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Radiation-Induced Trap Spectroscopy in Si Bipolar Transistors and GaAs Diodes

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Robert Fleming
Sandia National Labs

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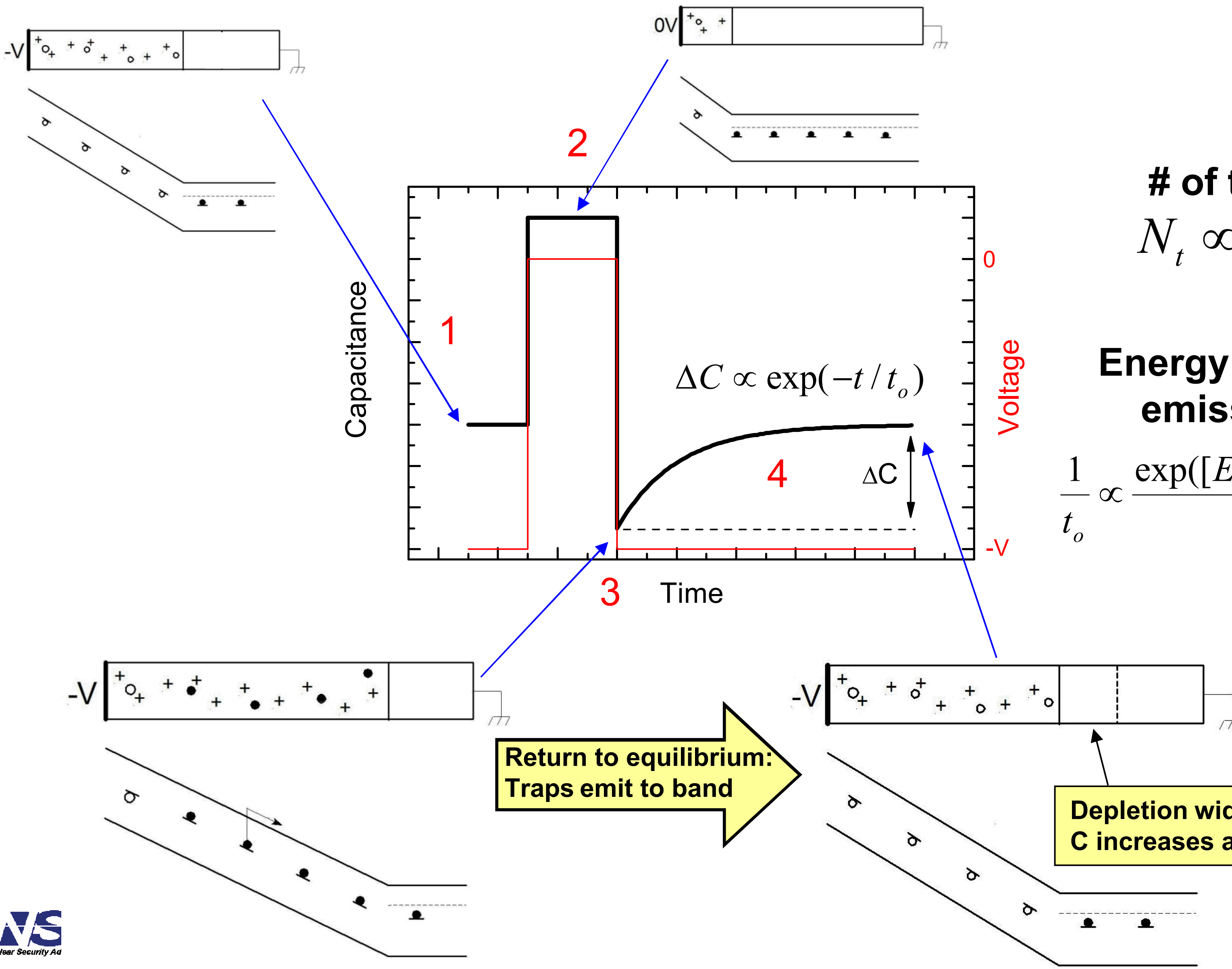
Outline

- Introduction – DLTS & transistor fundamentals
- Silicon – primarily n-type (P doping)
  - BJT collector – the silicon divacancy & its relatives
  - BJT base – the vacancy-donor (VP)
  - Correlating defects and BJT gain
- Defects in GaAs – Electrons & Neutrons
  - Phonon assisted tunneling – electric field enhanced emission

INTRODUCTION – DLTS FUNDAMENTALS

Capacitance Defect Spectroscopy



# of traps

$$N_t \propto \Delta C$$

Energy level from emission rate

$$\frac{1}{t_o} \propto \frac{\exp([E_c - E_t]/kT)}{T^2}$$

Depletion width decreases, C increases as traps emit

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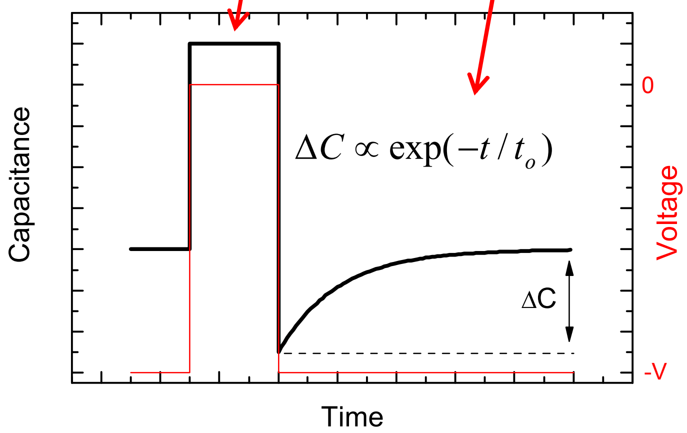
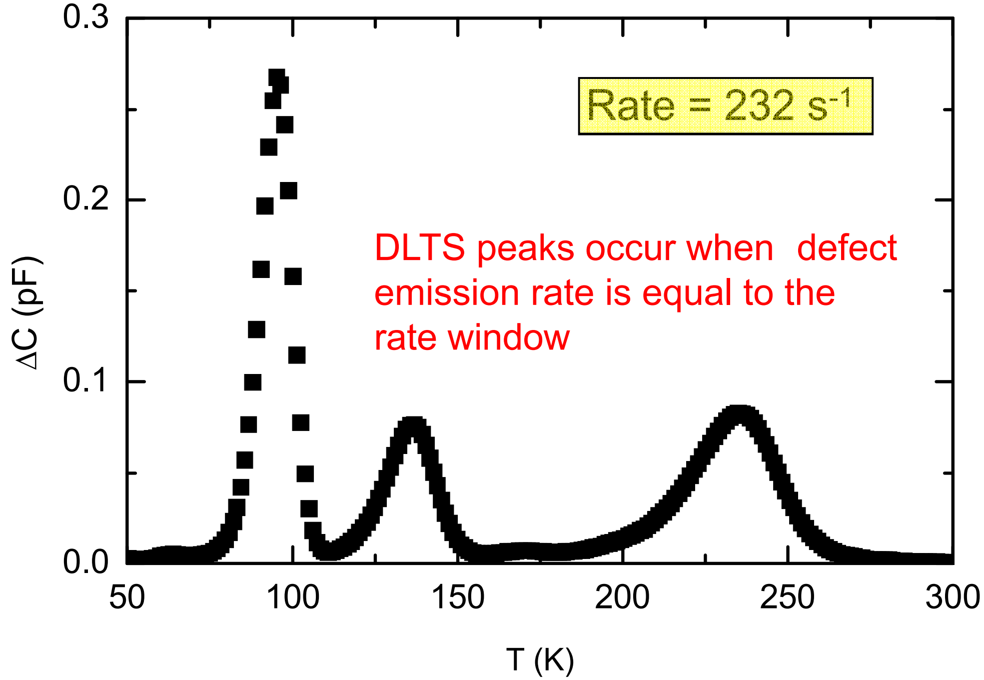
DLTS: Deep Level Transient Spectroscopy

Filling pulse: carrier capture

Transient: carrier emission





# of traps

$$N_t \propto \Delta C$$

Emission Rate

$$\frac{1}{t_o} \propto \frac{\exp([E_c - E_t]/kT)}{T^2}$$

Shallow (near E_c) ↔ Deep (near midgap)

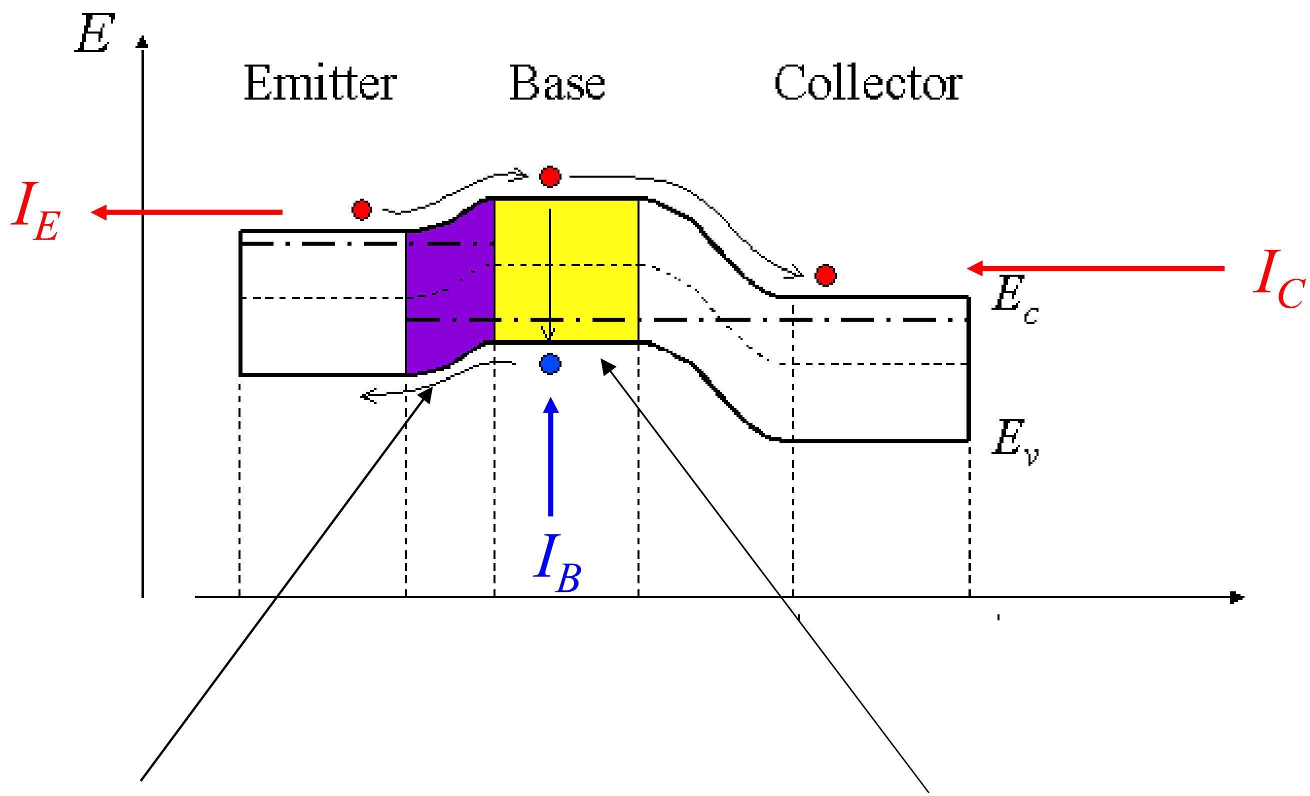
On the DLTS plots presented in this talk, the maximum temperature correspond to emission from ~ $E_g/2$

Research Objectives

- **Predict performance of bipolar transistors after exposure to <u>neutrons</u>**
  - Data from ion damaged devices
    - Avoid hazards of fast-burst neutron reactors
  - Models of defect evolution are used to connect ion data with neutron predictions (models not presented here)

- **Experimental Requirements**
  - Understand effects defect clustering
  - Correlate gain degradation of BJT's with specific defects (Si)
  - Understand effects of phonon-assisted tunneling (GaAs)

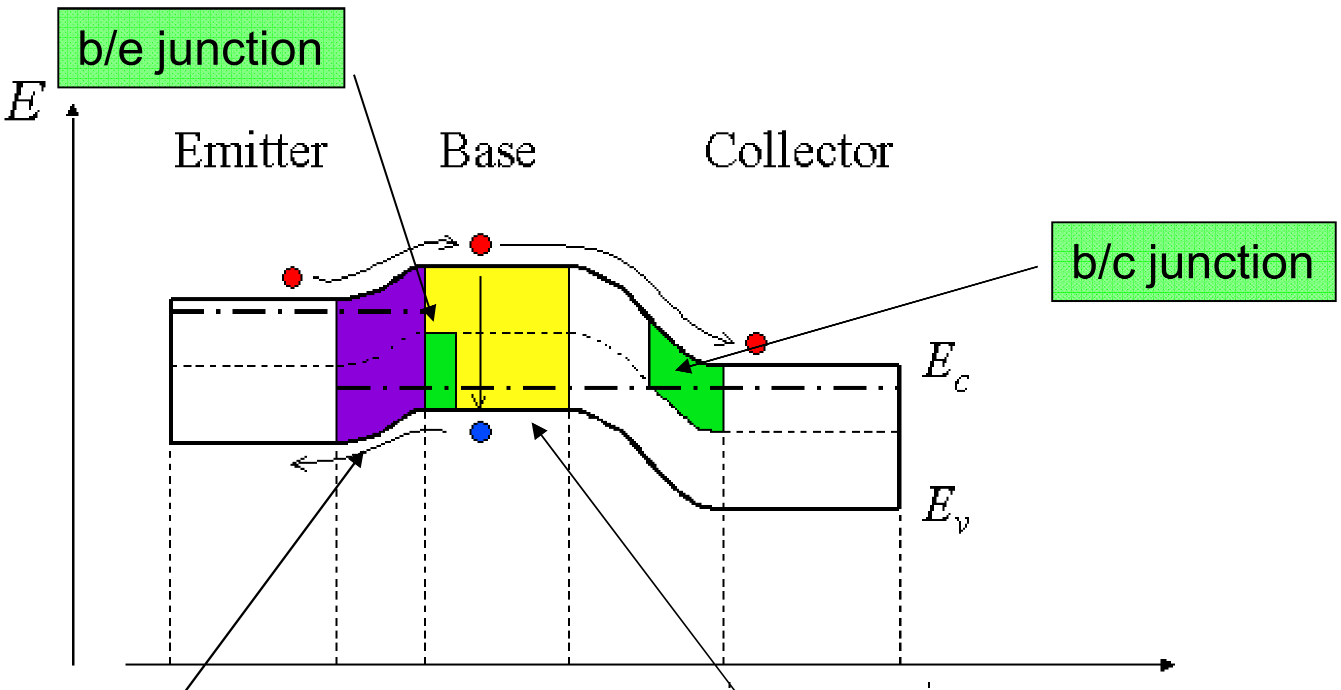
Location of Generation-Recombination



Recombination at low current in **b/e depletion region**

Recombination at high current in b/e depletion + **neutral base**

Location of DLTS Data



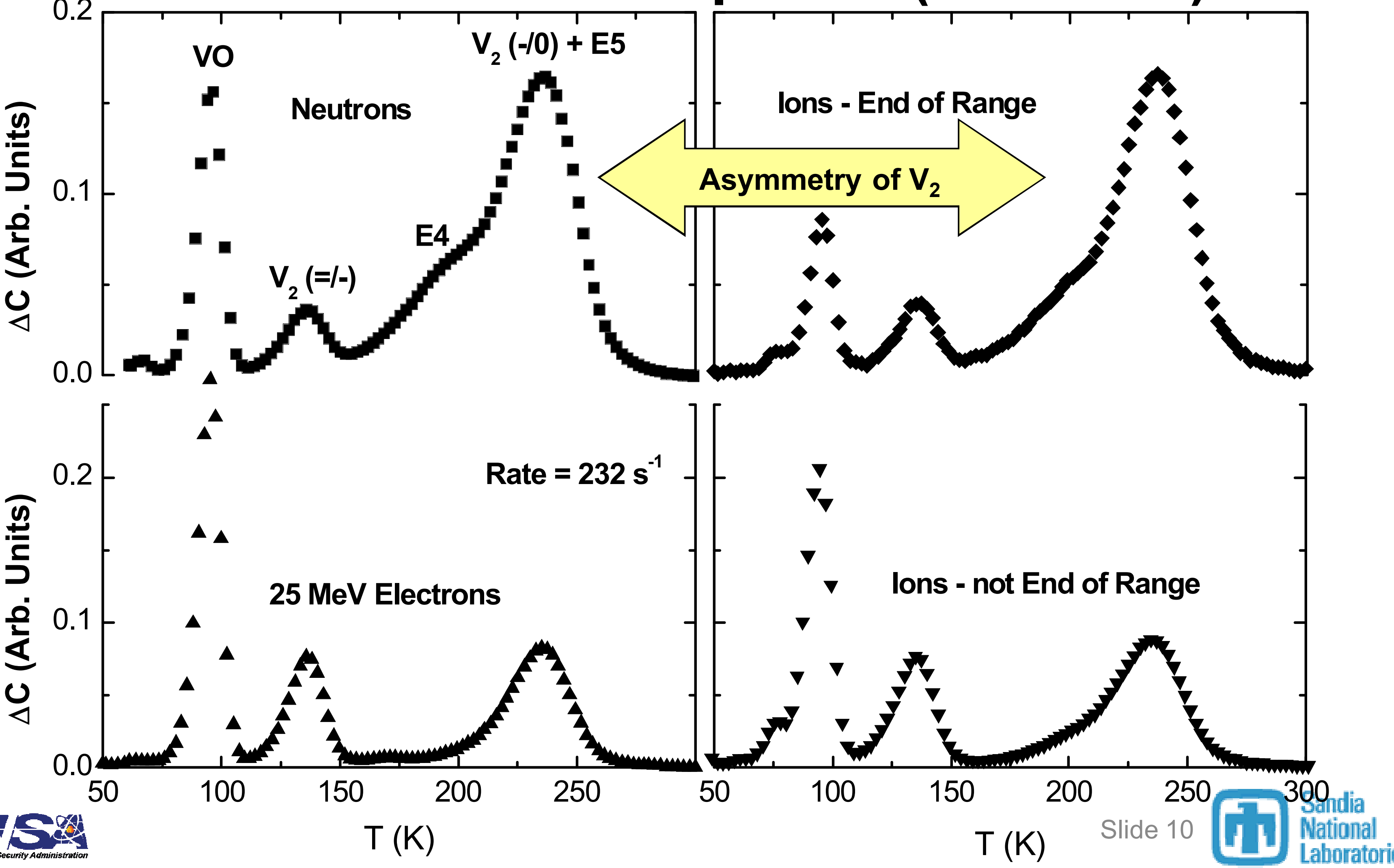
Recombination at low current in **b/e depletion region**

Recombination at high current in b/e depletion + **neutral base**

Silicon Bipolar Transistor Collector: Doping ~ 10^{15} cm^{-3}

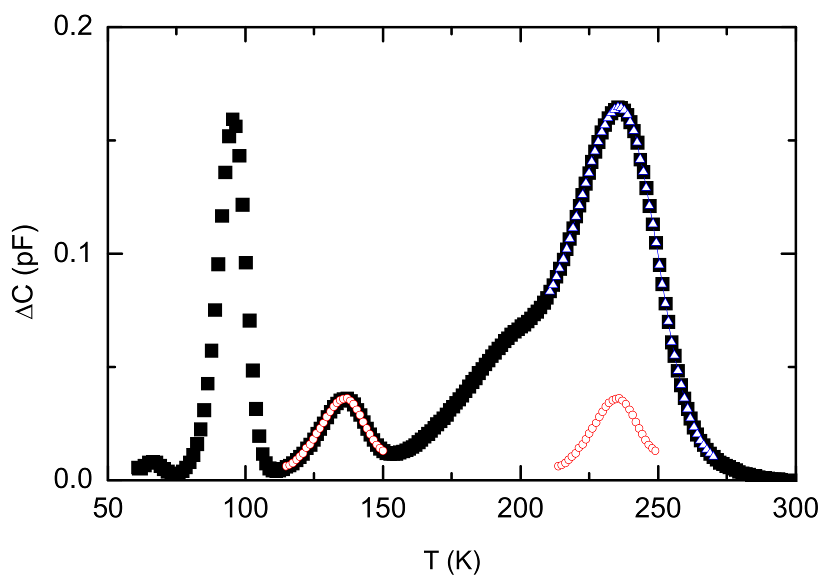
NEUTRON AND ION DAMAGE

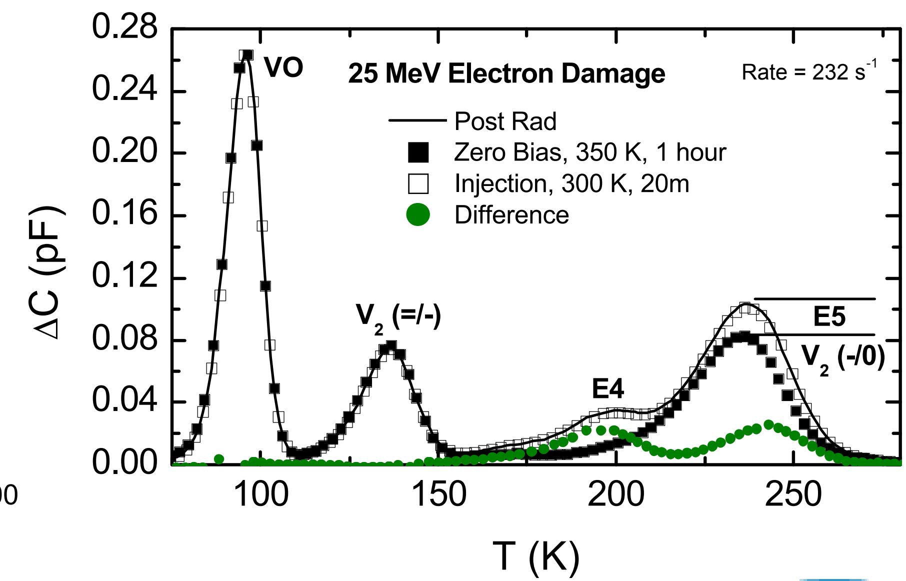
Point defect spectra (electrons) are related to clustered defect spectra (neutrons)



Three Types of V_2 defects

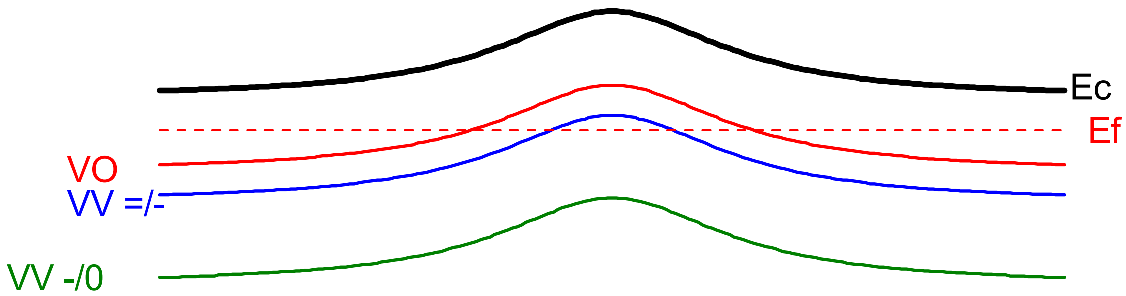
- **Normal V_2** – two equal acceptor levels
- **Strained V_2** – single acceptor level
- **Bistable V_2** - two bistable acceptor levels





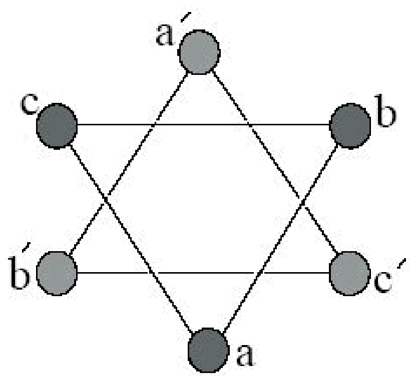
Mechanisms producing a V_2 asymmetry

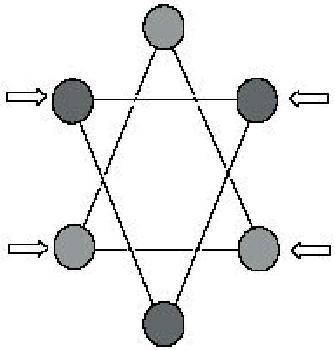
- Partial filling of the shallow V_2 level because of clustered defects and local band bending.



- 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

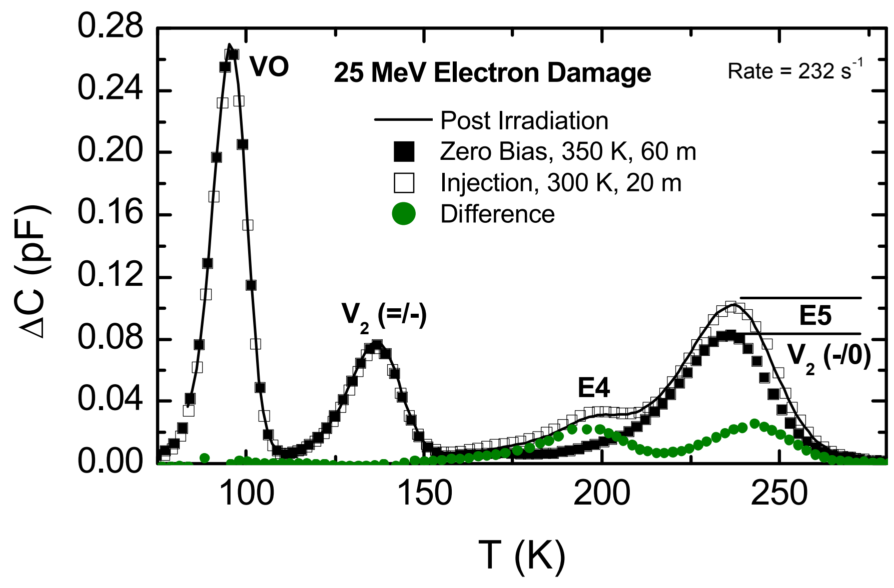


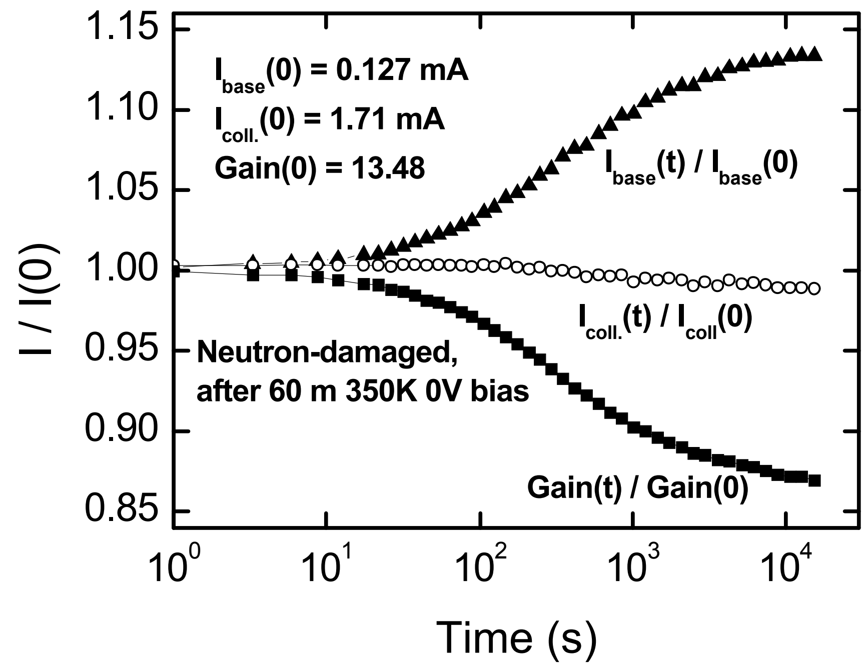


JT Distorted
T < 20 K
or strained Si

Gain and Defect Bistability

Injection of minority carriers at 300 K causes E4 and E5 to become visible. Annealing at 350 K (80 C) removes E4 and E5.





R. M. Fleming, C. H. Seager, D. V. Lang et al., Appl. Phys. Lett. **90**, 172105 (2007).

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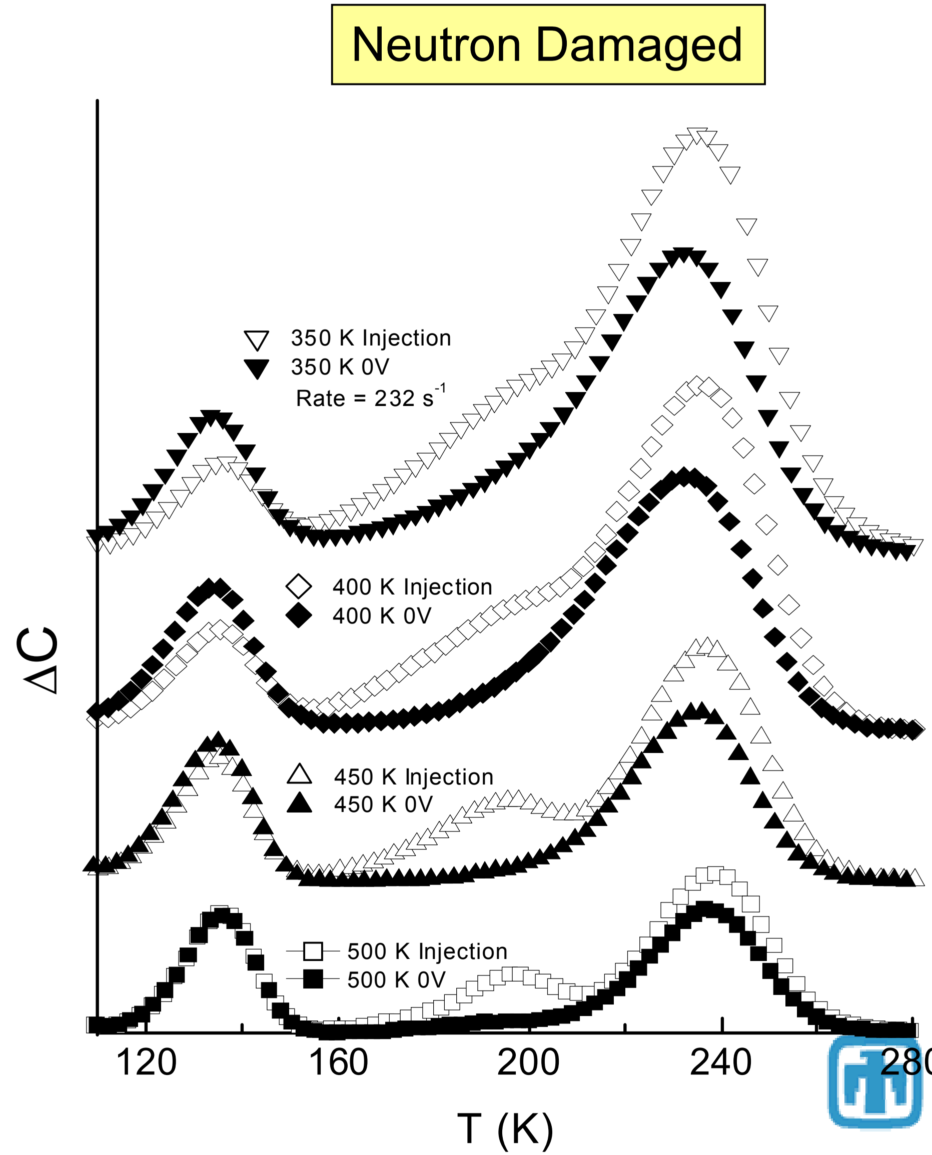
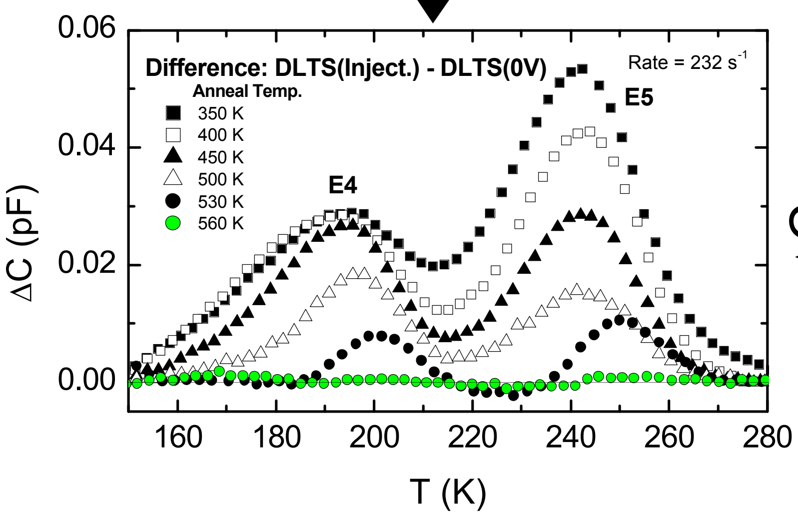
Annealing of Bistable E4-E5

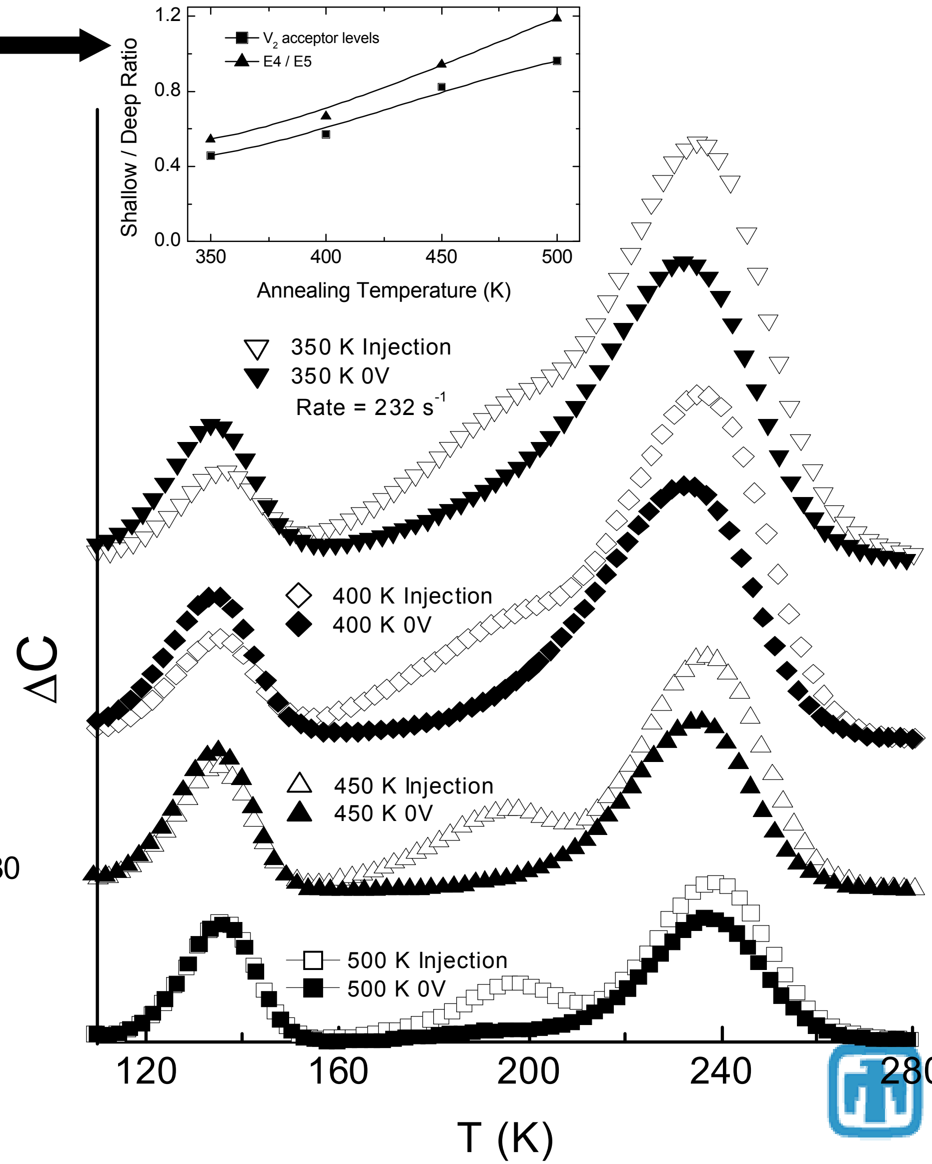


Annealing of Bistable E4-E5

- Bistable E4-E5 has the same asymmetry as V_2
- Asymmetry of E4-E5 acceptor level amplitude is gone after 500 K

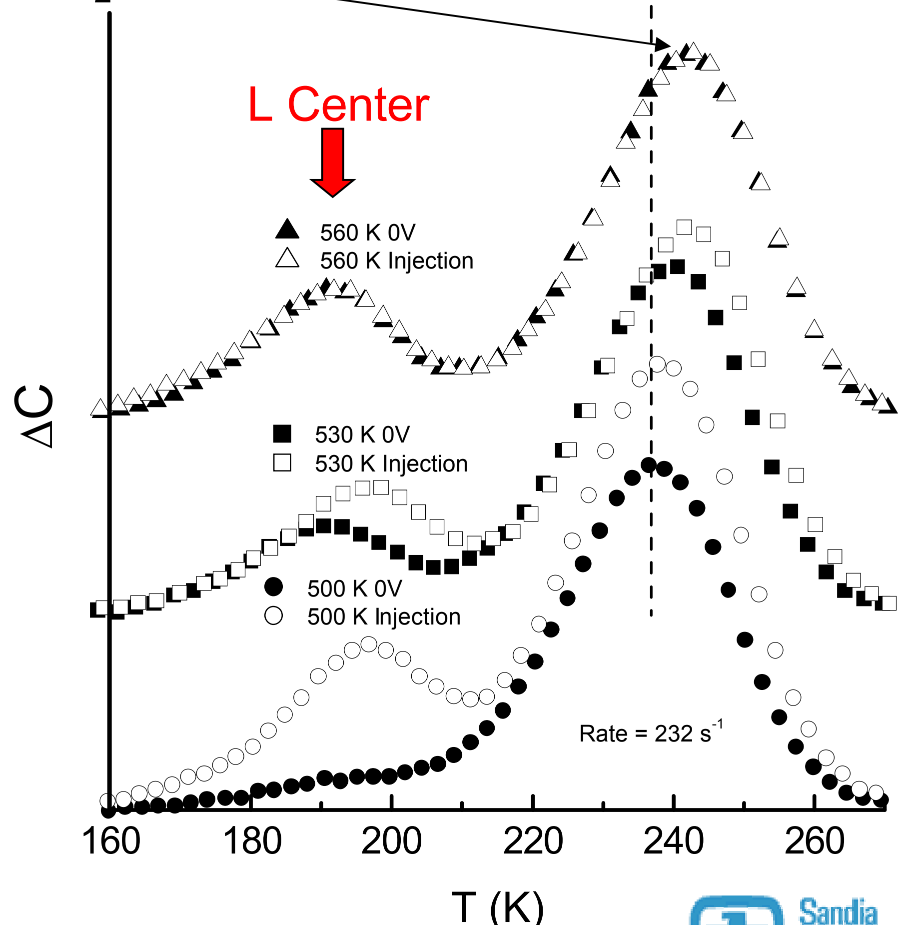


- Bistability remains until 560 K



Annealing above 500 K – Bistability goes away, but V_2 – like defect remains

Shift of V_2 is associated with transition to V_2O

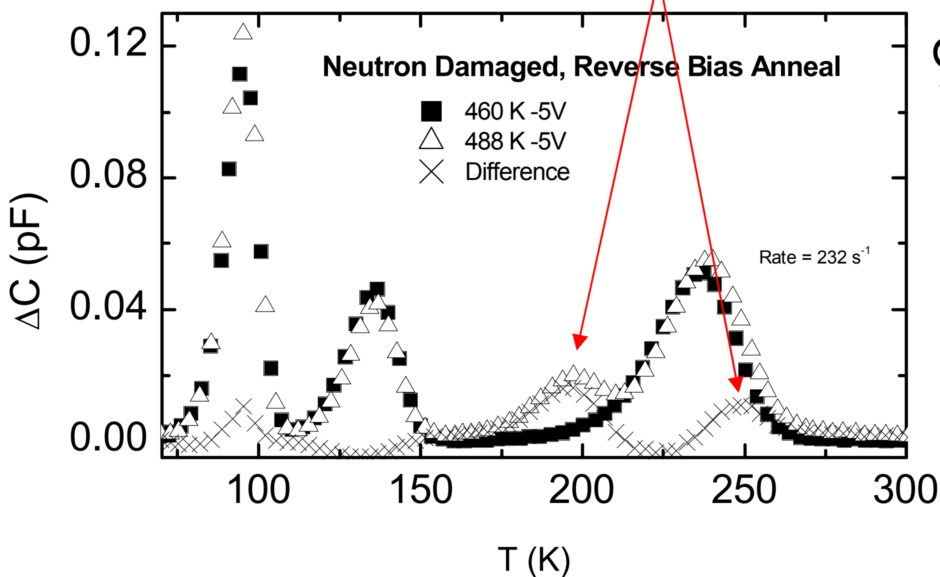


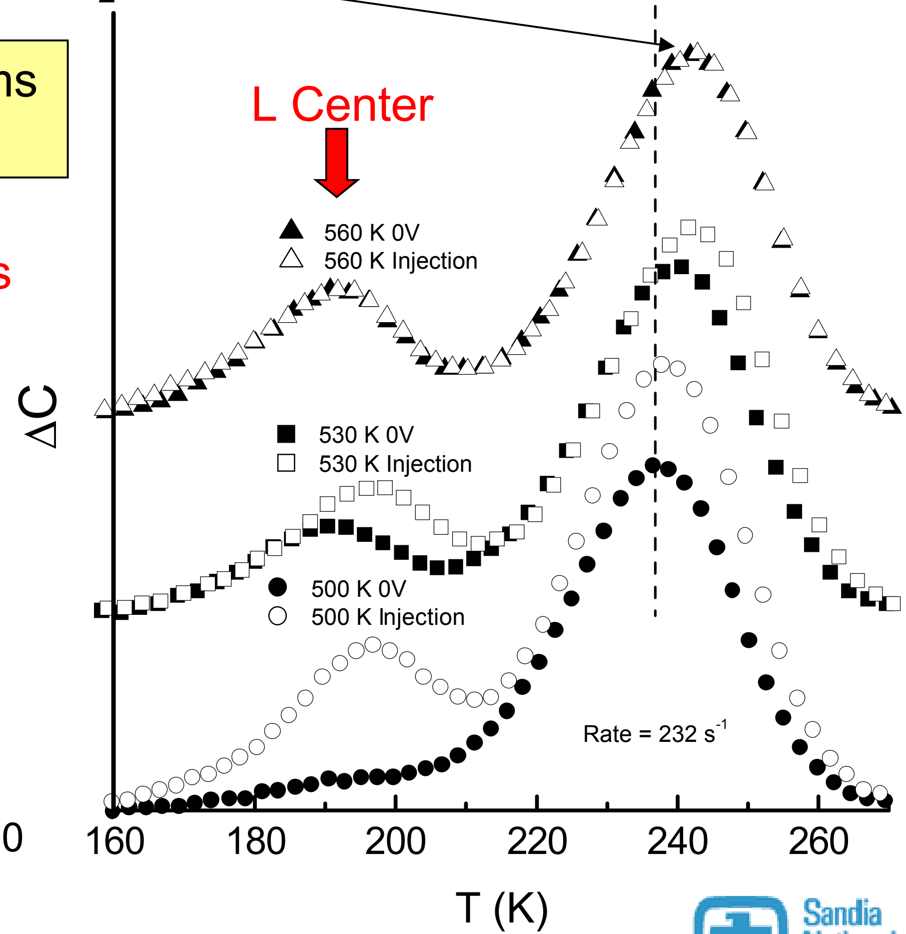
Annealing above 500 K – Bistability goes away, but V_2 – like defect remains

Shift of V_2 is associated with transition to V_2O

Above 500 K, bistable E4-E5 transforms to the stable L center with two levels.

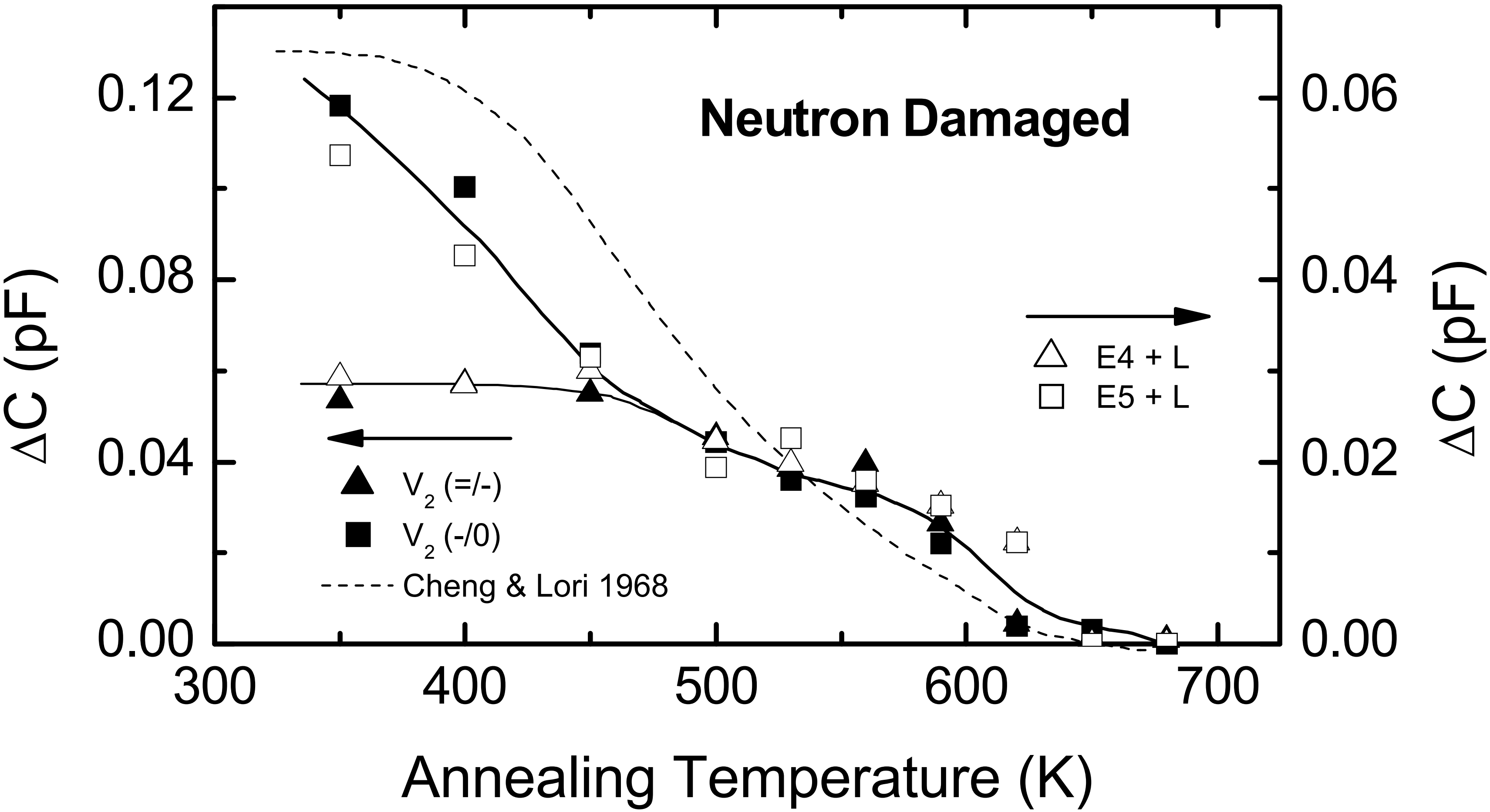
L Center has two levels





Bistable E4-E5 and V_2 Annealing

E4-E5 has the same annealing characteristics and level asymmetry as the normal V_2 seen after neutron or other clustered damage.



Fleming, et al., J. Appl. Phys. **104**, 083702 (2008)

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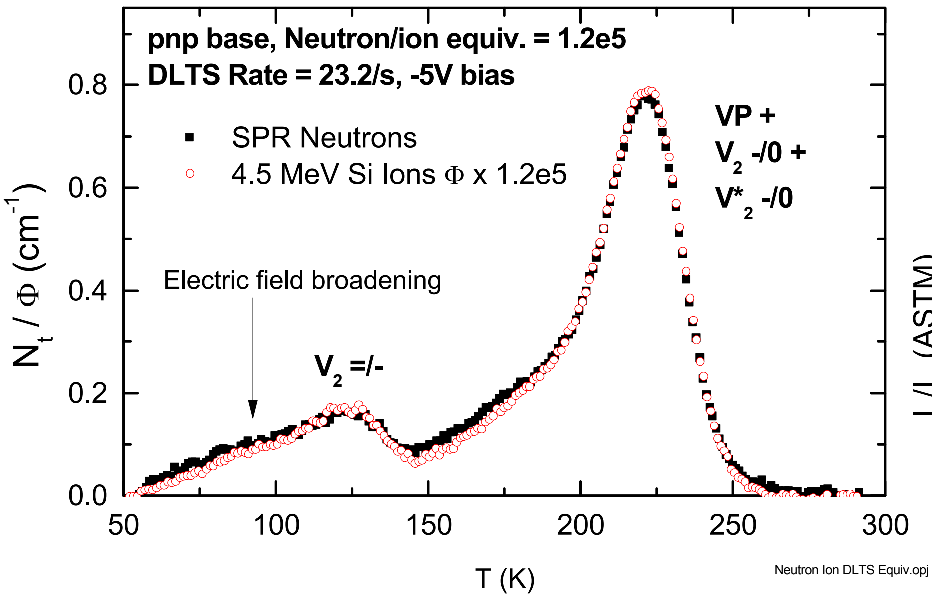
Silicon Bipolar Transistor Base: Doping ~ 10^{17} cm^{-3}

NEUTRON AND ION DAMAGE

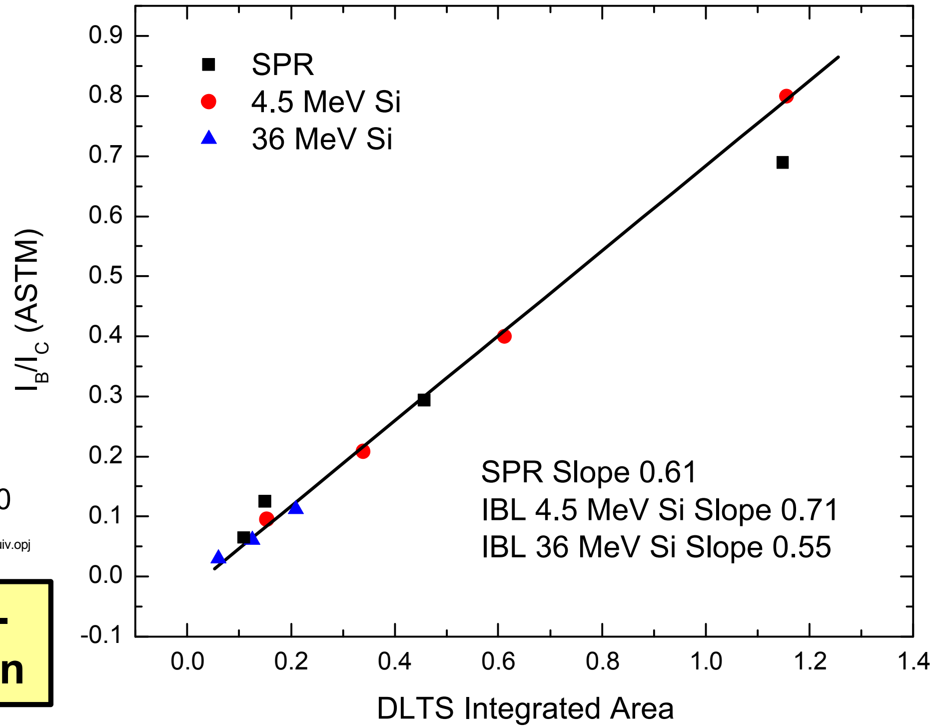
Neutron – Ion Equivalence using EOR Silicon Ions

Exact match of neutron & ion DLTS spectra

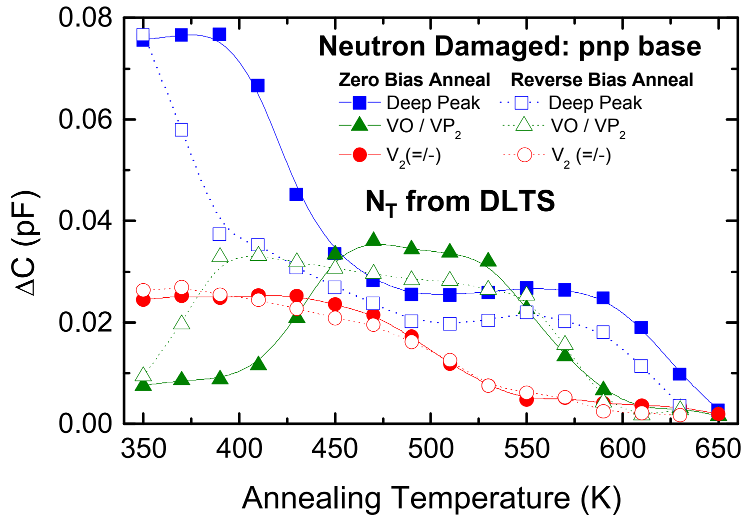


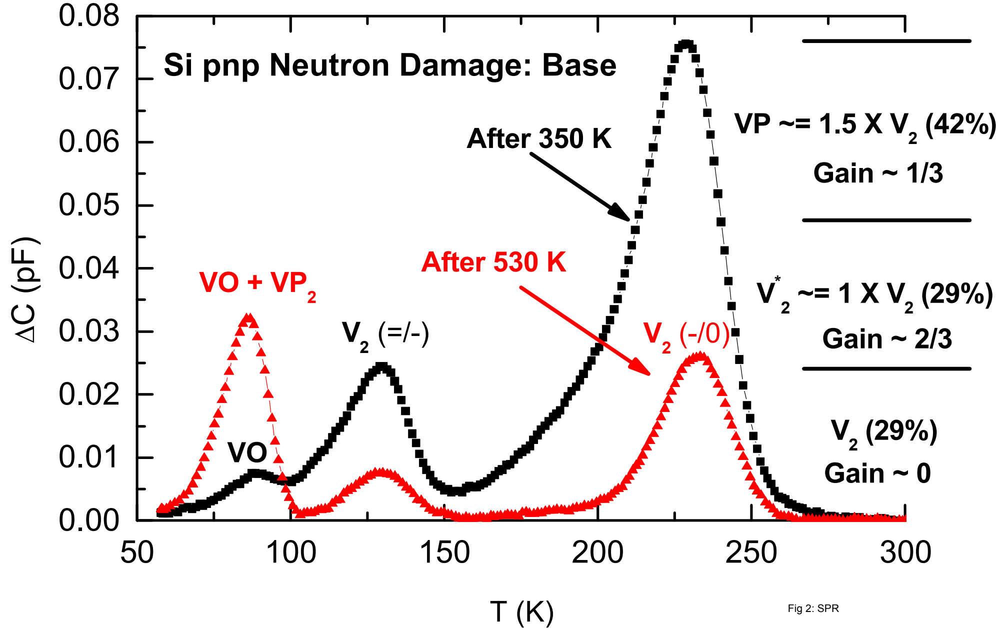
Si ion energy chosen to place the ion end-of-range (EOR) at the emitter-base junction

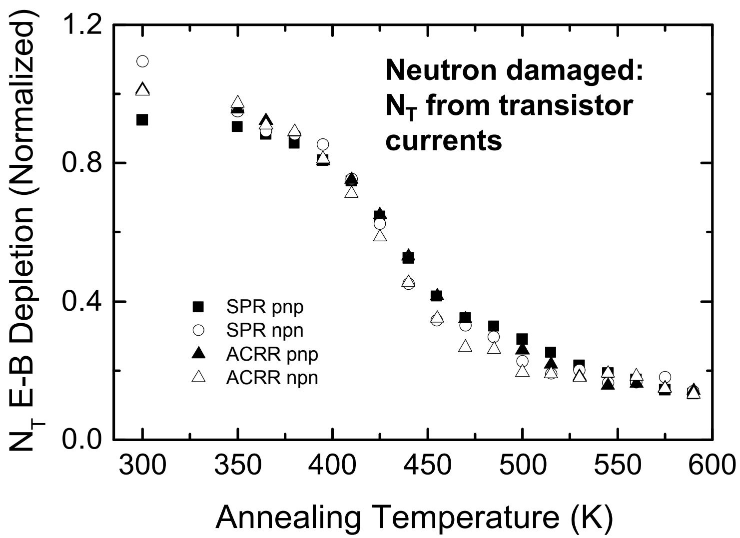
Linear relationship between inverse gain and DLTS amplitude



Remove defects by annealing to assign relative importance of defects to gain reduction.





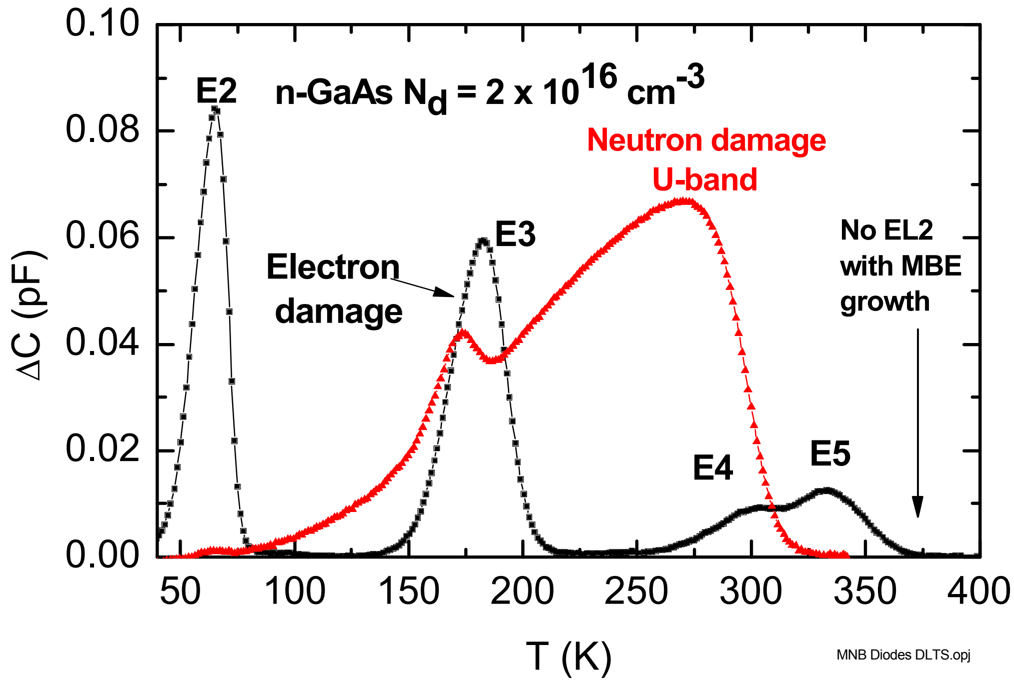


$$\Delta C \sim [VP]\, f_{vp} + [V_2^*]\, f_v + [V_2]$$

Fleming, et al., J. Appl. Phys. **107**, 053712 (2010).
Fleming, et al., J. Appl. Phys. **108**, 063716 (2010).

DEFECTS IN GaAs – ELECTRON & NEUTRON DAMAGE

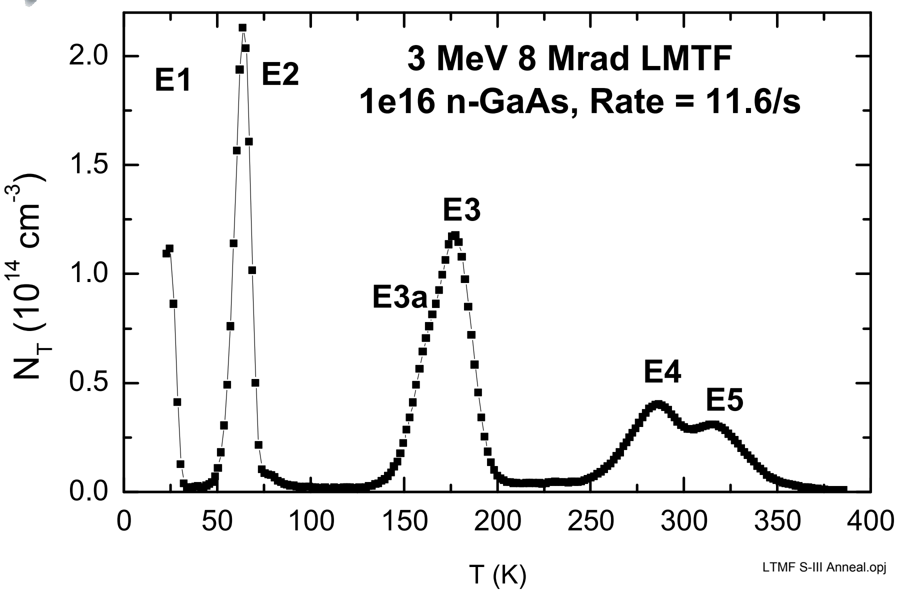
DLTS in GaAs : Analysis is more complex

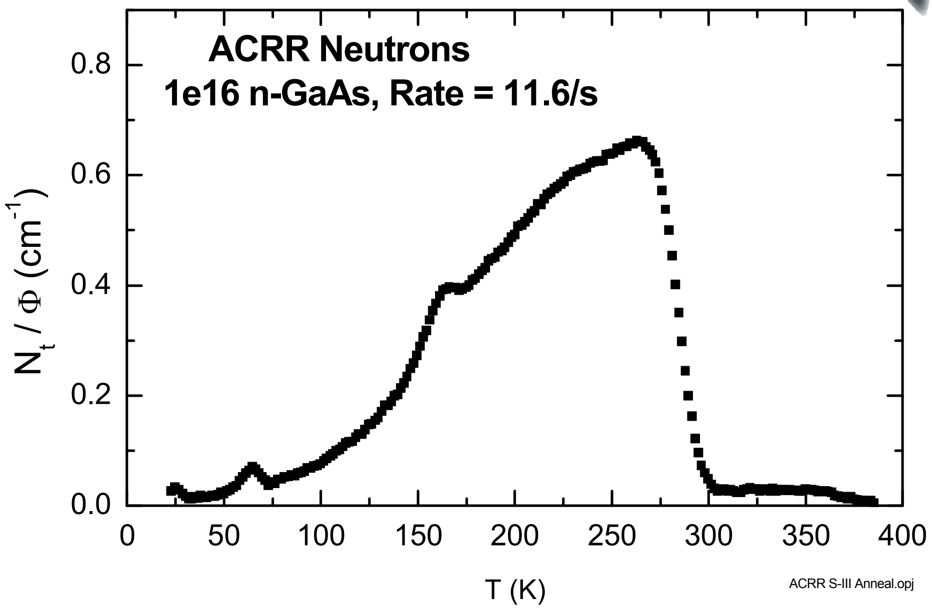


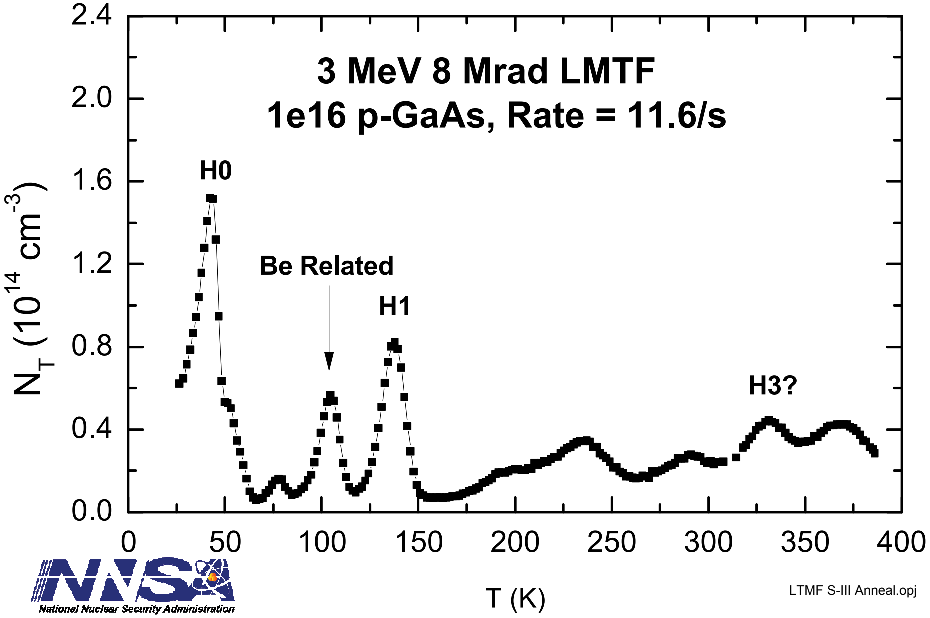
- **Neutron spectra is radically different from electron damage.**
- **The broad features after neutron/ion damage are known as the "U-band" (n-GaAs) and the "L-band" (p-GaAs)**

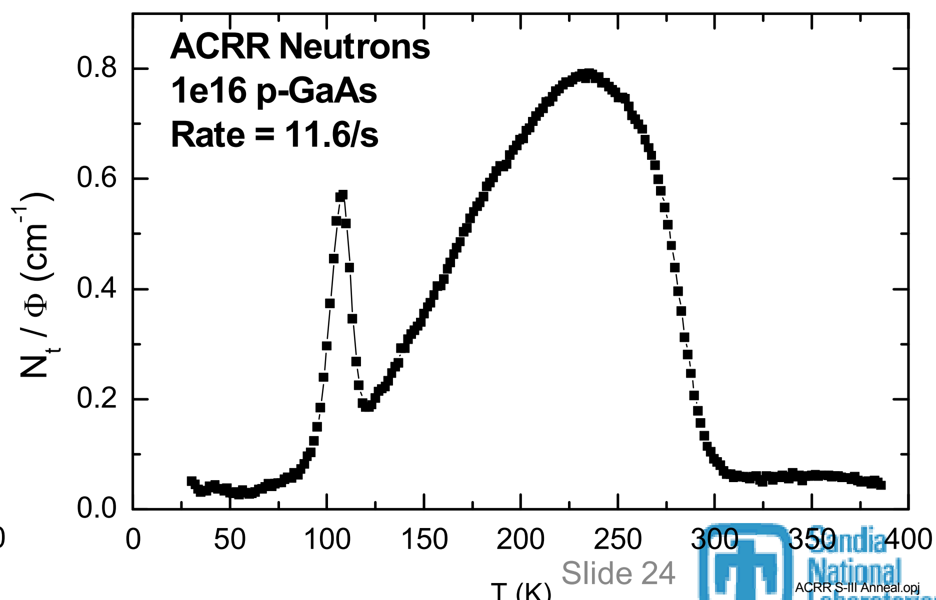
	Silicon	GaAs
Defect library from prior work	Extensive (from EPR/DLTS)	Minimal (EPR not effective)
Additional defect species in clusters	A few, e.g. bistable V_2, strained V_2	Unknown at present, work in progress
Electric-field enhanced emission from defects (phonon assisted tunneling)	Minimal	Extensive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

Clustered & Non-clustered Damage









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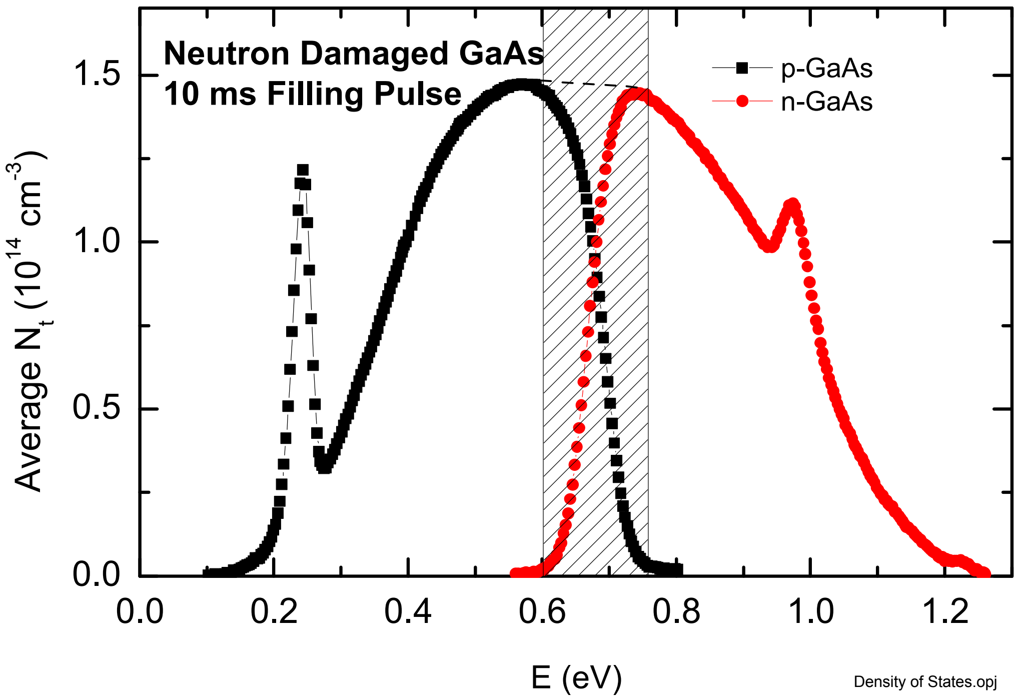
Neutron Damaged GaAs



- **Neutron damage causes expansion of the GaAs lattice**
  - Decrease of GaAs bandgap
- **Bandgap decrease of 0.16 eV results in overlap of U- and L-bands & apparent continuous distribution of defect states across midgap**
- **Cause?**
  - Inhomogeneous broadening , e.g. strain broadened defect levels
  - Homogeneous broadening, e.g. electric-field dependent emission rate

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Fleming, et al., J. Appl. Phys. **107**, 123710 (2010).

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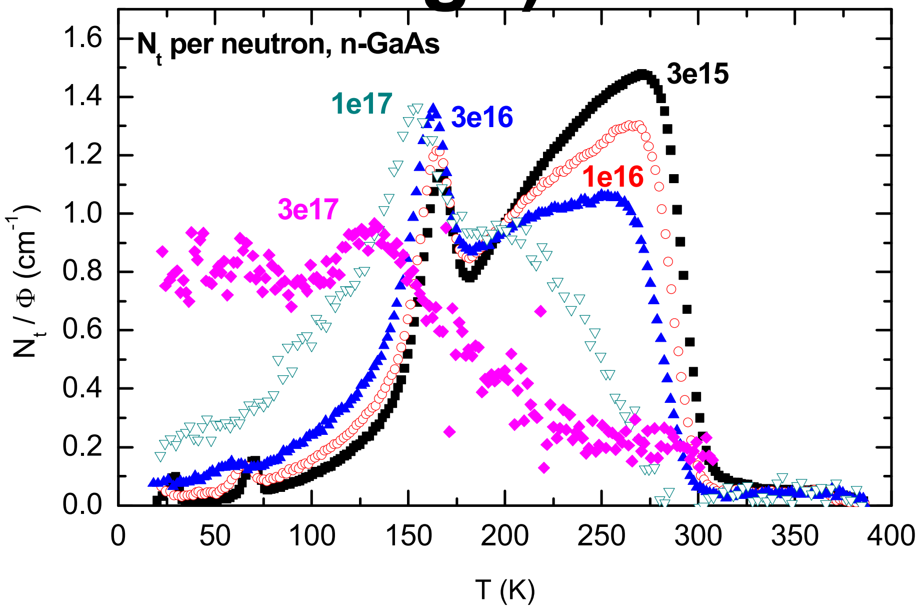
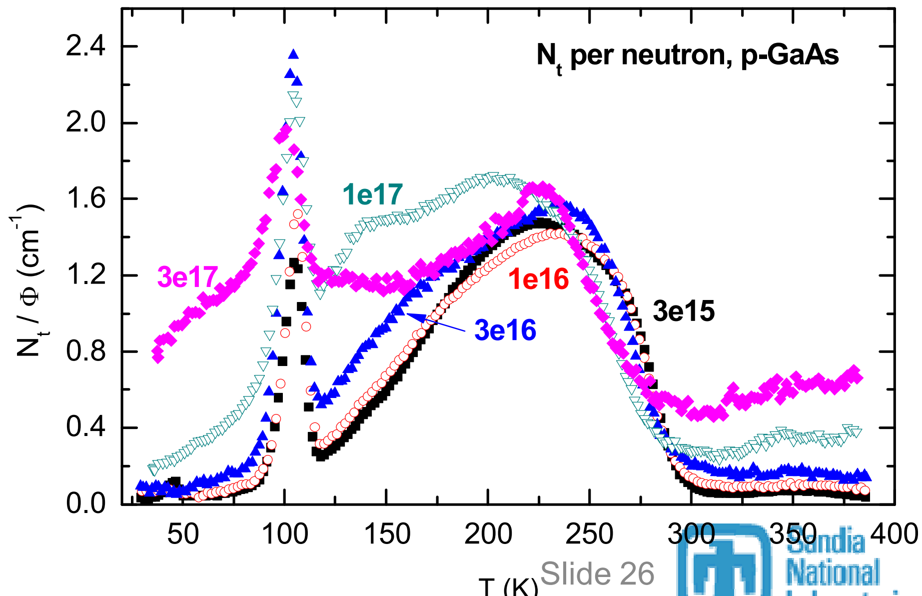
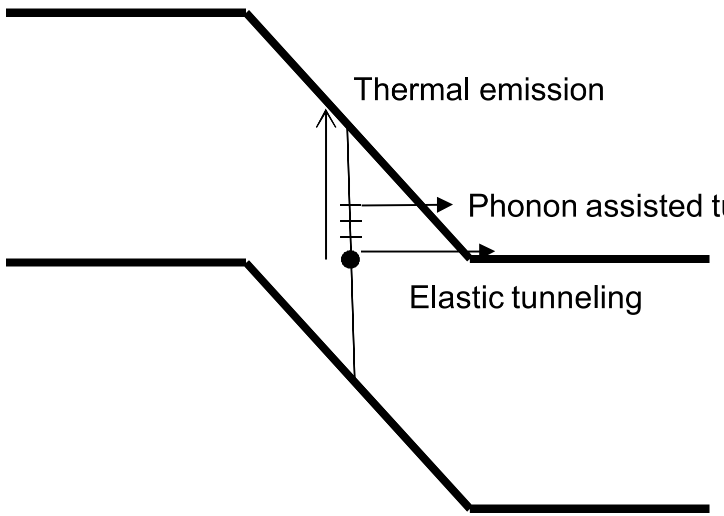
Broad U- & L-bands at high doping (neutron damage)



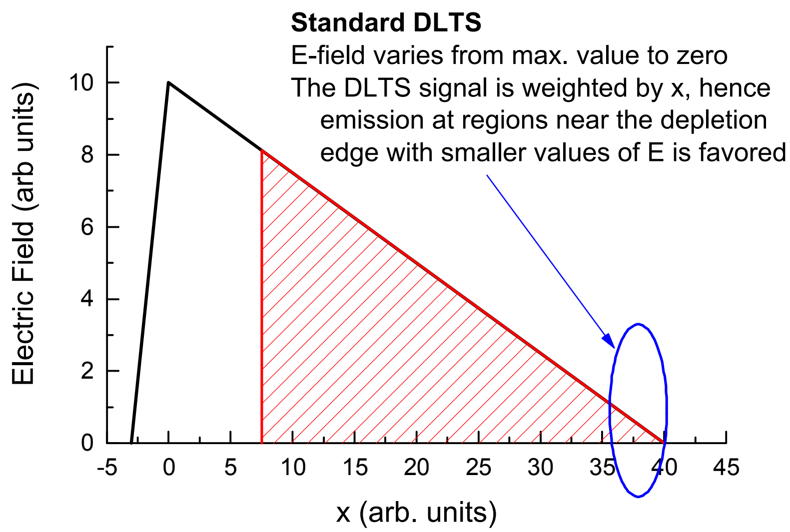
- Depletion widths are narrower at high doping, hence fields are higher
- Broadening is suggestive of field-dependent emission

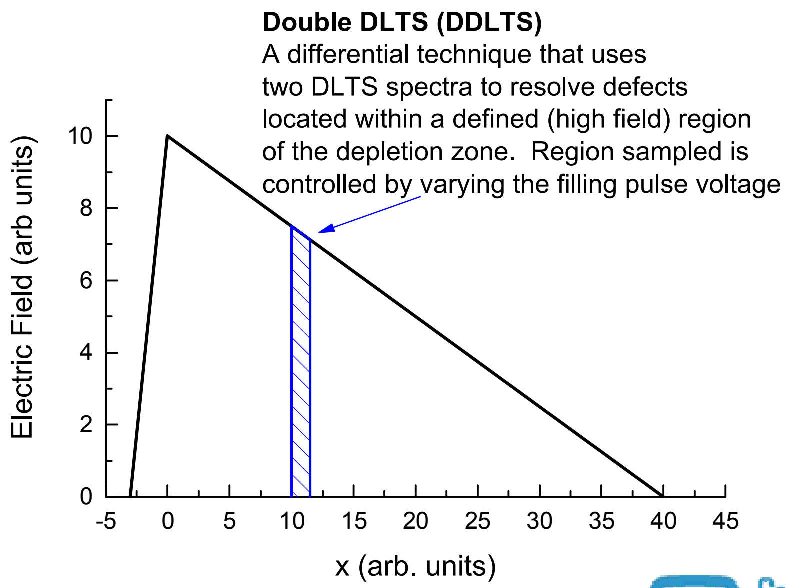


Double DLTS (DDLTS)

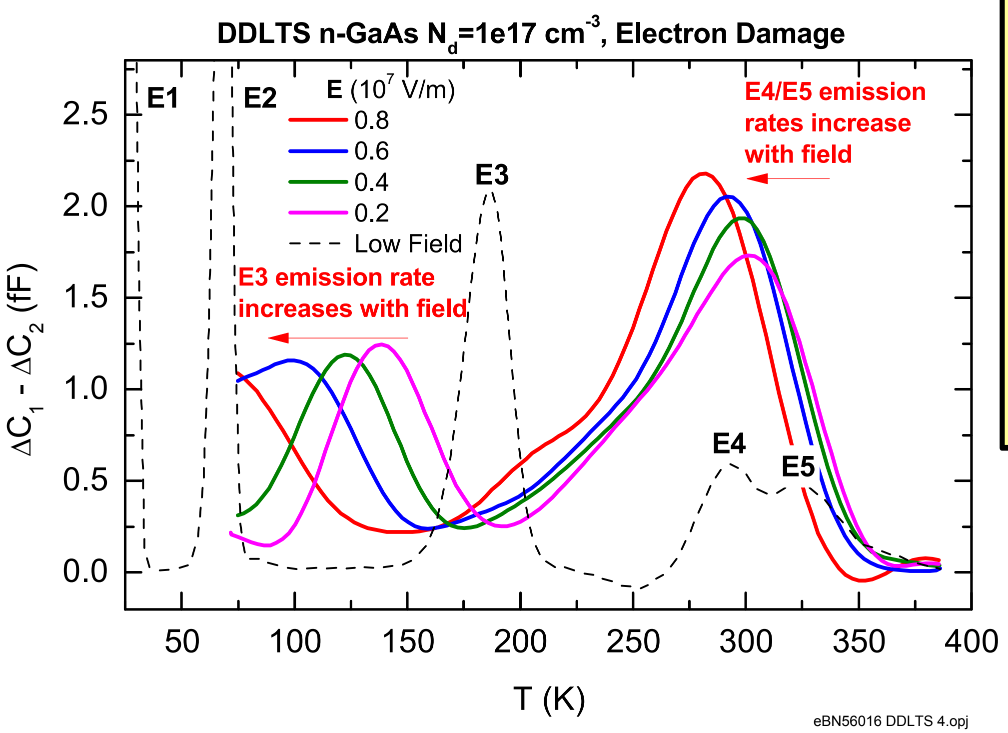


- If emission from a trap is controlled by tunneling, the emission rate will depend on the E-field (and on doping).
- Standard DLTS involves emission from regions with varying E-field, hence DLTS peak shapes will be distorted if tunneling is important.



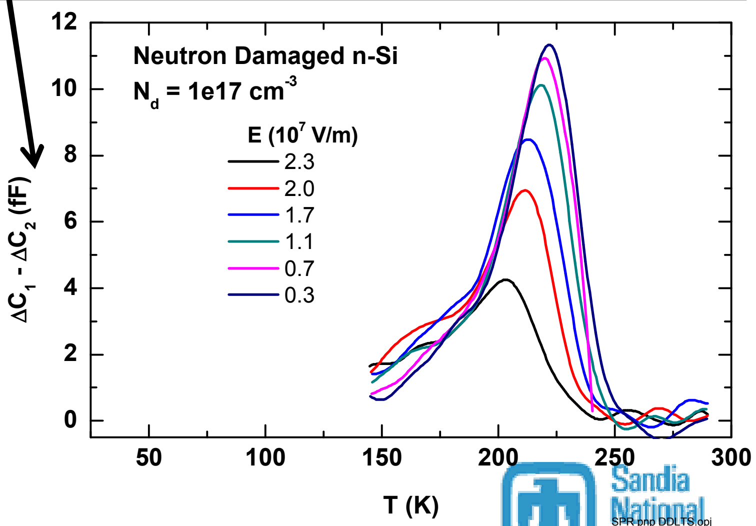


DDLTS: Measure Emission Rate at ~ Constant E-field



E-field dependent emission rate in GaAs:
Goodman, et al., Jpn. J. Appl. Phys. **33**, 1949 (1994).
Auret, et al., Semicond. Sci. Technol. **10**, 1376 (1995).

- Electron damage, no clusters
- Emission rates increases with applied E-field
- Attributed to phonon-assisted tunneling
  - Schenk, Solid State Electronics **35**, 1585 (1992).
- Much smaller rate increase in silicon (Frenkel-Poole emission)



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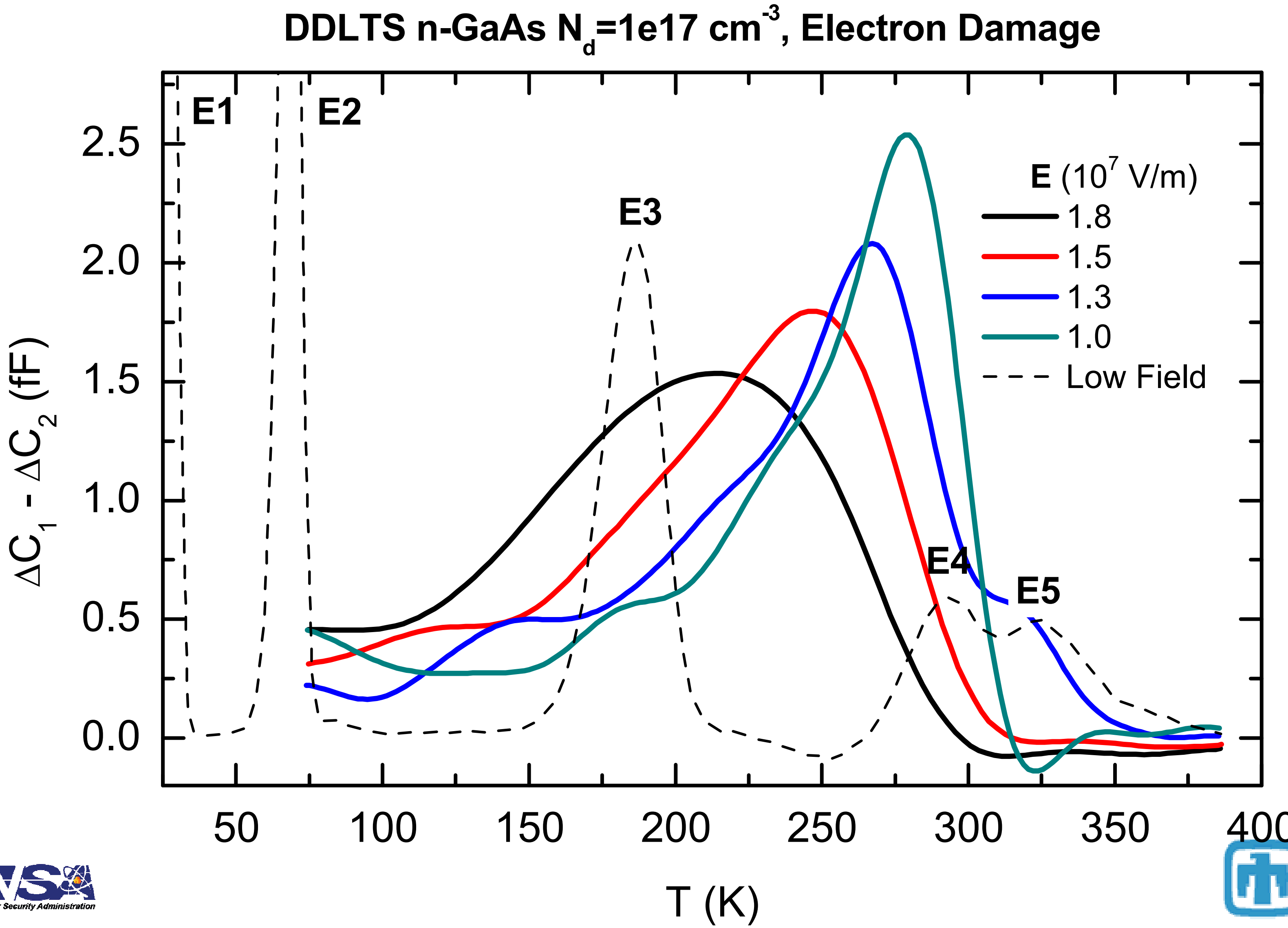
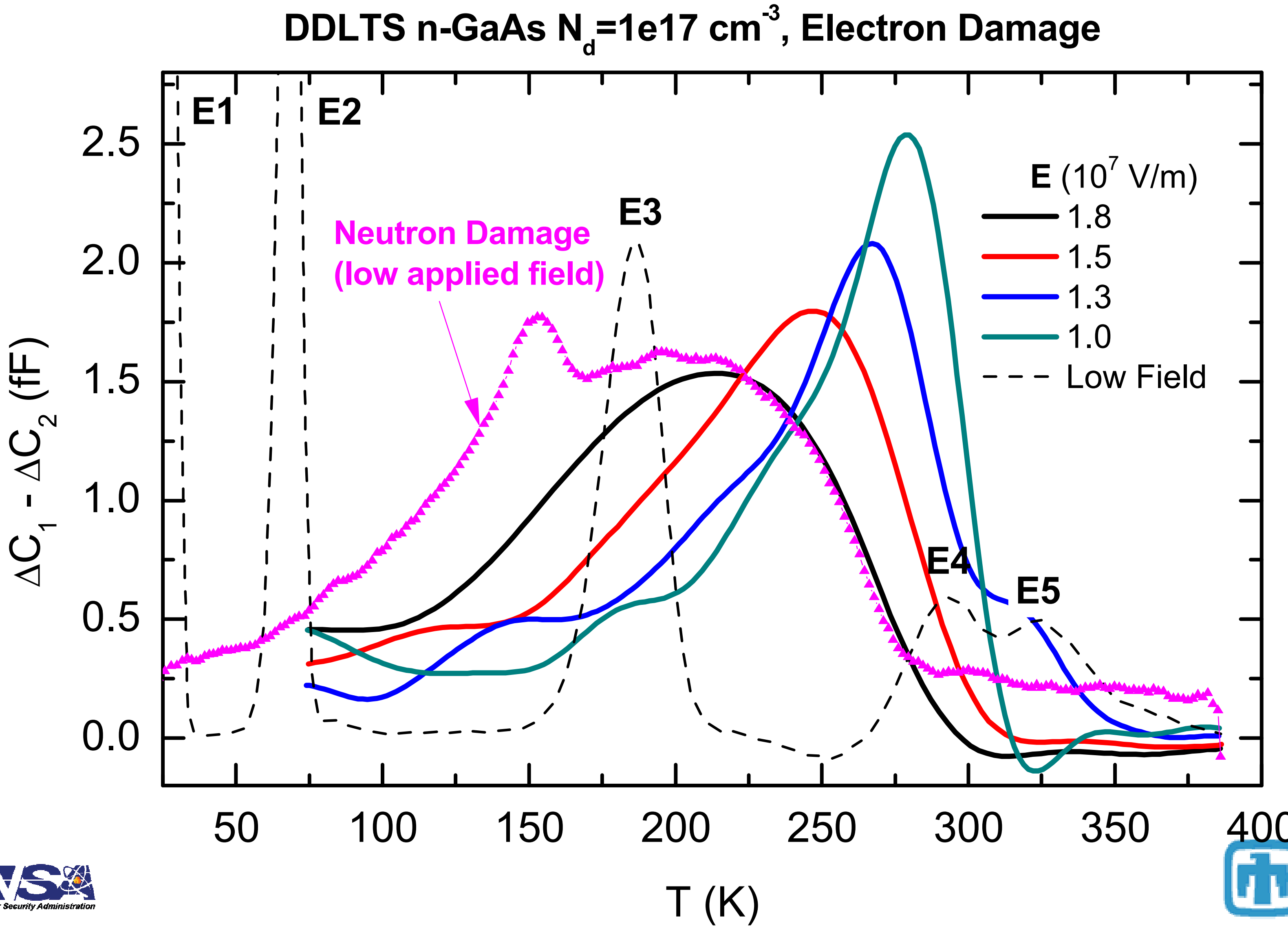
Higher Fields: E5 Resembles U-band



Higher Fields: E5 Resembles U-band



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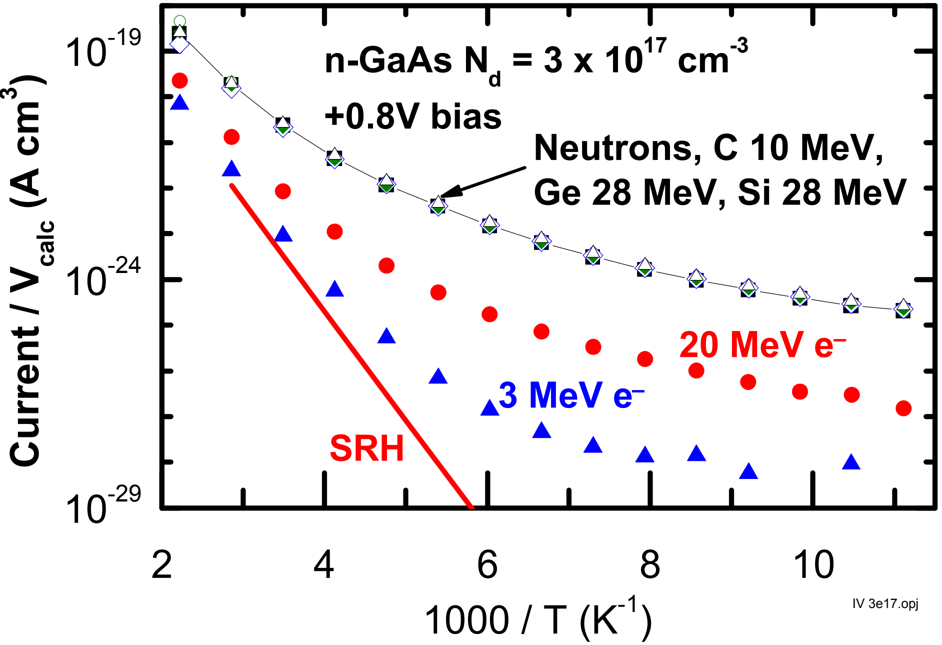
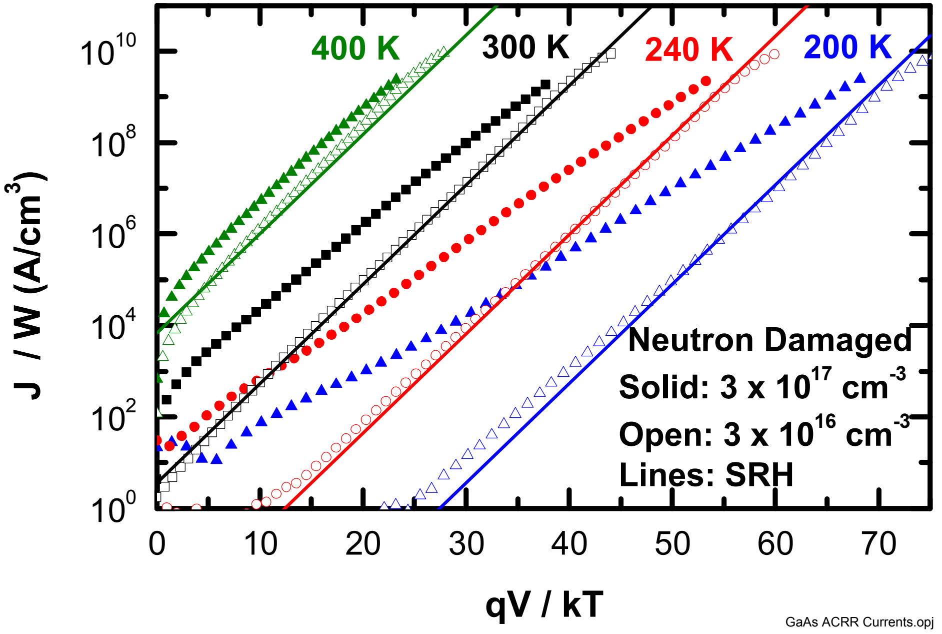
Consequences of Tunneling





- Larger GR currents at high doping due to higher E-fields
- Larger GR currents at lower T SRH is small, but tunneling ~ constant with temperature
- Decrease in excess GR currents as forward bias increases due to lower E-field

Conclusions: Silicon

- Clustered damage
  - DLTS spectra of clustered damage similar to point defect spectrum
    - EOR Si ions produce DLTS spectrum similar to neutrons
  - Additional V_2-like defects – e.g. “strained V_2”
- Ion – neutron damage equivalence
  - DLTS of EOR ion and neutron damage related by simple scale factor
- Defects that affect gain: VP, V_2* and V_2 in BJT base
  - Use annealing to selectively remove defects
  - Requires knowledge of annealing in low-doped collector

Conclusions: GaAs

- Emission from GaAs defects is highly electric-field dependent
  - Consequences on both DLTS and device currents
- DLTS
  - Electric-field broadened DLTS of electron-damaged diodes resembles DLTS of neutron damage diodes
  - U- and L-bands (neutron & ion damage) are likely a combination of field-broadened DLTS & the effects of additional electric fields from damage clusters
- Device currents
  - Excess current in FB diodes beyond standard SRH

Acknowledgements

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