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

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Outline

- **Introduction**
  - Research Objectives
  - DLTS & transistor fundamentals
- **Silicon**
  - BJT collector – the silicon divacancy & its relatives
  - BJT base – the vacancy-donor (VP)
  - Correlating defects and BJT gain
- **GaAs**
  - Phonon assisted tunneling – electric field enhanced emission

Research Objectives

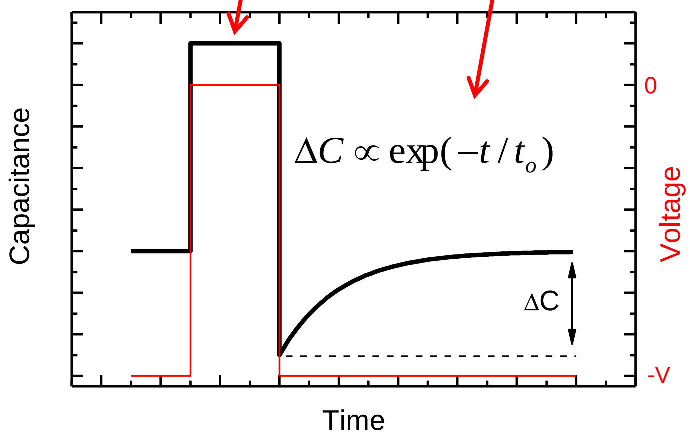
- **Predict performance of bipolar transistors after exposure to <u>neutrons</u>**
  - Data from ion damaged devices
    - Avoid hazards of fast-burst neutron reactors
  - Models of defect evolution are used to connect ion data with neutron predictions [models are not presented in this presentation, see Myers, et al., J. Appl. Phys. **104**, 044507 (2008)]

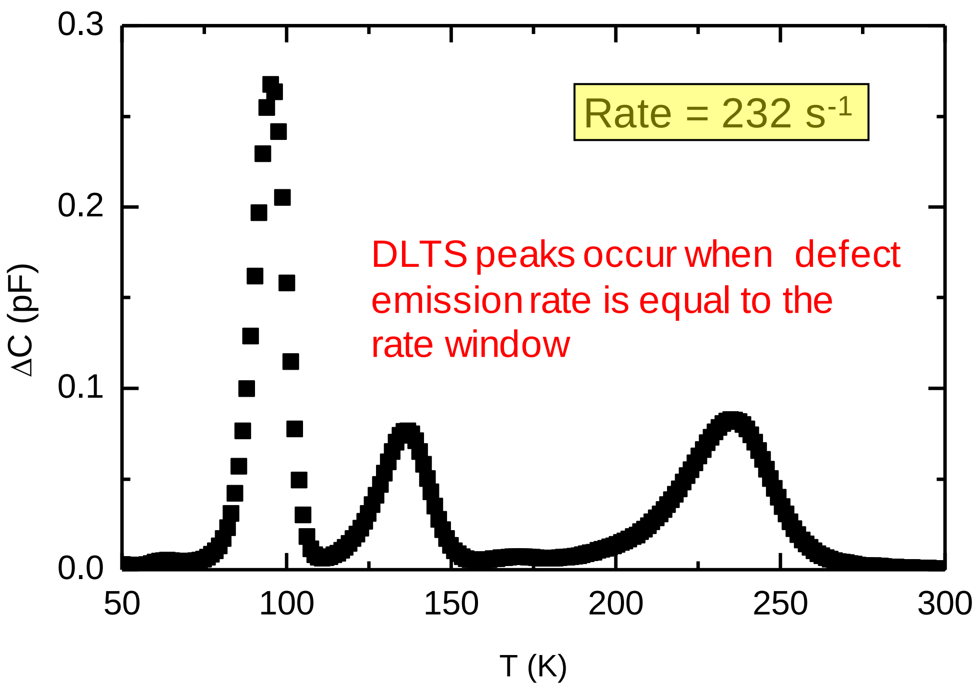
- **Experimental Objectives**
  - Understand effects of defect clustering (DLTS & transistor gain)
  - Correlate gain degradation of BJT's with specific defects (Si)
  - Understand effects of phonon-assisted tunneling (GaAs)

DLTS: Deep Level Transient Spectroscopy

Filling pulse: carrier capture

Transient: carrier emission





# of traps

$$N_t \propto \Delta C$$

Emission Rate

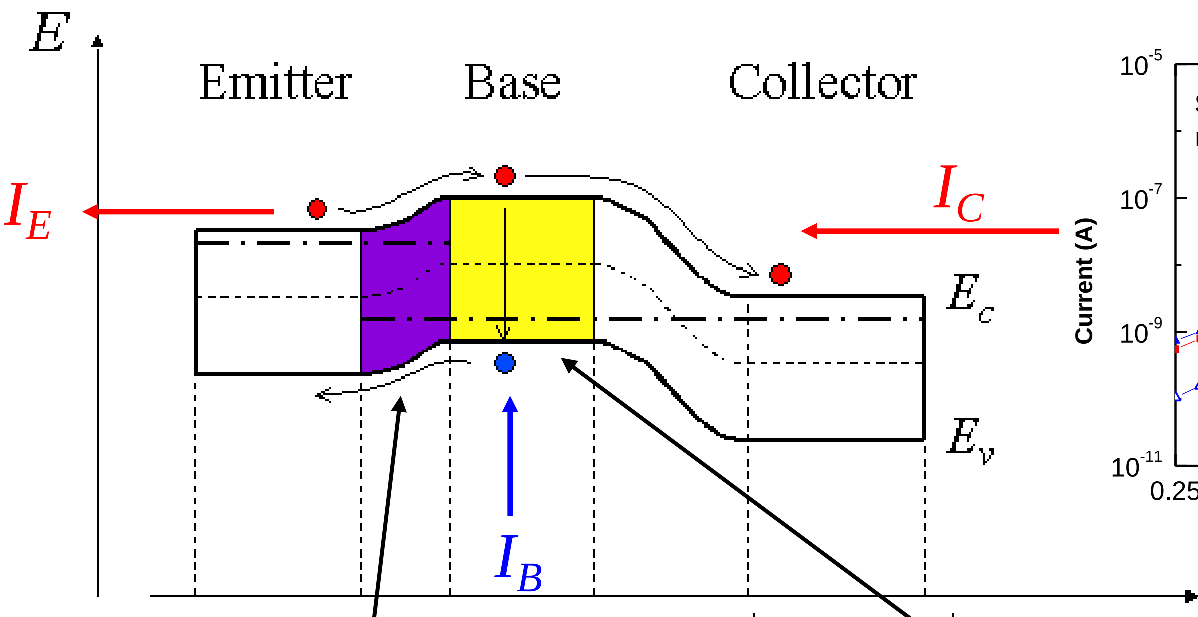
$$\frac{1}{t_o} \propto \frac{\exp([E_c - E_t]/kT)}{T^2}$$

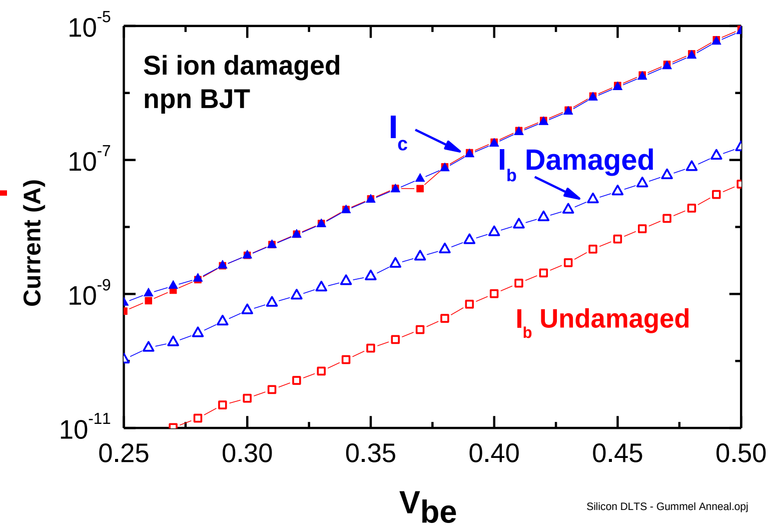
Shallow (near E_c)

Deep (near midgap)

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

Location of Generation-Recombination



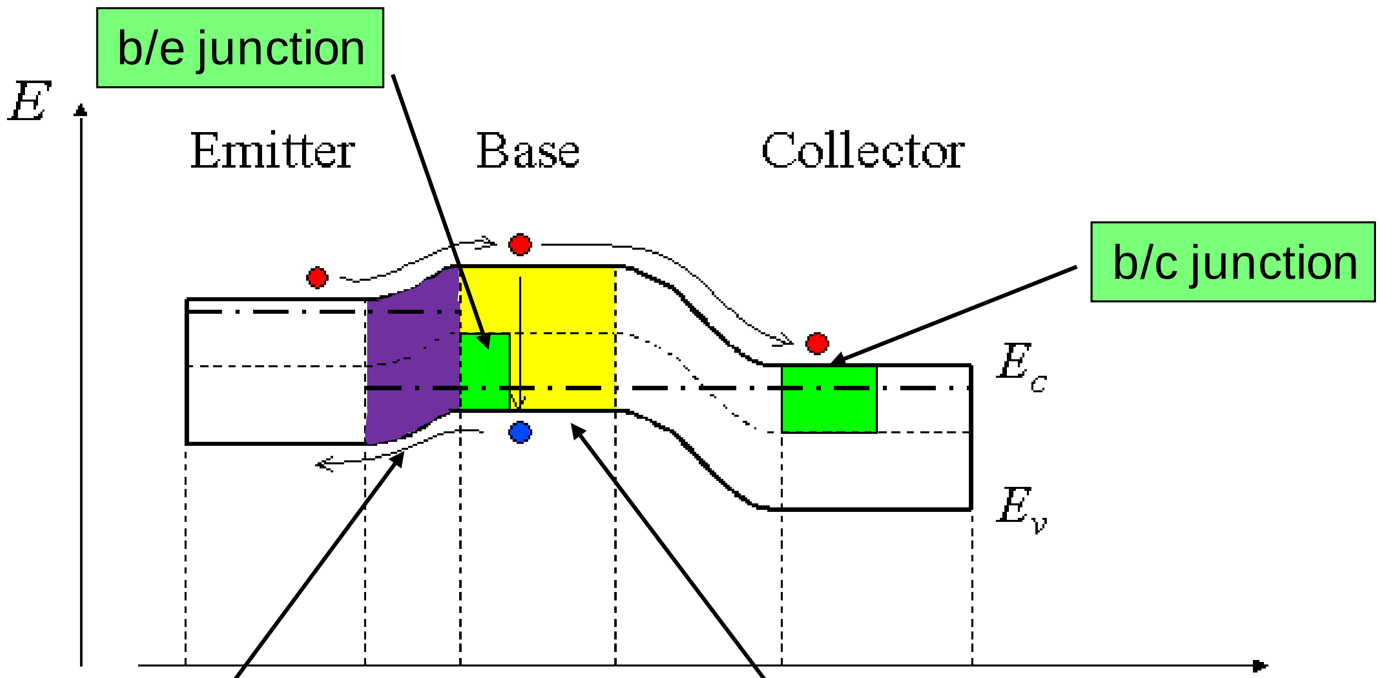


$$\text{Gain} = I_c / I_b$$

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

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

DLTS Locations



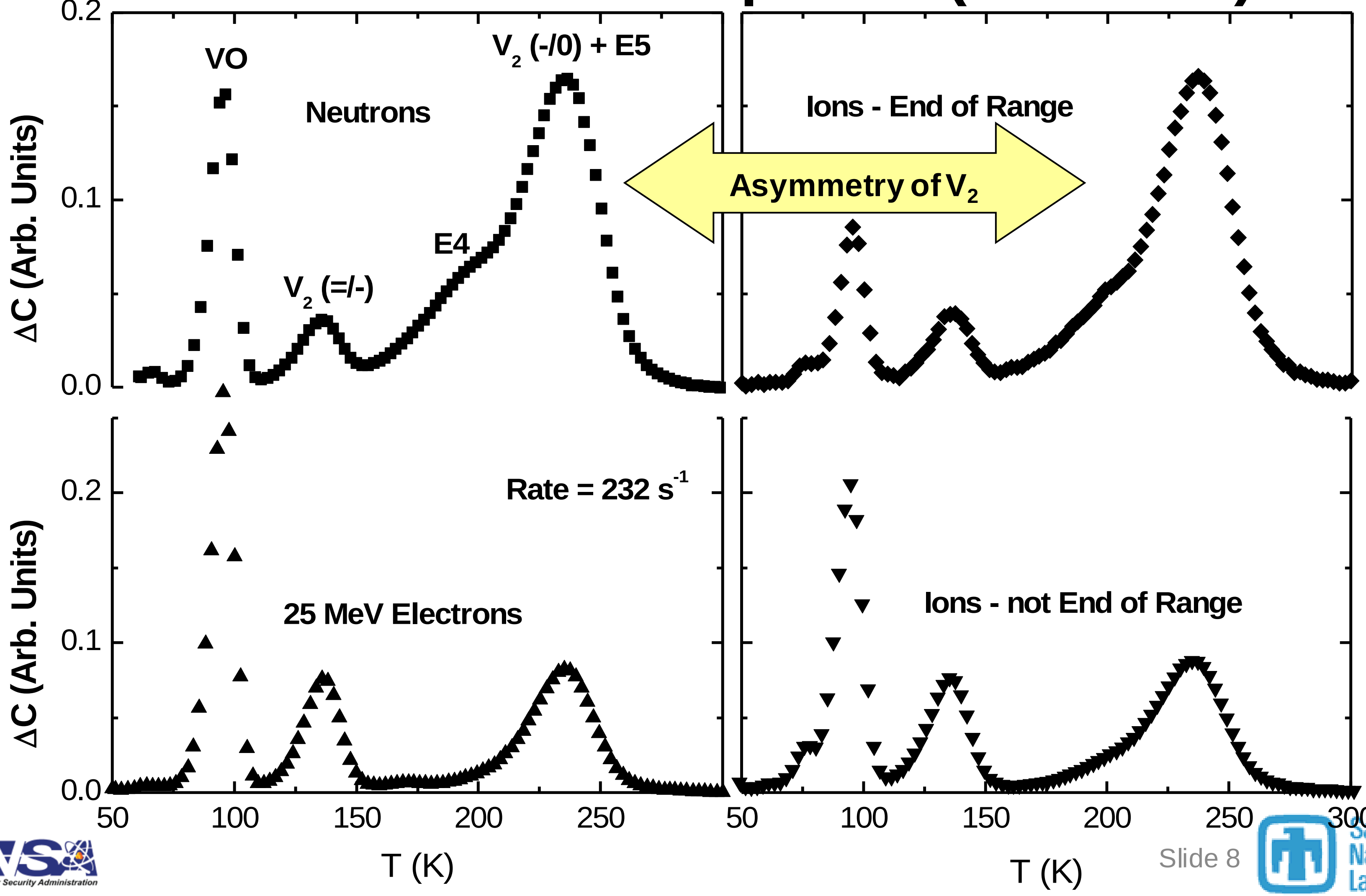
Recombination at low current in **b/e depletion region**

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

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

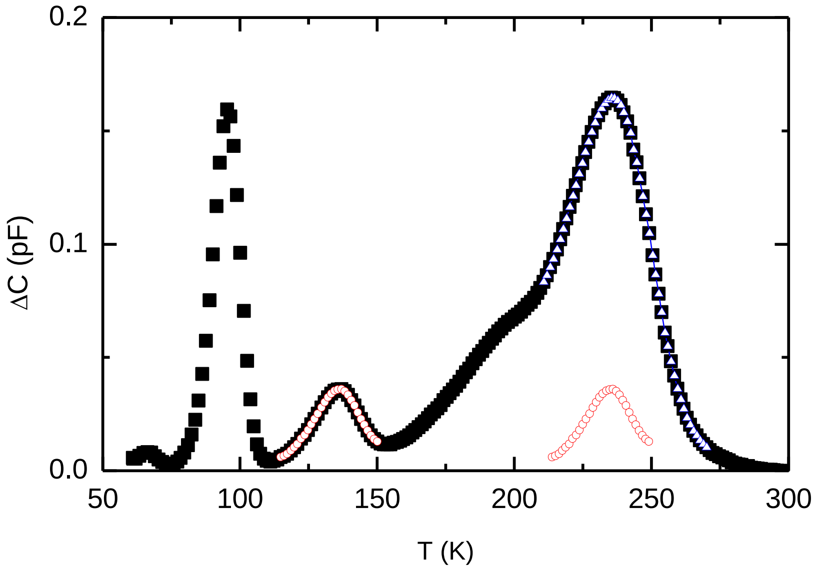
NEUTRON AND ION DAMAGE

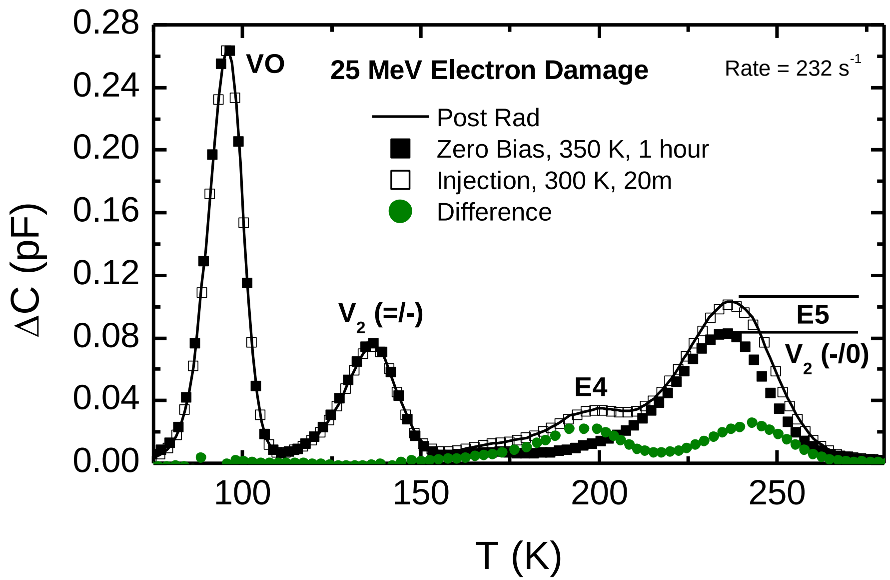
Point defect spectra (electrons) are related to clustered defect spectra (neutrons)



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

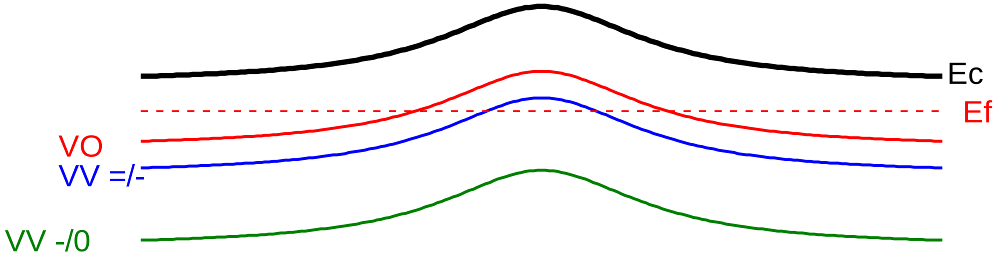




Note the quotes around "V_2". We do not know the exact structure or composition of the strained or bistable "V_2".

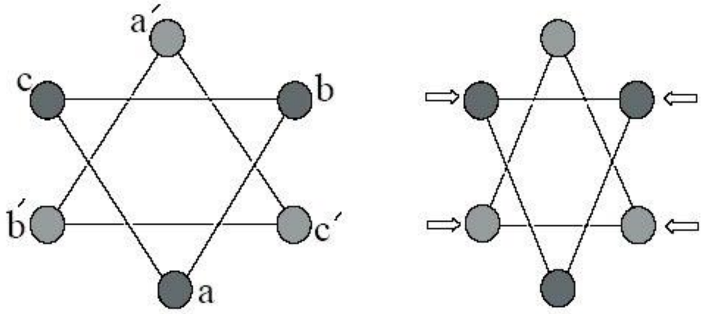
Why is there a V_2 asymmetry?

- Partial filling of the shallow V_2 double acceptor level.



- 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

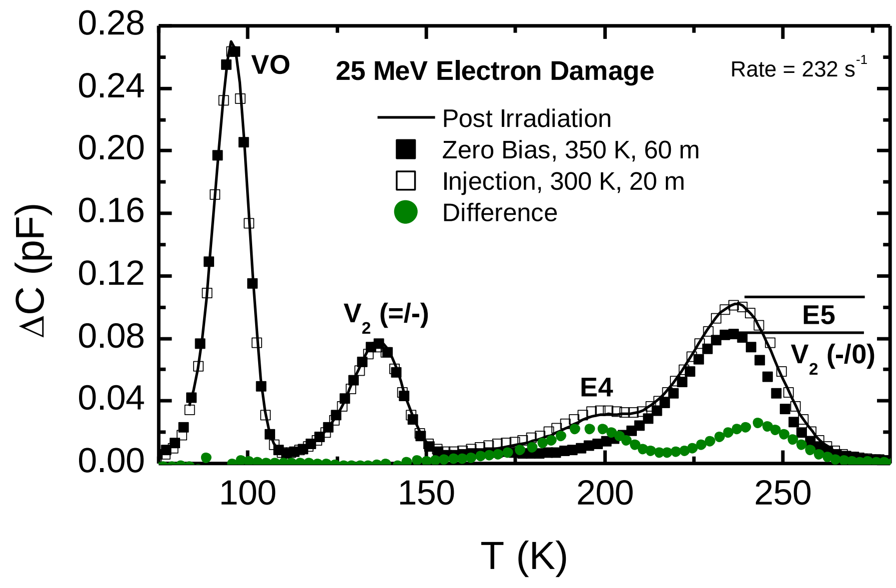


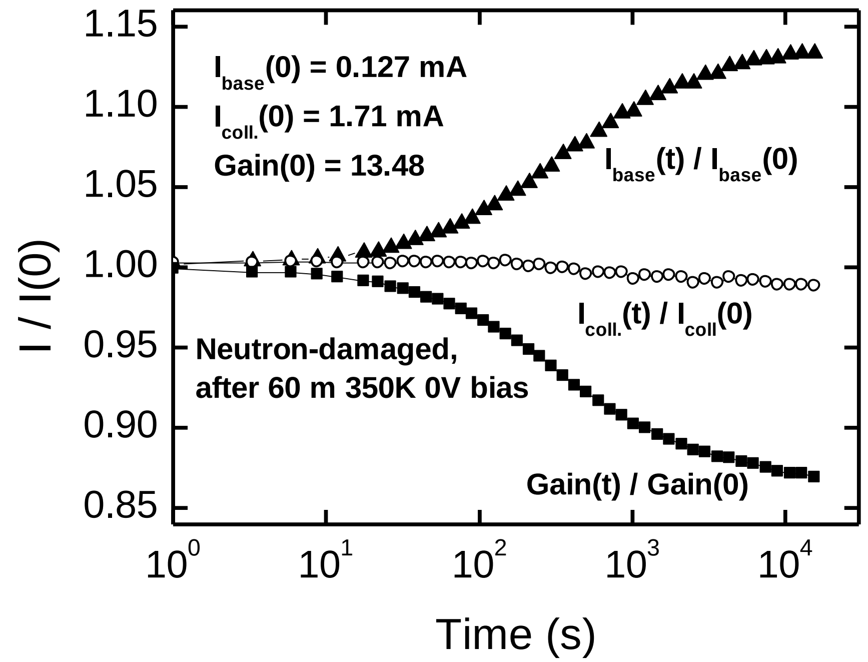
JT Distorted
T < 20 K
or strained Si

- Different structure of the defect, e.g. $V_2 + I_n$

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.

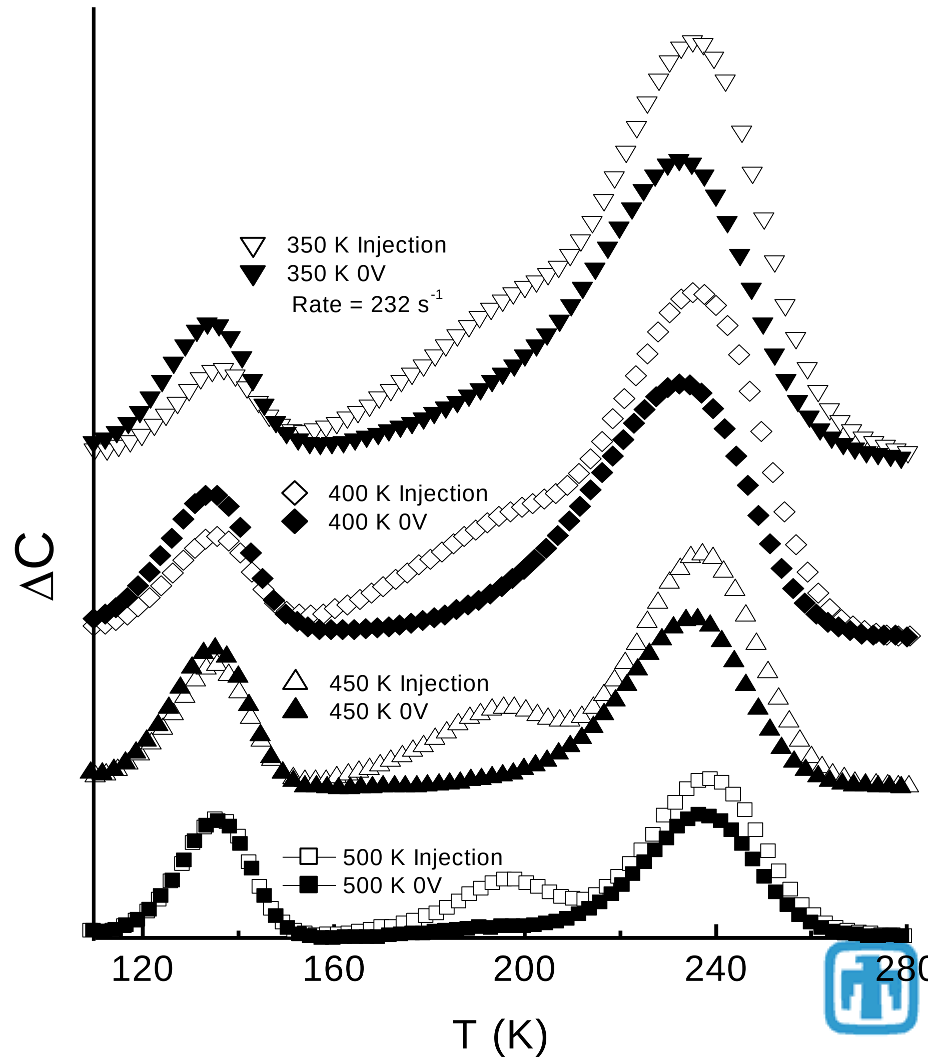




R. M. Fleming, C. H. Seager, D. V. Lang et al., Appl. Phys. Lett. **90**, 172105 (2007).

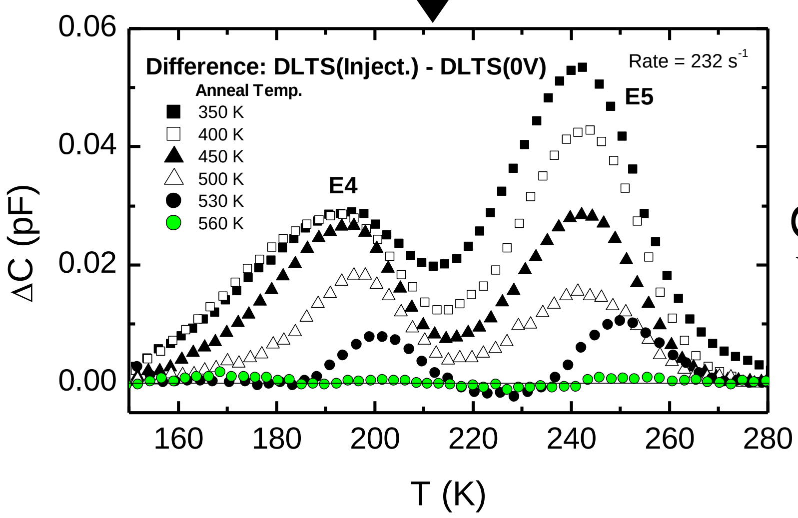
Annealing of Bistable E4-E5

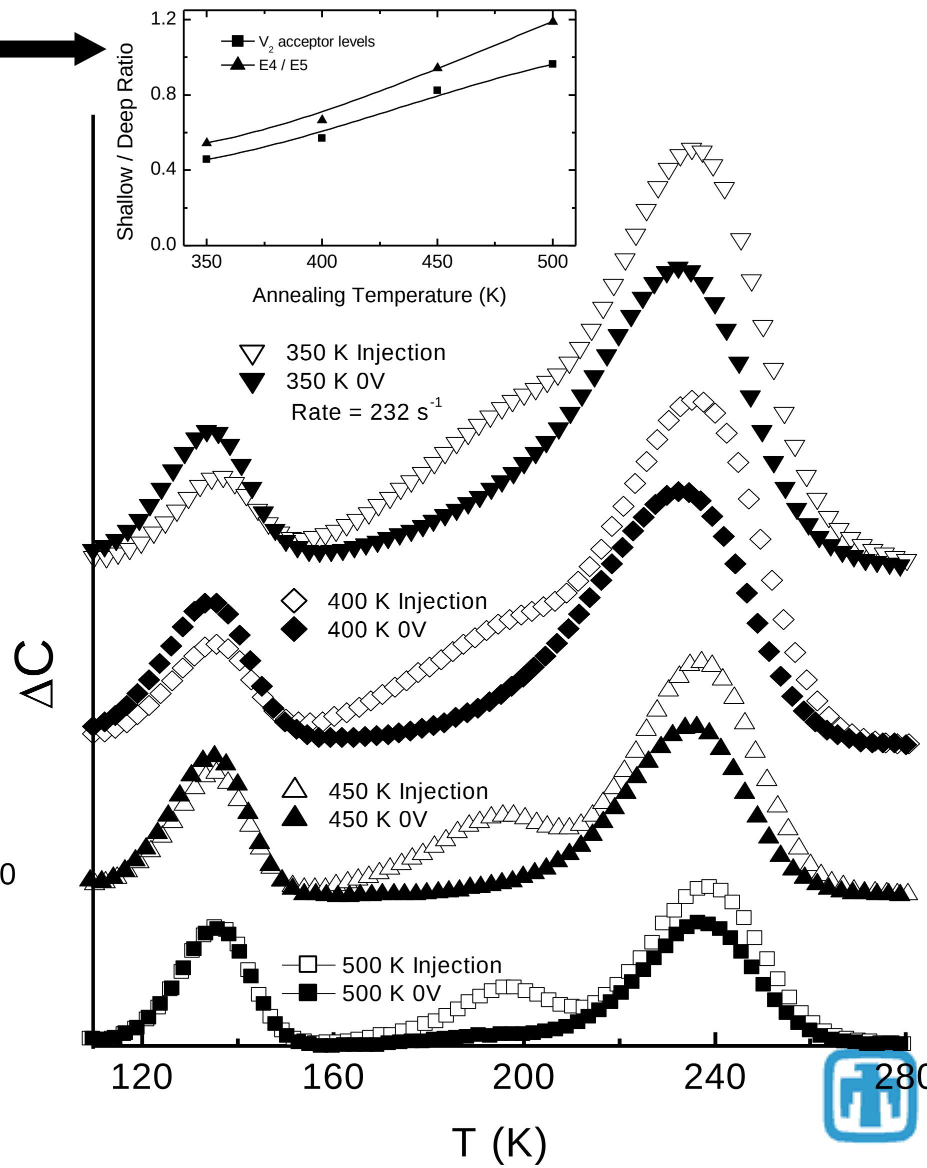
Neutron Damaged



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

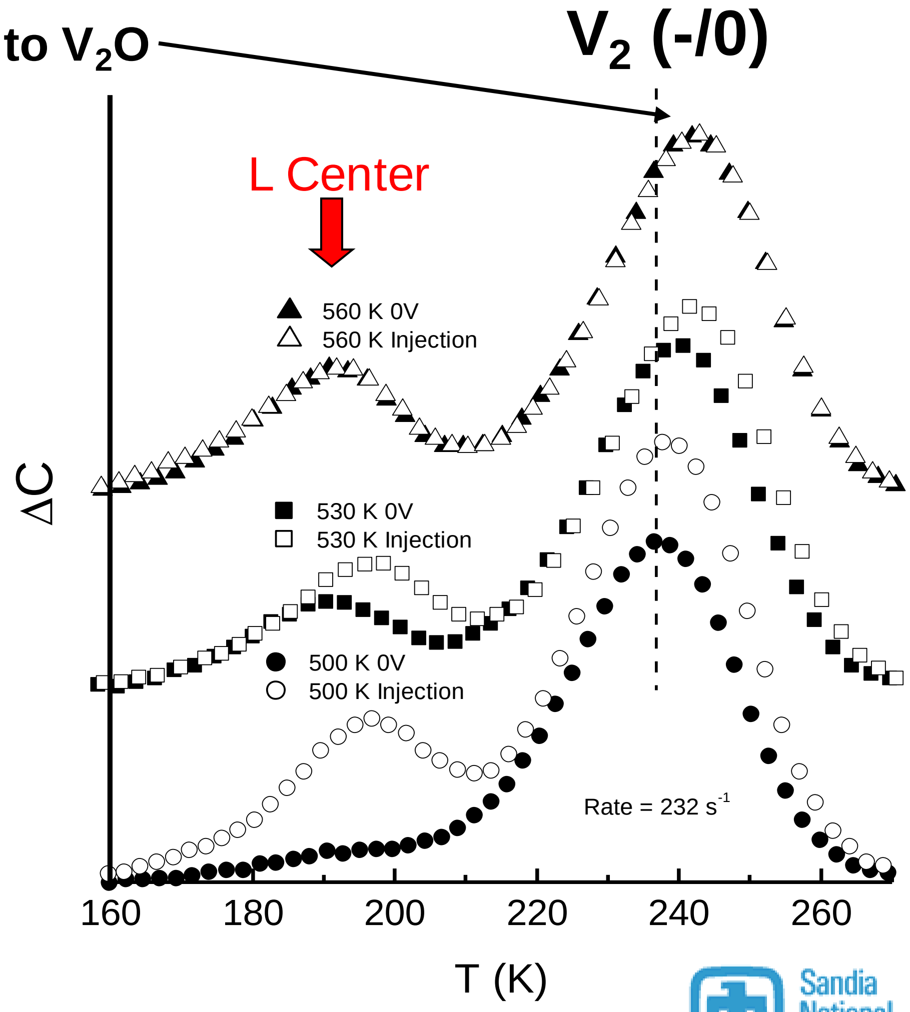




- Bistability remains until 560 K

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

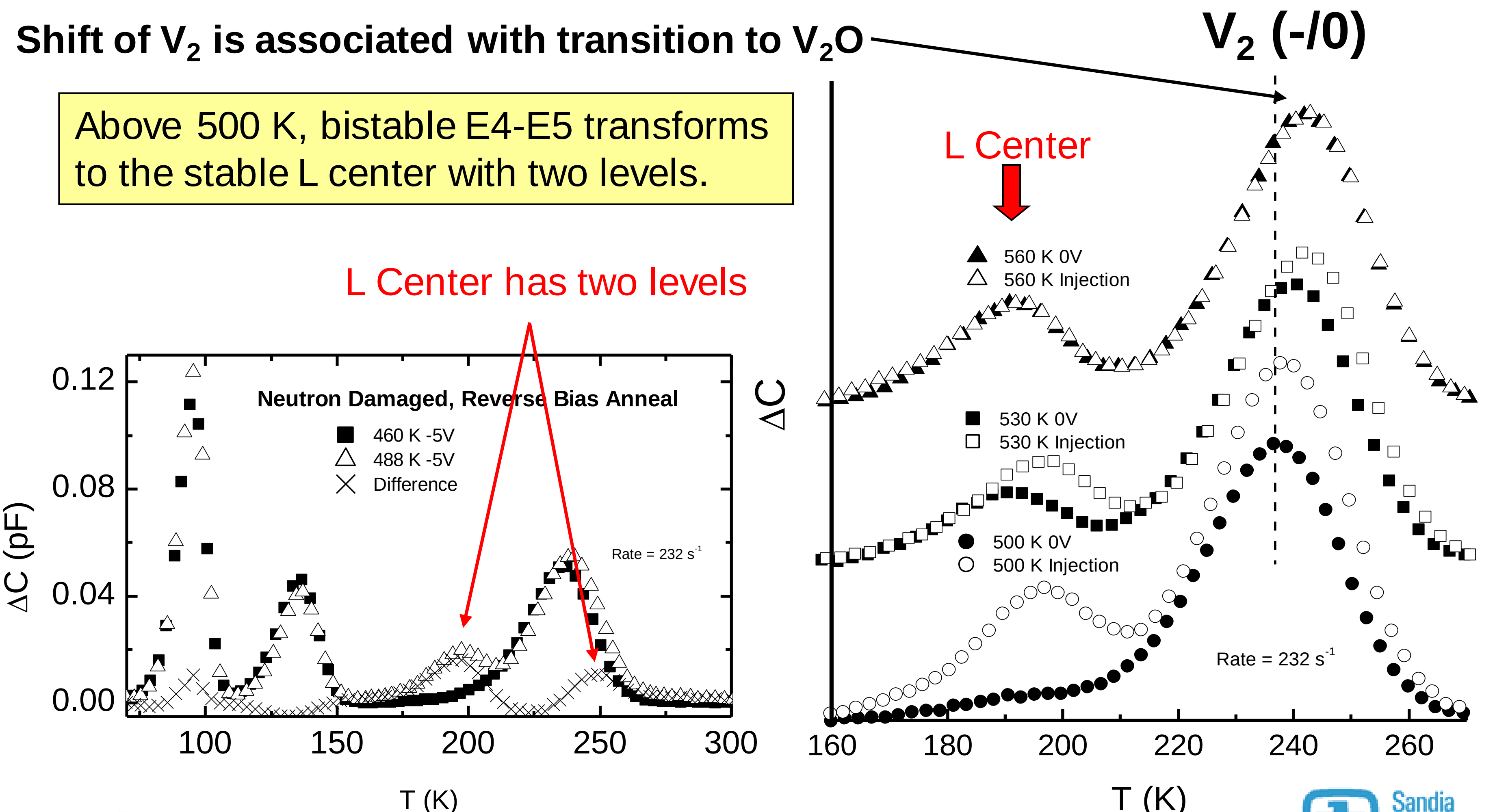
Shift of V_2 is associated with transition to V_2O



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

Shift of V_2 is associated with transition to V_2O

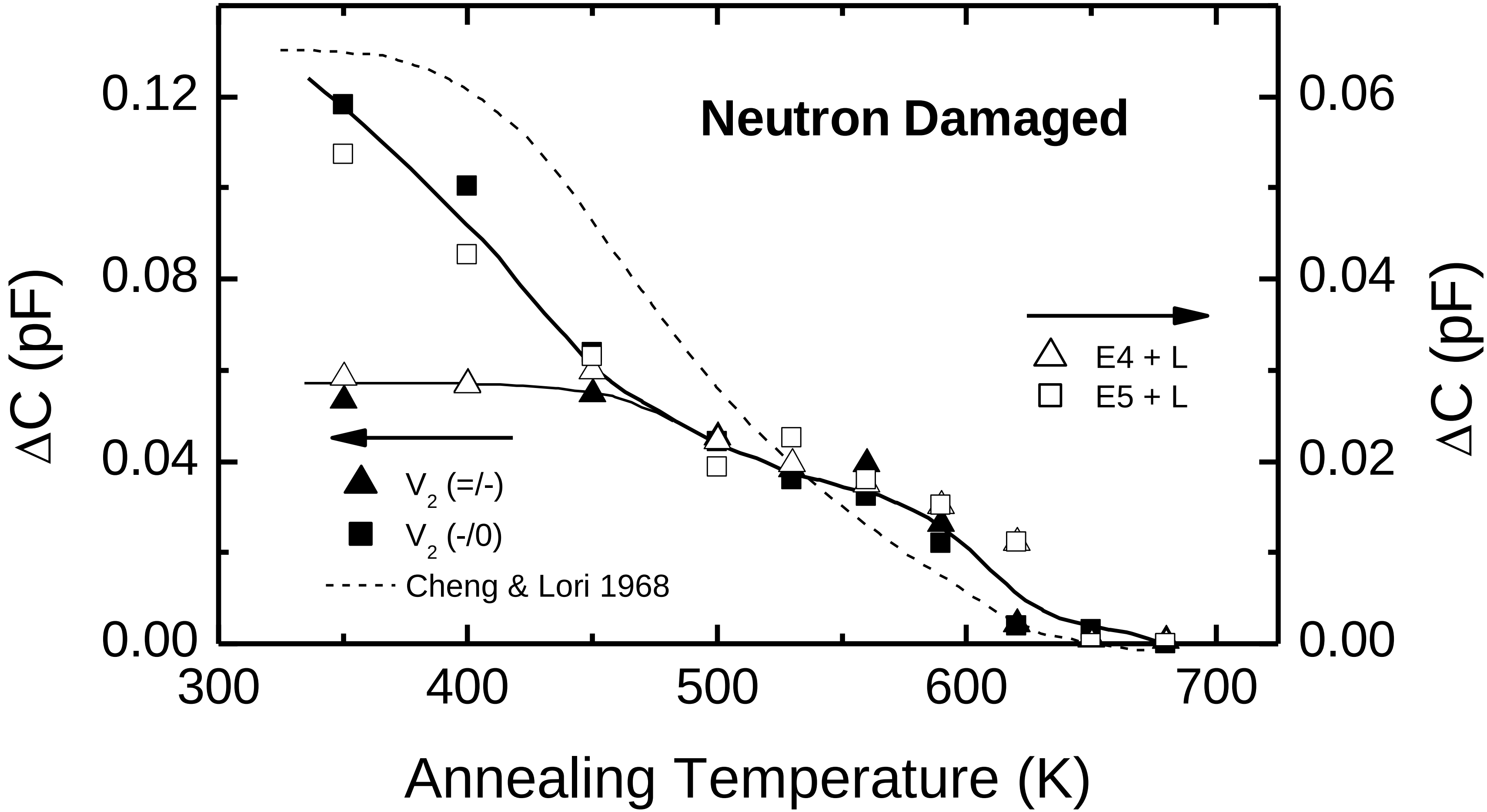
Above 500 K, bistable E4-E5 transforms to the stable L center with two levels.



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

Bistable E4-E5 and V_2 Annealing

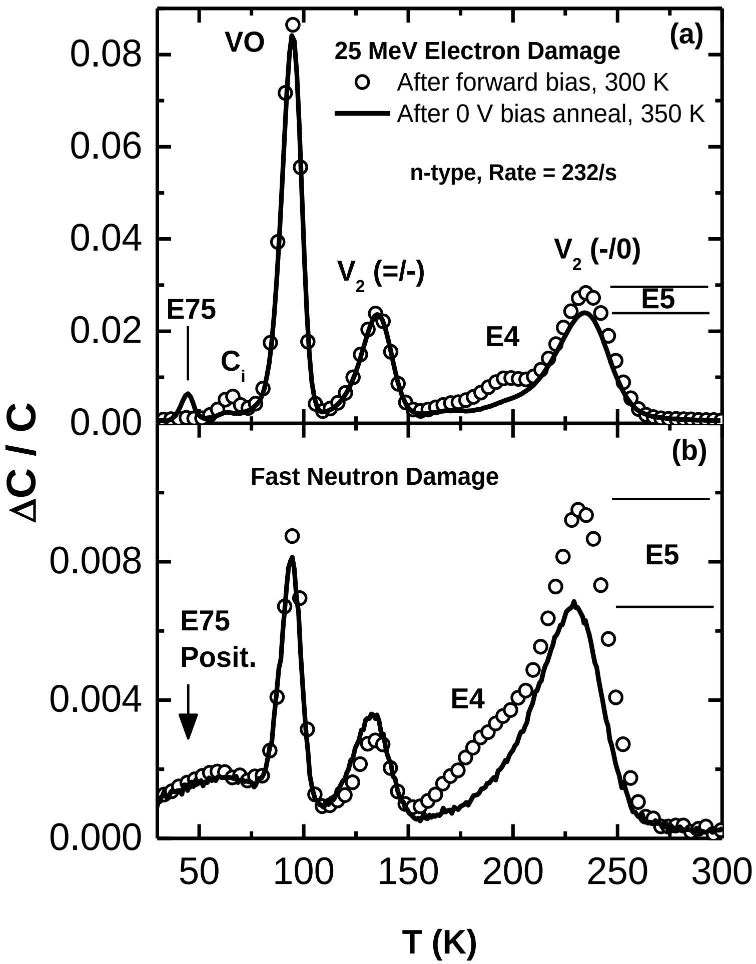
E4-E5 has the same annealing characteristics and level asymmetry as the strained V_2 seen after neutron or other clustered damage.

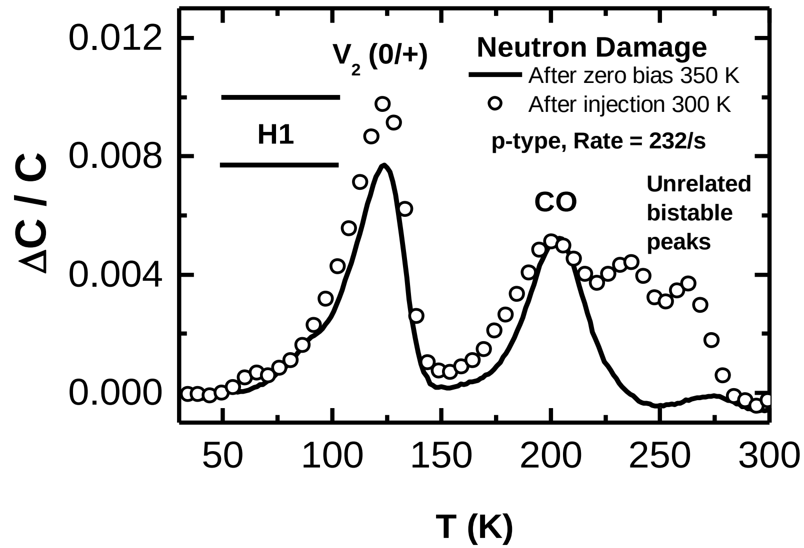


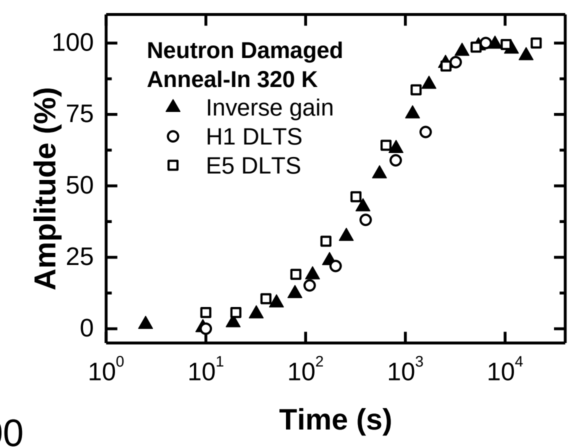
Fleming, et al., J. Appl. Phys. **104**, 083702 (2008)

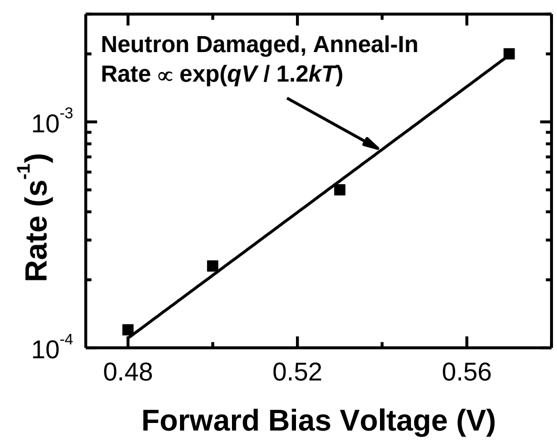
Kinetics of Bistable V_2

Stable phase: E75
Metastable phase: E4, E5, H1









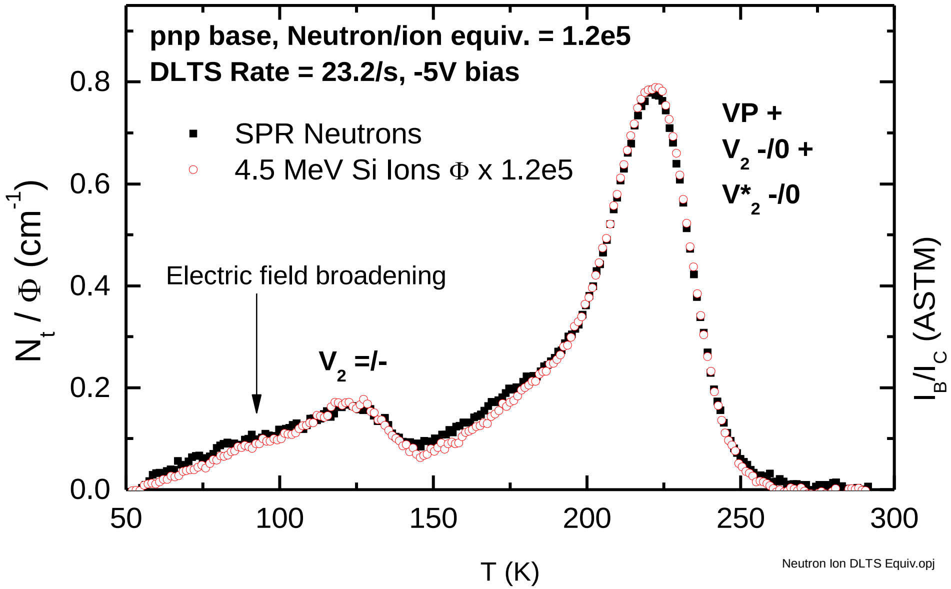
Fleming, et al., J. Appl. Phys. **111**, 023715 (2012)

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

NEUTRON AND ION DAMAGE

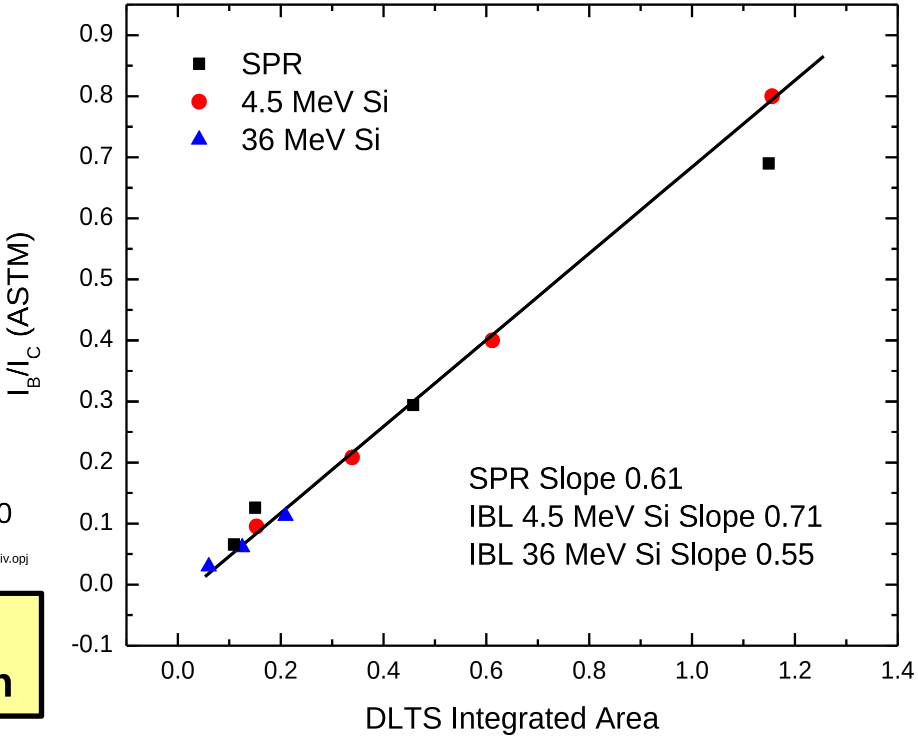
Neutron – Ion Equivalence using EOR Silicon Ions

Exact match of neutron & ion DLTS spectra in pnp base

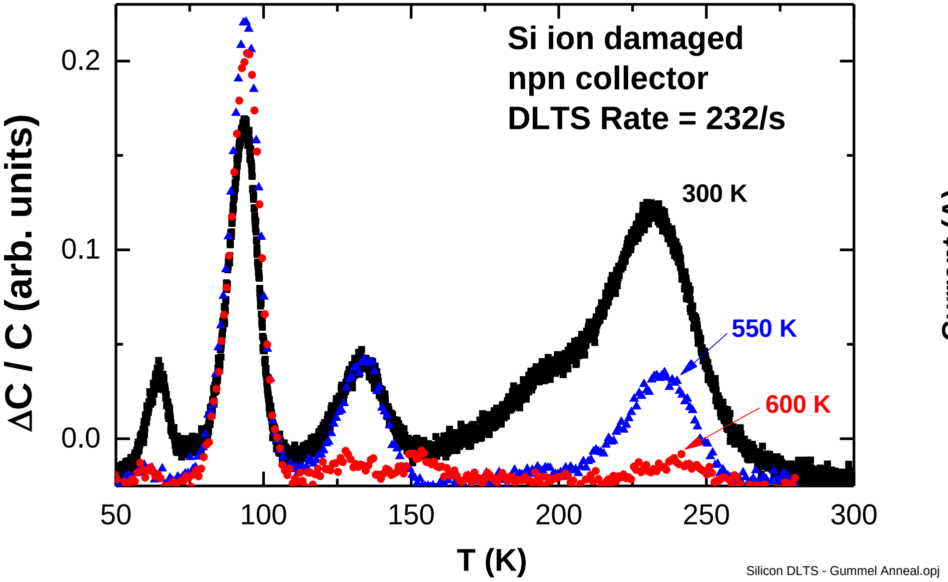


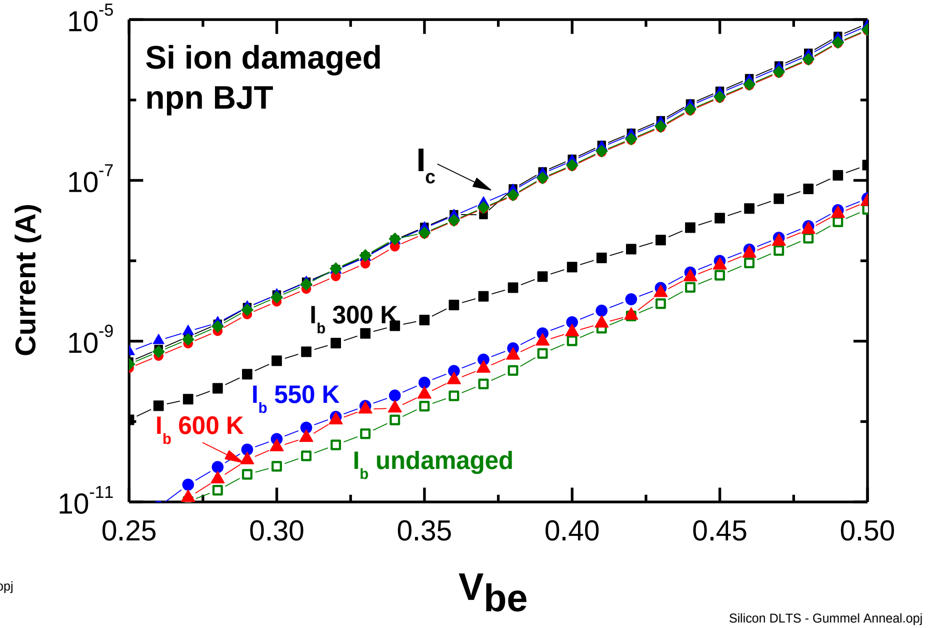
Si ion energy chosen to place the ion end-of-range (EOR) at the emitter-base junction

Linear relationship between inverse gain and DLTS amplitude



Correlating DLTS & Gain

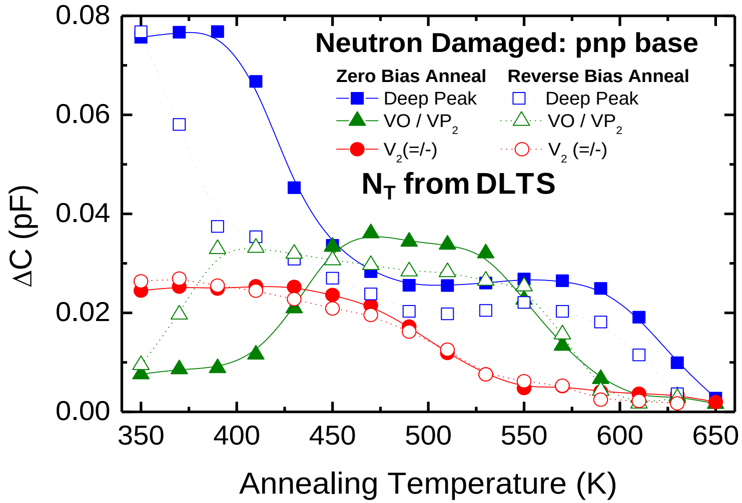


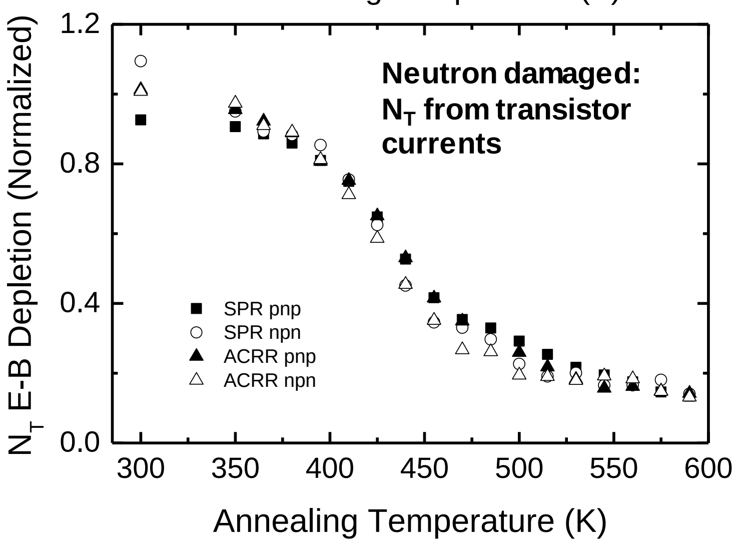


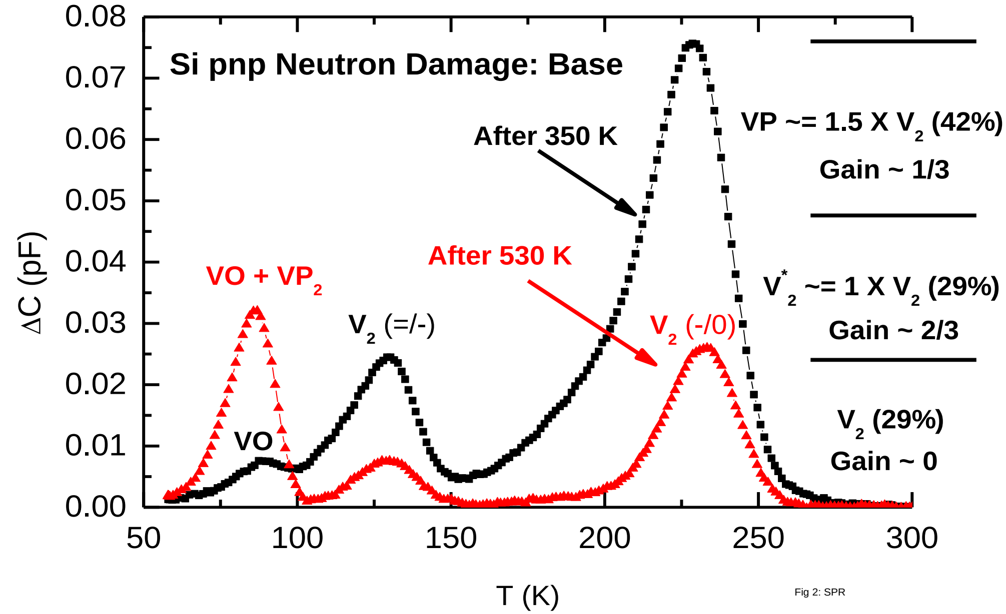
In the npn collector after 550 K, normal V_2 remains while the strained V_2 has annealed away. Little additional gain recovery occurs after 600 K where the normal V_2 anneals.

Similar results are obtained for the pnp transistor. Correlate DLTS and gain using the pnp base.

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







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

Polynomial empirically determined from pnp base

Polynomial empirically determined from npn collector

= constant

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

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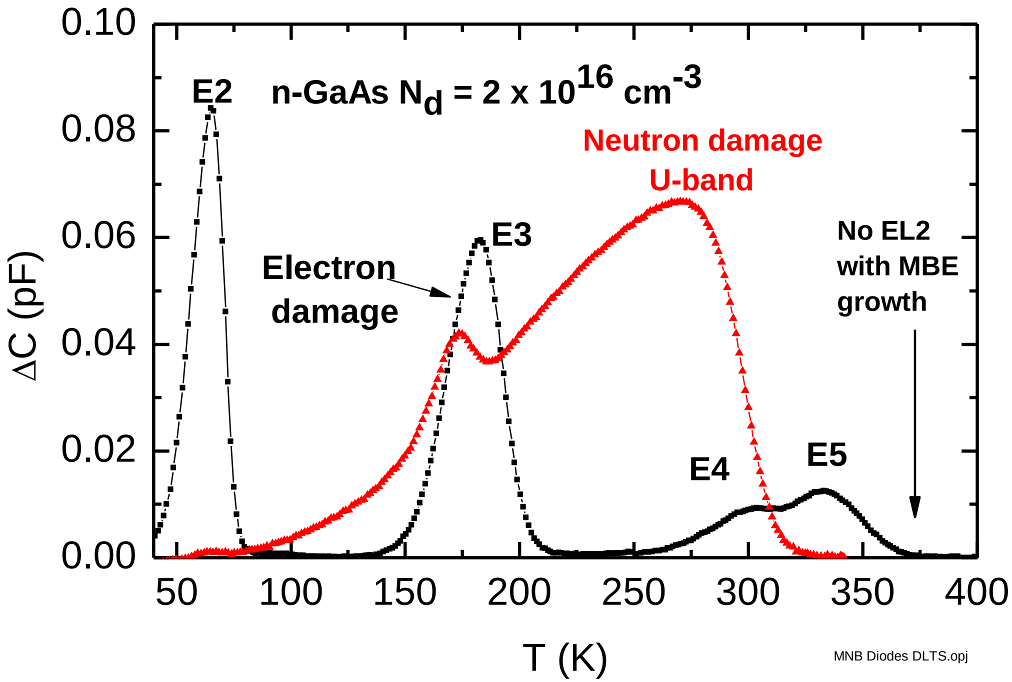
DEFECTS IN GaAs – ELECTRON & NEUTRON DAMAGE

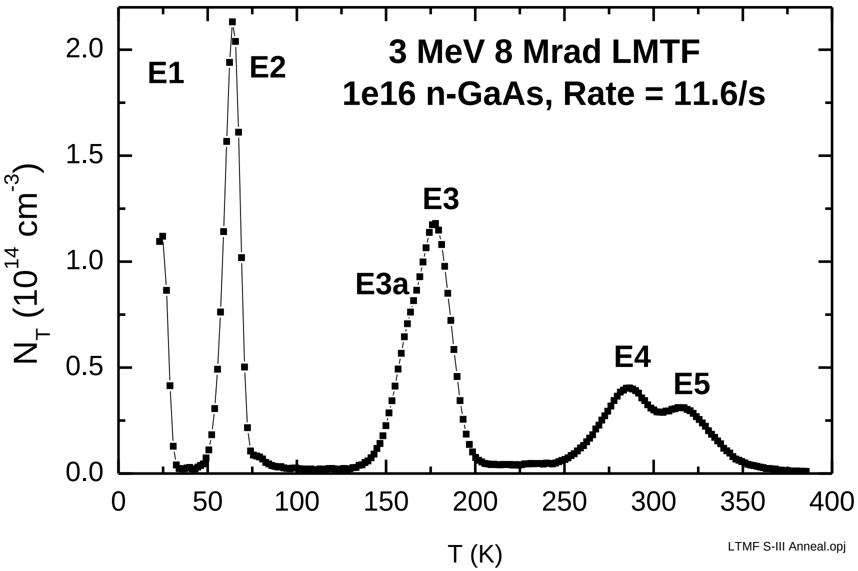
DLTS in GaAs : Analysis is more complex

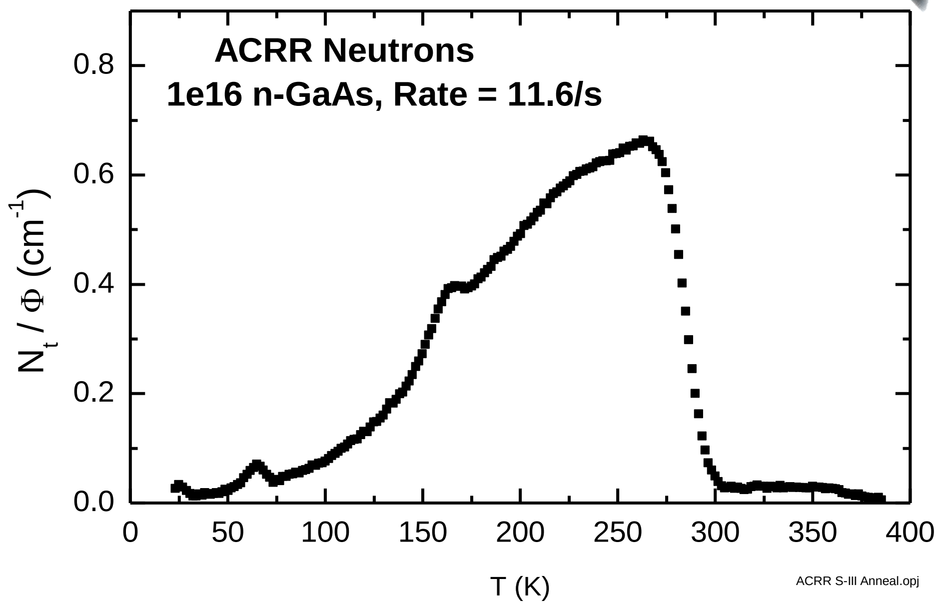


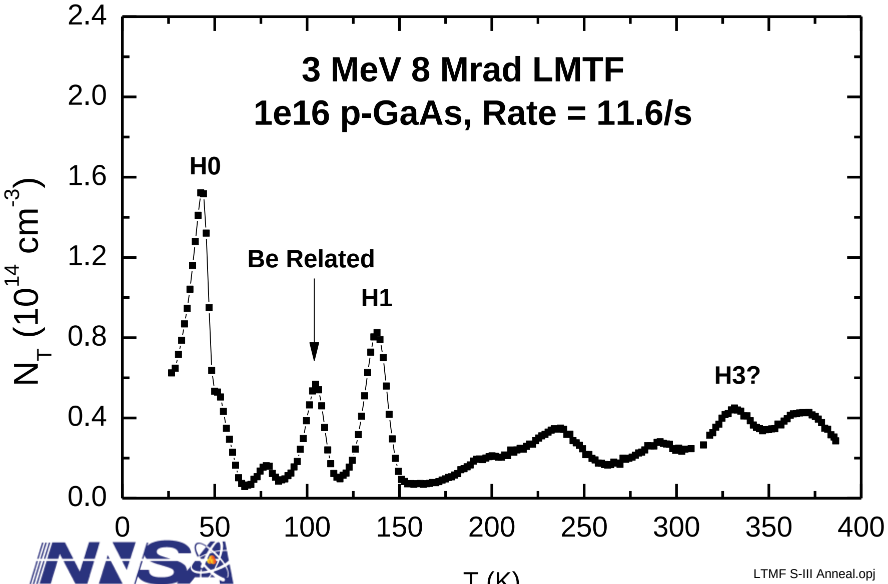
- **Neutron spectra is radically different from electron damage.**
- **The broad features after neutron/ion damage are known as the "U-band" (n-GaAs) and the "L-band" (p-GaAs)**

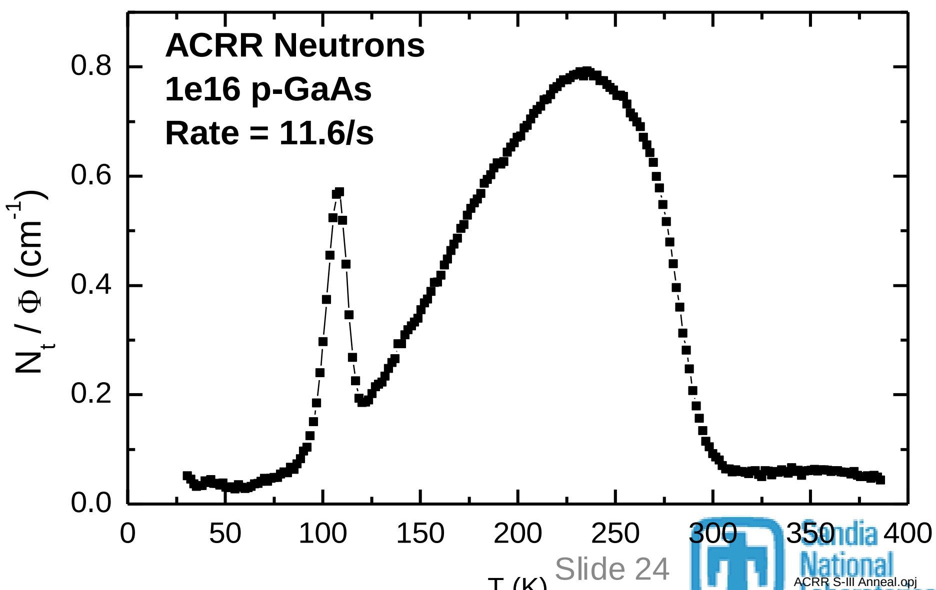
	Silicon	GaAs
Defect library from prior work	Extensive (from EPR/DLTS)	Minimal (EPR not effective)
Additional defect species in clusters	A few, e.g. bistable V_2, strained V_2	Unknown at present, work in progress
Electric-field enhanced emission from defects (phonon assisted tunneling)	Minimal	Extensive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

Clustered & Non-clustered Damage

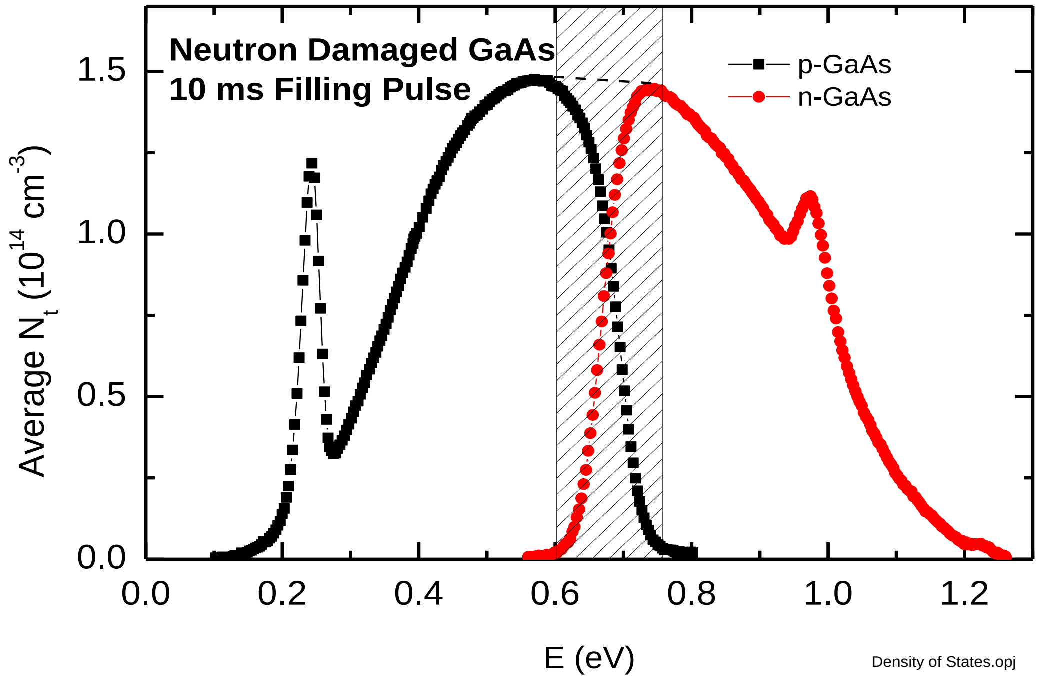








Neutron Damaged GaAs

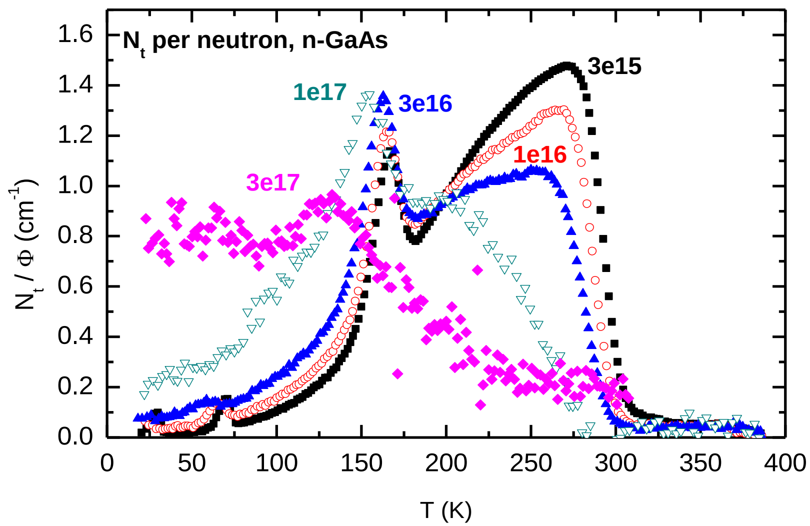


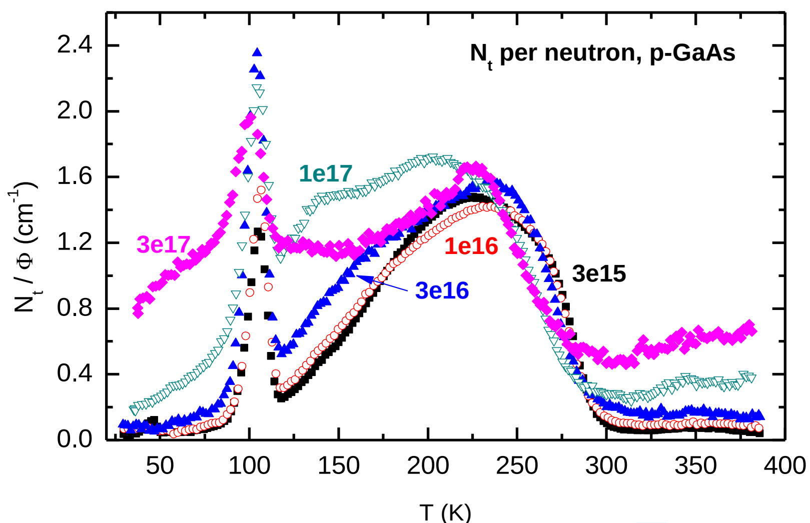
- **Neutron damage causes expansion of the GaAs lattice**
  - Decrease of GaAs bandgap
- **Bandgap decrease of 0.16 eV results in overlap of U- and L-bands & apparent continuous distribution of defect states across midgap**
- **Cause?**
  - Inhomogeneous broadening , e.g. strain broadened defect levels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

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

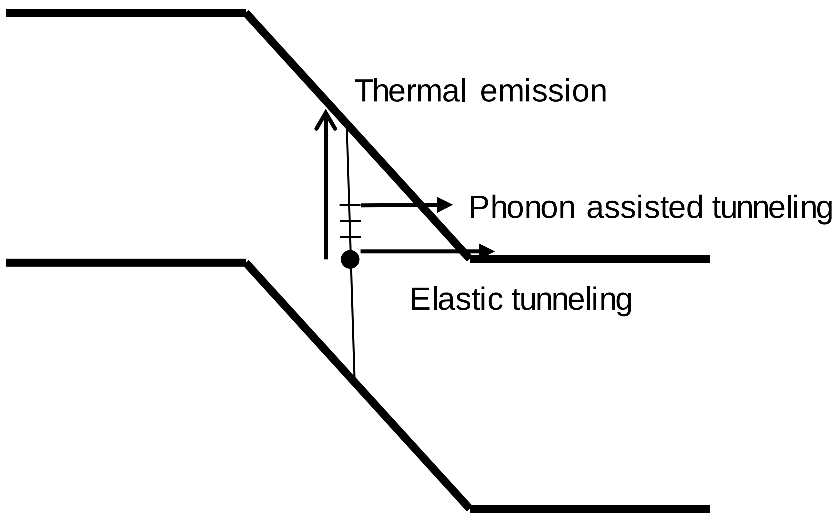
Broad U- & L-bands at high doping (neutron damage)

- U- and L-bands broaden as doping is increased
- Electric fields are higher in high-doped diodes (depletion widths are narrower)
- Broadening is suggestive of electric-field enhanced emission due to tunneling

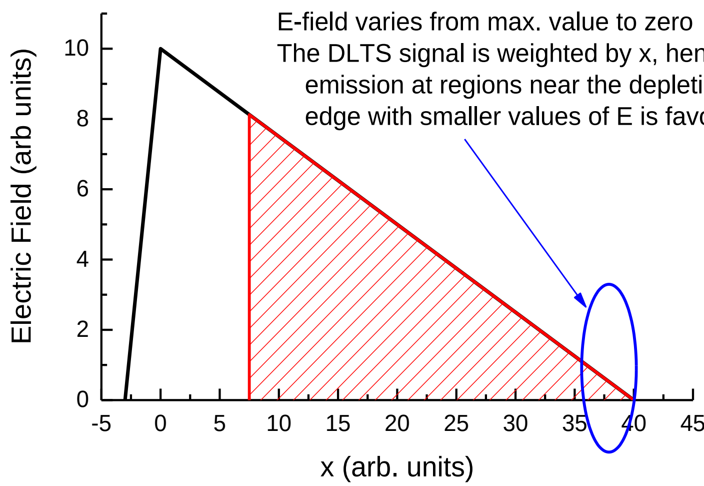


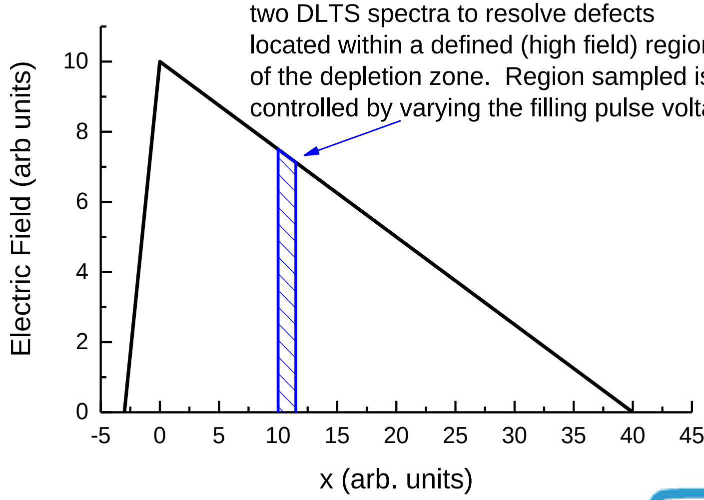


Double DLTS (DDLTS)

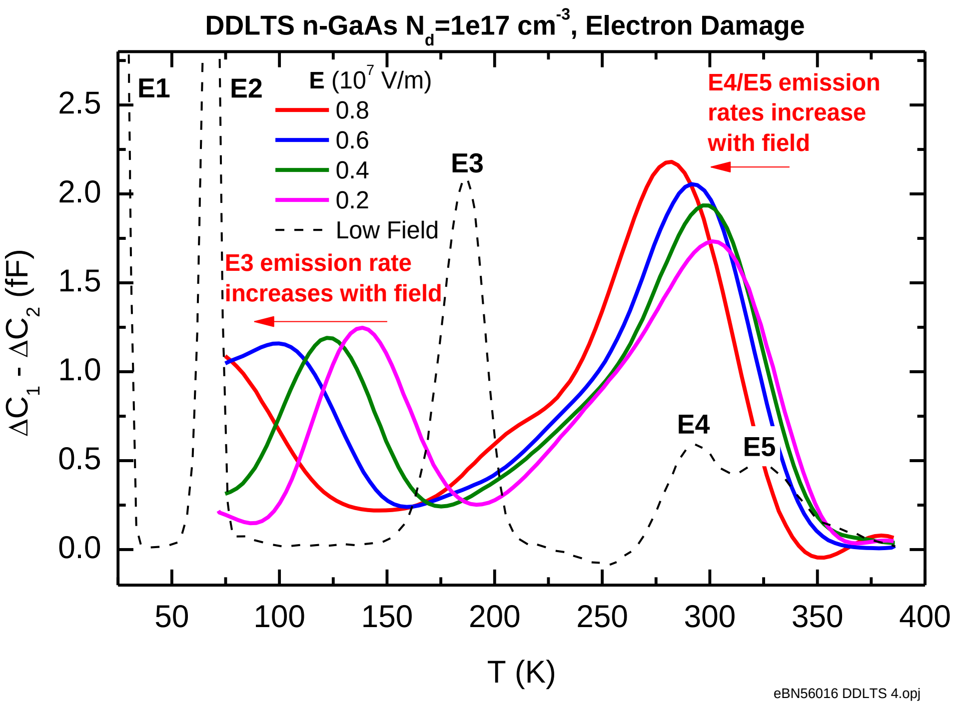


- If emission from a trap is controlled by tunneling, the emission rate will depend on the E-field (and on doping).
- Standard DLTS involves emission from regions with varying E-field, hence DLTS peak shapes will be distorted if tunneling is important.

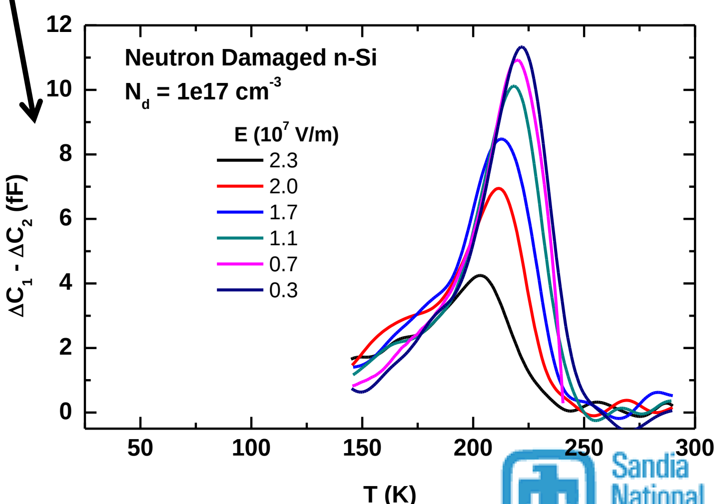




DDLTS: Measure Emission Rate at ~ Constant E-field



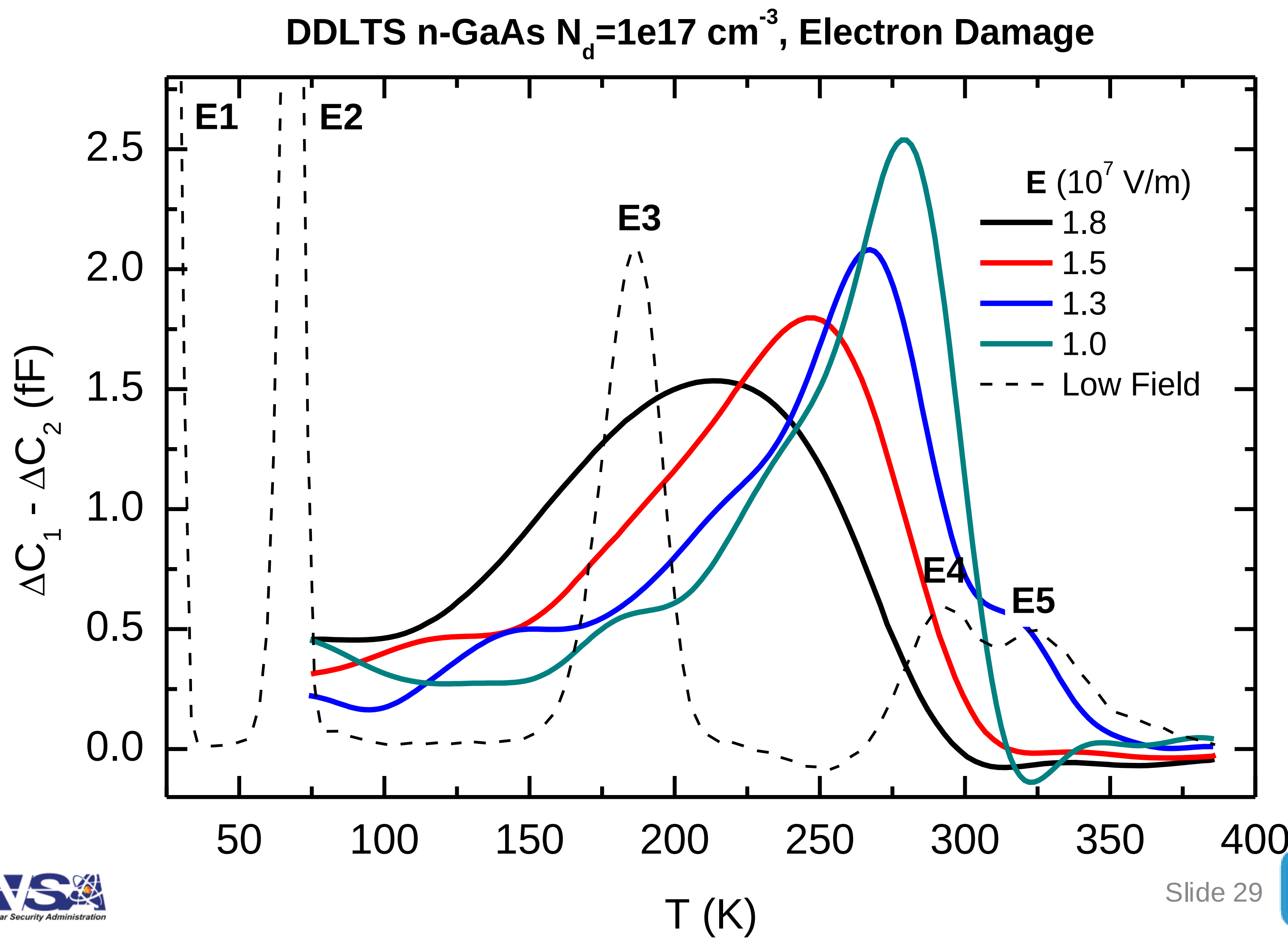
- **Electron damage, no clusters**
- **Emission rates increases with applied E-field**
- **Attributed to phonon-assisted tunneling**
  - Schenk, Solid State Electronics **35**, 1585 (1992).
- **Much smaller rate increase in silicon (Frenkel-Poole emission)**



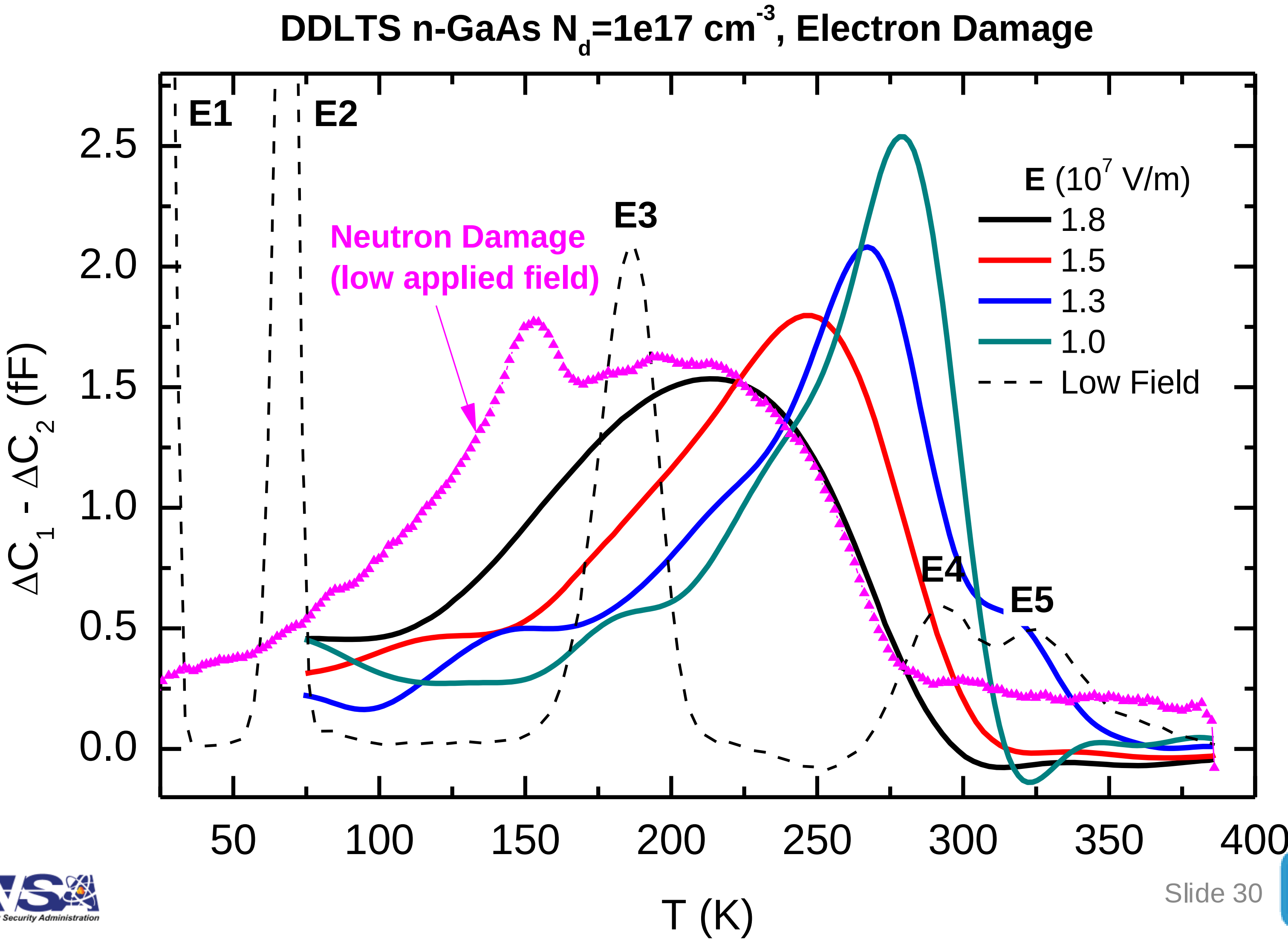
E-field dependent emission rate in GaAs:

Goodman, et al., Jpn. J. Appl. Phys. **33**, 1949 (1994).
Auret, et al., Semicond. Sci. Technol. **10**, 1376 (1995).

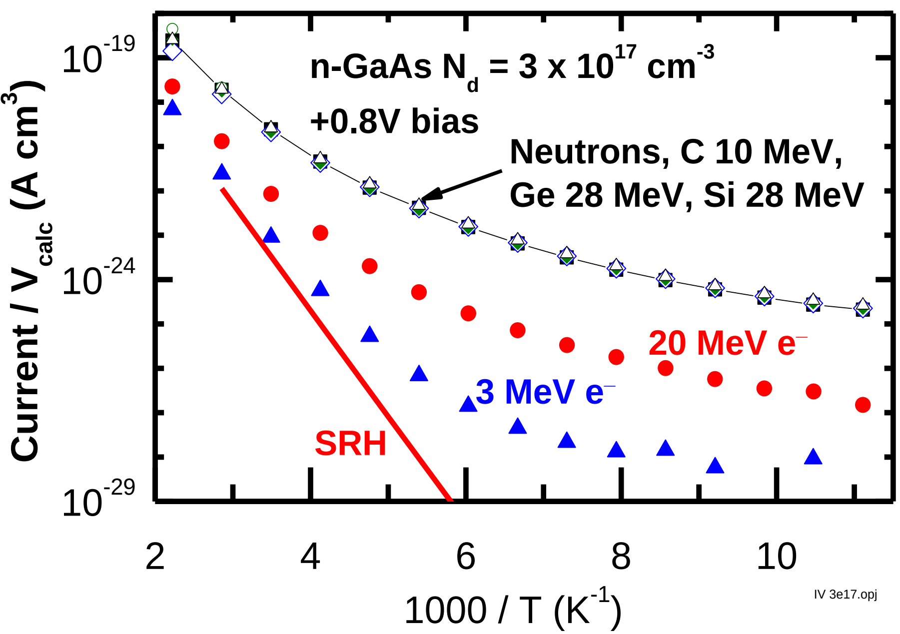
Higher Fields: E5 Resembles U-band

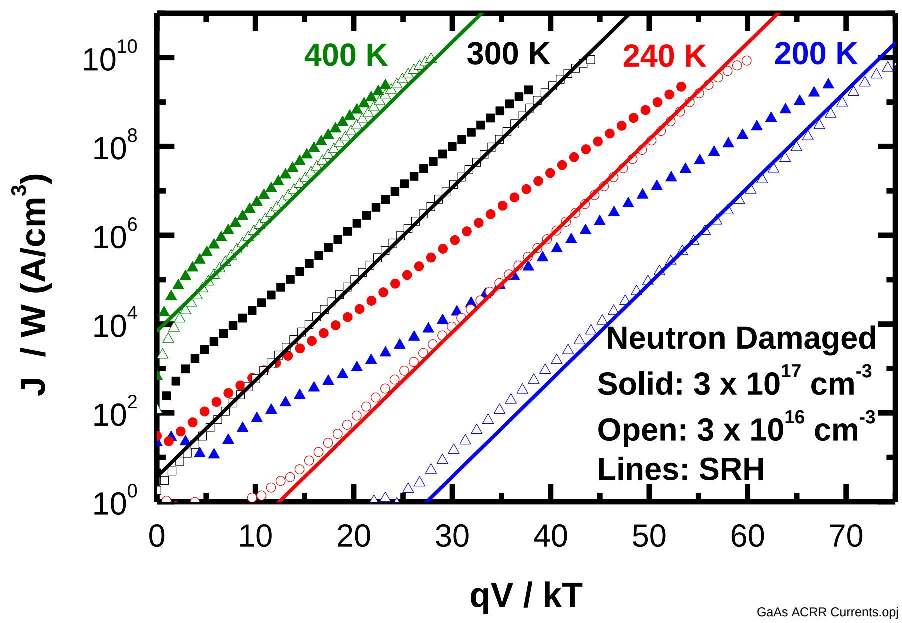


Higher Fields: E5 Resembles U-band



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 close to that of neutron damaged
  - Additional V_2-like defects – exact structures are not known
    - "Strained V_2" – No double acceptor, very broad annealing profile
    - "Bistable V_2" – Annealing kinetics match gain annealing kinetics
      - Metastable levels: E4, E4, H1 (like V_2) Single stable level: E75 (very shallow)
- **Use annealing to de-convolve defects in BJT base that affect gain: VP, V_2* and V_2**
  - Requires knowledge of annealing in low-doped collector
- **Establish ion-neutron equivalence**
  - Simple scale factor relates neutrons & EOR Si ions

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 currents in forward biased diodes beyond standard SRH**

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