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Comparison of displacement damage due to ion and neutron beam irradiations in silicon bipolar junction transistors

G. Vizkelethy, E. Bielejec, R.M. Fleming, D.B. King, and B.L. Doyle

Sandia National Laboratories, Albuquerque, NM, USA

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National Nuclear Security Administration

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Outline

- Motivation
- Basics of a BJT and the effect of neutron irradiation on it
- Metrics for damage equivalence
- Experiments
- Results
- Conclusion

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are needed to see this picture.

Motivation

- Neutron irradiation damages electronic devices
- One of Sandia's missions is to qualify electronic devices for various radiation environments including neutrons
- Testing in the past: Fast Burst Reactors (FBRs) such as Sandia's SPR-III
- We are searching for alternative ways to compare effects of different radiation conditions

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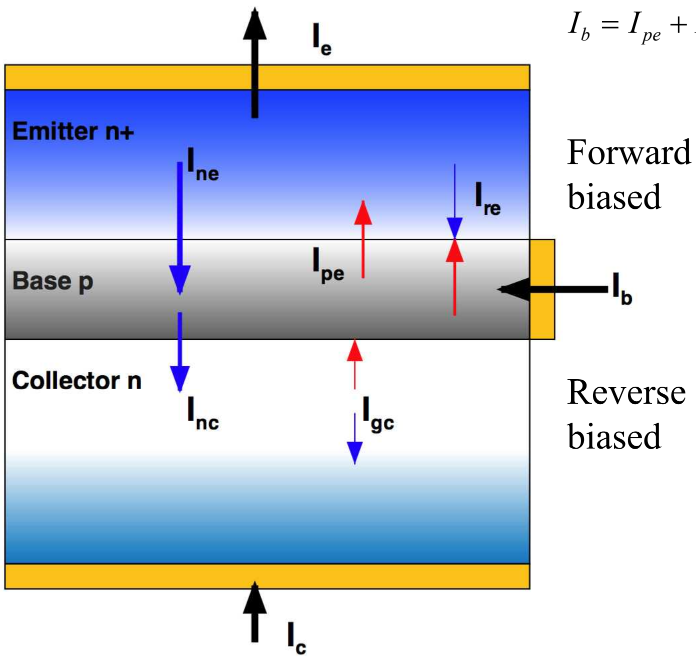
Basics of a BJT and effect of neutron irradiation

Constant emitter current configuration



Damaged

$$I_e = I_{ne} + I_{pe} + I_{re}$$
$$I_c = I_{nc} + I_{gc}$$
$$I_b = I_{pe} + I_{re} - I_{gc} + (I_{ne} - I_{nc})$$

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

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

Common emitter gain $G = \dfrac{I_c}{I_b} = \dfrac{\eta \cdot \alpha_T}{1 - \eta \cdot \alpha_T} : \dfrac{W_b^2}{L_b^2}$

Neutron 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

Metrics for damage equivalence: Late time gain

For moderate damage after infinite long time

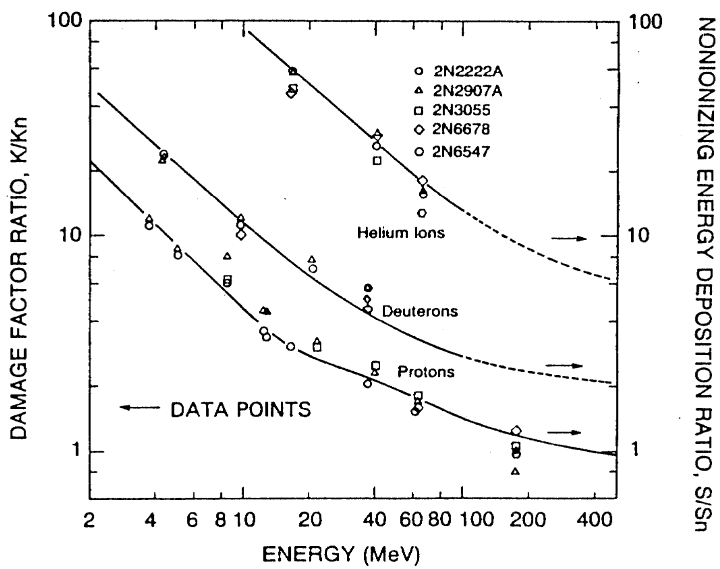
$$\frac{1}{G} : \frac{1}{L_B^2} = \frac{1}{D_B \cdot \tau} \qquad \frac{1}{\tau}(t) = \frac{1}{\tau_0} + A \cdot N_t(t)$$

Since the life time is inversely proportional to the number of defect and the number of defect is linearly proportional to the neutron fluence

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

*Messenger-Spratt equation

Damage factor is proportional to NIEL independent what particle creates the damage



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

*G. C. Messenger and M. S. Ash, *The Effects of Radiation on Electronic Systems*. (Van Nostrand Reinhold, New York, 1986).

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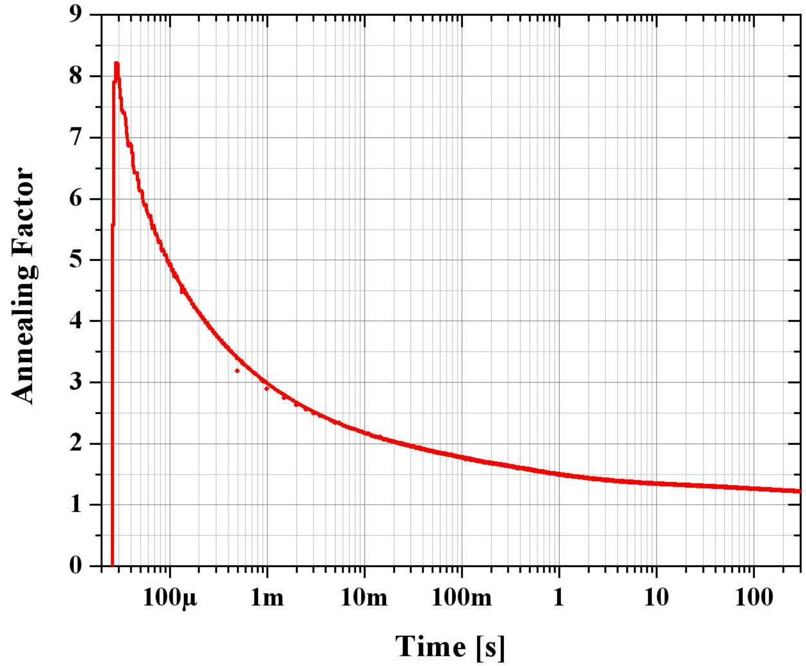
Metrics for damage equivalency: Annealing factor

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

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



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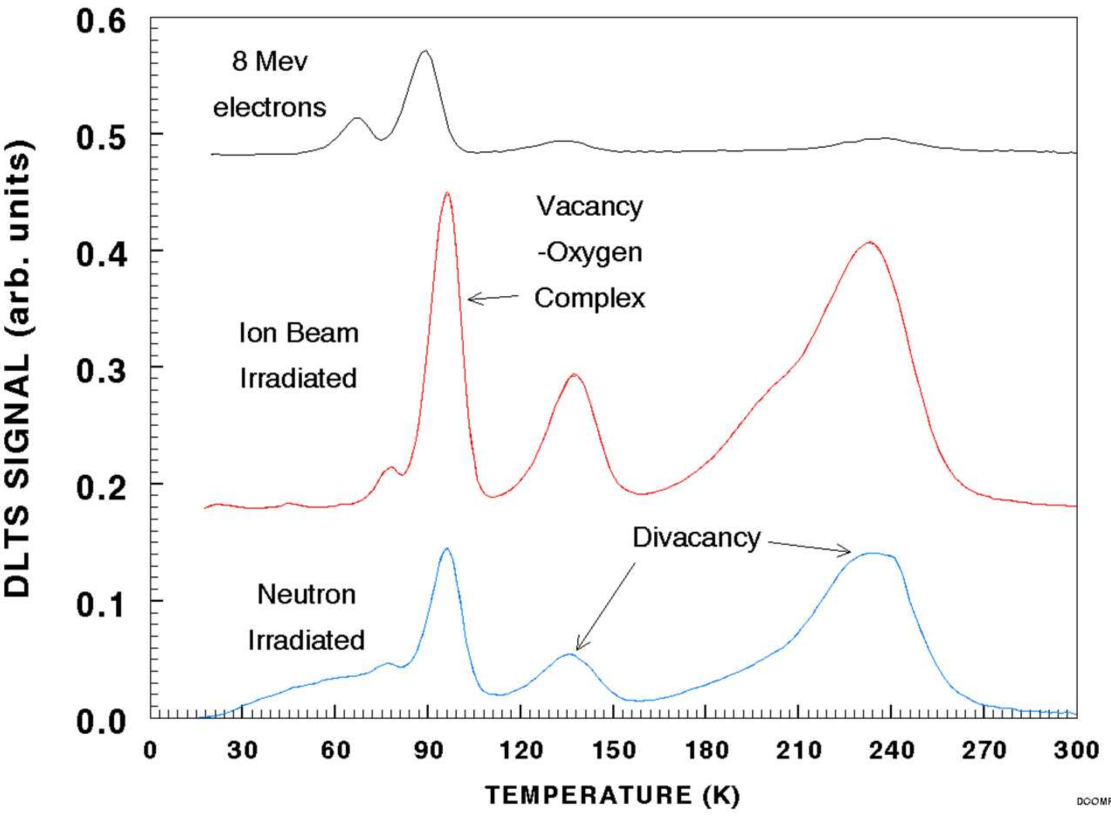
Metrics for damage equivalency: DLTS, number of defects

- **DLTS measures the number of defects and their energy in the bandgap**
- **It can identify defects**
- **It is slow, cannot measure the transient**



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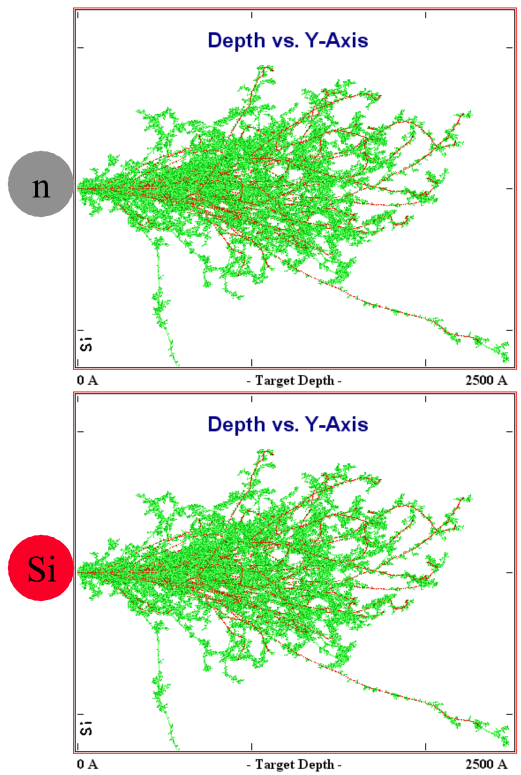
Ions create displacement damage like neutrons

Gain degradation in BJTs is due to displacement damage created by silicon atoms knocked out by neutrons in the base-emitter junction.



Instead of a neutron generating a cascade we can use directly Si ions.

- Easily can be changed on a wide scale:
  - Ion fluence
  - Pulse length
- No radiation safety concerns

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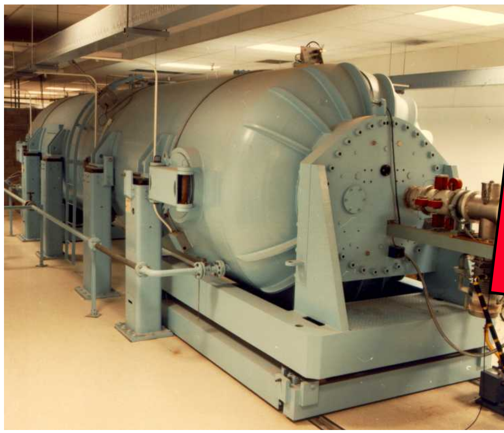
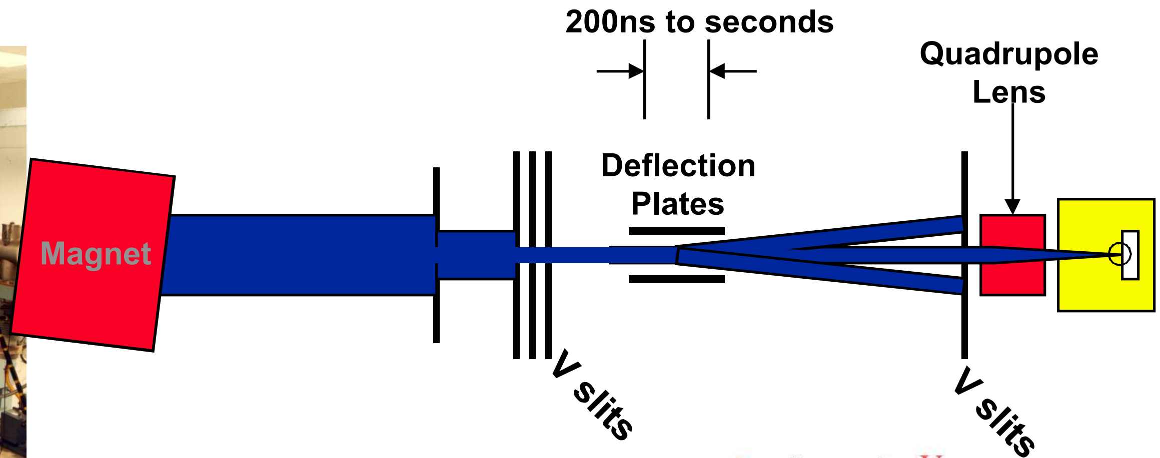
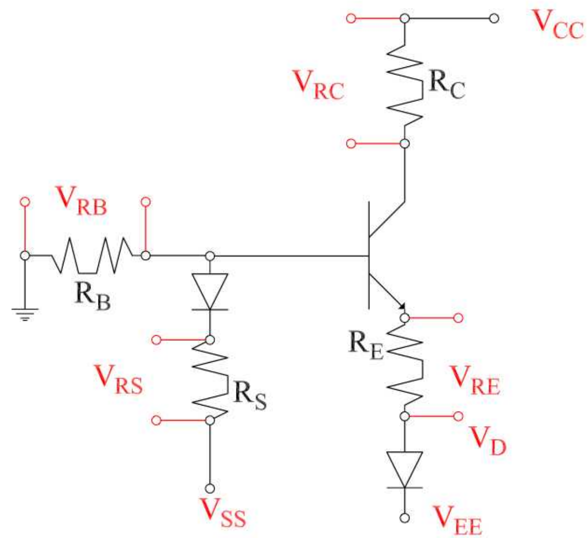
Ion beam experiments





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



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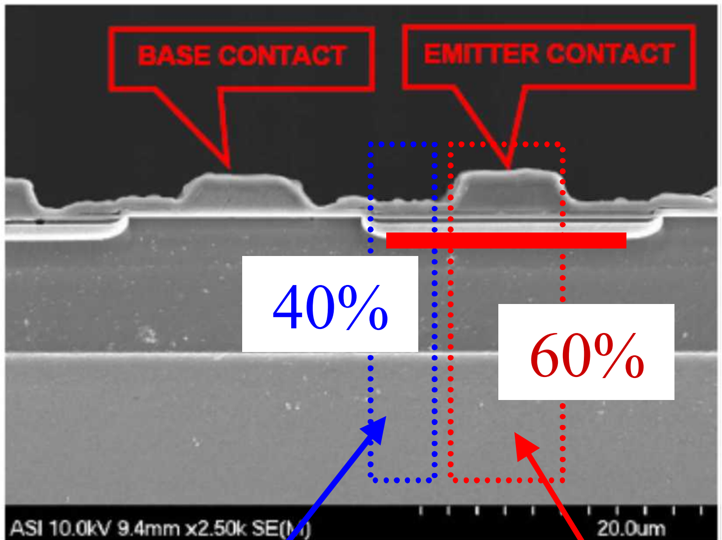
Microsemi 2n2222 BJT used in the experiment

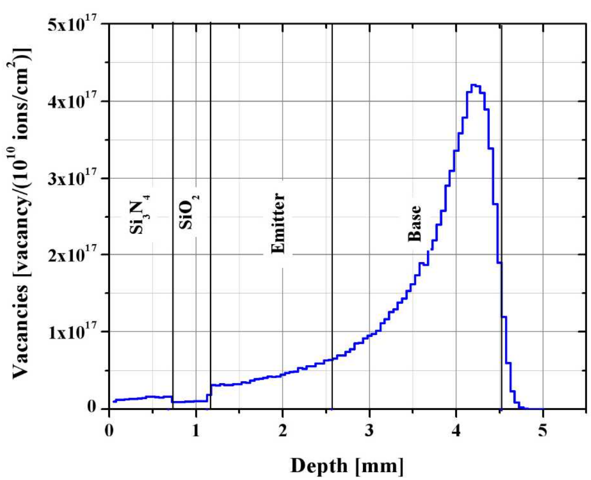
Critical Region: Base-Emitter Junction for low emitter currents

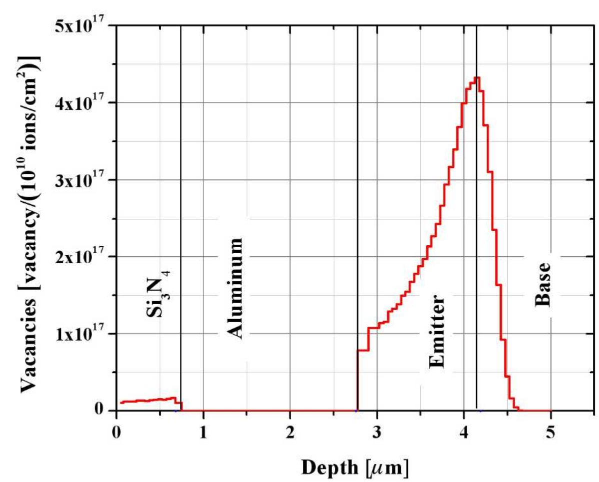


- **Ions lose energy as they travel through the device**
- **Ion/energy combinations need to be tailored to specific device geometry**

Field Oxide

Emitter Contact





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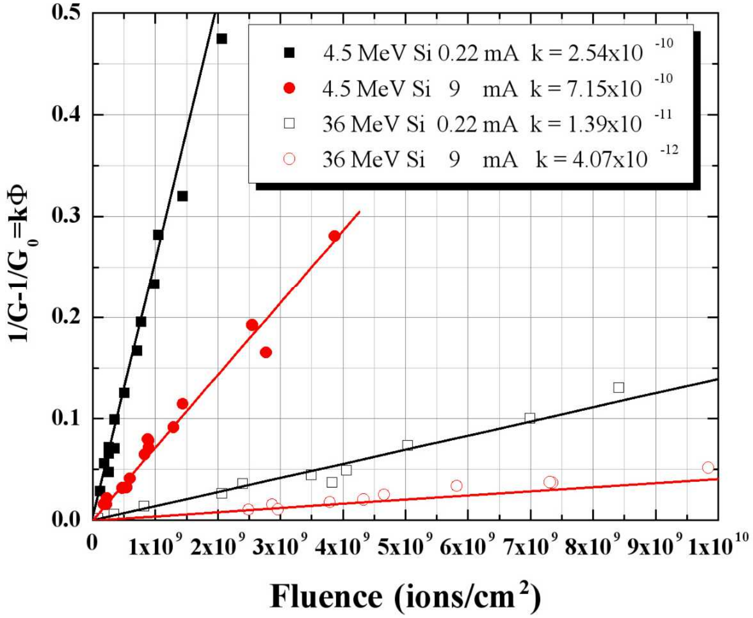
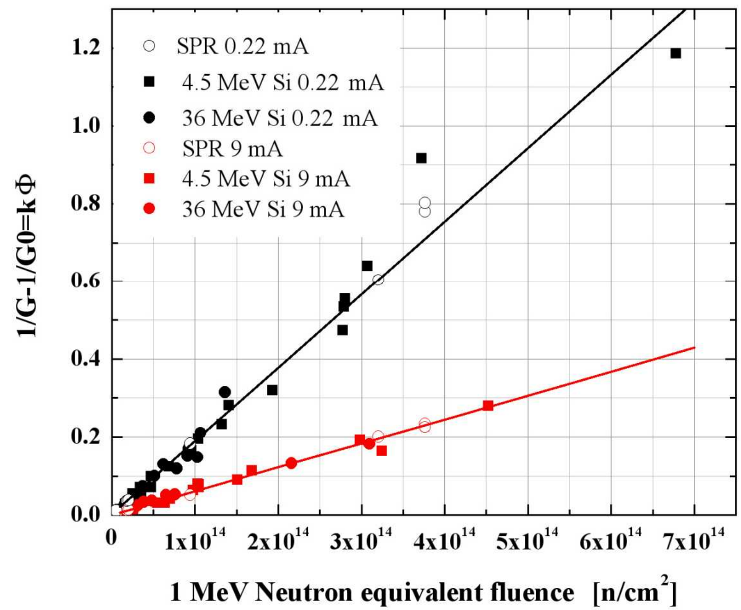
Messenger-Spratt relation





The inverse gain dependence follows the Messenger-Spratt equation for a wide range of fluences.

$$\Phi_n = \frac{k_{ion}}{k_n}\Phi_{ion}$$

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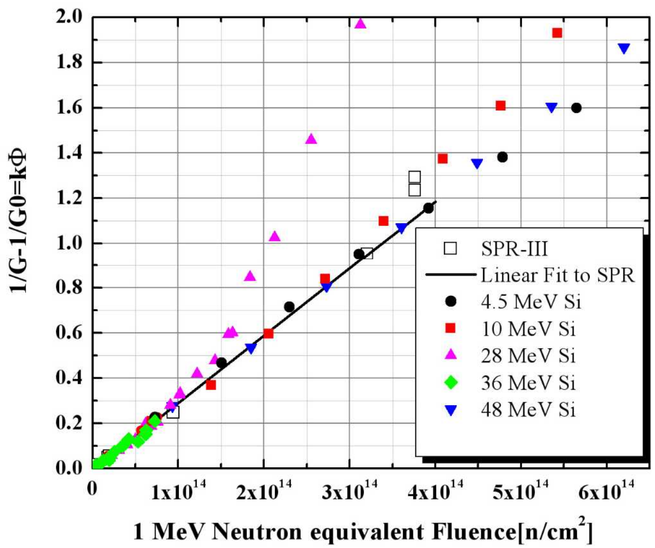
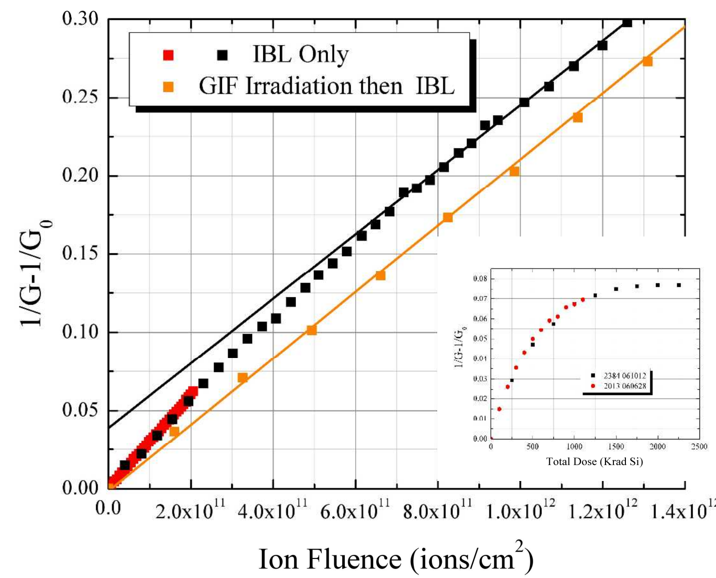
Deviation from the Messenger-Spratt relation



12 MeV He



The inverse gain degradation becomes super linear at high fluences

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

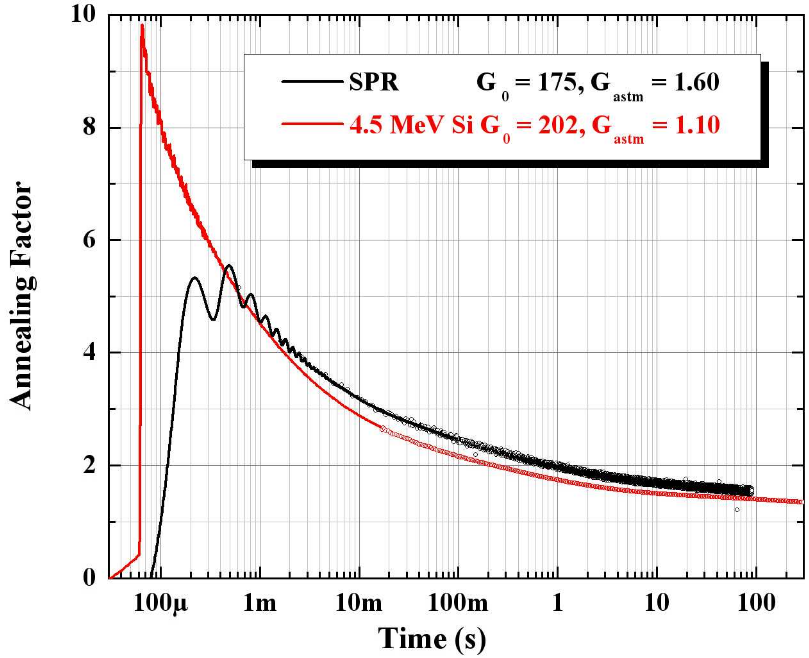
Ionization in the field oxide of the BJT causes gain degradation, too.

Empirical description of gain degradation by highly ionizing ions:

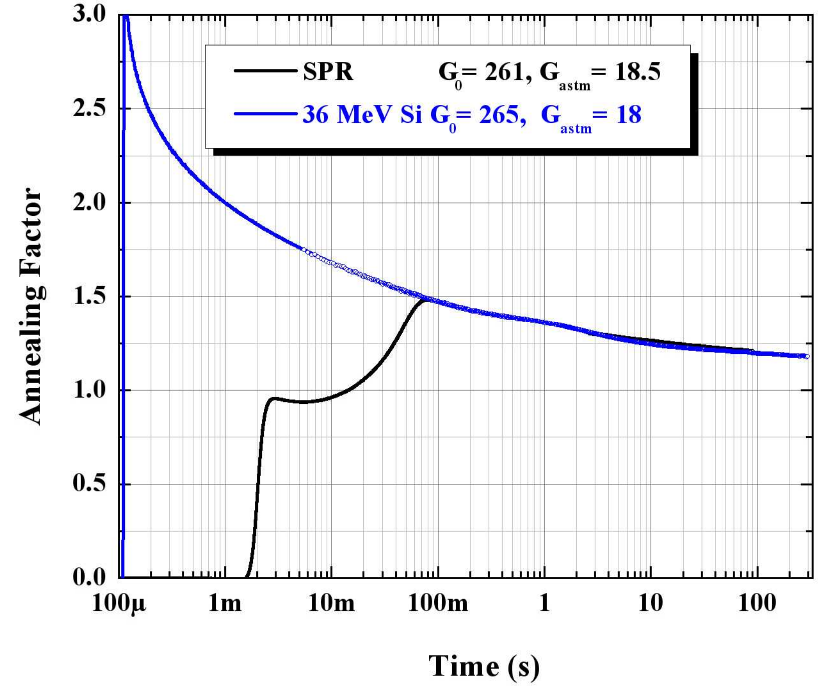
displacement damage — ionization

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

Annealing factor



High fluence shot.
SPR pulse is more like Gaussian while the ion pulse is square



Low fluence shot.
Late time gammas do not allow measurement of AF up a ms.

The transients of both high and low fluence SPR shots can be simulated with ion beams by matching the final gains!

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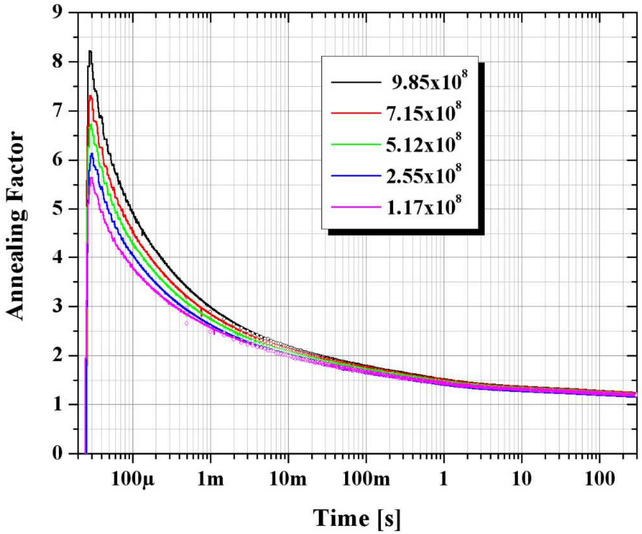
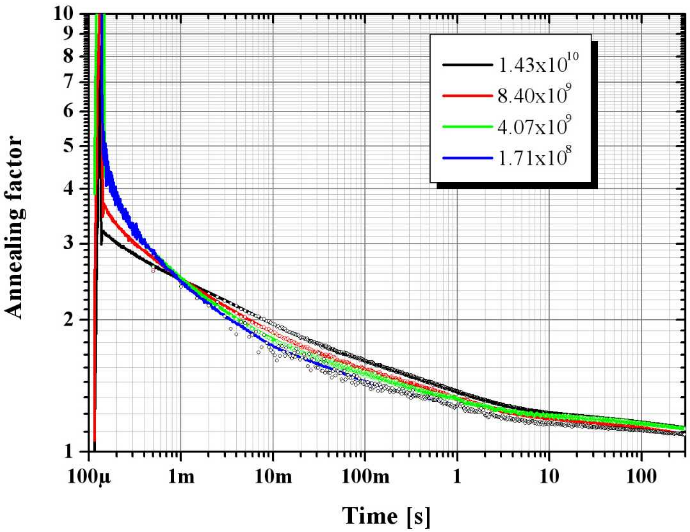
New discoveries about the annealing factor





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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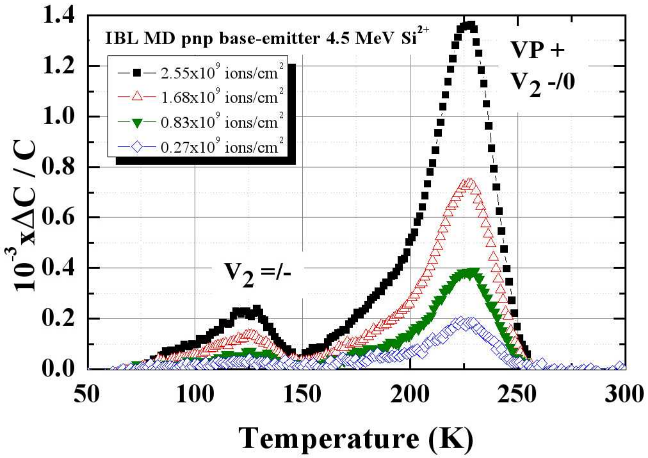
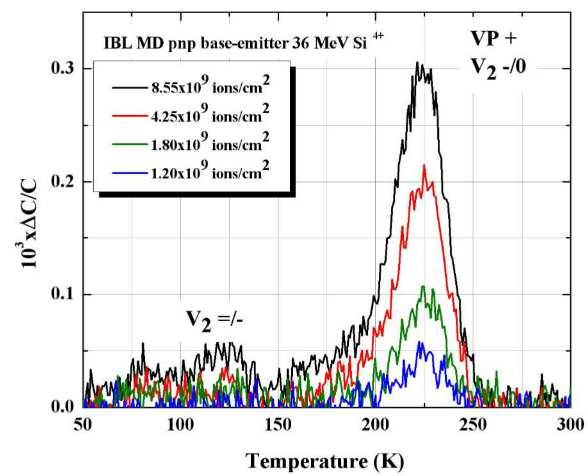
DLTS for SPR and ions

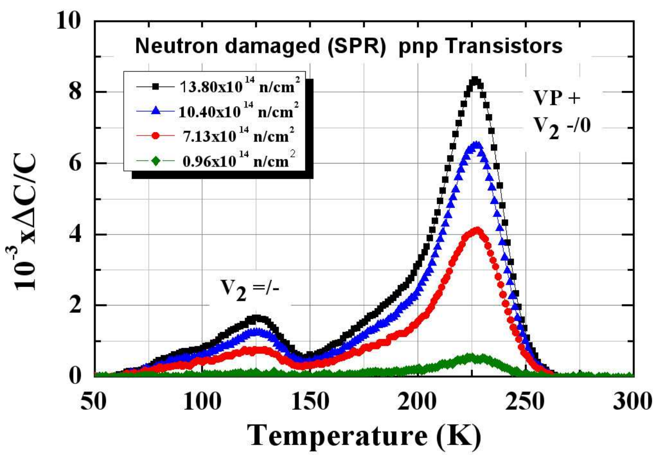
4.5 MeV Si└



36 MeV Si└



SPR neutrons



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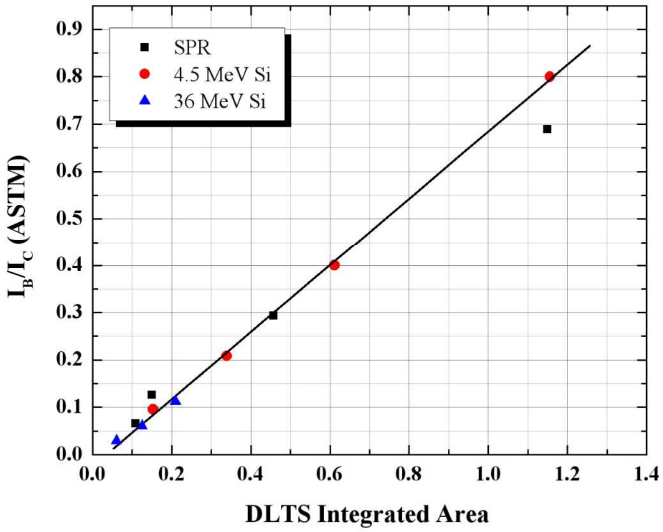
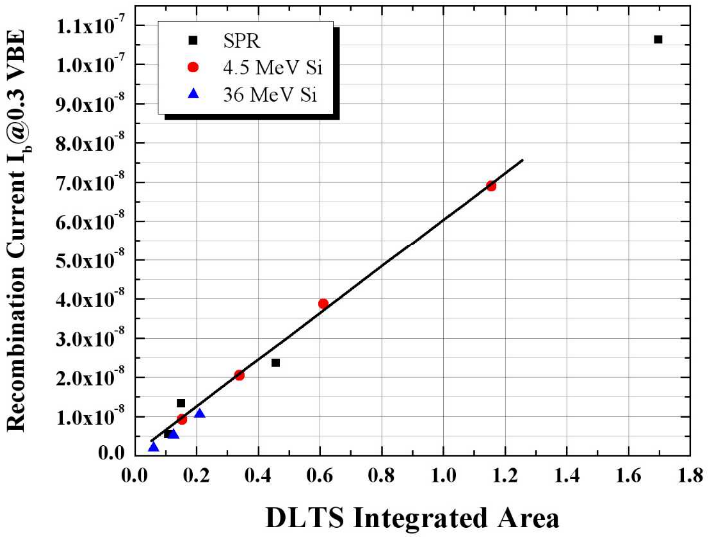
Neutron and ion damages are the same





The same number of defects (defect introduction rates) cause the same amount of gain degradation and the same amount of increase in the recombination current independent of the type of irradiation (neutron or ion).

Conclusion

- Ion beams can match damage of short high fluence neutron pulses with same pulse length
- Ion beams can reproduce annealing factors of neutron bursts if the final gains are matched
- DLTS shows that same type of defects are created by neutrons and ions, and the same number of defects causes the same gain degradation
- There is non-linearity for both neutron and ion irradiations for extremely high fluences
- For light ions there is a non-linerary due to trapped charge in the field oxide at low fluences
- The annealing factor as defined in the past was found to be fluence dependent

More details

- Bielejec, E., et al., *Damage Equivalence of Heavy Ions in Silicon Bipolar Transistors.* IEEE Transaction on Nuclear Science, 2006. **53**(6): p. 3681-3686.

- Bielejec, E., et al., *Metrics for comparison between displacement damage due to ion beam and neutron irradiation in silicon BJTs,* IEEE Transaction on Nuclear Science, December 2007 Issue

- Fleming, R.M., et al., *Defect-driven gain bistability in neutron damaged, silicon bipolar transistors.* Applied Physics Letters, 2007. **90**(17).

- Fleming, R.M., et al., *Effects of clustering on the properties of defects in neutron irradiated silicon.* Journal of Applied Physics, 2007. **102**: p. 043711.

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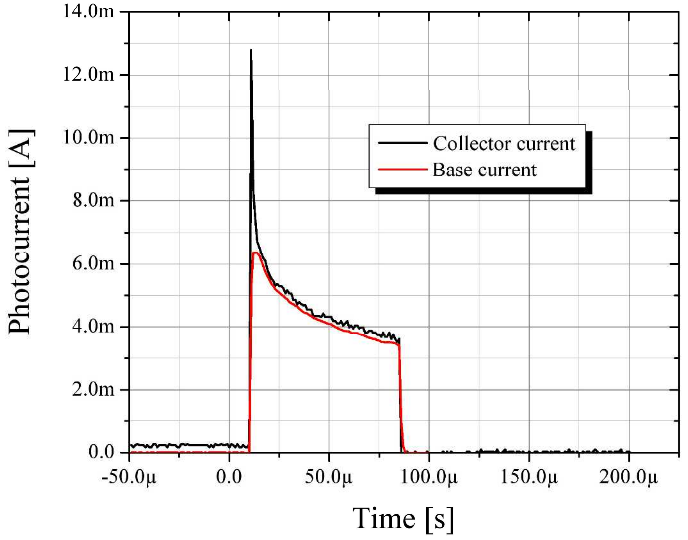
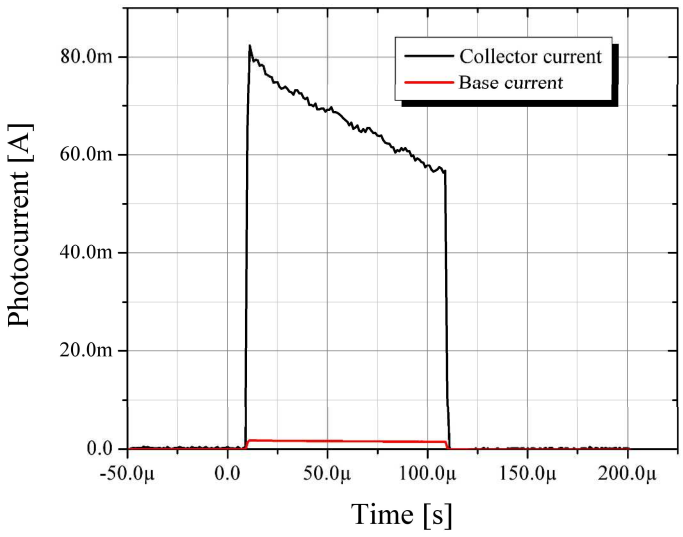
Role of the base leg diode

10 MeV Si
Small photocurrent



28 MeV Si
Large photocurrent



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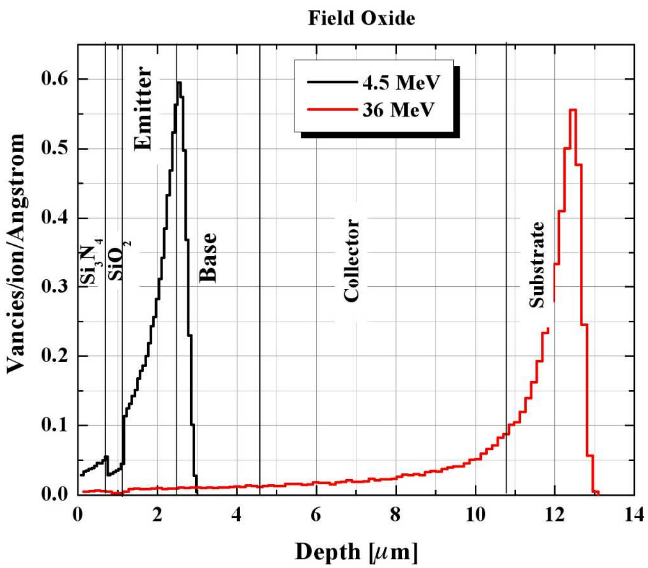
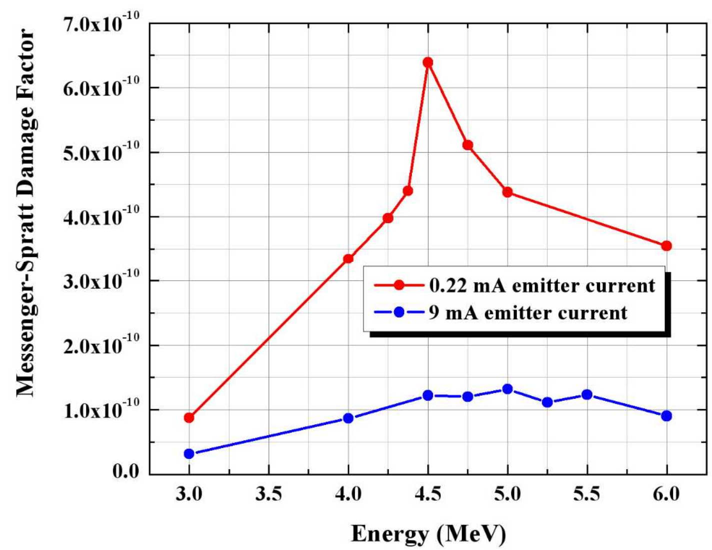
Choice of ion beam energies





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 most the gain degradation while for higher emitter currents the neutral base plays a role, too.