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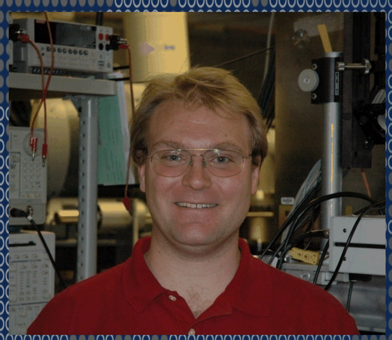

Reverse Annealing Comparisons of PnP and Npn III-V HBTs under Ion Irradiation – Probing the Effects of Thermal and Current Injection Annealing

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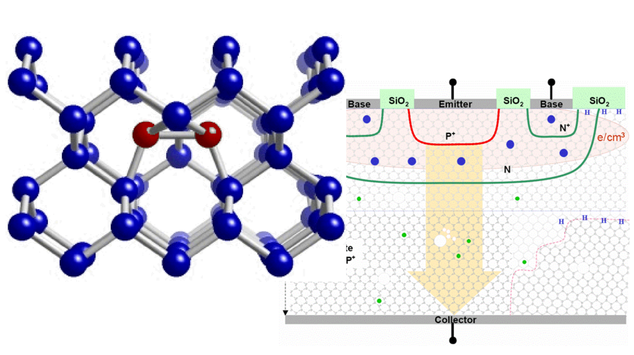
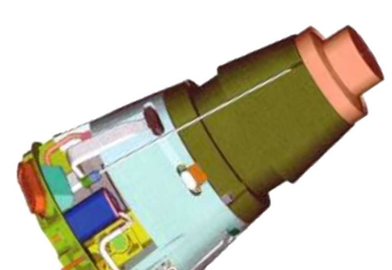
Abstract

We present a comparison of early-time reverse annealing in PnP and Npn HBTs. We find that while the PnPs demonstrate reverse annealing, for equivalent conditions (ion species, temperature, etc…) Npns show a much stronger current injection annealing due to difference in current density under the same operating conditions.

Defect Study Motivation

Radiation Effects





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

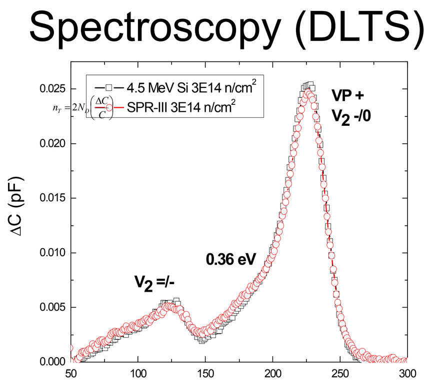
Fundamental Radiation Induced Defects

Degradation of Device/Circuit Performance

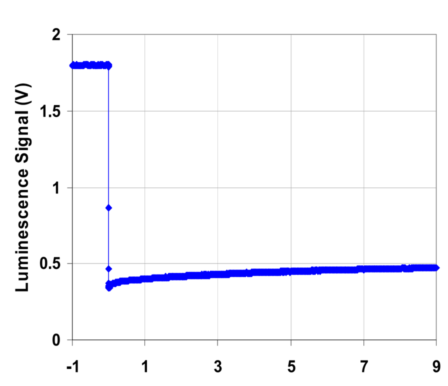
Experimental Techniques

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

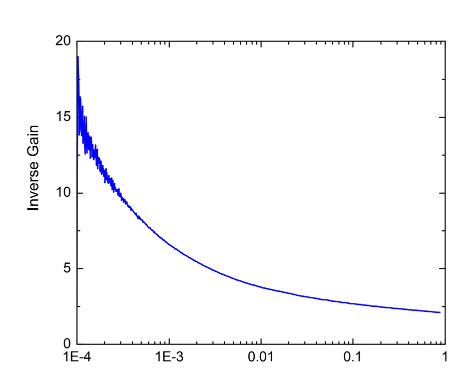
Deep-level Transient Spectroscopy (DLTS)



Photoluminescence



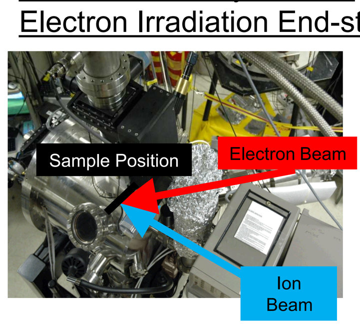
Active Gain

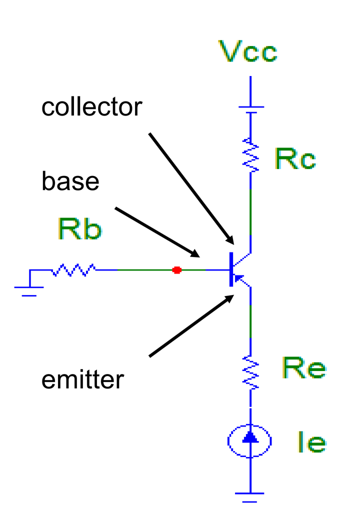


Measurement Setup and Gain Response

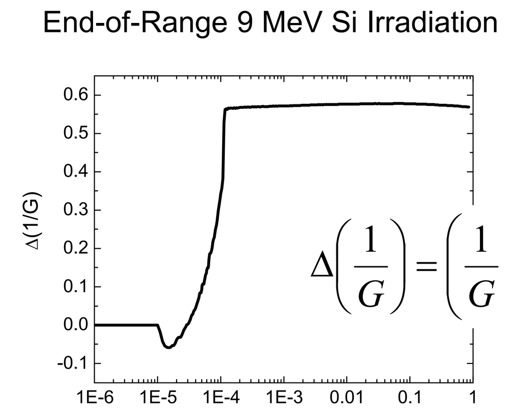
6 MV Tandem Accelerator

Combined Heavy Ion and Electron Irradiation End-station





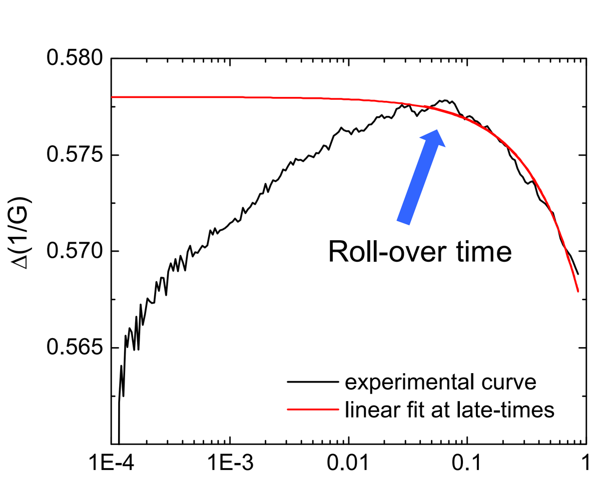
End-of-Range 9 MeV Si Irradiation

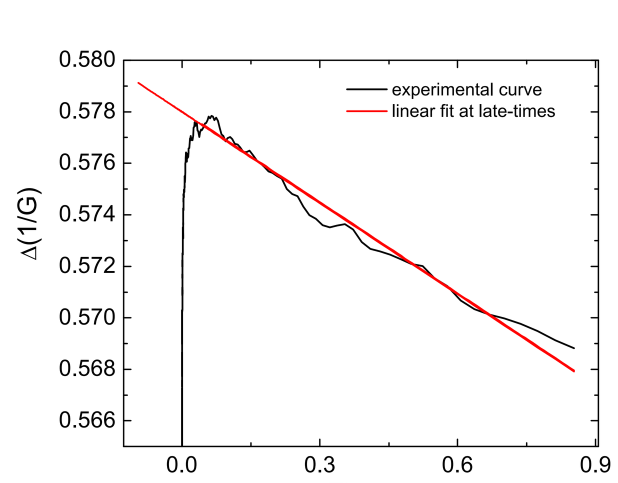


$$\Delta\left(\frac{1}{G}\right) = \left(\frac{1}{G} - \frac{1}{G_0}\right) = k\Phi$$

All devices operated at fixed emitter current of 0.22 mA, with a V_{BC} of 4 V

The Effect: Post-Irradiation Gain Degradation



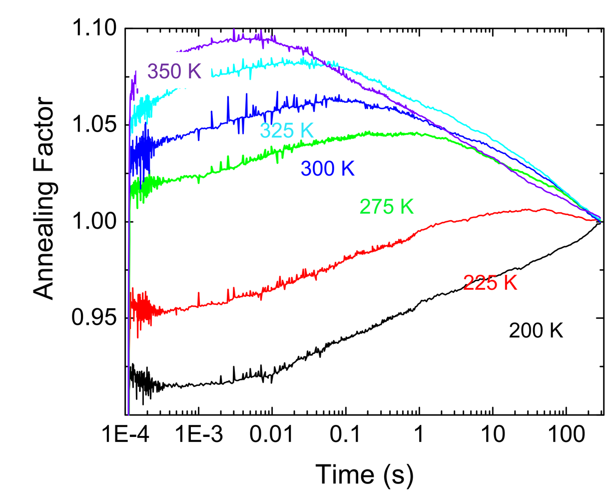


Δ(1/G) increases during the pulse due to damage, BUT does not show annealing immediately after the irradiation rather it shows damage continuing to build in for ~0.1 s after the pulse (reverse annealing).

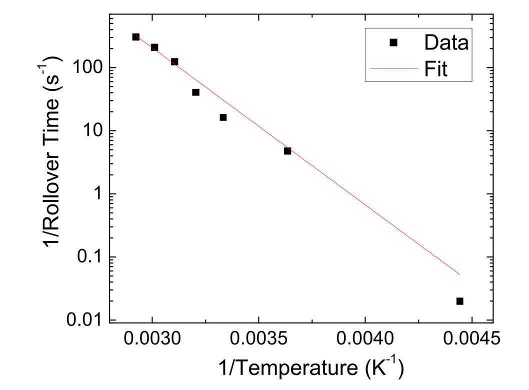
Exploration of Post-Irradiation Gain Degradation

- **Late-time ions:**
  No late-time ions observed
- **Heating Effects:**
  Negligible Ion Heating Effects
- **Temperature Dependence:**
  Strong temperature effect observed in continuous-on experiments

Temperature Dependence of the Reverse Annealing

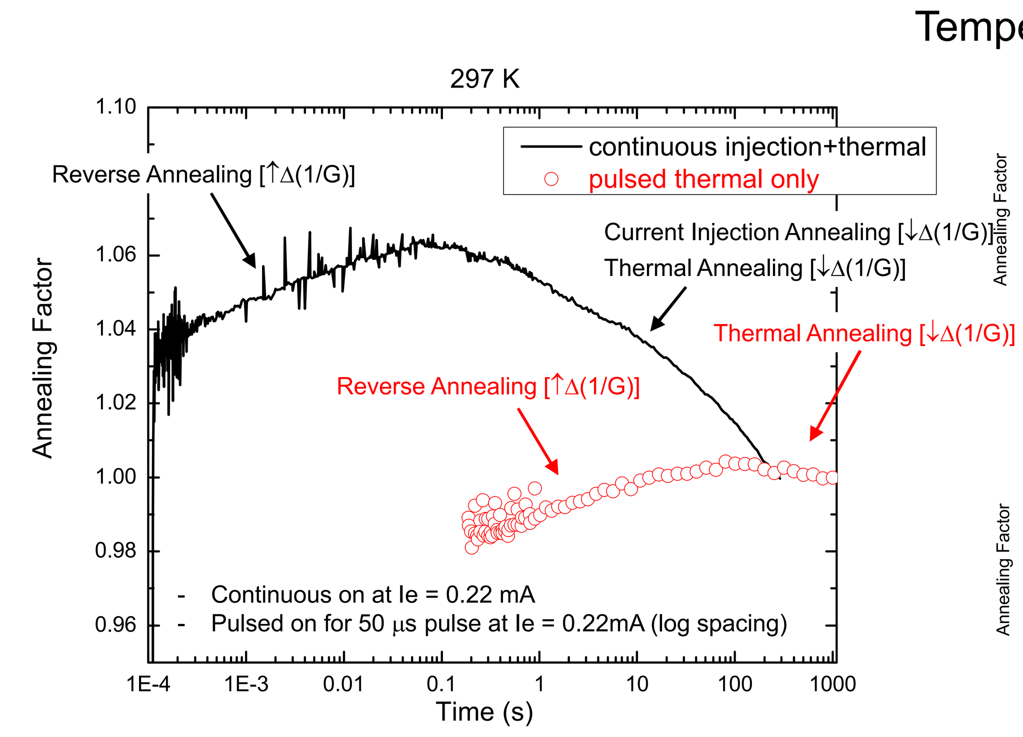


$$AF(t) = \frac{\frac{1}{G(t)} - \frac{1}{G_0}}{\frac{1}{G_\infty} - \frac{1}{G_0}} \propto \frac{N(t)}{N(\infty)}$$

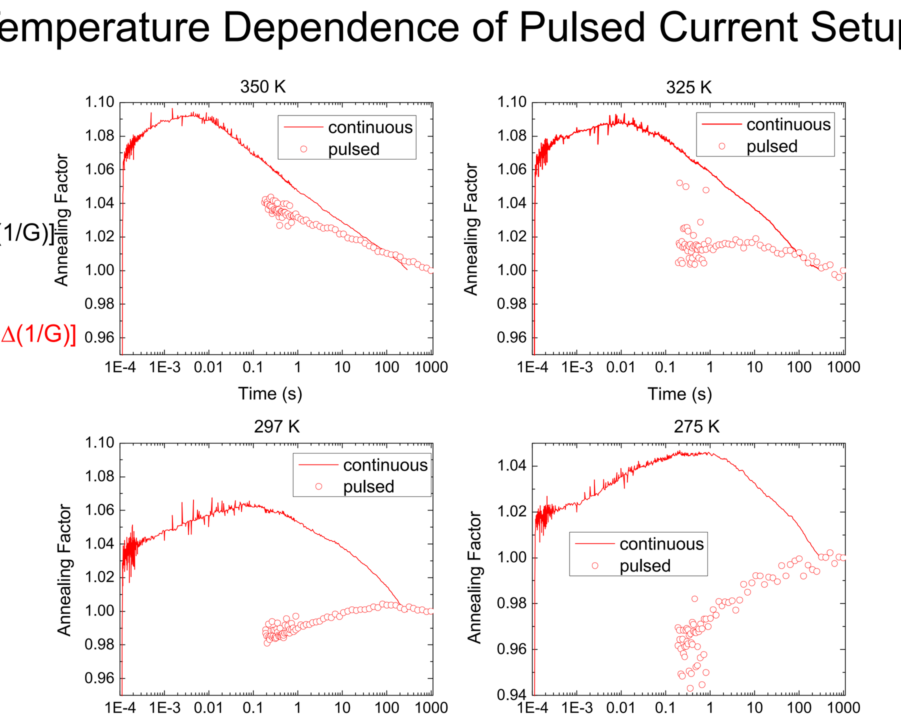


Observe a dramatic temperature dependence, plotting 1/roll-over time we find an Arrhenius behavior with a 0.5 eV activation energy

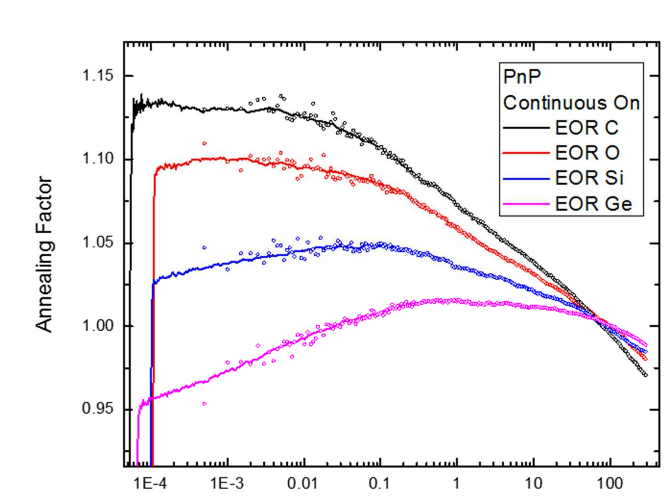
Pulsed Current Setup Isolating Thermal vs. Injection Annealing



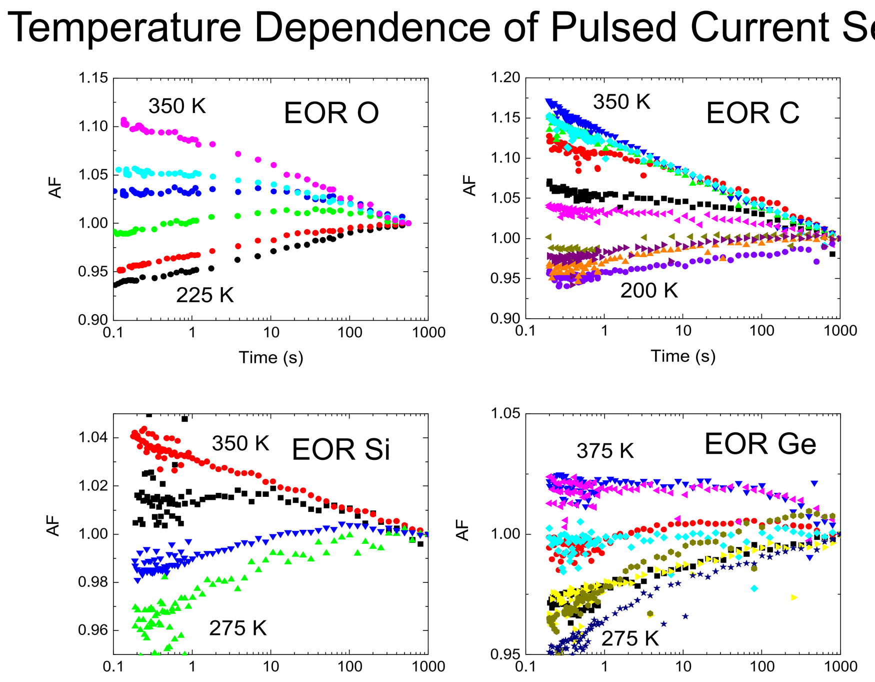
Temperature Dependence of Pulsed Current Setup



Ion Species Dependence of the Reverse Annealing



Temperature Dependence of Pulsed Current Setup



Potential Interpretation - Local Cluster Environment Effects

From 1960's n-type GaAs work we know neutron and electron damage have different annealing stages

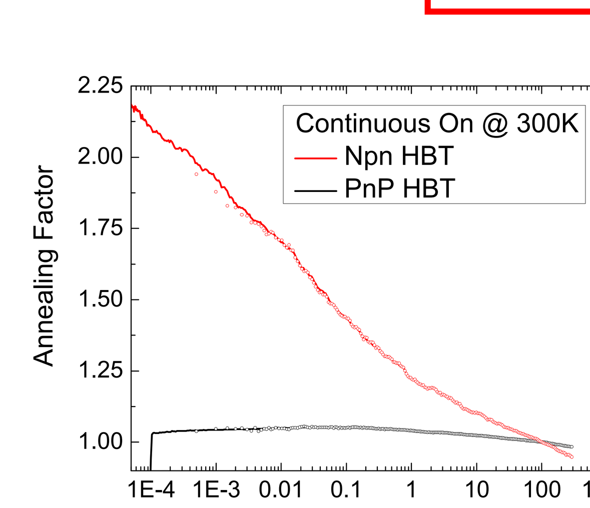
Radiation Effects in GaAs by L. W. Aukerman, P. W. Davies, R. D. Graft, and T. S. Shilliday, *J. Appl. Phys.* 34, 3590 (1963)

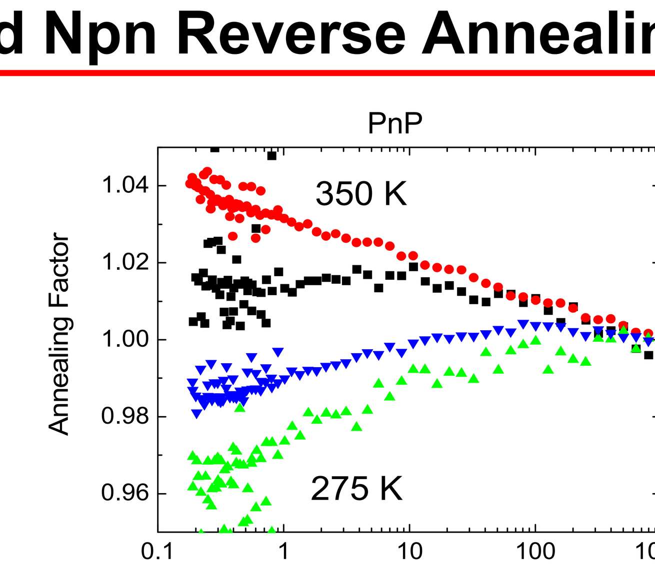
Electron	*Fast Neutron*
Stage I 493 K (complete recovery)	Stage I 493 K
	Stage II 723 K
	Stage III 873-973 K

This suggests that it is the local clustering environment that is responsible from the change in the annealing behavior when changing ion species:

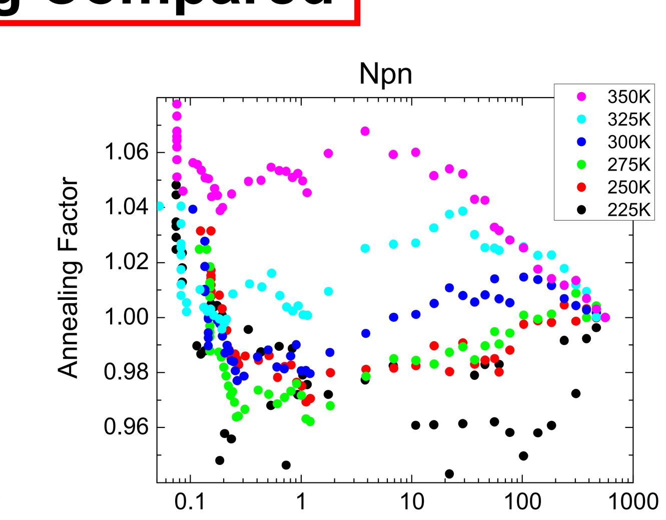
- C → smallest clustering, fastest annealing even at low temperatures (200 K)
- Si → intermediate clustering, we bracket the annealing behavior
- Ge → largest clustering, slowest annealing even at high temperatures (375 K)

PnP and Npn Reverse Annealing Compared





25x85 mm² device → 2125 mm² area



10x50 mm² device → 500 mm² area

Conclusion

With ion irradiations we can explore transient annealing at very short times after the irradiation and have found a reverse annealing component in PnP and Npn HBTs. One potential explanation is that we are observing a thermally activated defect evolution that results in a defect complex with a larger carrier recombination cross-section that further lowers the gain after the initial Frenkel pair production has stopped. We have explored the temperature and ion species dependence of the reverse annealing and found a clear correlation between the size of the damage cluster and the extent of the reverse annealing, with larger damage clusters producing a larger reverse annealing component.

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