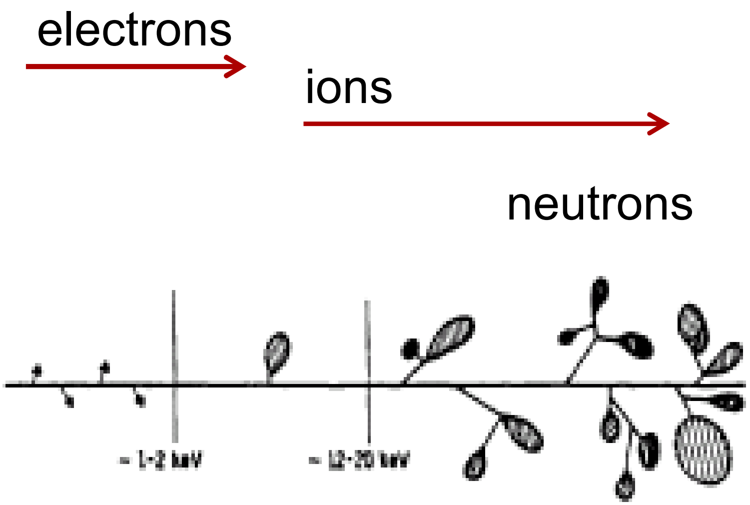
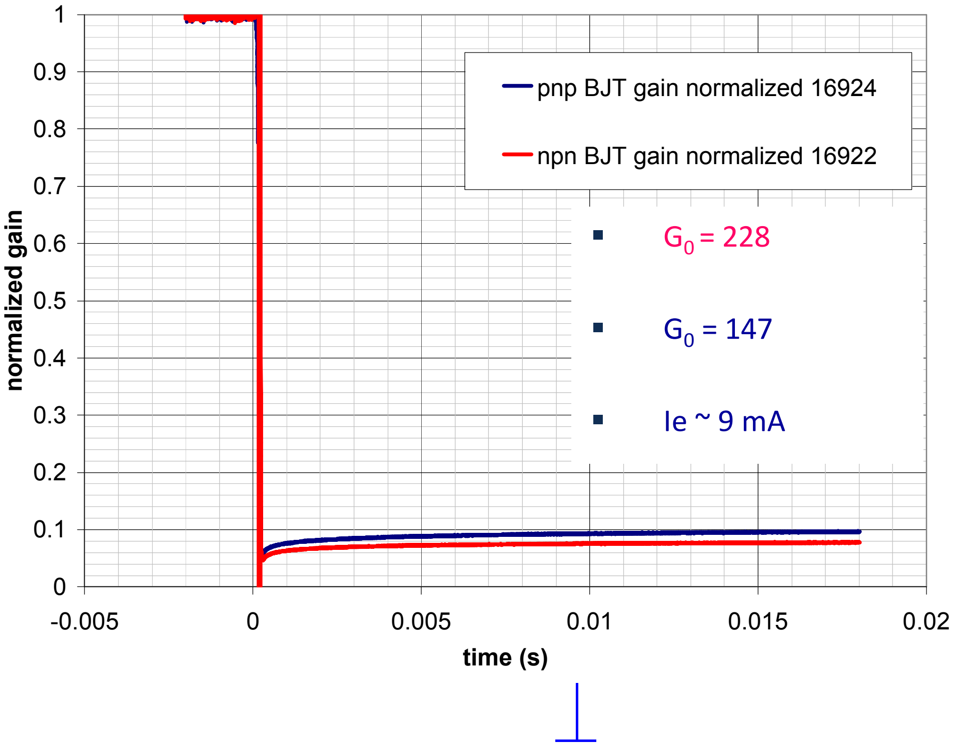


Neutrons create displacement damage in bipolar junction transistors (BJTs)

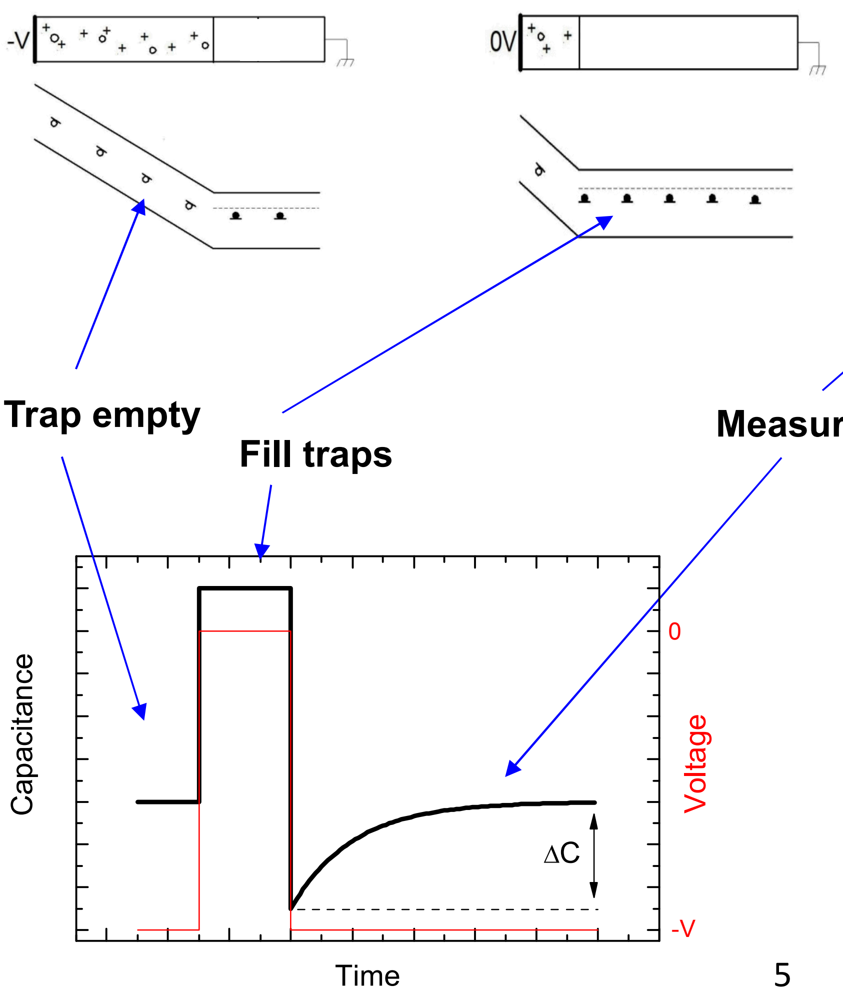


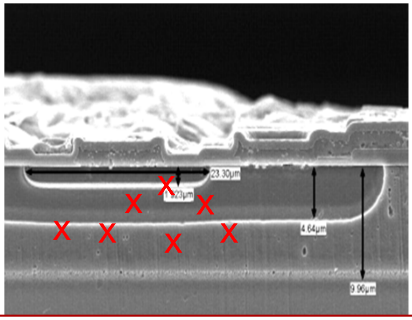


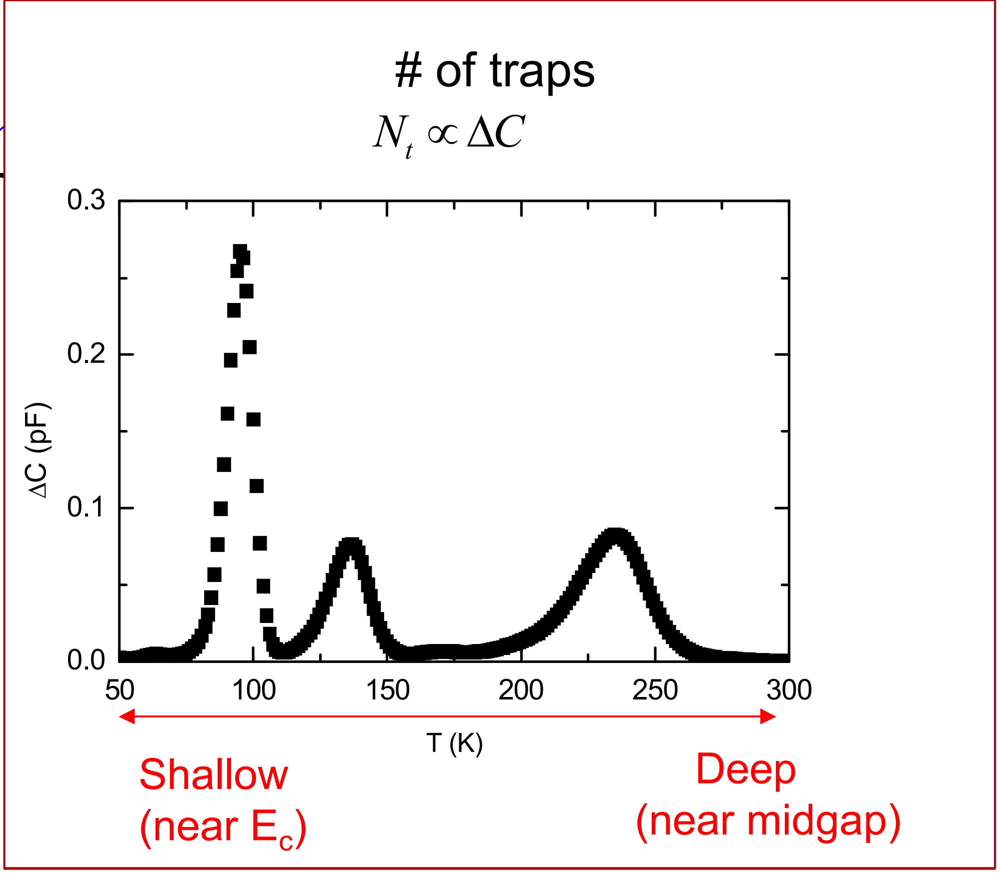
Gain: $\beta = I_c/I_b$ β typically 100 to 300

BJT: a small Ib controls a large Ic → GAIN

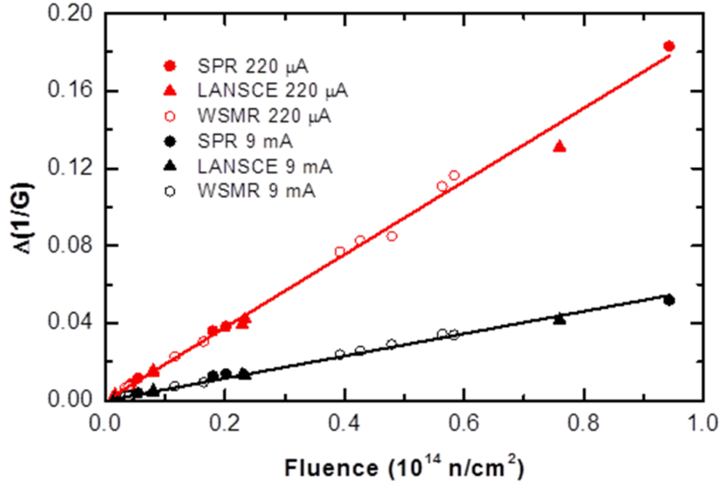
DLTS is used to identify defects by probing at the atomic level

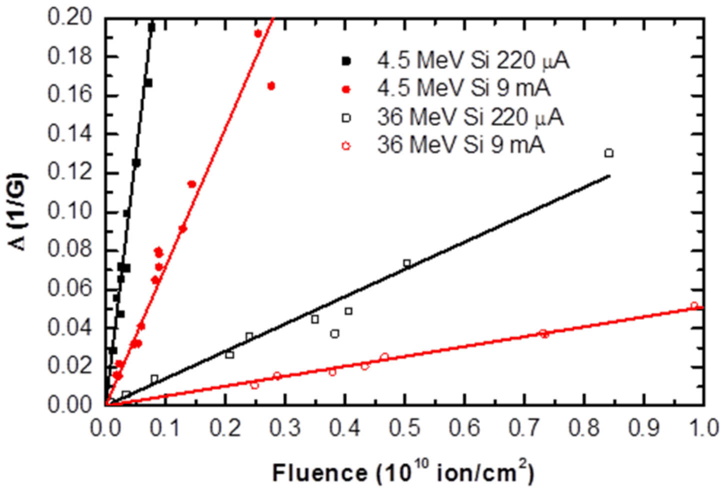






Particle fluence can be related across ion and neutron facilities using the late time gain metric and Si BJTs





$$\left(\Delta \frac{1}{G}\right) = \frac{1}{G_\infty} - \frac{1}{G_0} = k\Phi$$

G_0: pre radiation gain
G_∞ : late time gain
k: damage factor
Φ: particle fluence

$$\Phi_{neutron} = \frac{k_{ion}}{k_{neutron}} \Phi_{ion}$$

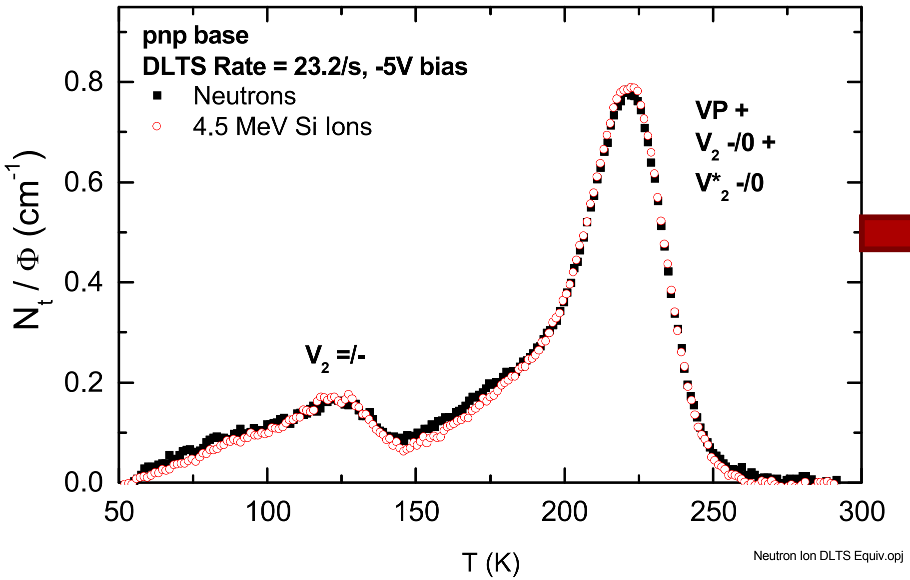
Si Energy	$k_{\text{ion}}/k_{\text{neutron}}$
4.5 MeV	134,000
36 MeV	7,300

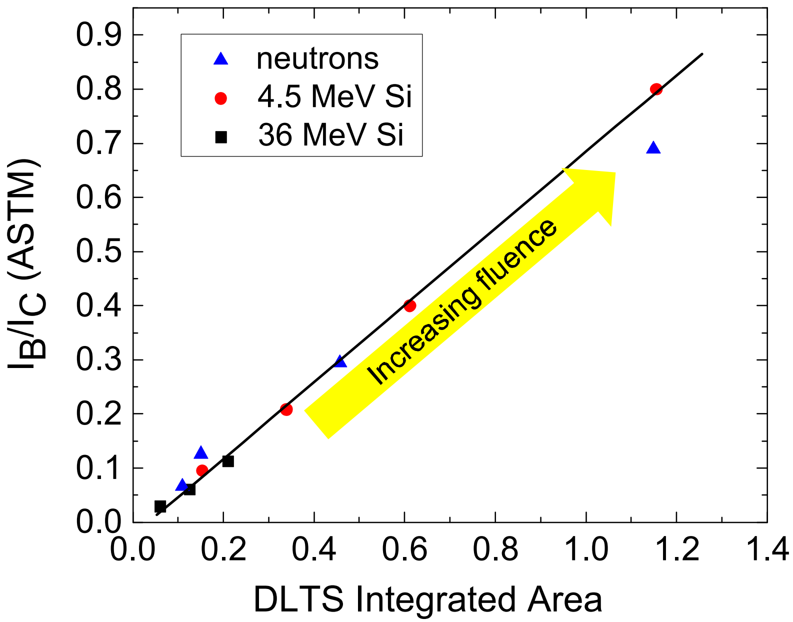
6

For 36 MeV Si 5E13 n/cm2 ~ 6.85E9 ions/cm^2
For 4.5 MeV Si 5E13 n/cm^2 ~ 3.73E8 Si ions/cm^2

DLTS is used directly in the Si BJT to identify the defect spectra responsible for late time gain degradation

DLTS defect identification based on decades of research reported in literature



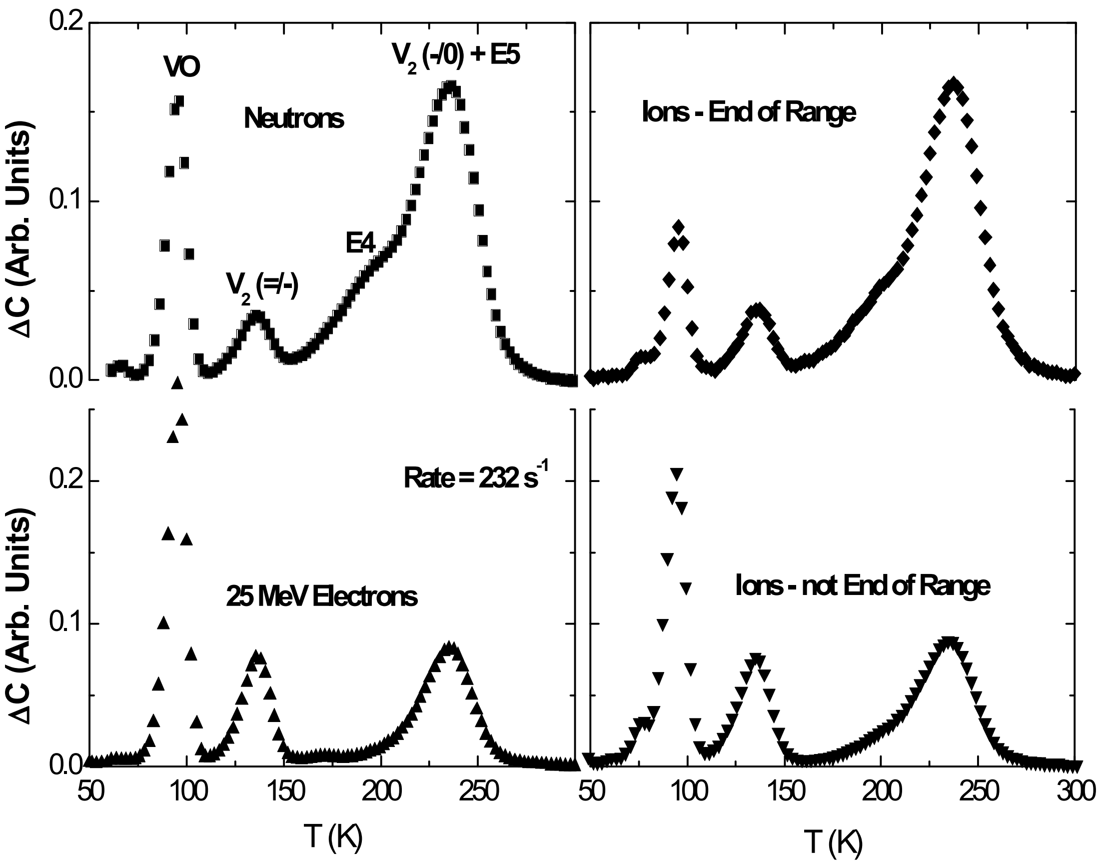


$$\Phi_{neutron} = \frac{k_{ion}}{k_{neutron}} \Phi_{ion}$$

A given *number of defects* produces the same late-time gain reduction for neutron and ion irradiations.

DLTS - Basic science technique to explore fundamental defect properties

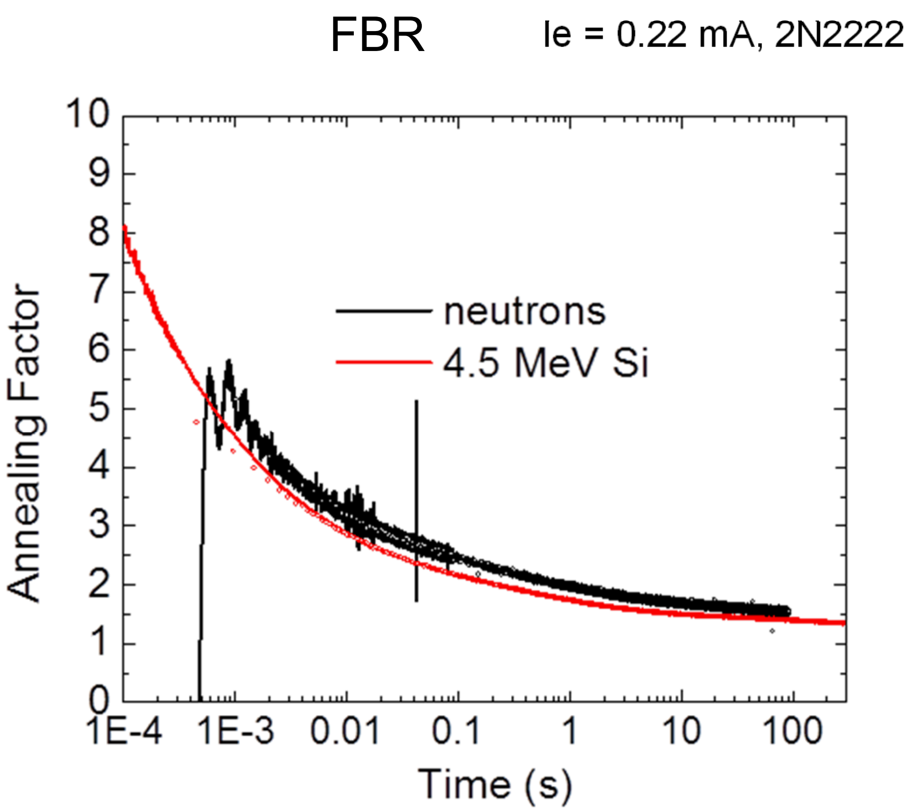
Clustered damage produces larger single-acceptor V_2



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

- Developed by a QASPR team member - **D. V. Lang, JAP, 45, 3023 (1974)**
- Extended from diodes to actual devices (BJT's) by QASPR
- 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)**

Matching late time gain and defect spectra at FBR and IBL results in agreement of AFs at all test times for Si npn BJTs



Annealing Factor

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

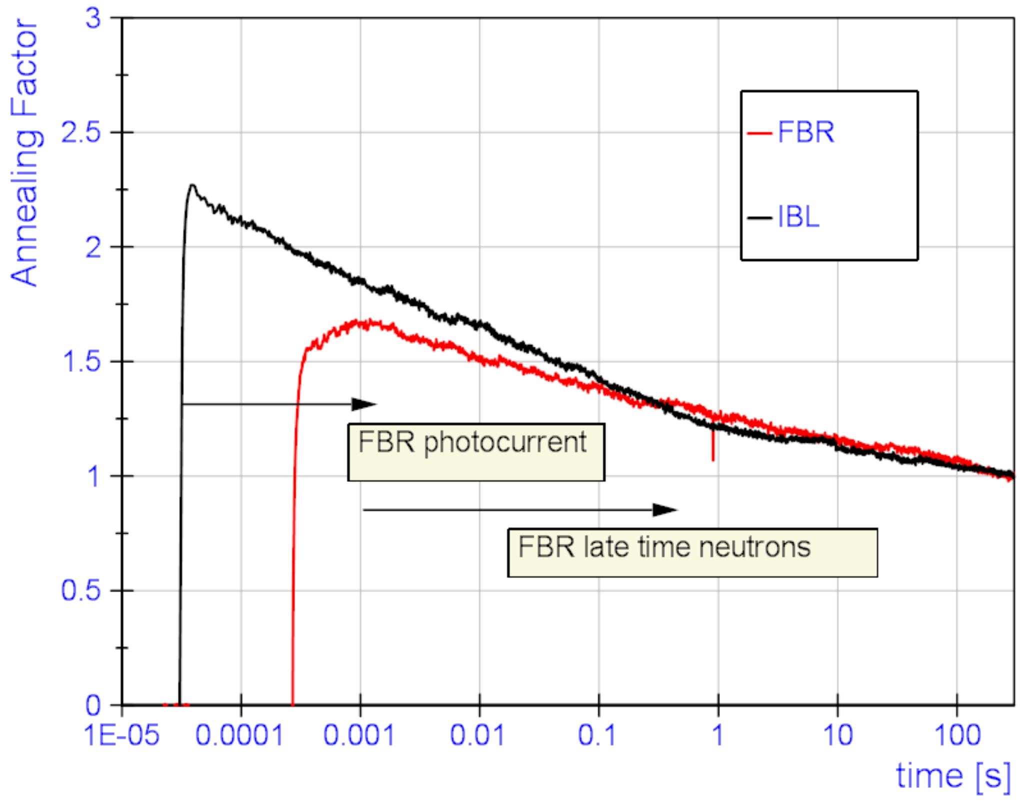
$\delta AF < 5\%$

reactor gamma environment delays gain measurement compared to IBL

Agreement between the annealing factors indicates that the annealing kinetics are similar for ion and neutron irradiations – critical for early-time predictive capabilities

Late-time equivalent damage is demonstrated between IBL and FBR for Npn HBTs using late-and early-time gain metrics

Npn HBT, IE = 0.22 mA



$$\left(\Delta \frac{1}{G}\right) = \frac{1}{G_\infty} - \frac{1}{G_0} = k\Phi$$

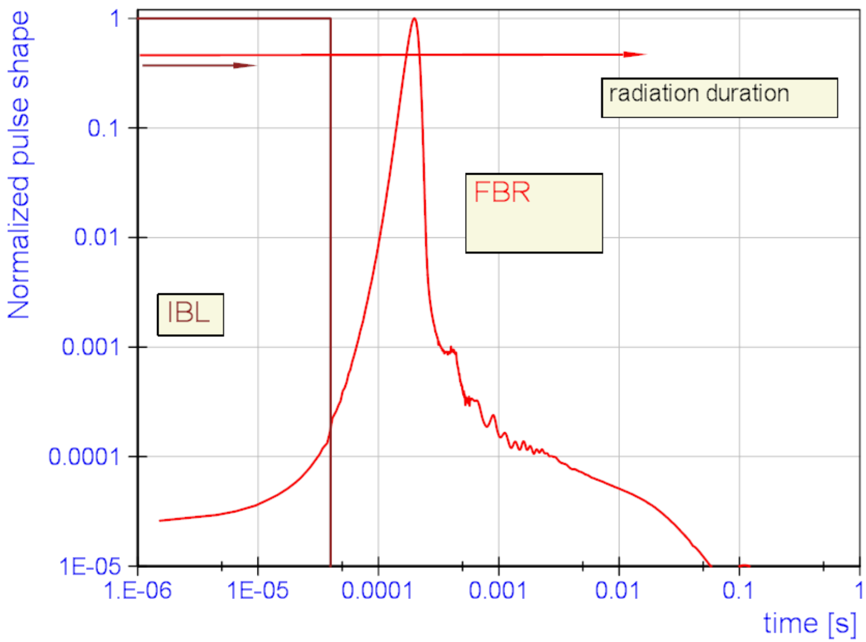
7.5 MeV Si: k_{Si} = 4.91E-11
Neutron: k_n = 1.05E-16
k_{Si}/k_n = 4.7E5

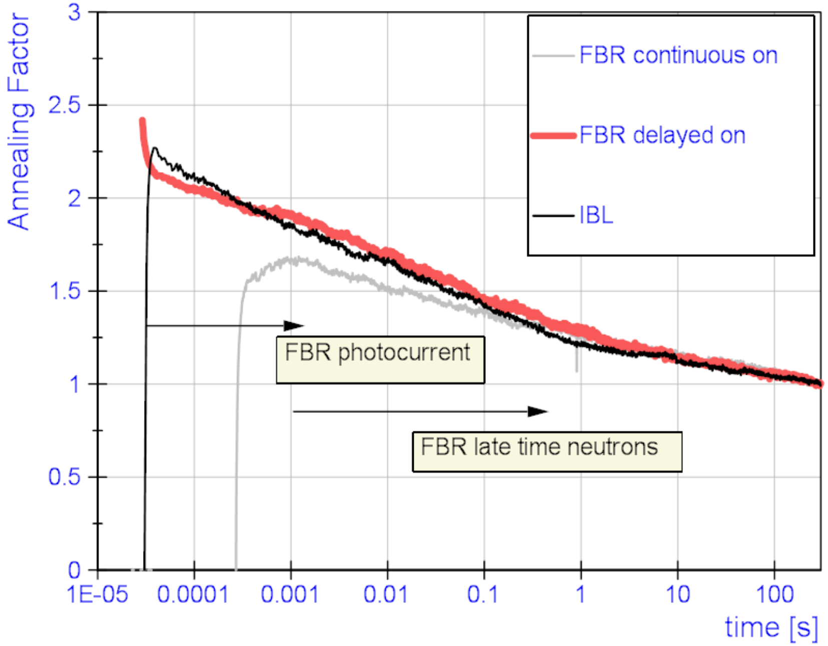
For 7.5 MeV Si, 5E13 n/cm^2 ~ 1.1E8 Si/cm^2

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

- FBR gamma and late time neutron environments prevent match until 0.1 s
- Matching of annealing factors after 0.1 s indicates that defect annealing kinetics are similar

Equivalent damage is demonstrated between IBL and FBR for Npn HBTs using late-and early-time gain metrics and delayed turn on





- HBTs do not anneal at room temperature for over 1000 s
- We can delay turn on of HBT until all FBR neutrons are delivered
- Matching of annealing factors after 0.1 s indicates that defect annealing kinetics are similar

DLTS in GaAs : Analysis is more complex

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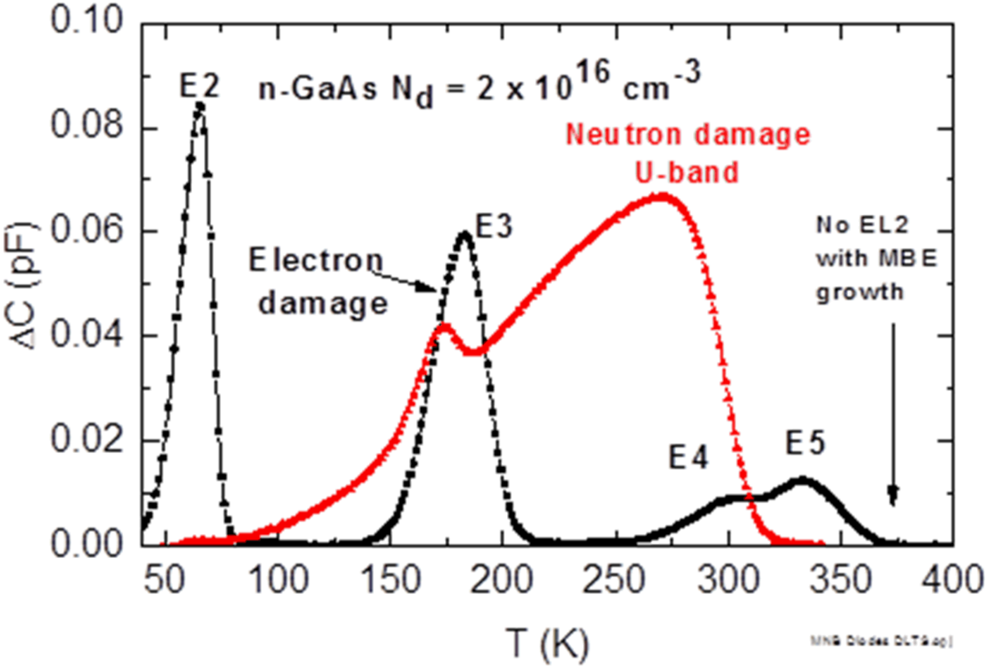


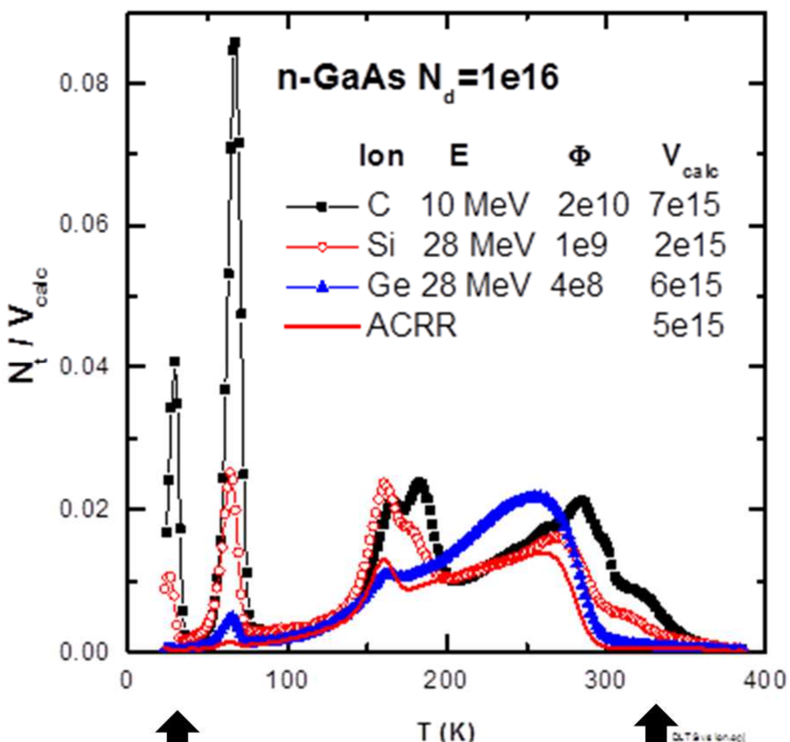
- **neutron spectra is radically different from electron damage.**
- **The broad features after neutron/ion damage are known as the “U-band” (n-GaAs) and the “L-band” (p-GaAs)**

	Silicon	GaAs
Defect library from prior work	Extensive (from EPR/DLTS)	Minimal (EPR not effective)
Additional defect species in clusters	A few, e.g. bistable V_2, strained V_2	Unknown at present, work in progress
Electric-field enhanced emission from defects (phonon assisted tunneling)	Minimal	Extensive – Contributes to broad DLTS features after clustered damage (U-band, L-band)

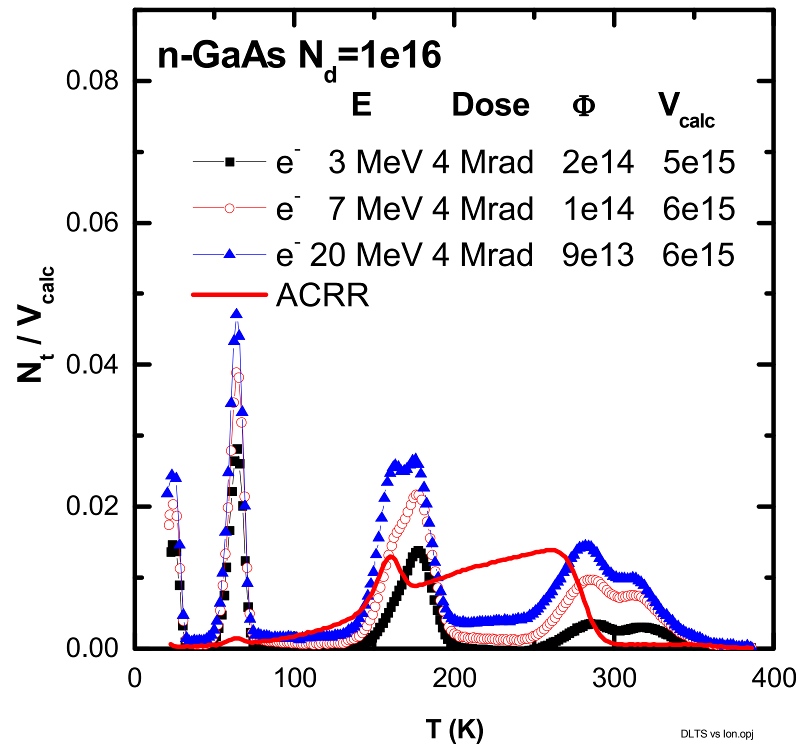
Lack of an experimental structural tool in GaAs (minimal information with EPR) requires QASPR to develop theoretical tools (e.g. DFT) to calculate defect structures.

Ions and electrons can produce spectra characteristics between point and Uband

Ions



Electrons



HT roll-off decreases with clustering (BG narrowing & PAT)

Shallow peaks sensitive to the degree of clustering (charging & PAT)

Experimental and modeling teams work closely together to identify simple intrinsic defects in GaAs

P.A. Schultz and O.A. von Lilienfeld, MSMSE **17**, 084007 (2009), 35pp.

Density Functional Theory

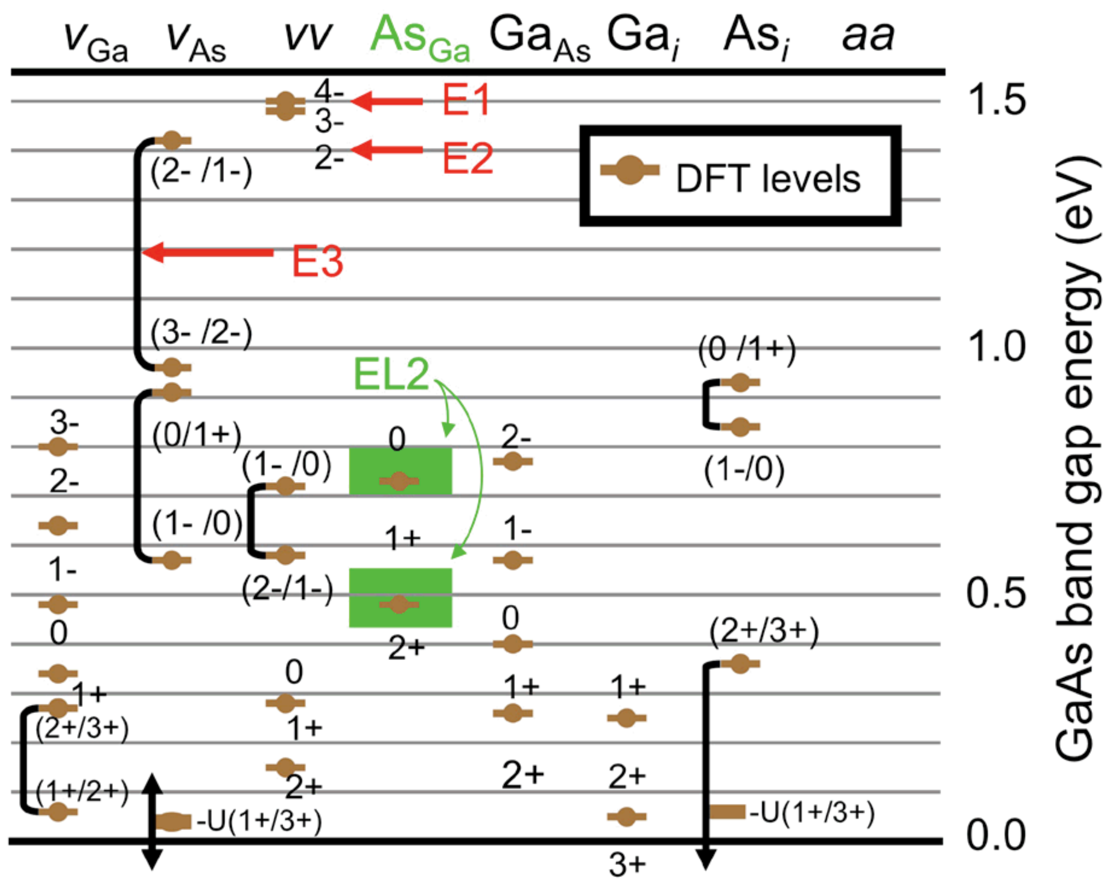
Defect band gap = ~1.54 eV

Validation: band gap (1.52)

As_{Ga}= EL2 levels

VV = E1, E2

V_{As} = E3



Pure prediction: a GaAs radiation defects Rosetta Stone

Conclusions

- Engineering test metrics (gain) and basic research (DLTS) have led to improved understanding of defects and device performance in neutron/ion environments for Si BJTs
- Ion to neutron damage equivalence has been demonstrated for BJTs
- Engineering test metric (gain) has led to improved understanding of device performance in neutron/ion environments for HBTs
- Reactor gamma and late-time neutron environment prevented early-time gain comparisons but delayed turn on allows early-time comparisons
- DLTS has not conclusively identified defects responsible for gain degradation in HBTs – work continues to understand defect characteristics