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Radiation damage in bipolar junction transistors (BJTs)

Gyorgy Vizkelethy, Edward Bielejec, Robert M. Fleming, Donald B. King, William R. Wampler, and Samuel M. Myers
Sandia National Laboratories
Albuquerque, NM, USA

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Overview

- Motivation
- Why use ions to study displacement damage?
- How does a BJT works?
- The Messenger-Spratt relation
- Metrics we can use to characterize displacement damage in BJTs
- Planning the experiment
- Results
- Modeling
- A brief look into III-V HBTs if time permits

Recommended reading

- G.C. Messenger, M.S. Ash, The Effects of Radiation on Electronic Systems, 2nd ed., Van Nostrand Reinhold, New York, 1992.
- E. Bielejec, G. Vizkelethy, R.M. Fleming, D.B. King, IEEE Transactions on Nuclear Science, 54 (2007) 2282-2287.
- E. Bielejec, G. Vizkelethy, R.M. Fleming, W.R. Wampler, S.M. Myers, D.B. King, IEEE Transactions on Nuclear Science, 55 (2008).
- E. Bielejec, G. Vizkelethy, N.R. Kolb, D.B. King, B.L. Doyle, IEEE Transaction on Nuclear Science, 53 (2006) 3681-3686.
- R.M. Fleming, C.H. Seager, E. Bielejec, G. Vizkelethy, D.V. Lang, J.M. Campbell, Journal of Applied Physics, 107 (2010).
- R.M. Fleming, C.H. Seager, D.V. Lang, E. Bielejec, J.M. Campbell, Applied Physics Letters, 90 (2007).
- R.M. Fleming, C.H. Seager, D.V. Lang, E. Bielejec, J.M. Campbell, Physica B: Condensed Matter, 401-402 (2007) 21-24.
- R.M. Fleming, C.H. Seager, D.V. Lang, E. Bielejec, J.M. Campbell, Journal of Applied Physics, 104 (2008) 083702-083710.
- R.M. Fleming, C.H. Seager, D.V. Lang, P.J. Cooper, E. Bielejec, J.M. Campbell, Journal of Applied Physics, 102 (2007) 043711.
- C.H. Seager, R.M. Fleming, D.V. Lang, P.J. Cooper, E. Bielejec, J.M. Campbell, Physica B: Condensed Matter, 401-402 (2007) 491-494.
- S.M. Myers, P.J. Cooper, W.R. Wampler,, Journal of Applied Physics, 104 (2008).
- S.M. Myers, W.R. Wampler, P.J. Cooper, D.B. King, Physica B-Condensed Matter, 401 (2007) 473-476.

Why do we want to study displacement damage in BJTs?

- There are many analog components which contain BJTs in control and diagnostic equipment used in high neutron and ion flux environments, such as nuclear reactors and large accelerators.
- Displacement damage reduces the gain of the BJT which can lead to degraded performance or even malfunction of the equipment.
- We need to be able to predict how a BJT's working parameters change due to different levels of displacement damage and how and on what scale it can repair itself (annealing).

Why not to use neutrons for displacement damage?

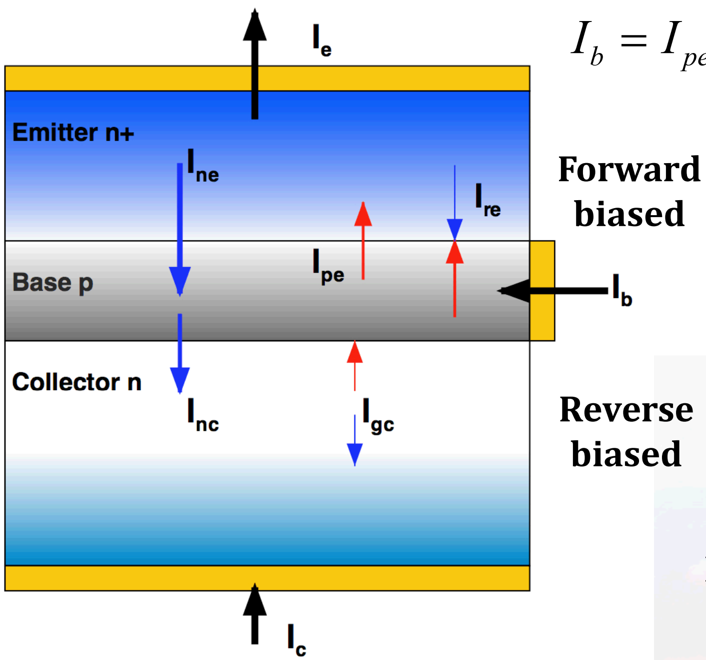
- **Activation! Both devices and test equipment.**
- Very complicated experiment set-up
- Reactors are expensive
- Neutrons irradiate large areas and volumes, it is hard to restrict to small volumes and areas
- There are always gamma rays in reactors, it is hard to separate the effects of ionization and displacement damage
- To measure time dependence of annealing, specialized reactors are needed that are not easily available

Why use ions to create the displacement damage?

- Even in neutron irradiation the displacement damage is done by the Si recoils. So why not start directly with the recoils?
- There is no activation at all!
- Small (few MV) accelerators are much cheaper to purchase, operate, and maintain.
- It is easy to irradiate small areas and volumes such as one device only in circuit.
- Flux, fluence, and pulse length can be easily controlled
- By changing ion species and energy the ionization to displacement ratio can be varied.

Basics of a BJT and effect of displacement damage

Constant emitter current configuration of a npn BJT



Damaged

$$I_e = I_{ne} + I_{pe} + I_{re}$$

$$I_c = I_{nc} + I_{gc}$$

$$I_b = I_{pe} + I_{re} - I_{gc} + \left(I_{ne} - I_{nc}\right)$$

Emitter injection efficiency $\eta = \frac{I_{ne}}{I_e}$

Base transport factor $\alpha_T = \frac{I_{nc}}{I_{ne}}$

Common emitter gain $G = \frac{I_c}{I_b} = \frac{\eta \cdot \alpha_T}{1 - \eta \cdot \alpha_T}$

Irradiation

□

Silicon recoil cascades

□

Frenkel pairs

□

Defects in the bandgap

□

Decreasing life time

□

Decreasing gain

Recombination in the base-emitter depletion layer:

- **increasing recombination current**
- **decreasing I_{ne}**
- **decreasing emitter injection efficiency**
- **decreasing gain**

Recombination in the neutral base:

- **decreasing I_{nc}**
- **decreasing base transport factor**
- **decreasing gain**

The Messenger-Spratt relation (G^{-1} vs. fluence)

- **Inverse gain:** $G = \frac{\eta \cdot \alpha_T}{1 - \eta \cdot \alpha_T} \Rightarrow \frac{1}{G} = G^{-1} = \frac{1}{\eta \cdot \alpha_T} - 1$
- **Minority lifetime:** $\frac{1}{\tau} = \frac{1}{\tau_0} + \sigma \cdot v_{th} \cdot N_T$
- **Inverse gain:**

$$G^{-1} = \cosh\left(\frac{W_B}{\sqrt{D_B \cdot \tau_n}}\right)\left(1 + \frac{N_B \cdot W_B}{D_B}\frac{D_E}{N_E \cdot W_E} + \frac{N_B \cdot W_B}{D_B} \cdot \frac{W_{EB}}{2n_i \cdot \tau_r} e^{-\frac{q \cdot V_{BE}}{kT}\left(1 - \frac{1}{n}\right)}\right) - 1$$

- **Moderate gain degradation: $L_B \gg W_B$, I_{RE} negligible**

$$G_\infty^{-1} - G_0^{-1} = \frac{1}{2}\frac{W_B^2}{D_B}\left(\frac{1}{\tau_\infty} - \frac{1}{\tau_0}\right) = K \cdot \Phi$$

The inverse gain change after infinite long time is proportional to the number of permanent defects. To compare different facilities ASTM annealing (80°C for two hours) has to be performed.

Where the Messenger-Spratt relation is not strictly valid

We keep the *cosh* expansion but do not neglect the recombination current in the base depletion layer

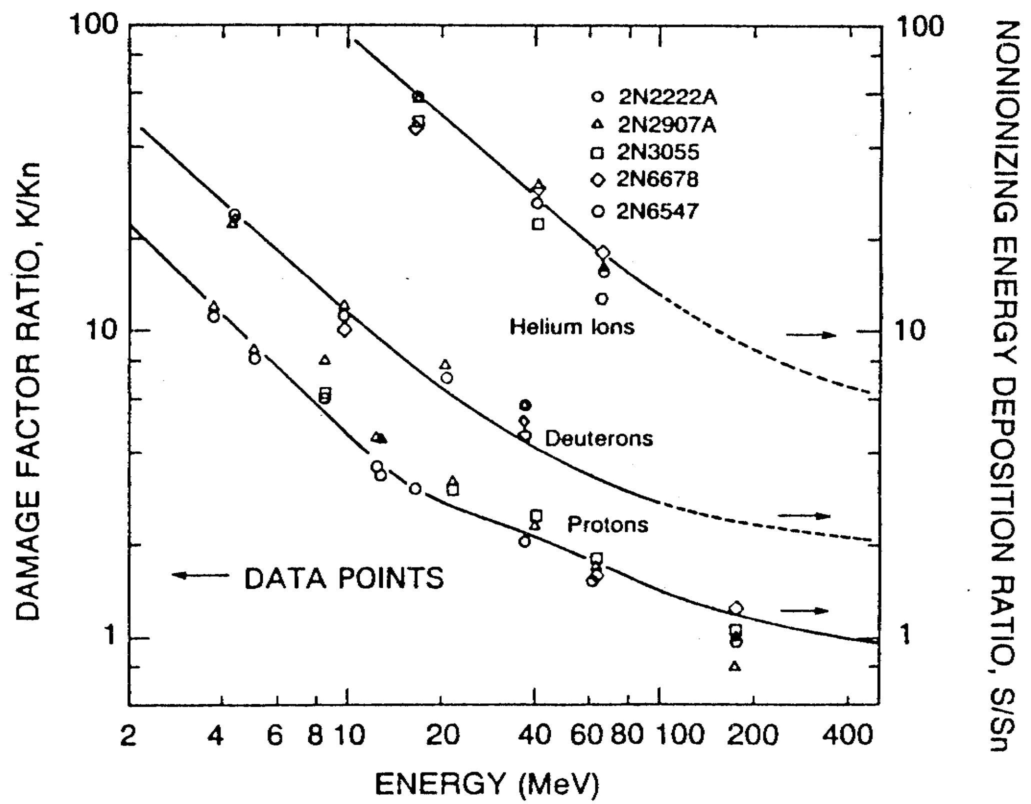
$$G^{-1} - G_0^{-1} = \underbrace{\frac{1}{2}\frac{W_B^2}{D_B}\left(\frac{1}{\tau_n} - \frac{1}{\tau_{n0}}\right)}_{\text{recombination in the neutral base}} + \underbrace{\frac{1}{2}\frac{N_B \cdot W_B}{D_B \cdot n_i} \cdot \left(\frac{W_{EB}}{\tau_r} e^{-\frac{q \cdot V_{BE}}{kT}\left(1-\frac{1}{n}\right)} - \frac{W_{EB0}}{\tau_{r0}} e^{-\frac{q \cdot V_{BE0}}{kT_0}\left(1-\frac{1}{n}\right)}\right)}_{\text{recombination in the depletion layer}}$$

V_{BE} and kT are constant

$$G^{-1} - G_0^{-1} = \frac{1}{2}\frac{W_B^2}{D_B}\left(\frac{1}{\tau_n} - \frac{1}{\tau_{n0}}\right) + \frac{1}{2}\frac{N_B \cdot W_B}{D_B \cdot n_i} \cdot W_{EB} \cdot e^{-\frac{q \cdot V_{BE}}{kT}\left(1-\frac{1}{n}\right)}\left(\frac{1}{\tau_r} - \frac{1}{\tau_{r0}}\right) = K' \cdot \Phi$$

The recombination current will always be linearly proportional the damage, it is the most sensitive at low emitter currents and high damage. Experimentally difficult measurement.

The damage factor is proportional to the displacement damage independent of the particle that creates the damage †



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

G.P.Summers et al, IEEE Trans. Nucl. Sci., NS-34 (1987), p 1134

† We will see later that it is not strictly true.

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Metrics for effect of displacement damage

- Damage factor: Messenger-Spratt relation
- Annealing factor: time dependence of defect annealing
- Deep Level Transient Spectroscopy (DLTS): types and amount of defects
- Photoluminescence (PL): Minority lifetime (It would be nice, but Si is not a direct bandgap semiconductor, so it will not work).
- Leakage and forward current changes in diodes (BJT is a forward and a reverse biased diode back-to-back)

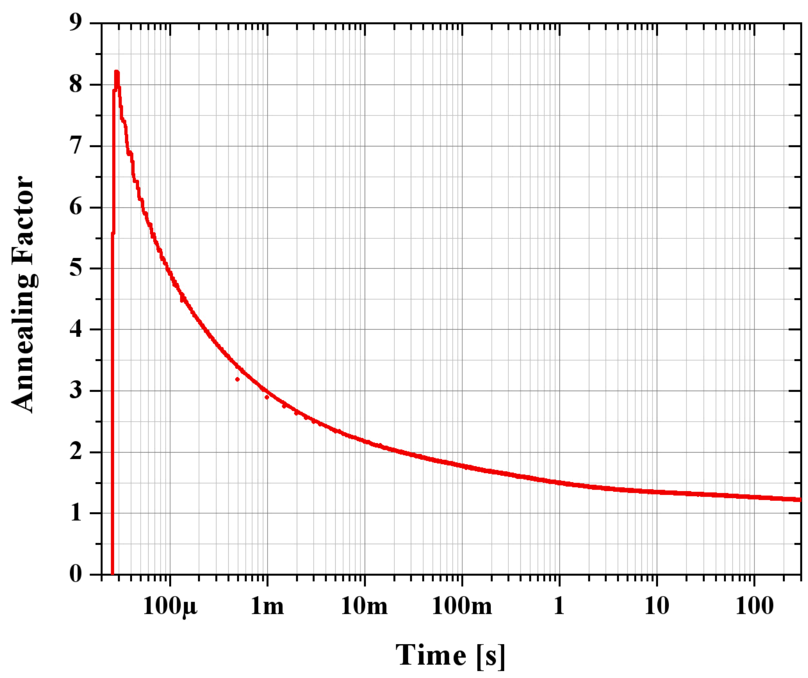
Annealing factor: Time dependence of defect annealing

The initial damage anneals out with time, the transient gain recovery is an important metric, it describes the time evolution of the defects.

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

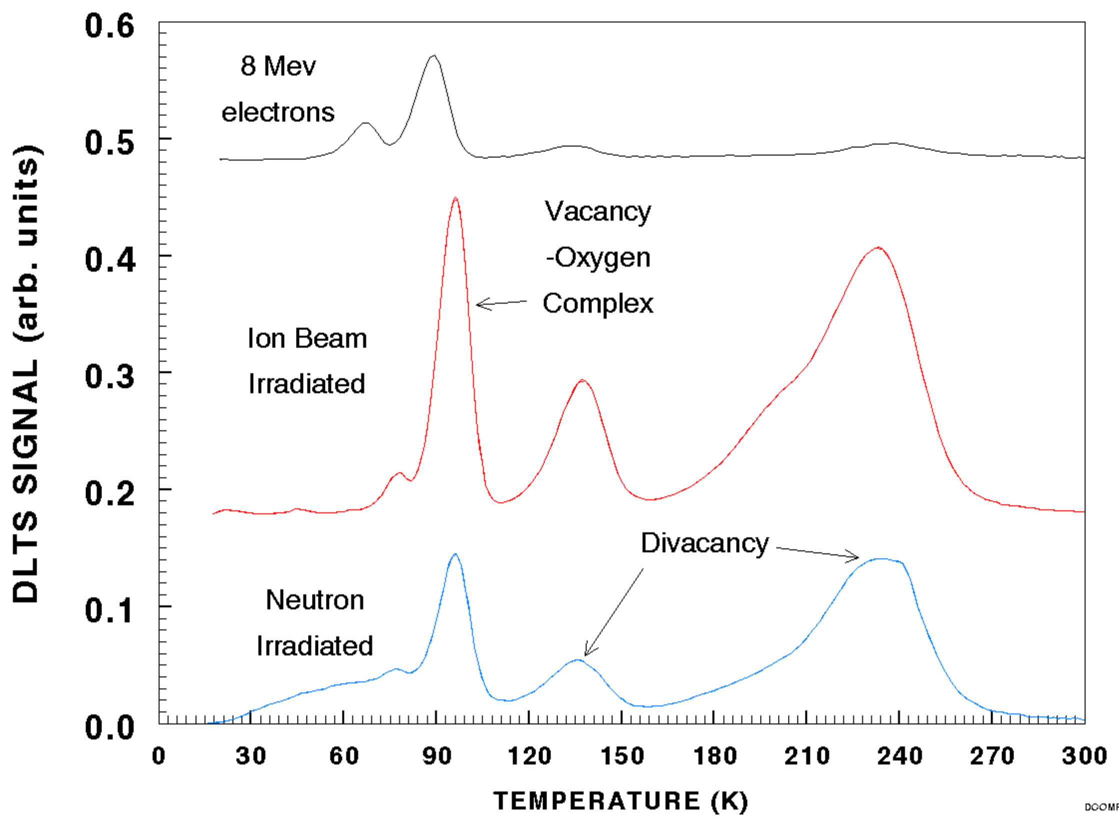
For a case where the Messenger-Spratt equation is valid the annealing factor is fluence independent

$$AF(t) = \frac{N(t)}{N_\infty}$$

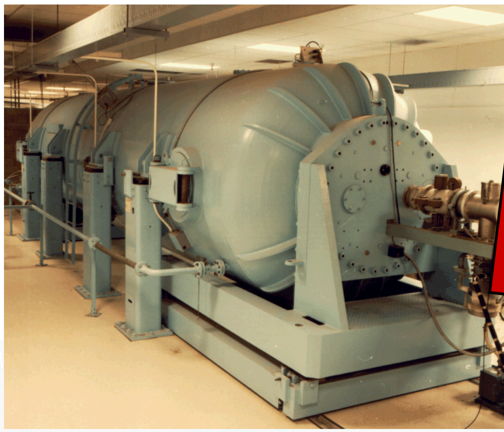


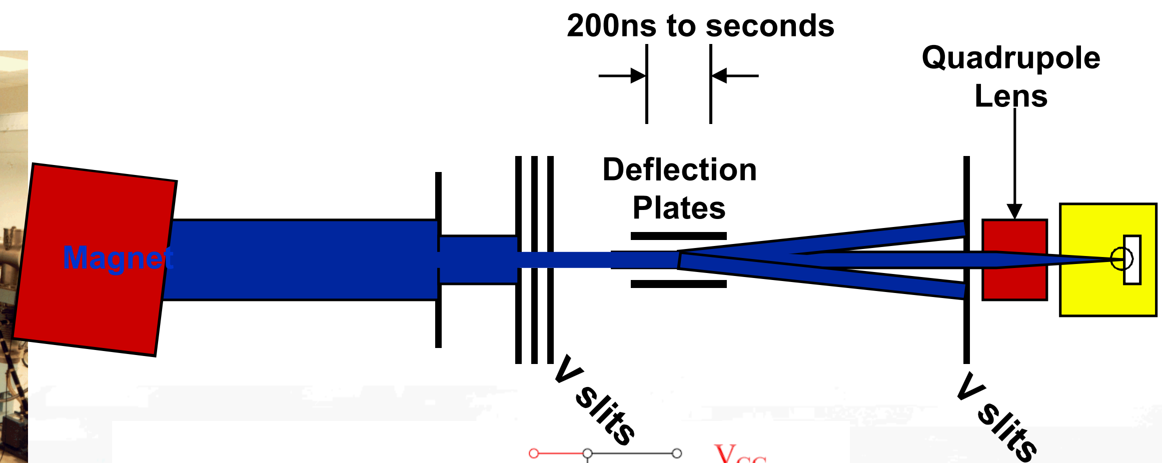
DLTS: number and types of defects

- DLTS measures the number of defects and their energy in the bandgap
- It can identify defects
- It is slow, cannot measure the transient
- It does not see traps in the built-in depletion depth
- Peaks are smeared in presence of electric field

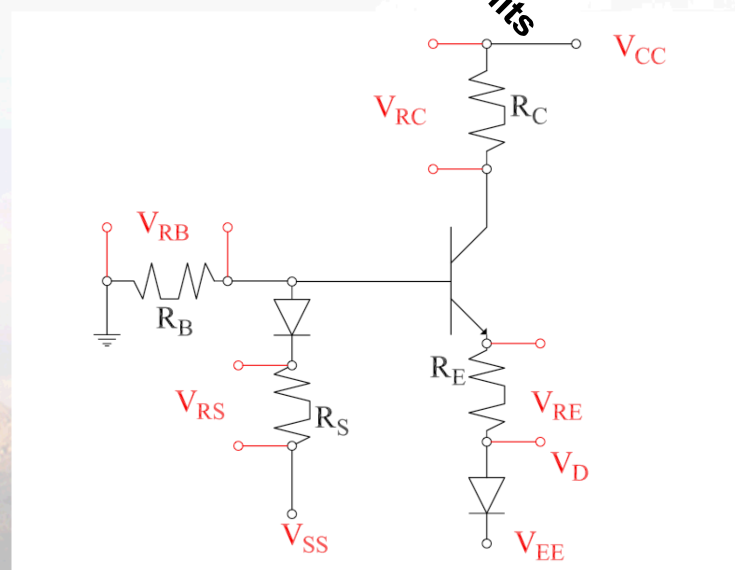


Ion beam irradiation





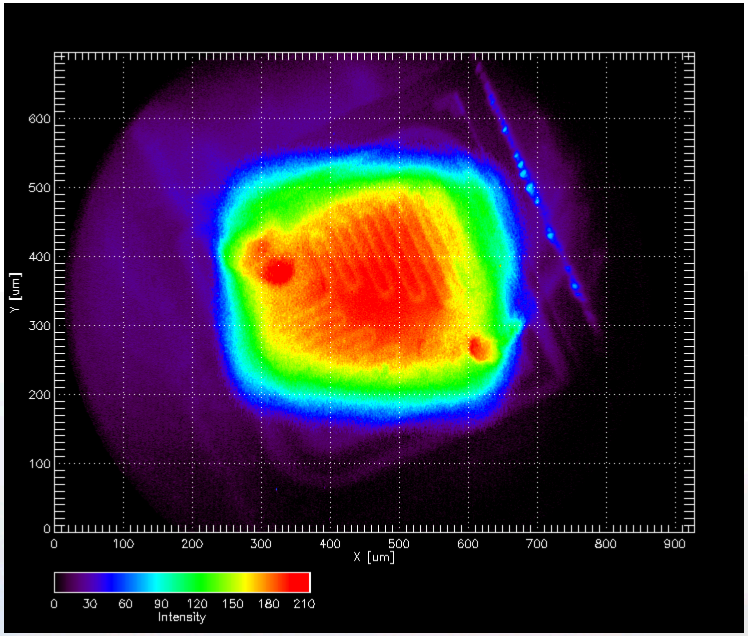
High intensity beams of high energy ions are focused into a micro-region on a sample to simulate neutron displacement damage conditions.

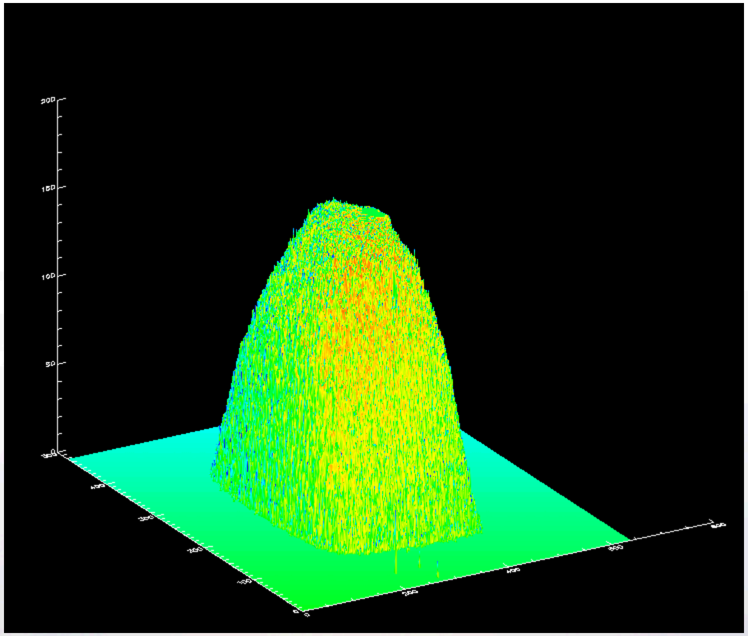


- Yokogawa DL750 oscilloscopes over the current viewing resistors
- fast –slow channels, high-low resolution channels

Beam diagnostics: area determination

Using ion luminescence on thin phosphors we can determine the beam area





Standard deviation over the beam area: 55 %
Standard deviation over the device: 18 %

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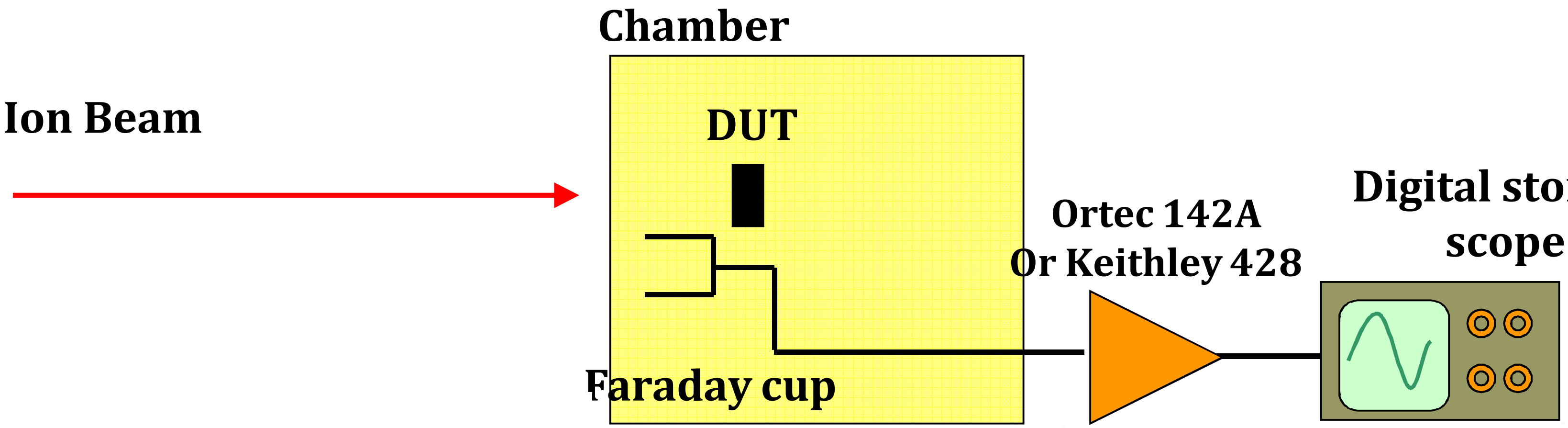
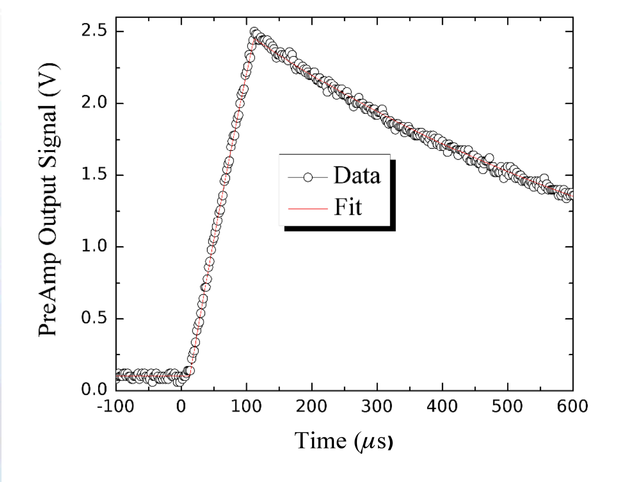
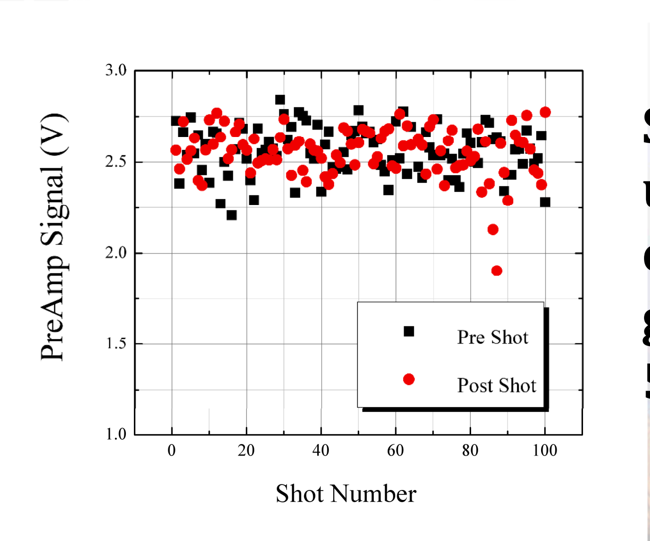
Beam diagnostics and fluence determination



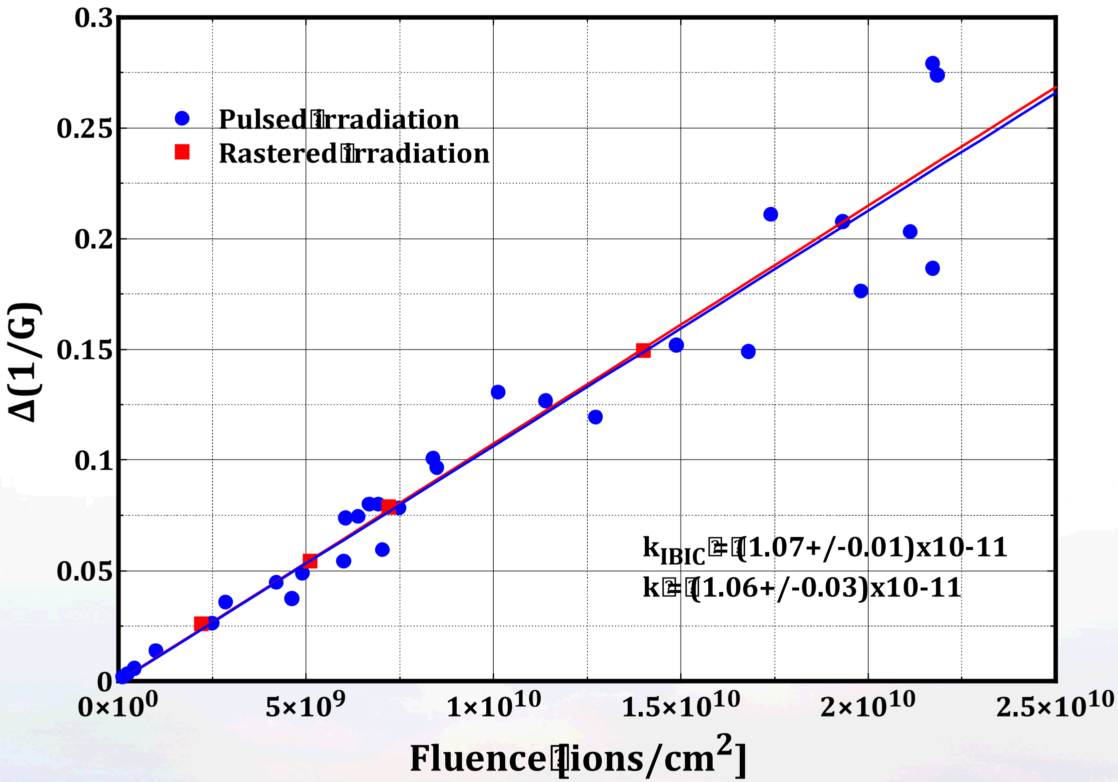




Statistical uncertainty of fluence, generally < 5%

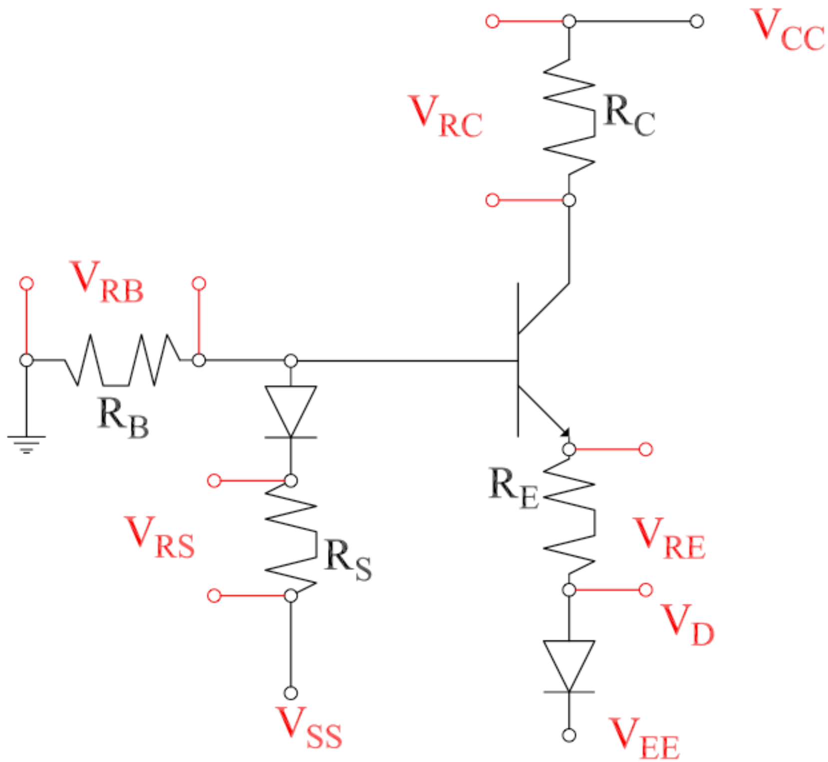
Fit gives pulse length and fluence

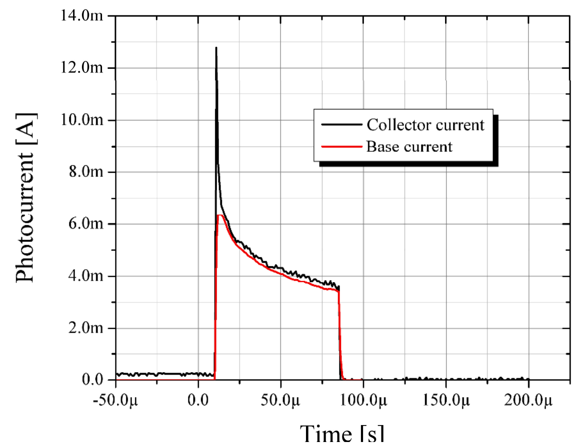
IBIC measurement confirms fluence calculations



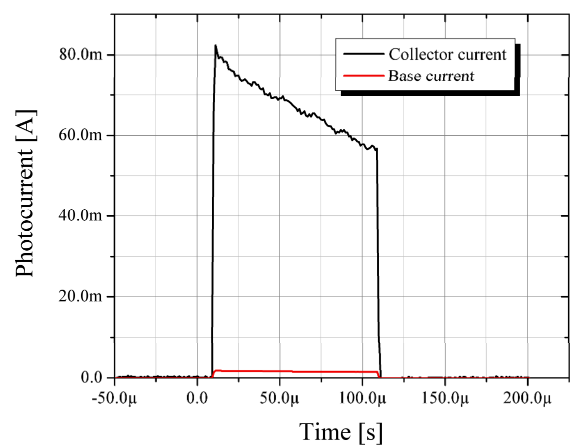
- Transistors were irradiated using a nuclear microprobe rastering a 36 MeV Si beam.
- Each ion hit was measured using the charge generated in the base-collector junction (IBIC).
- The fluence measurements using the two different methods are in excellent agreement.

Reducing the photocurrent effect on the measurement precision





10 MeV Si
Small photocurrent

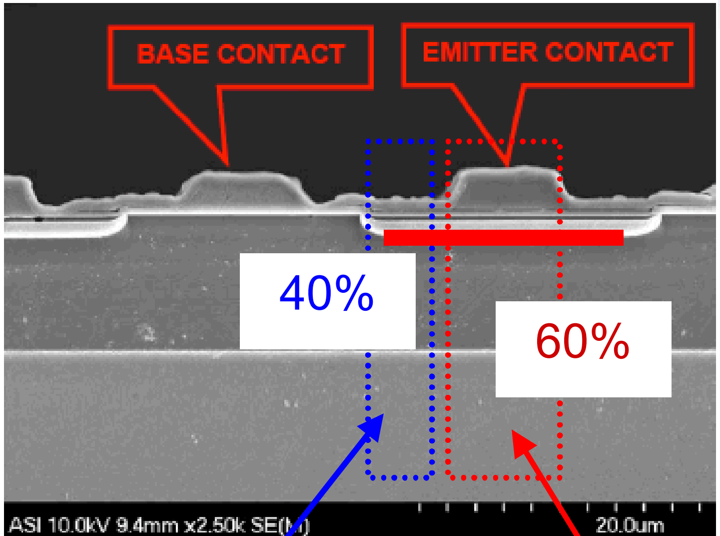


28 MeV Si
Large photocurrent

High precision measurement of the base current (large R_B), but base-collector junction kept reverse biased

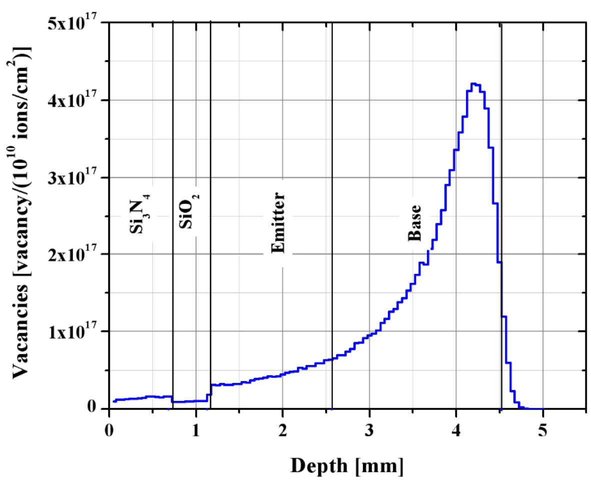
Calculating damage profiles in the actual device (using BCA codes)

Critical Region: Base-Emitter Junction for low emitter currents

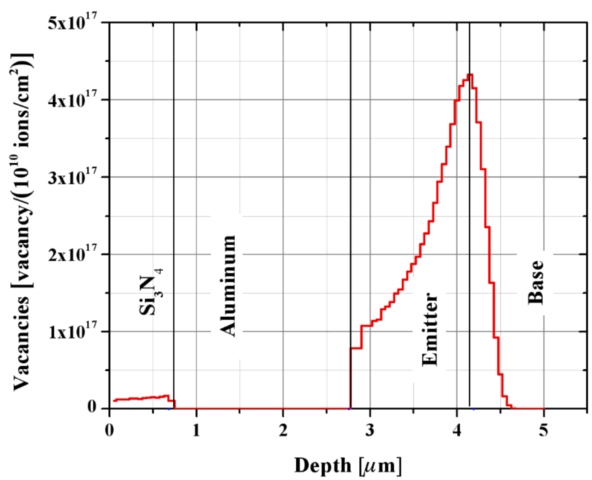


- Ions lose energy as they travel through the device
- Ion/energy combinations need to be tailored to specific device geometry

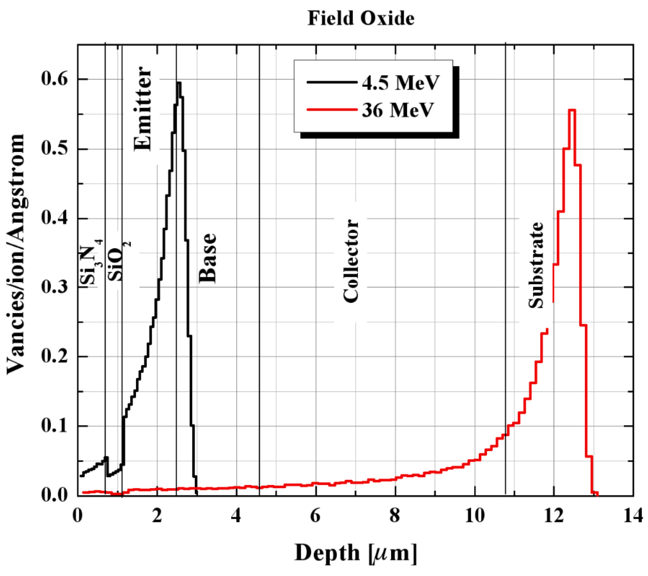
Field Oxide

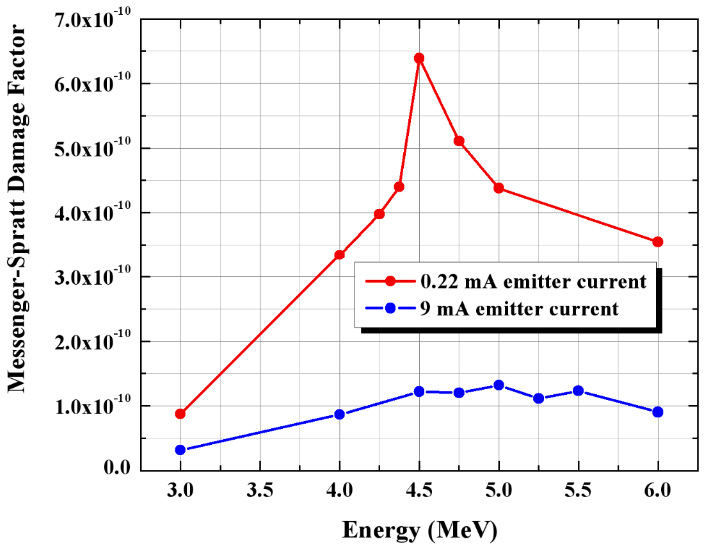


Emitter Contact



Picking the right ion beam energies





4.5 MeV - Maximum damage in base-emitter junction

36 MeV - uniform damage in the base

Energy scan proved that for low emitter currents the damage in the base-emitter junction effects the gain degradation while for higher emitter currents the neutral base plays a role, too.

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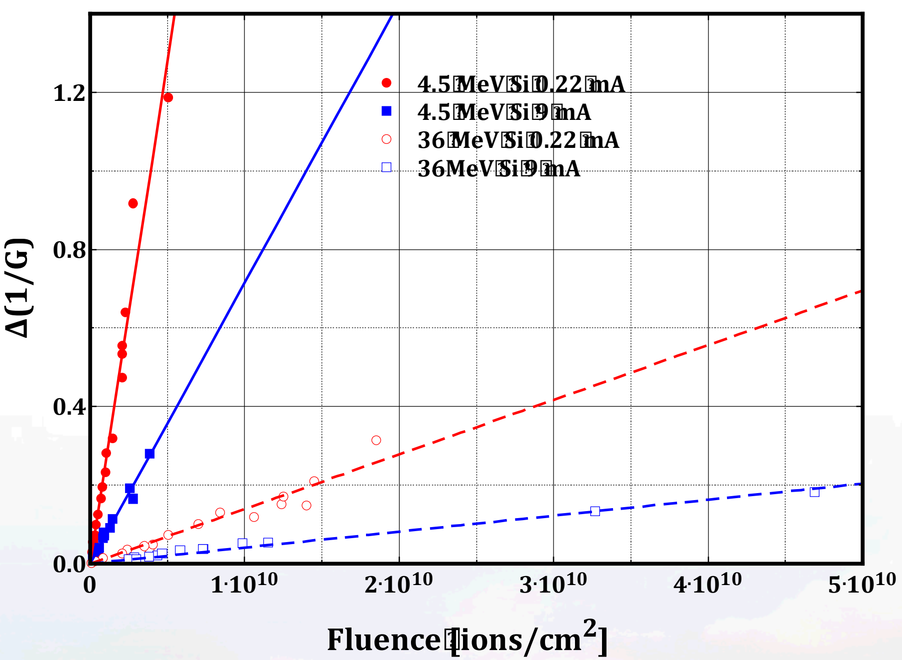
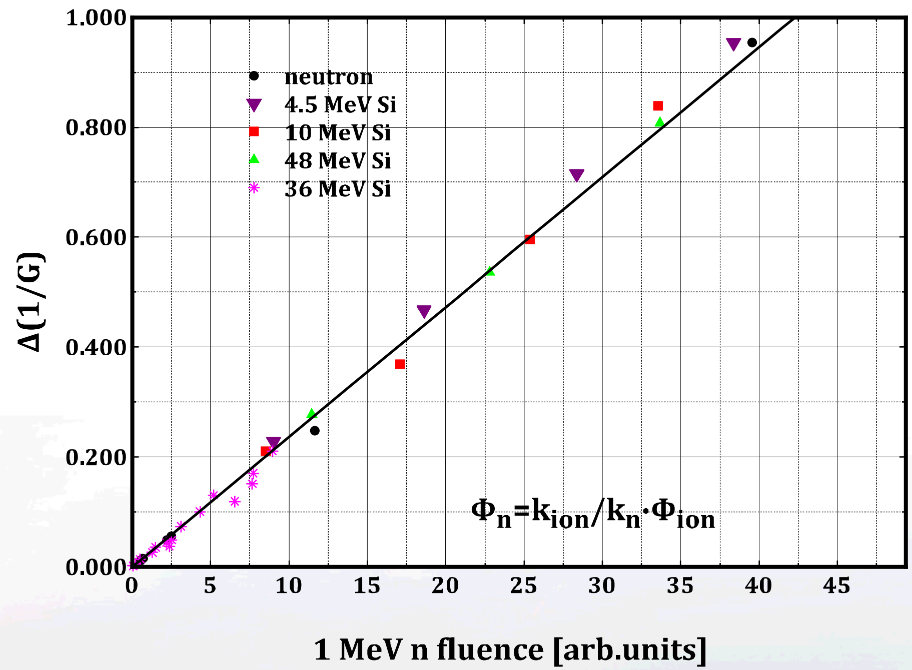
Messenger-Spratt curves and fluence scaling

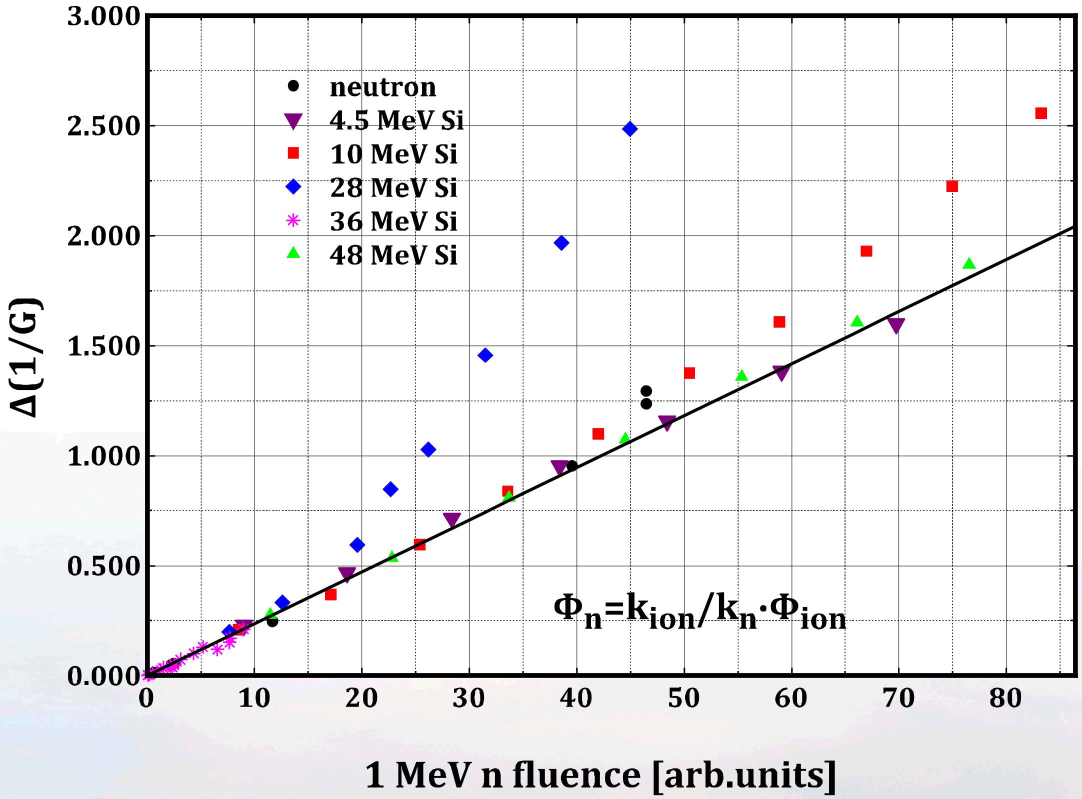




The damage factor depends on the device, emitter current, energy and type of ion.

At moderate damage levels the ion fluence can be simply scaled to 1 MeV neutron equivalent fluence.

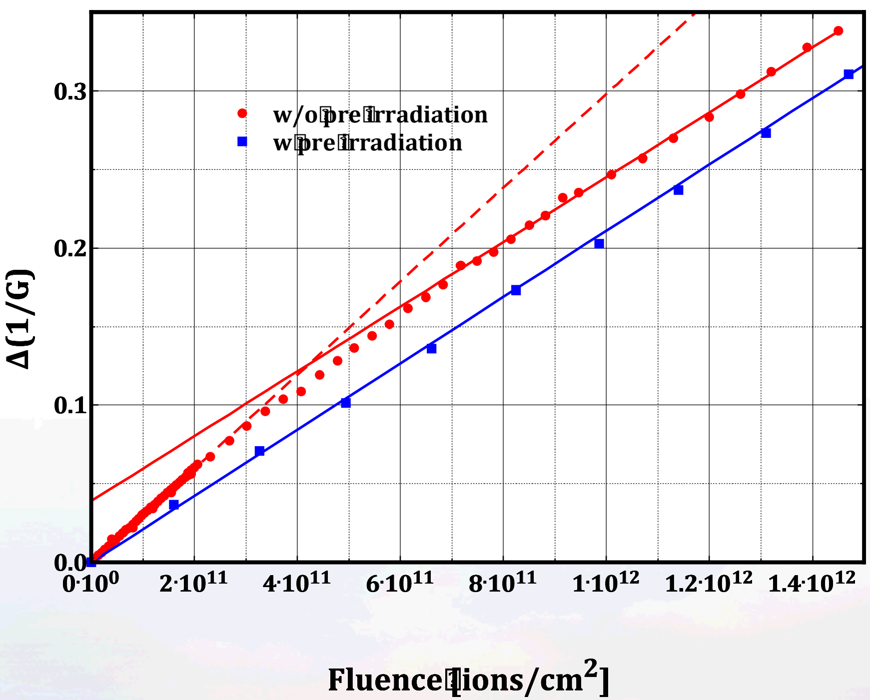
Deviation from MS relation: high damage

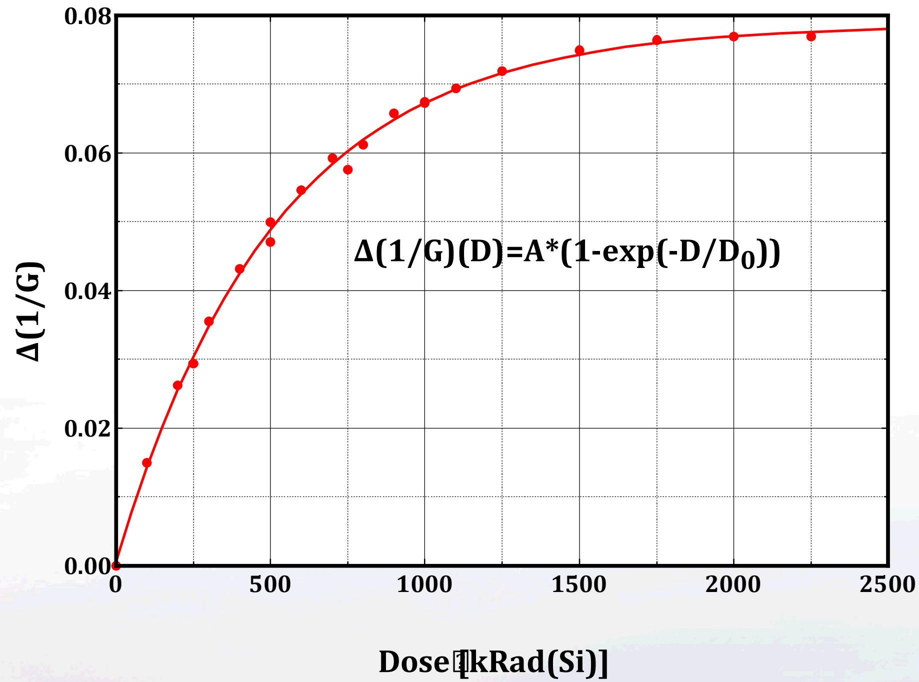


The inverse gain degradation becomes super linear at high fluences

- Compensation of the collector
- L_b reduced to less than width of base

High ionization to displacement damage ratio





$$\frac{1}{G}-\frac{1}{G_0}=k\cdot\Phi+\alpha\cdot\left(1-\exp(-\frac{\Phi}{\Phi_0})\right)$$

Irradiation by gamma-rays, pure ionization

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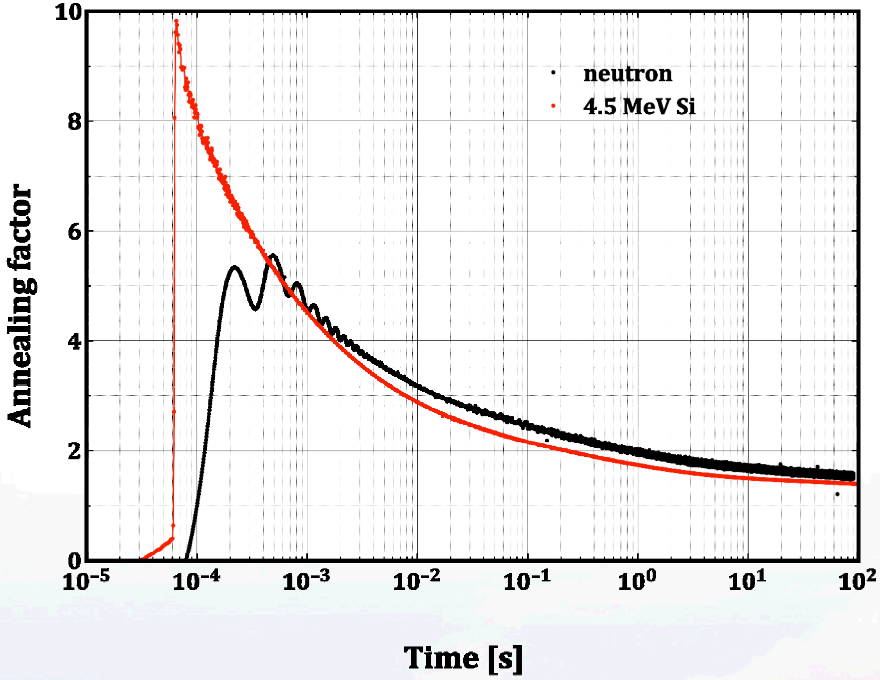
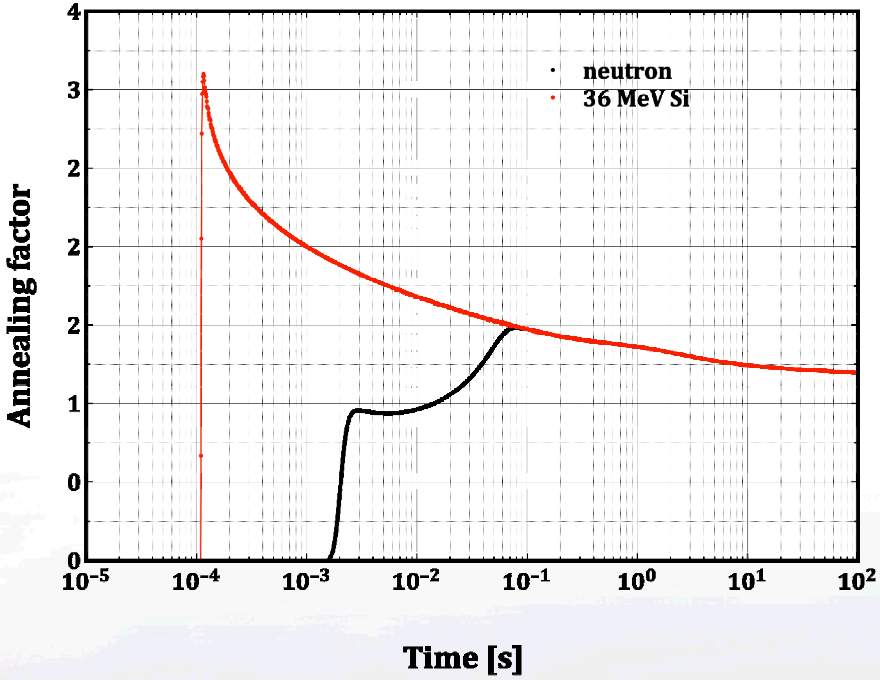
Matching the annealing factor



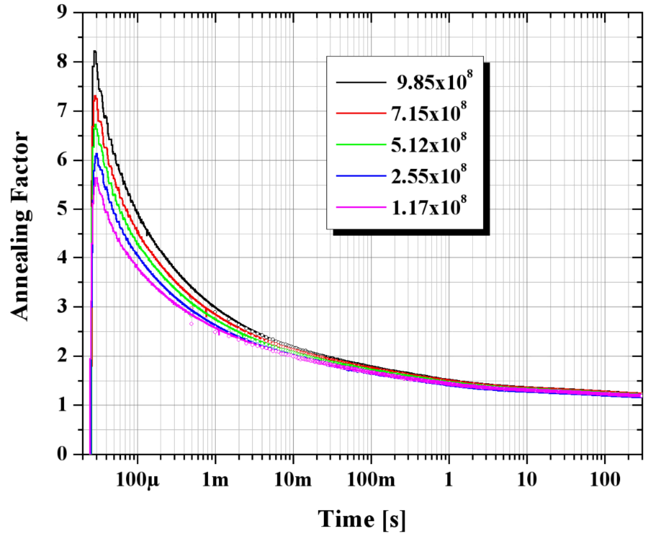


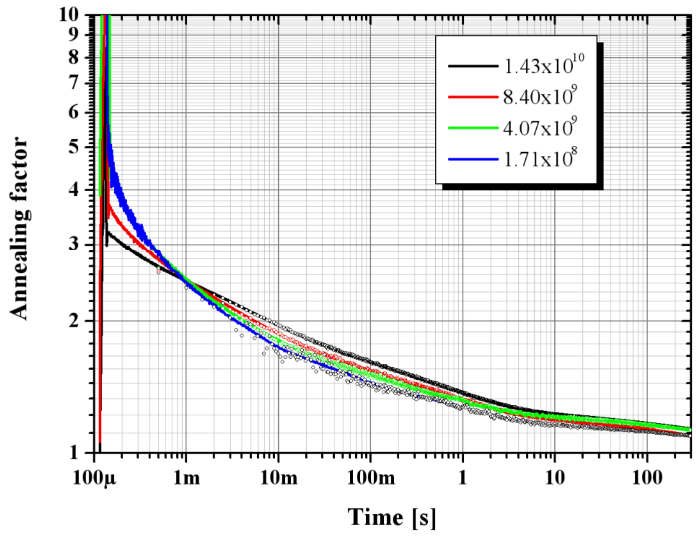
High fluence (damage), G_∞~1

Low fluence (damage), G_∞~20

Transistors with the same final gain were chosen. Late time gammas do not allow the AF measurement in the neutron environment for some time after the shot.

What does the annealing factor tell us? Ideally it should be fluence independent.





4.5 MeV Si fixed pulse length, I_e = 0.22 mA

- **AF changes monotonically increases with fluence**
- **Recombination current plays a significant role, changes V_{BE}**
- **Much less dependence for 9 mA**

36 MeV Si fixed pulse length, I_e = 0.22 mA

- **AF immediately after the shot decreases with fluence**
- **Large photocurrent causes significant annealing during the pulse.**

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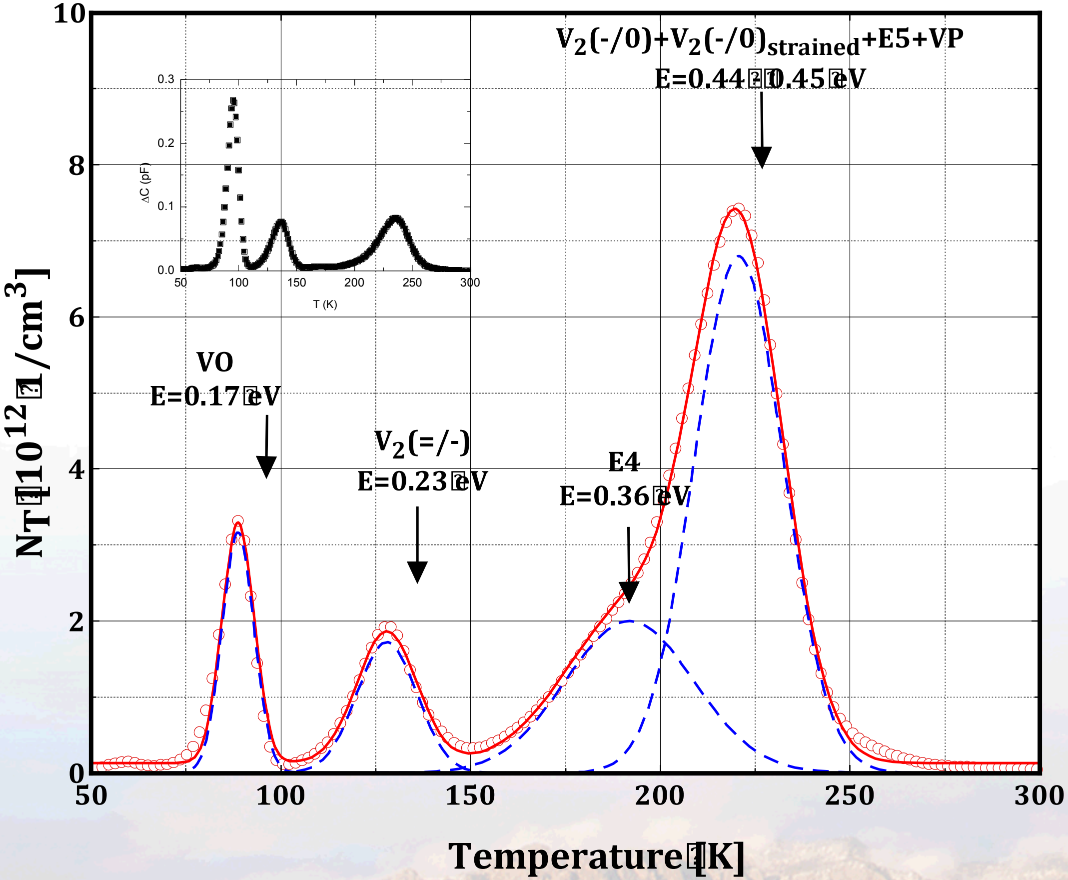
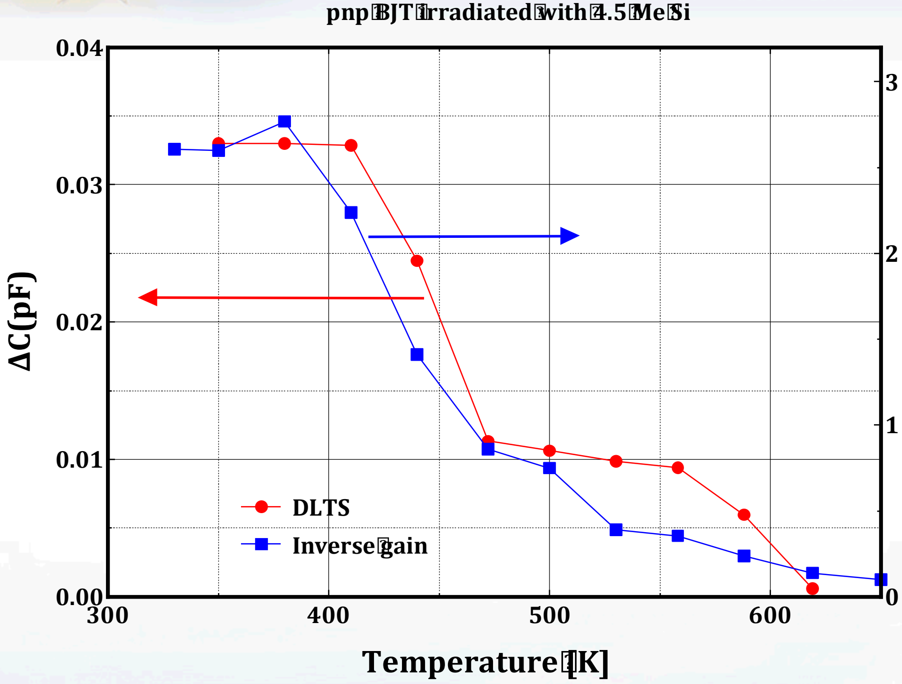
What kind of defects does the DLTS see in Si?

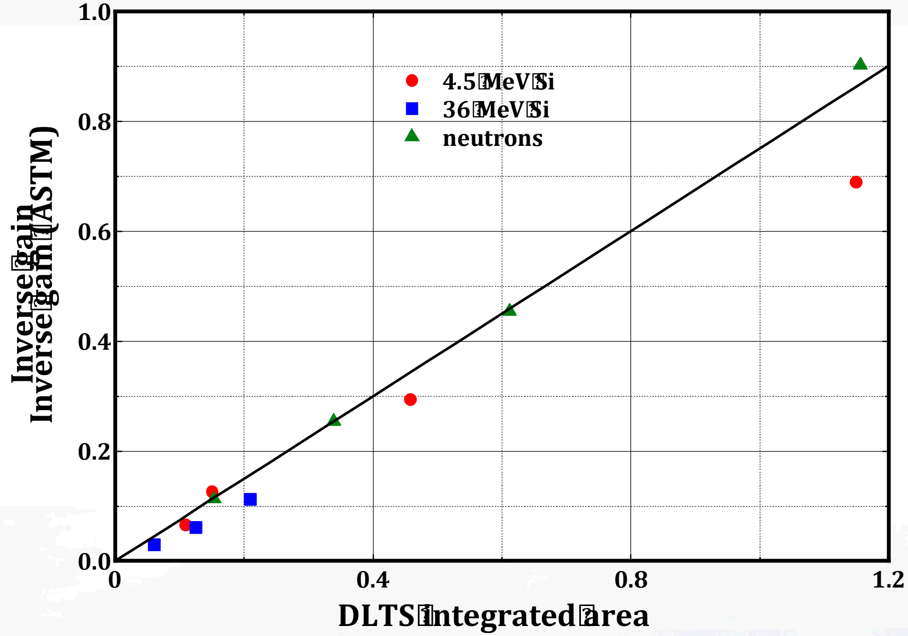


V2 peaks are not symmetric as for electron irradiation!

- 1-2 MeV e ⇒ point defects
- Neutrons, ions ⇒ clusters
  - Band bending (incomplete filling)
  - Strain
  - E4-E5 bi-stable defect
  - VP in higher doped samples

Does DLTS measure the defects that affect the gain of the transistors?





The DLTS peaks in the base of the pnp transistor anneal the same way as the inverse gain.

Inverse gain is linearly proportional to the DLTS signal independent of the particle type or energy.

Answer: YES!

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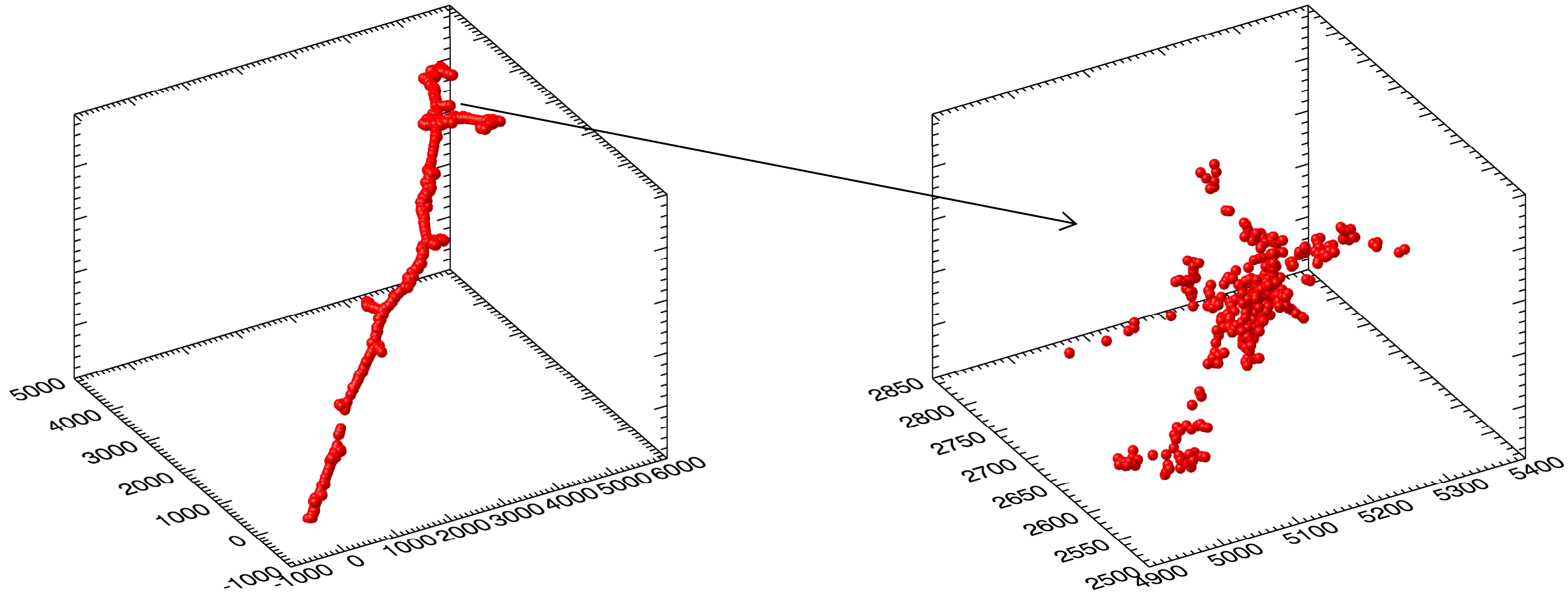
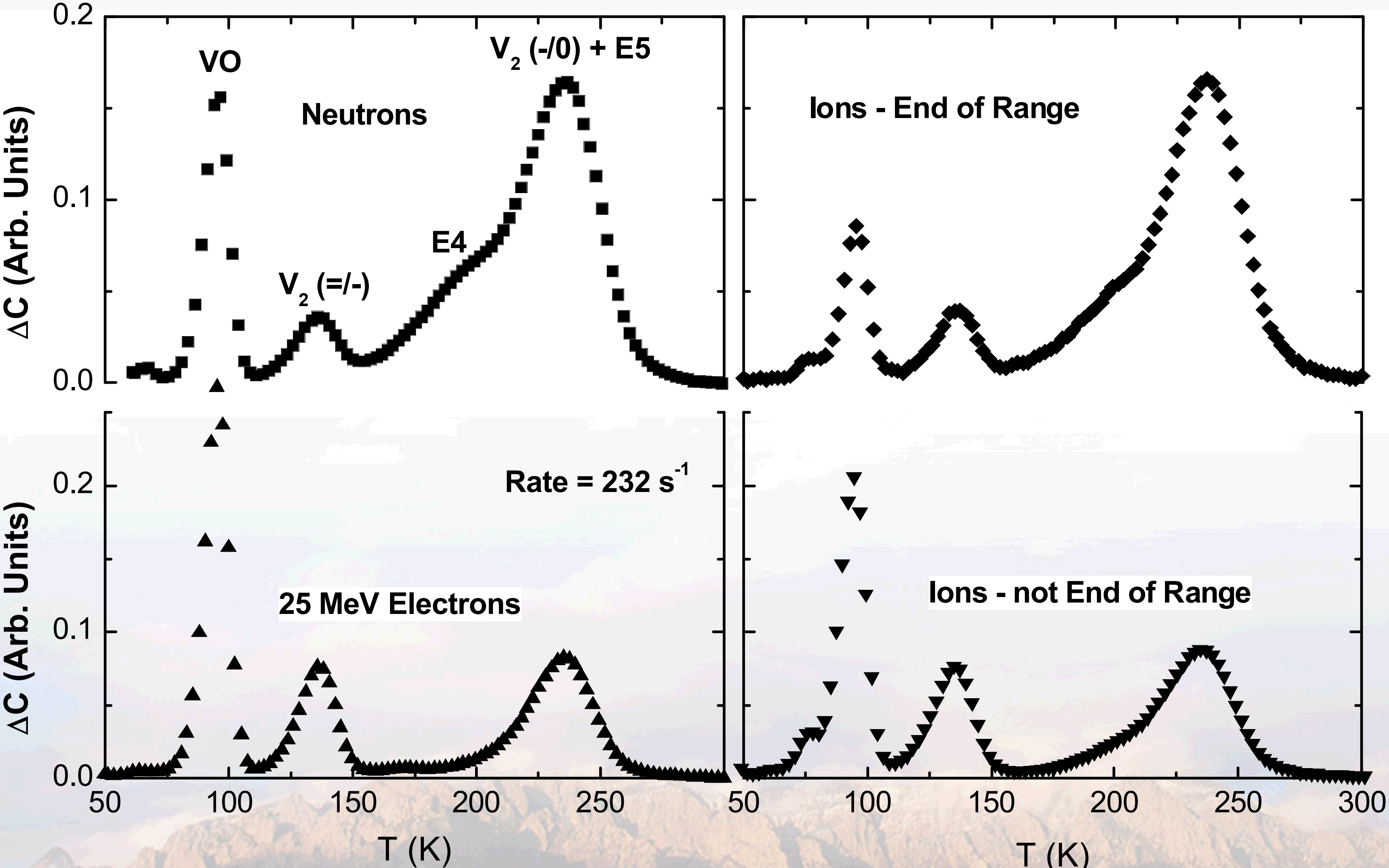
Clustering



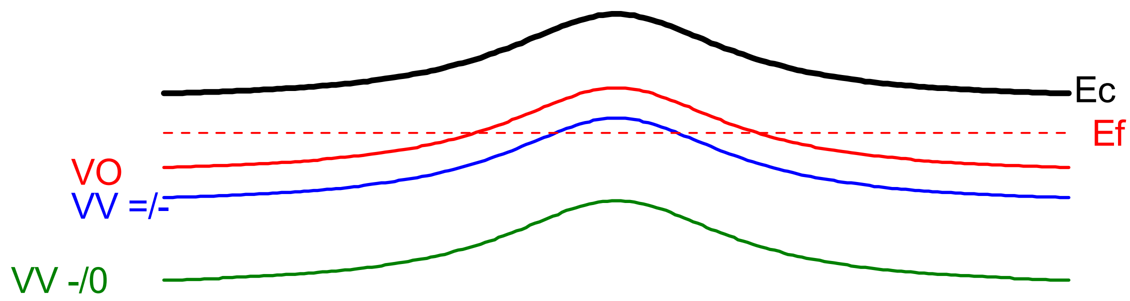
For heavy ion and neutron radiation vacancies are in clusters. These clusters can contain significant charge that can effect the electric field.

Electrons, neutrons, ions EOR and not EOR. Who is similar to whom?



Mechanisms producing a V_2 asymmetry

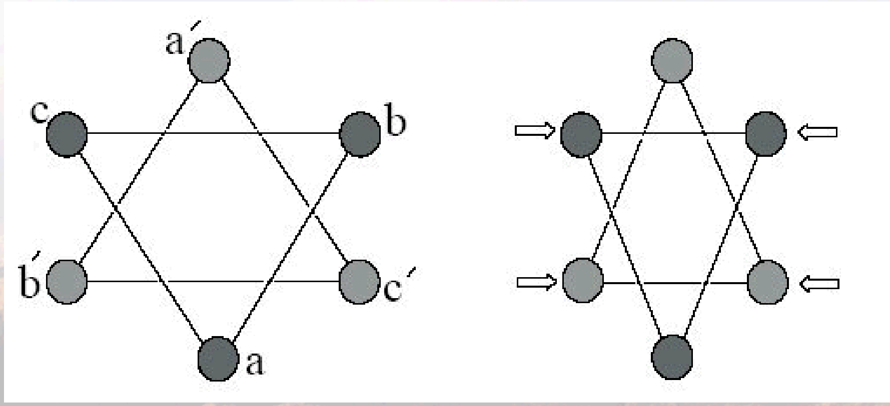
- **Partial filling of the shallow V_2 level because of clustered defects and local band bending.**



R. M. Fleming, C. H. Seager, D. V. Lang et al., J. Appl. Phys. **102**, 043711 (2007).

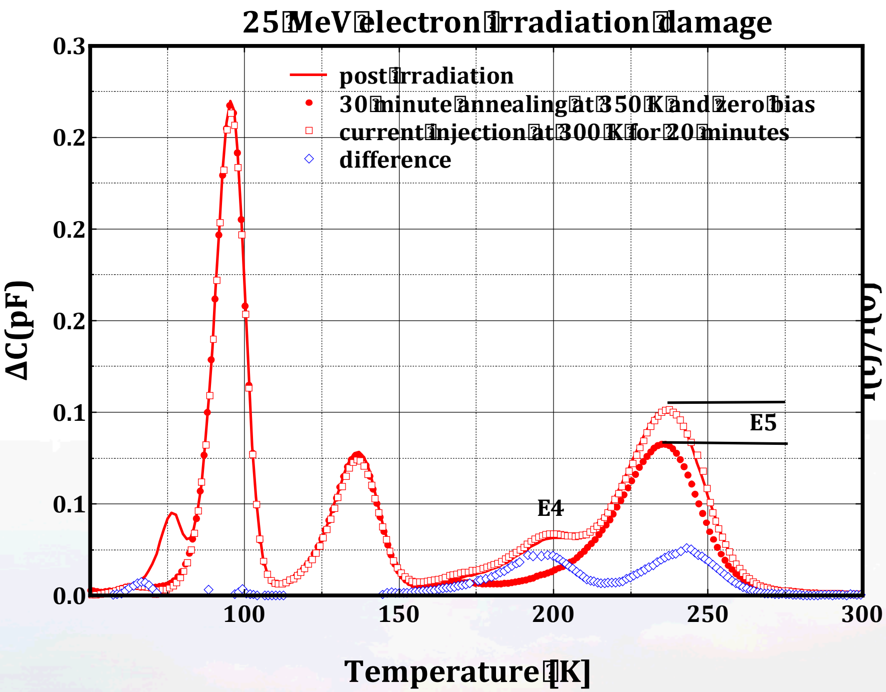
- **Strain-induced inhibition of bond averaging of Jahn-Teller distortion of V_2** **Svensson, et al., Phys. Rev. B 43, 2292 (1991)**

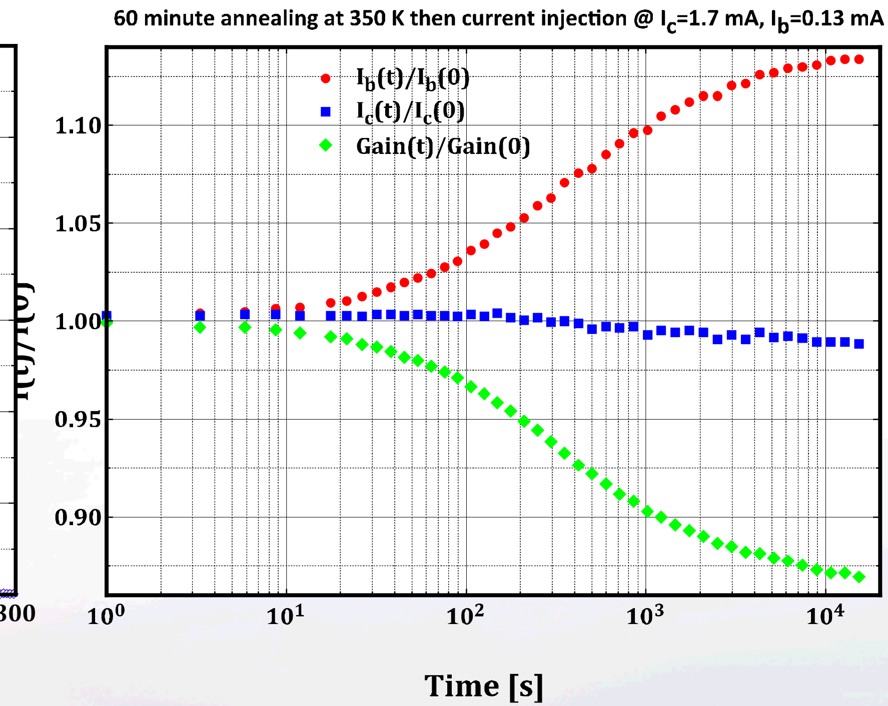
Undistorted
T > 20 K in c-Si
or $V_2^=$ charge state



JT Distorted
T < 20 K
or strained Si

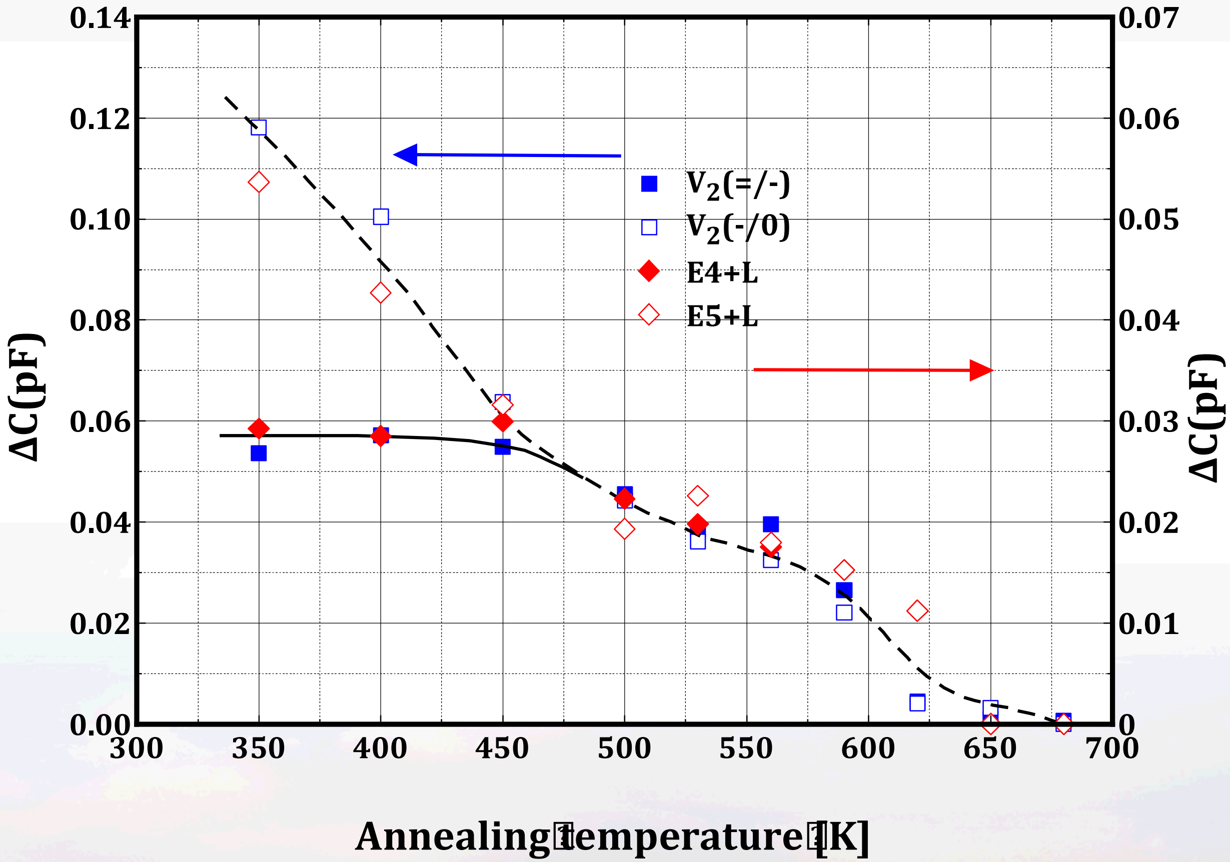
Gain and defect bi-stability





- Annealing 350 K (80oC) at zero or reverse bias removes E4 and E5.
- After injection of minority carriers to the base (forward bias) at 300 K E4 and E5 reappear.

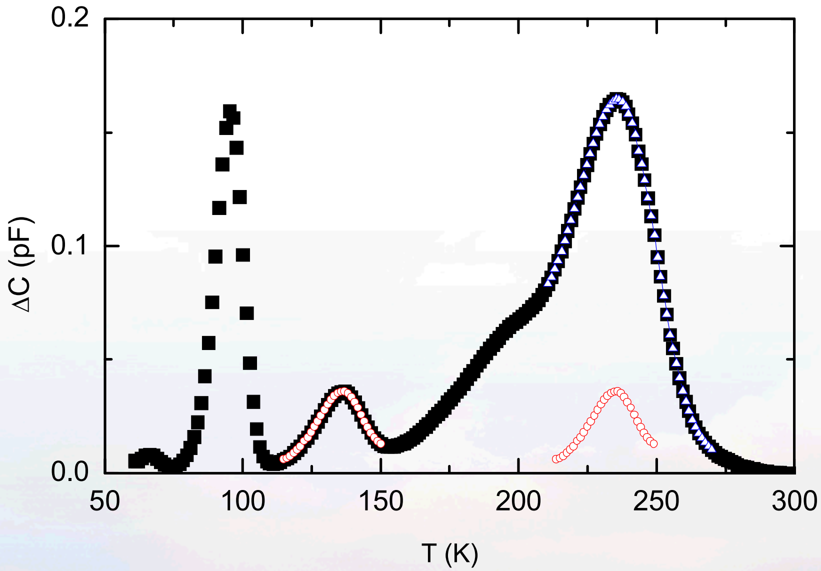
Annealing the bi-stable E4-E5 and V_2

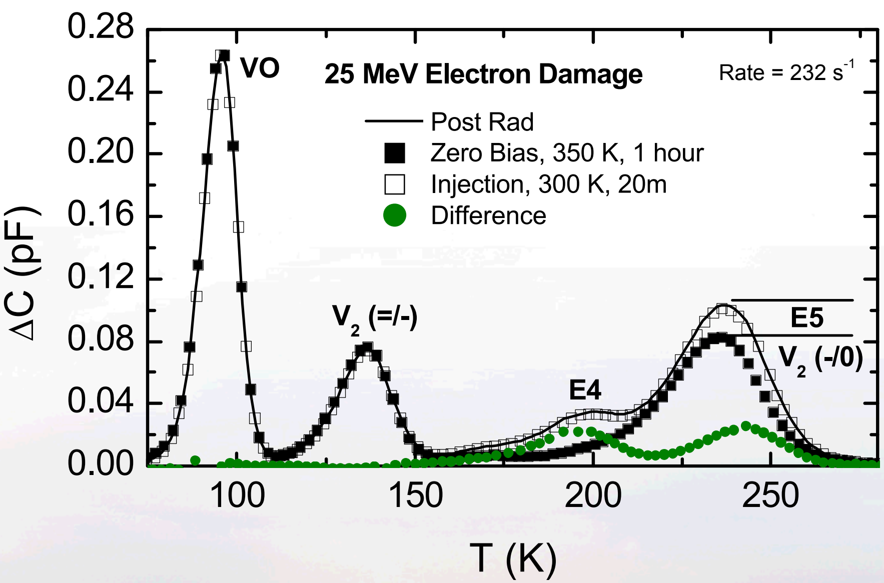


E4-E5 has the same annealing characteristics and asymmetry as the normal V_2 after clustered damage⇒E4-E5 is di-vacancy like.

There are three type of di-vacancy defects!

- Normal V2 - two equal acceptor levels
- Strained V2 - single acceptor level
- Bi-stable V2 - two bi-stable acceptor level





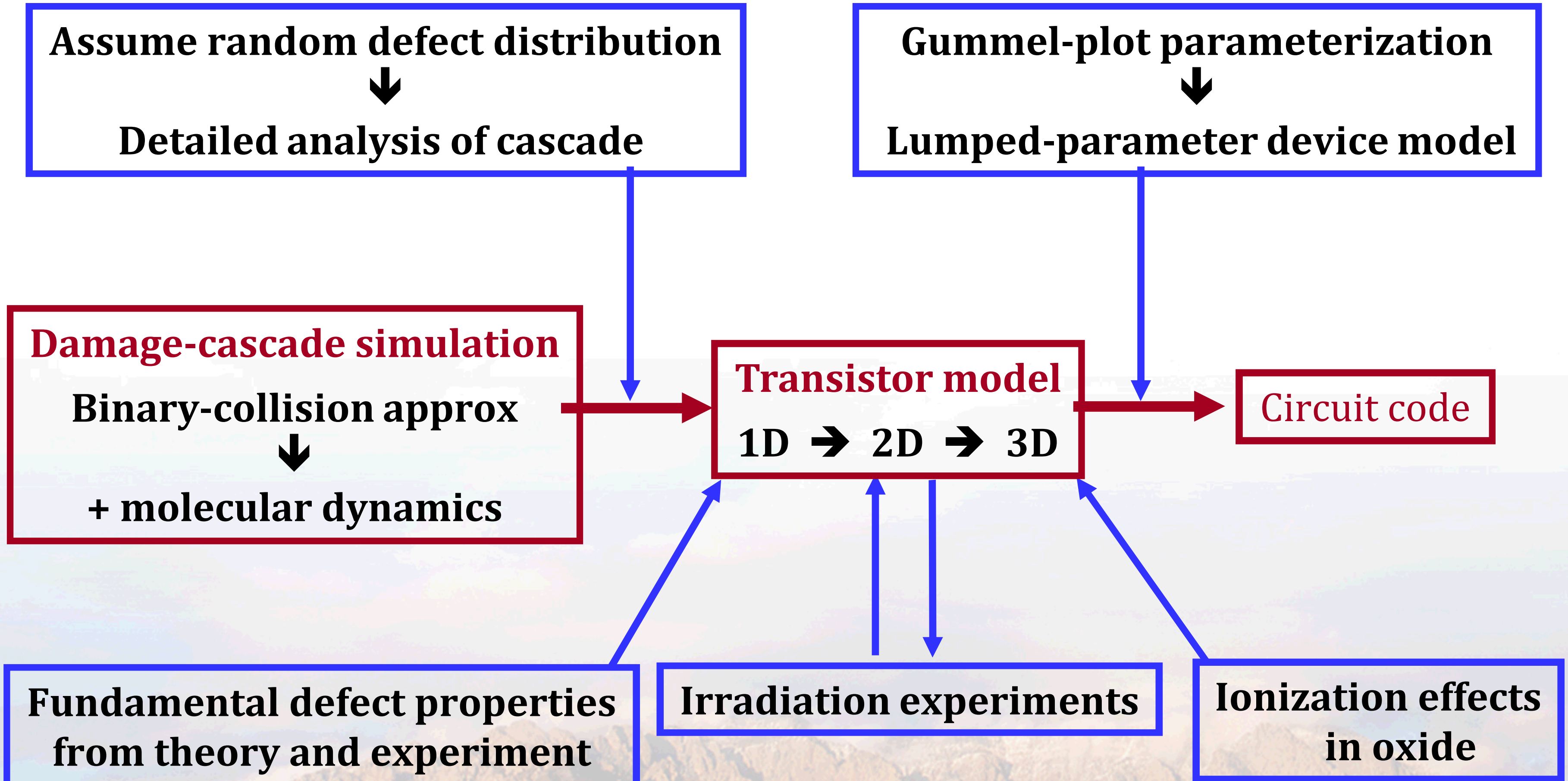
The deep level defects affect the transistor gain with the addition of VP in highly doped bases.

Modeling

- Ion-solid interaction: BCA codes such as MARLOWE, MD codes
- Defect levels and materials parameters:
  - DFT calculations
  - Measured parameters
- Defect evolution: drift-diffusion model
- Device operation: drift-diffusion model, TCAD
- Circuit operation: SPICE or similar codes

Generally, the models need validation or parameters adjusted to measurements.

Modeling overview



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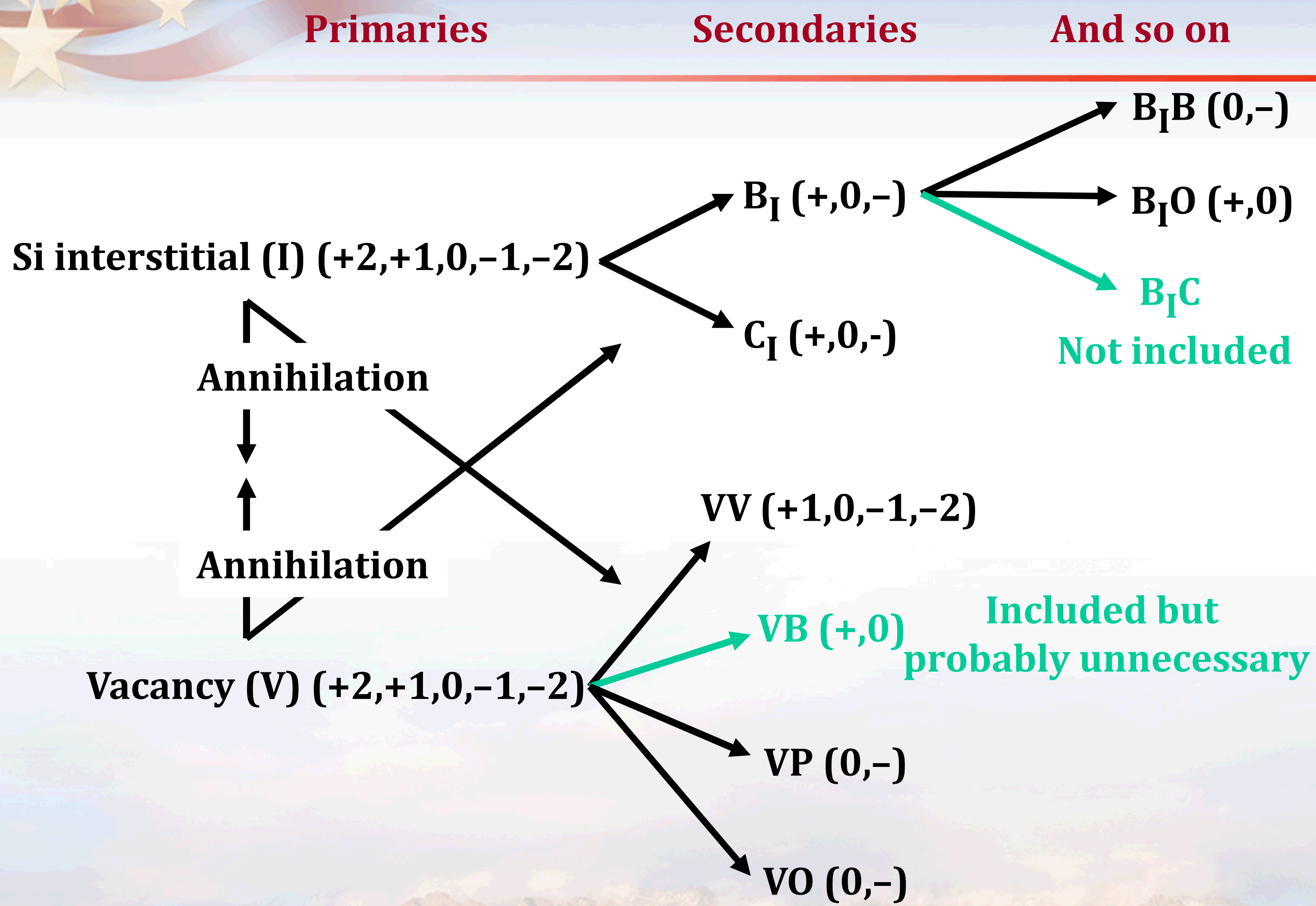
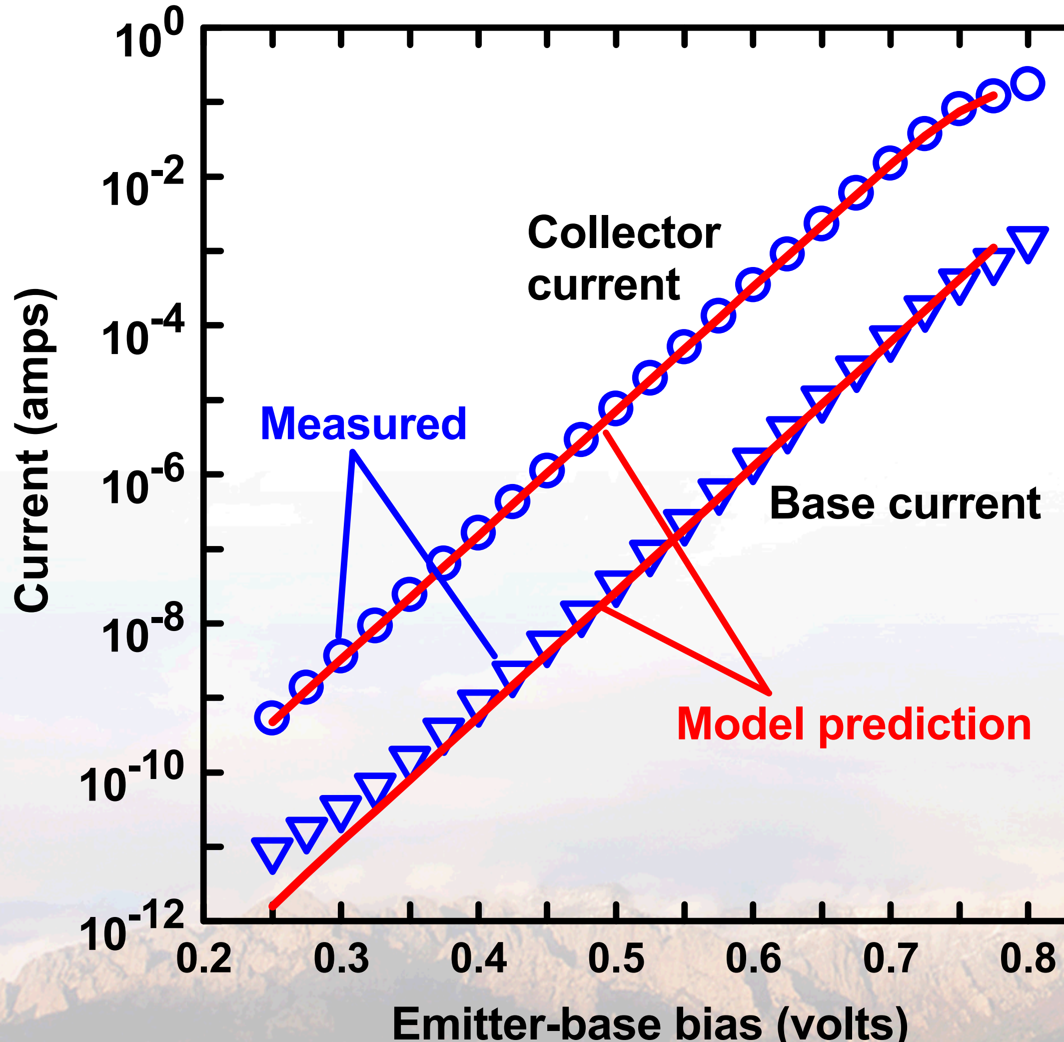
Defect evolution in the Si transistor



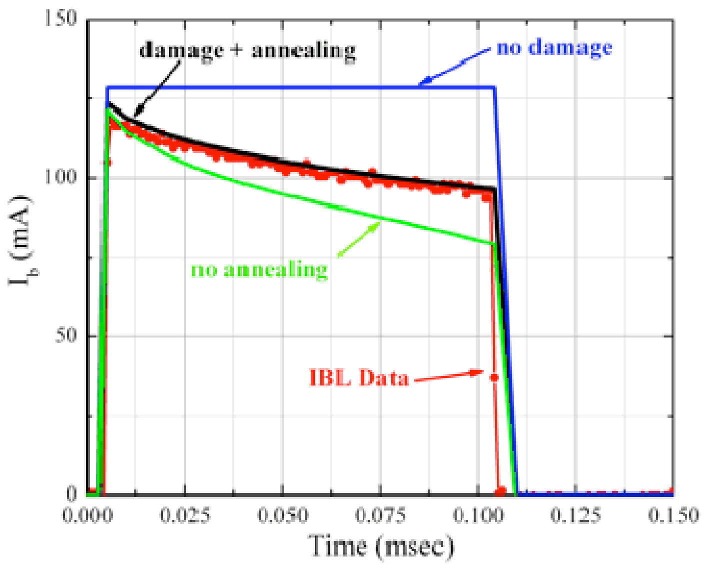
- The model describes diffusion, field-drift, and all reactions of the conduction electrons, holes, and irradiation defects.

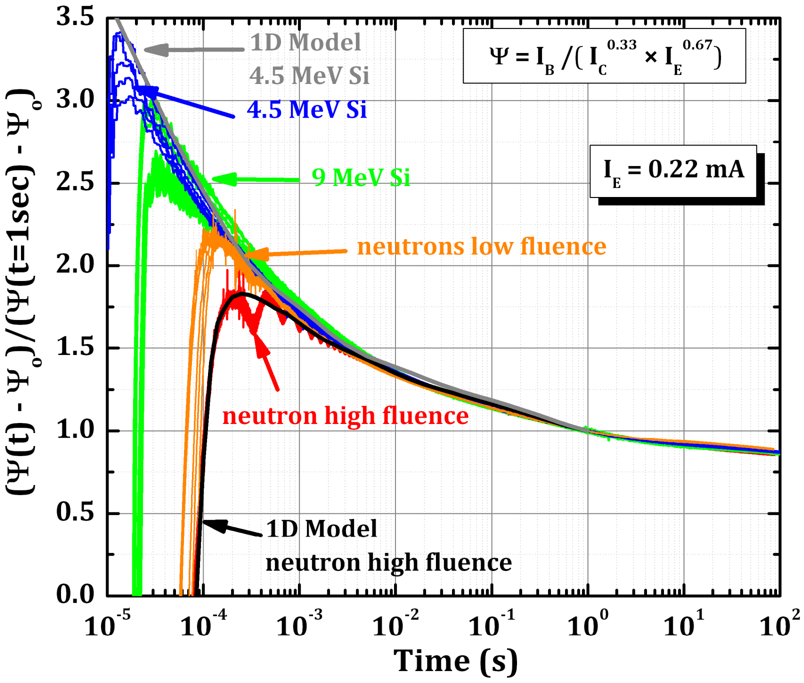
Finite-element model of NPN transistor without irradiation

No free parameters



Modeling the photocurrent and damage





Summary

- The effect of displacement damage on transistor gain was studied using various techniques.
- It was established that DLTS measures reasonably well the number of detects that effect the BJT gain.
- At moderate damage levels heavy ions produce the same defects as neutrons and the damage can be scaled to 1 MeV n fluence.
- A bi-stable di-vacancy like defect was identified that can be annealed out at 350 K, but after current injection it will reappear.
- Modeling efforts using the combination of BCA, DFT, and drift-diffusion model could predict photocurrent and gain degradation.

Modeling displacement damage and its effects on the gain in Si BJTs is a success story!

III-V (GaAs): Work in progress (complications)

- DLTS spectrum is complicated (U and L band)
- Shape changes with fluence (band narrowing)
- Problem matching shape
- Injection annealing dominated
- Large effect of clusters
- Cluster distribution is not known, BCA and MD calculations need to be validated
- PL is promising to be another technique for establishing damage equivalency