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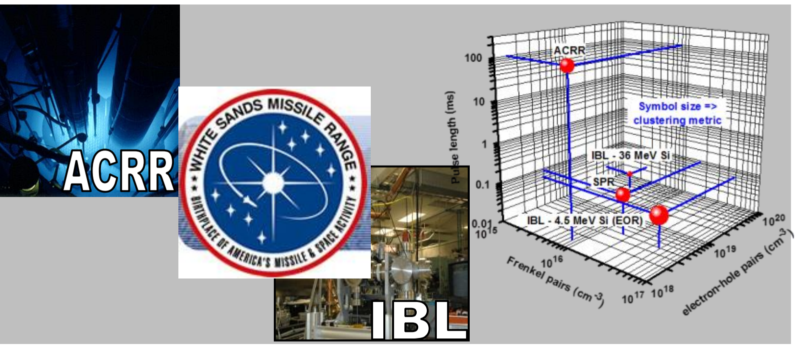
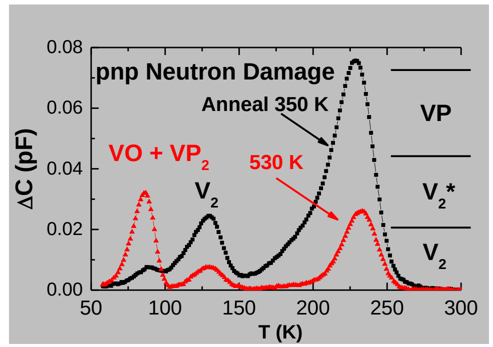
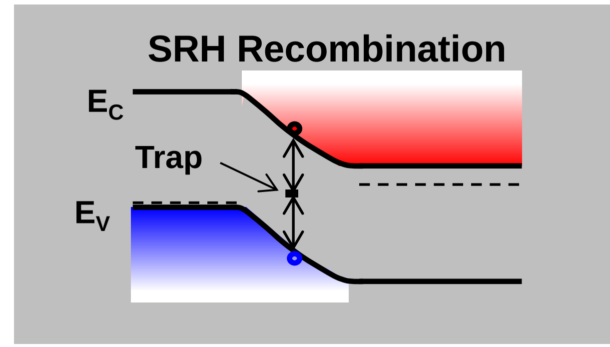
QASPR Qualification & Technical Readiness Review – Nov 19, 2015 , SNL/NM




# Novel applications of deep level transient spectroscopy (DLTS) for QASPR devices

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(1123)

U.S. DEPARTMENT OF ENERGY  NNSA National Nuclear Security Administration

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# Outline

- Introduction
  - DLTS fundamentals – Silicon BJT
  - DLTS from clustered versus non-clustered radiation damage
  - Recombination currents in GaAs Diodes – Clustered vs. non-clustered
- Radiation defects in GaAs
  - The U- and L-bands
  - Electric field induced emission in GaAs
- Measurements of capture cross section
  - Injection-DLTS in transistor structures – A new technique
  - Injection-DLTS in silicon BJT's
  - Injection-DLTS in III-V large-area HBT's

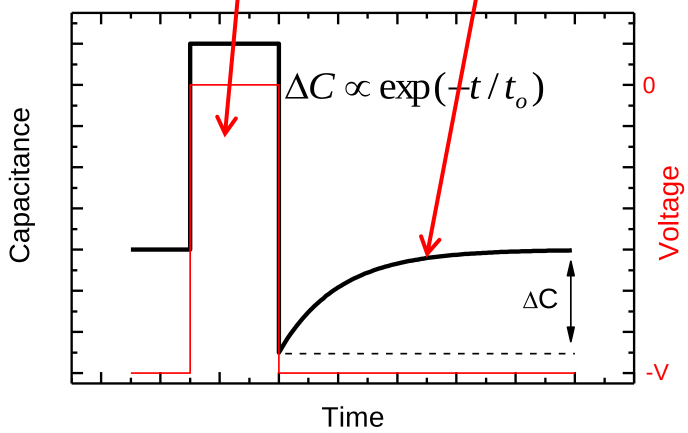
# BACKGROUND: DLTS AND DEFECTS IN THE SILICON BJT

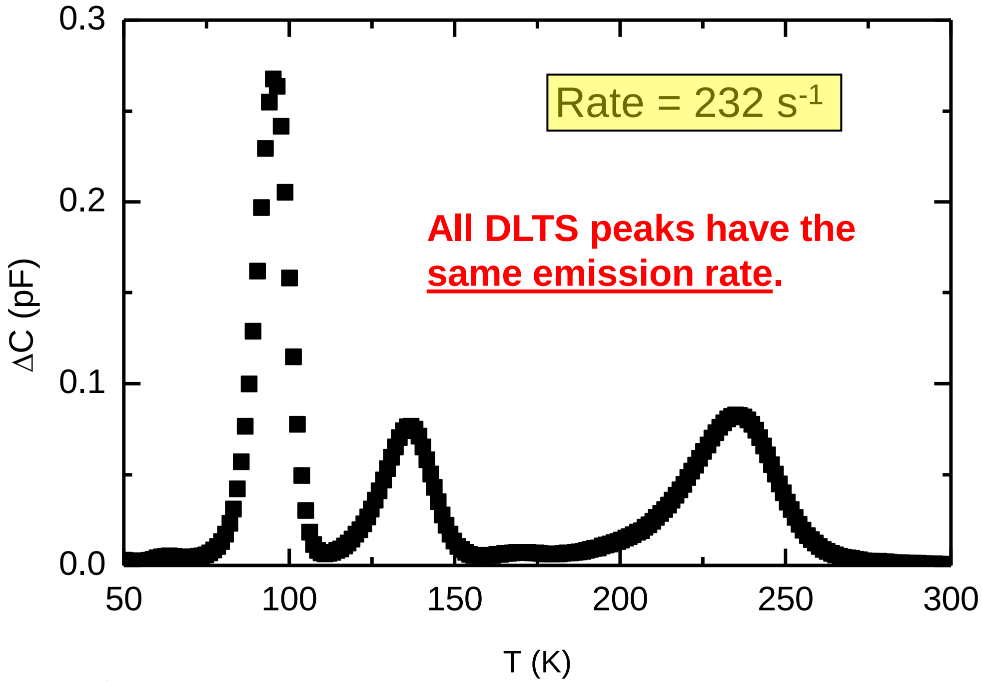
# DLTS: Deep Level Transient Spectroscopy

## Measures Concentrations & energy levels of point defects

**Fill pulse: carrier capture**

**Capacitance transient: carrier emission**




\# of traps

$$N_t \propto \Delta C$$

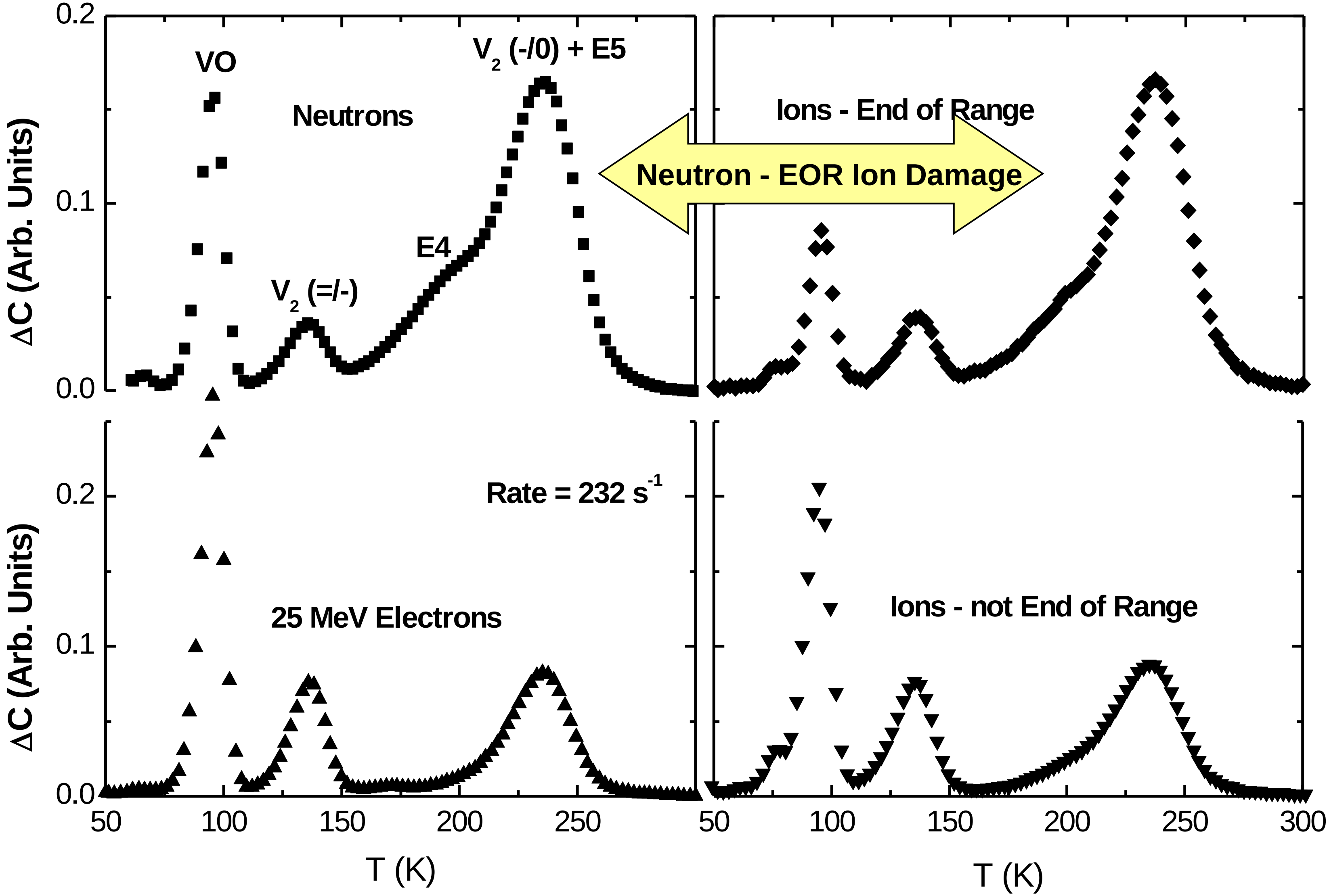
Emission Rate

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

Shallow Traps (near $E_c$ or $E_v$) ⟷ Deep Traps (near midgap)

The maximum temperature of a DLTS scan is adjusted so that traps near $E_g/2$ emit (Si ~ 300K, GaAs ~ 400 K)

# BJT Collector: Point defects (electrons) & Clustered defects (neutrons & ions)




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

# Neutron – Ion Equivalence using end-of-range (EOR) Silicon Ions

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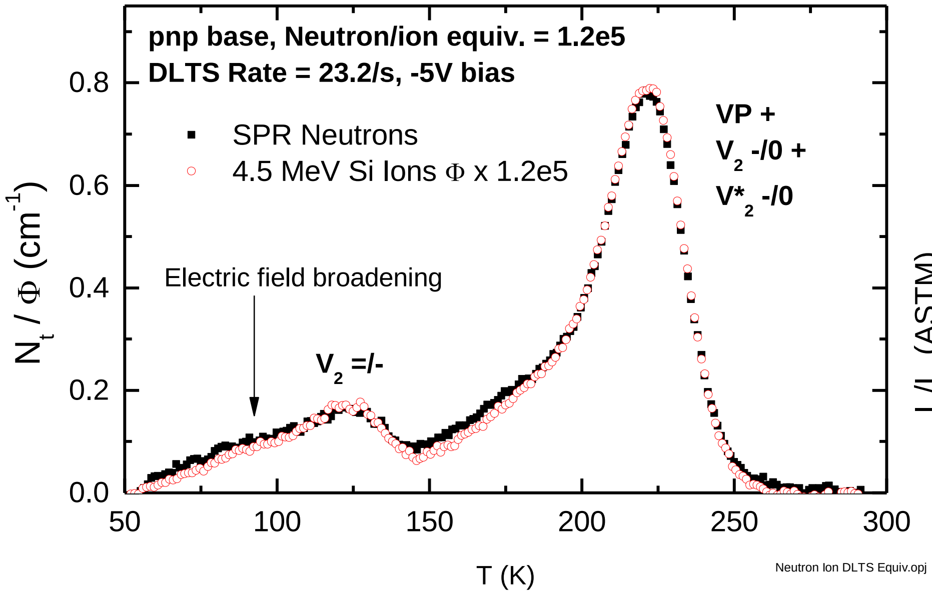
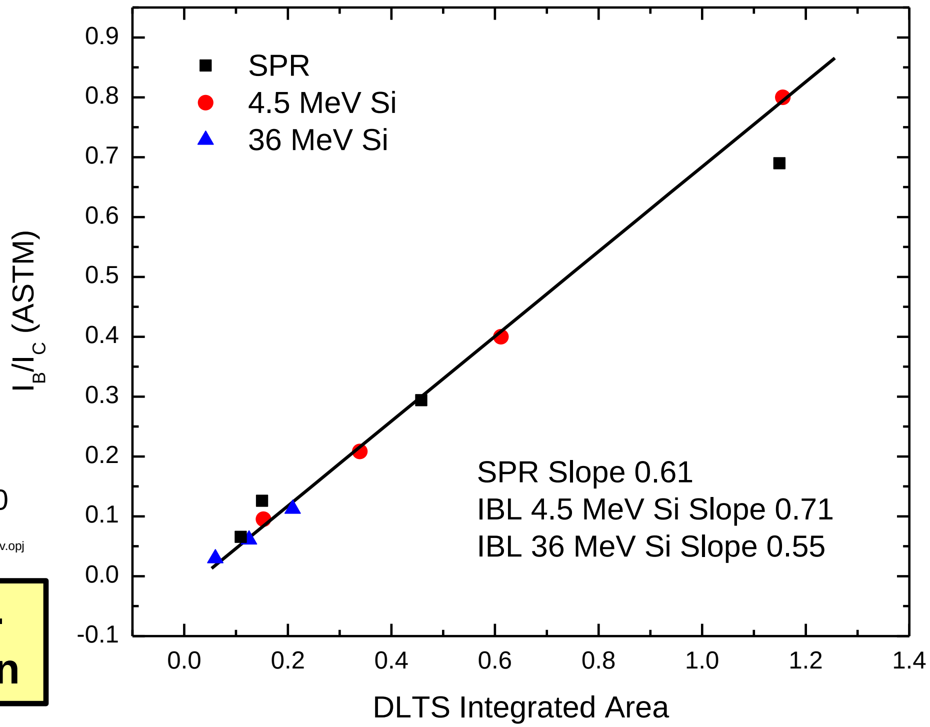
**Exact match of neutron & ion DLTS spectra in pnp base**

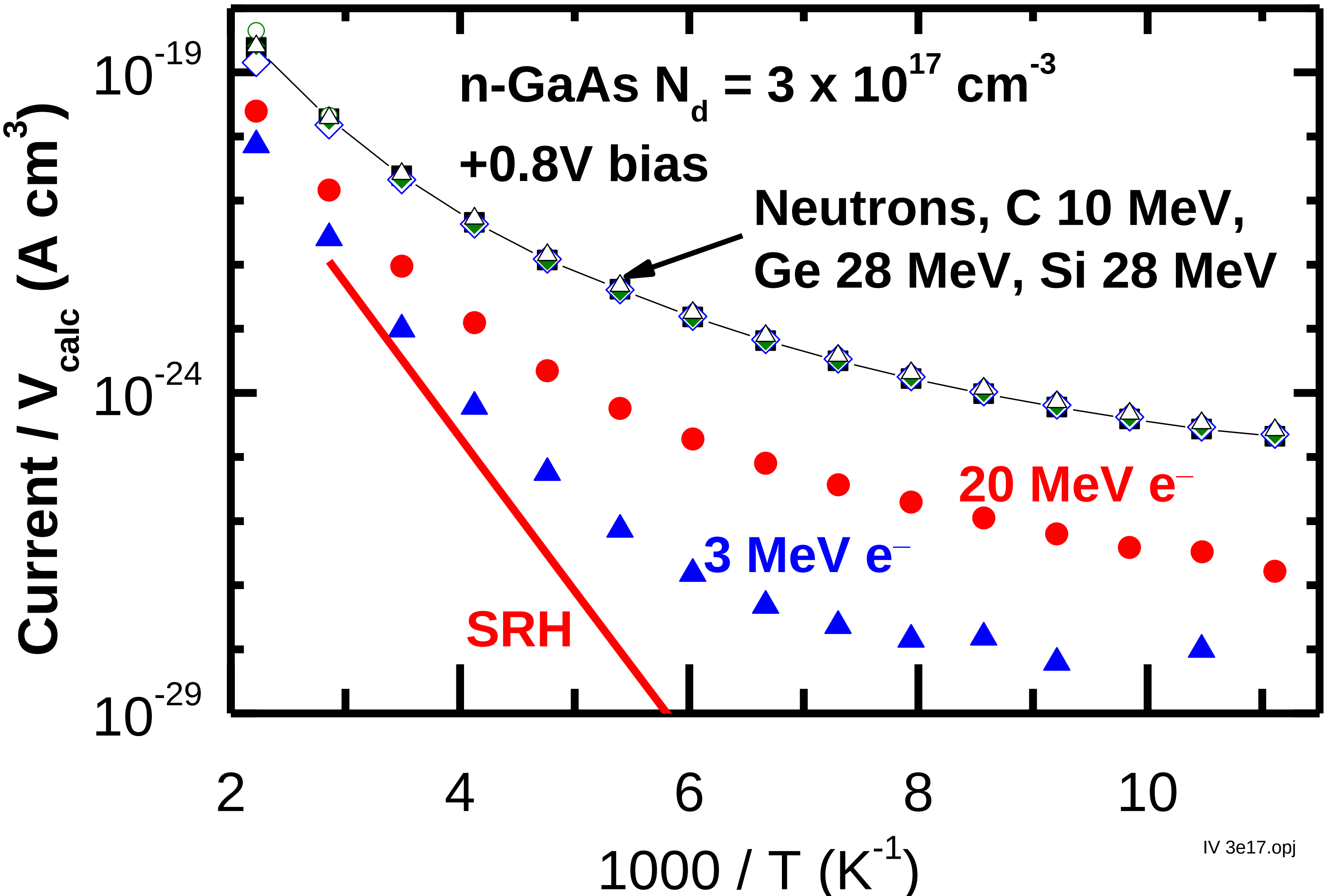



**Si ion energy chosen to place the ion end-of-range (EOR) at the emitter-base junction**

**Linear relationship between inverse gain and DLTS amplitude**

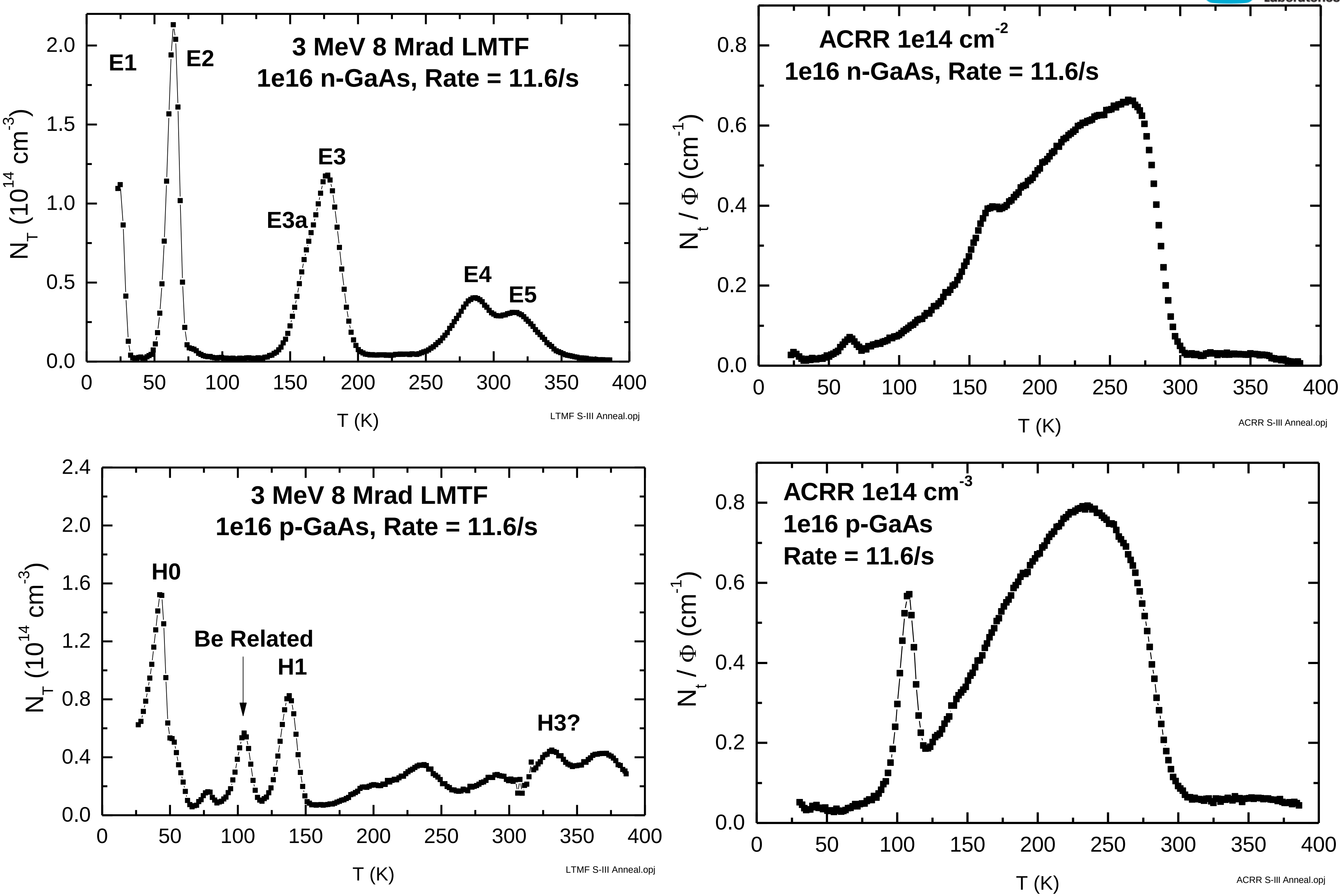


# Normalized GR Currents: GaAs Diodes

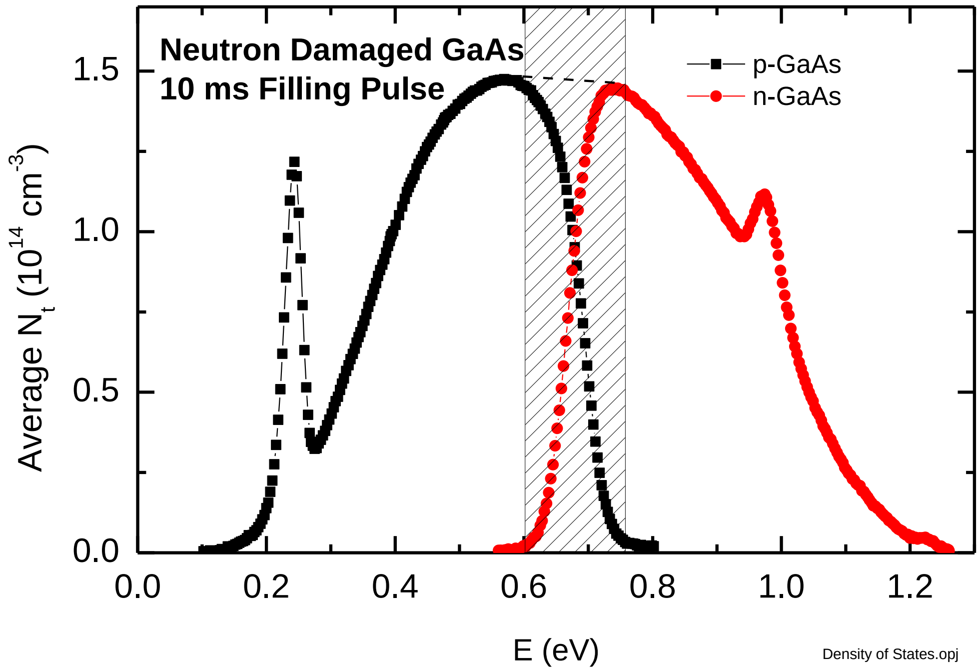


# RADIATION INDUCED DEFECTS IN GaAs

# GaAs: DLTS after electrons & neutrons are different !!



# Neutron Damaged GaAs

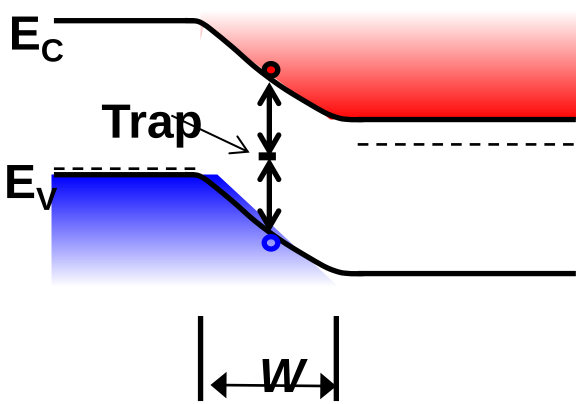



- **Neutron damage is known to cause expansion of the GaAs lattice**
  - Decrease of GaAs bandgap
- **Bandgap decrease of 0.16 eV results in overlap of U- and L-bands & apparent continuous distribution of defect states across midgap**
  - Similar to amorphous semiconductors
- **Cause?**
  - Inhomogeneous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

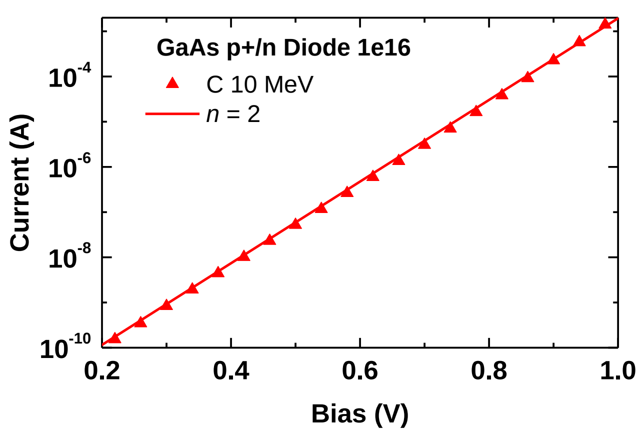
Fleming, et al., J. Appl. Phys. **107**, 123710 (2010).

# INFLUENCE OF ELECTRIC FIELDS ON SRH CURRENT

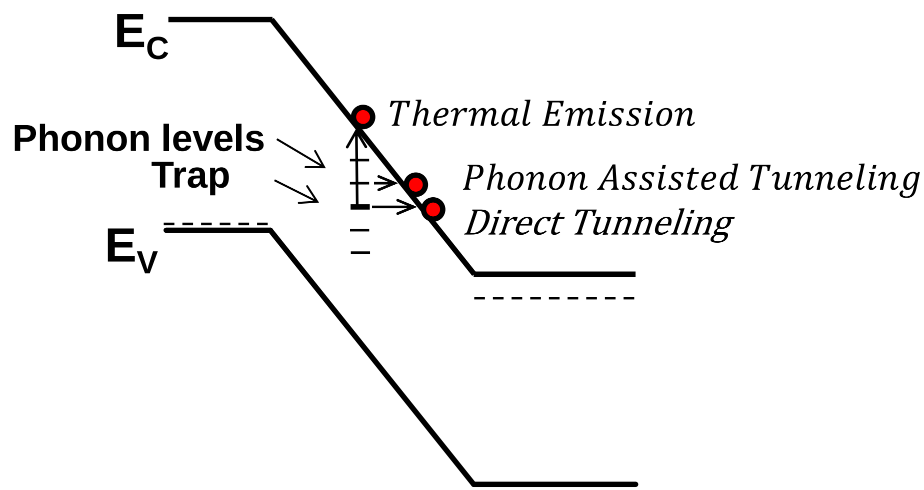
# Shockley-Read-Hall Recombination (SRH)

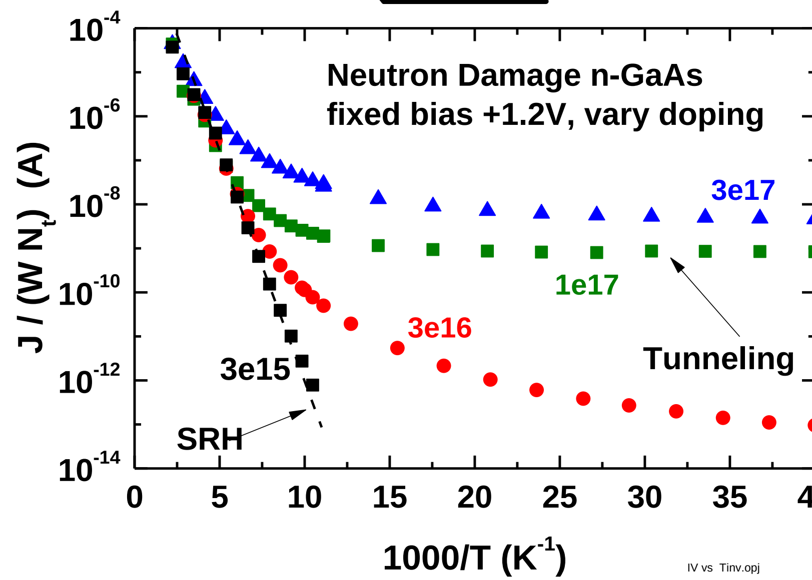



SRH: $J_r = \frac{qW}{2} \sigma N_\tau \upsilon_{th} n_i \exp(qV/nkT)$

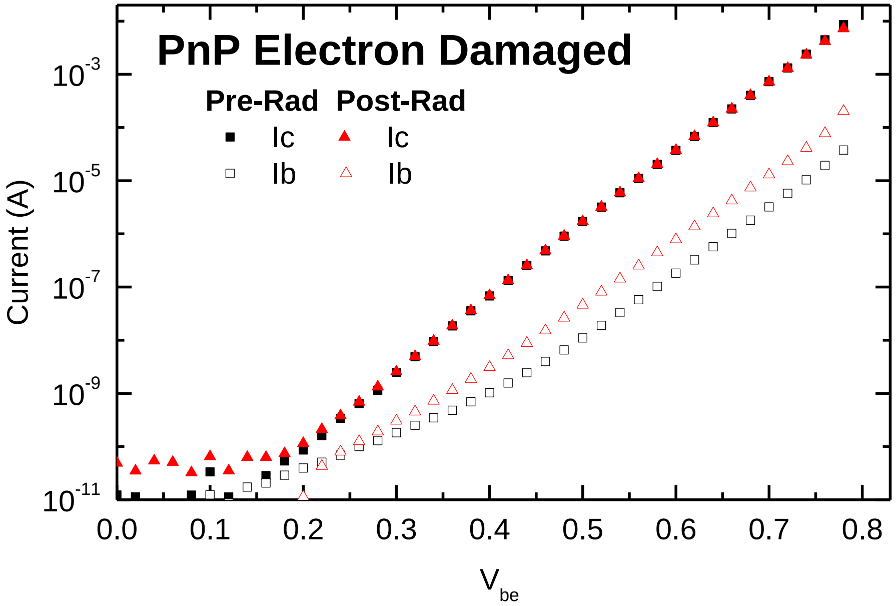


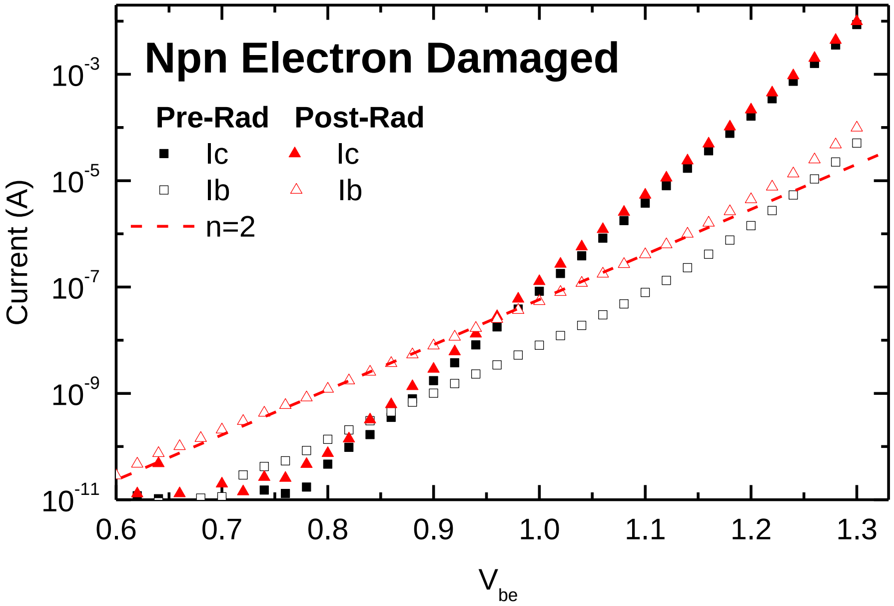

# Phonon Assisted Tunneling Multi-Phonon Emission



# HBT Gummels: SRH-only models predict neutral base recombination

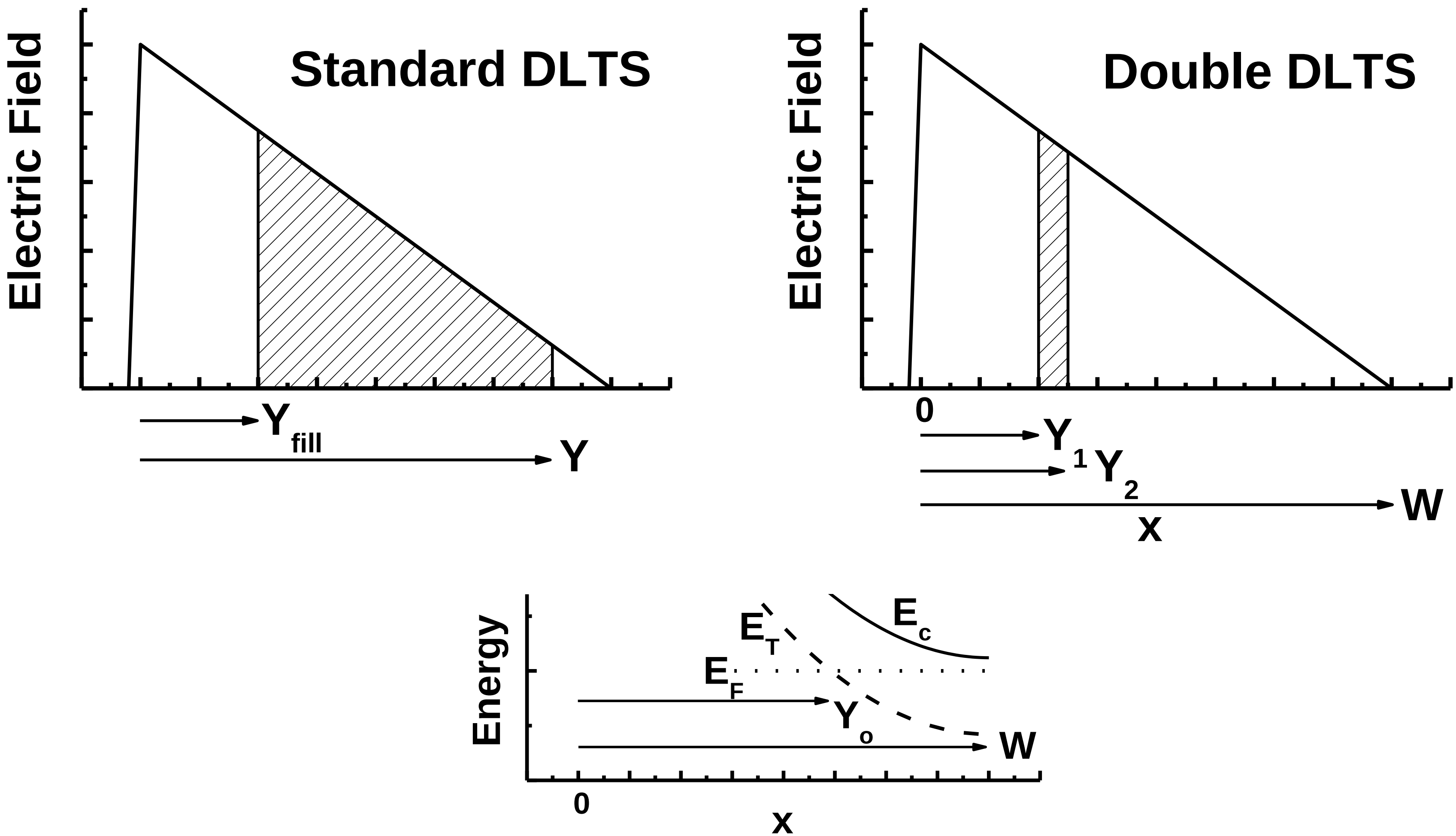


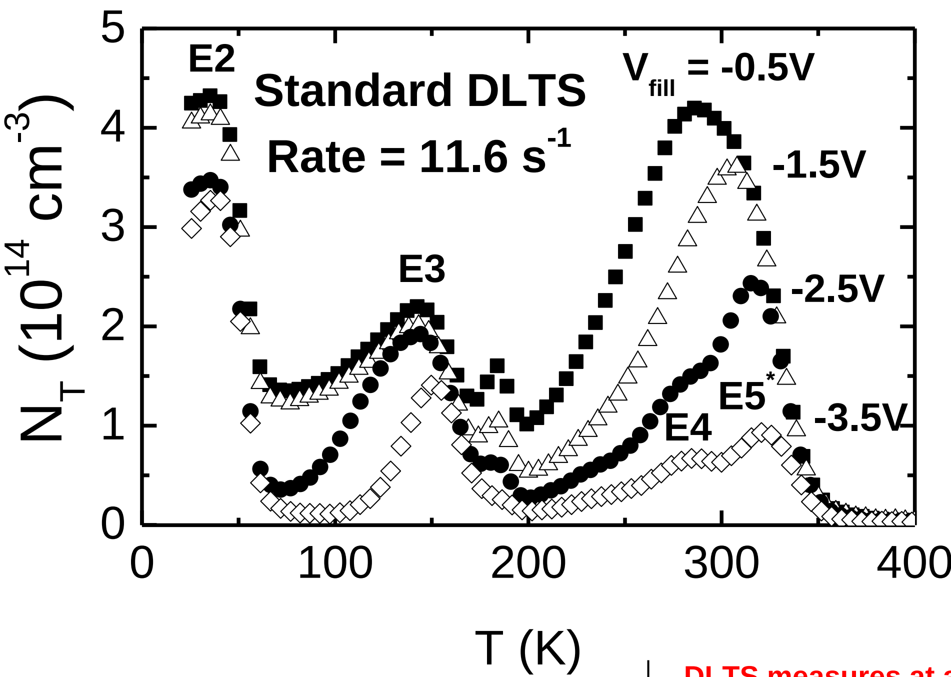

- **PnP**
  - ✓ Base current slope is not changed by electron damage
  - ✓ Consistent with neutral base recombination (as predicted by numerical models)

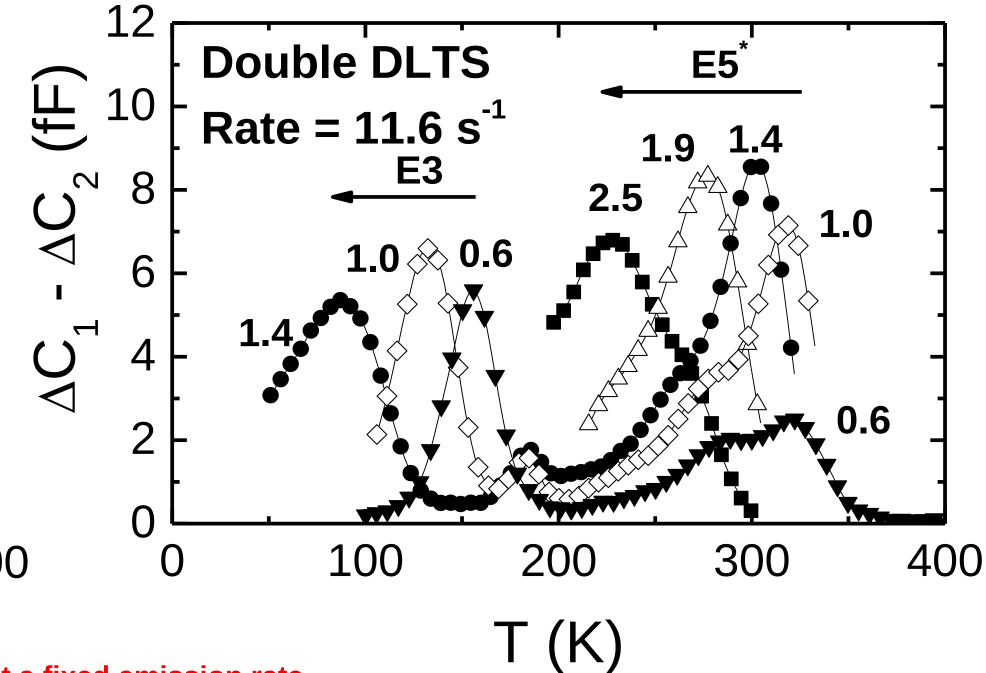
- **Npn**
  - ✓ Base current slope is shallow (n ~ 2) after electron damage
  - ✓ Suggests recombination in emitter-base depletion region

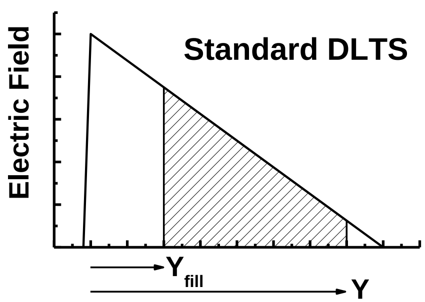
# Use double-DLTS to measure emission rate versus E-field

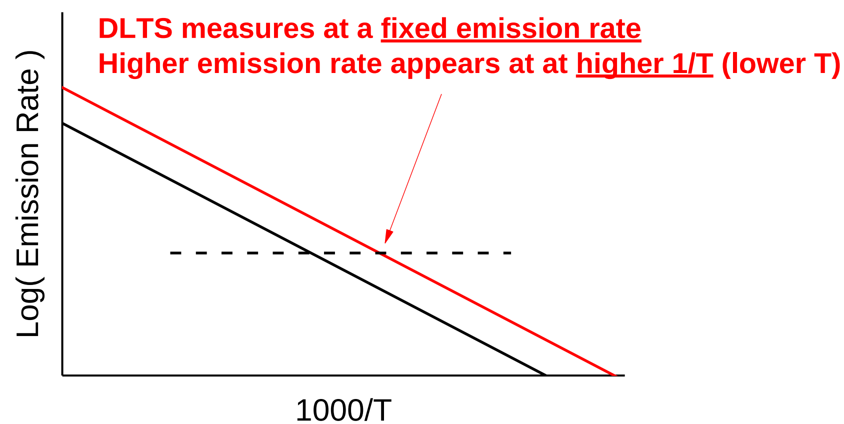


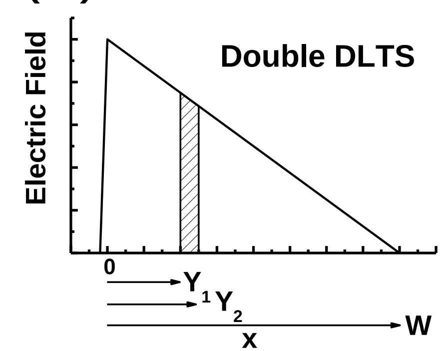
# Standard vs. Double DLTS



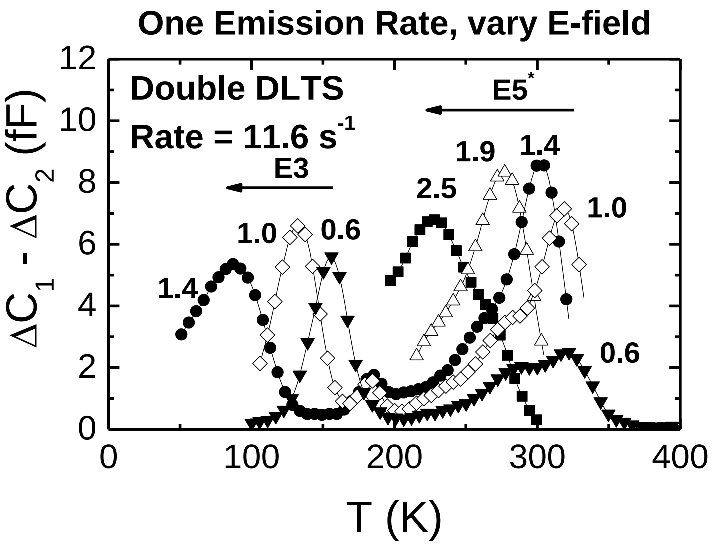



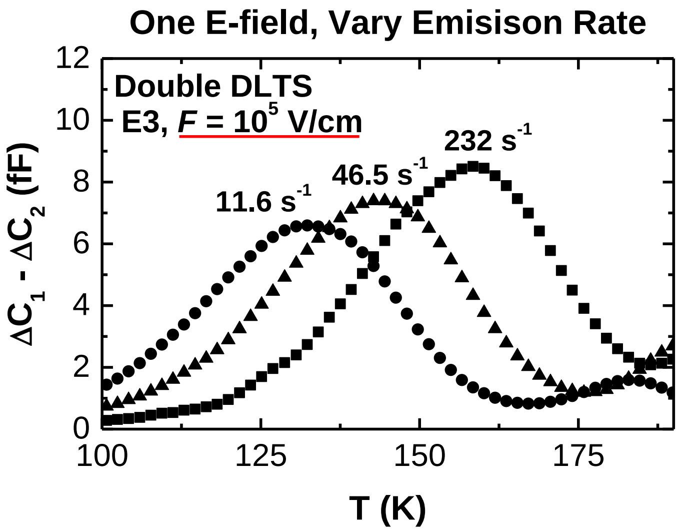



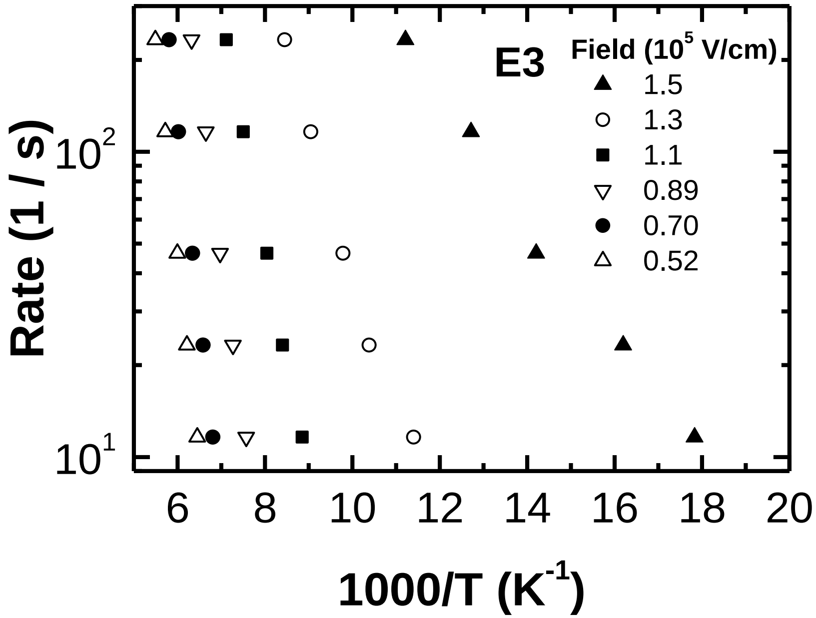



# Measure Emission Rate vs. *F* & *T*



# Fits to Schenk Theory

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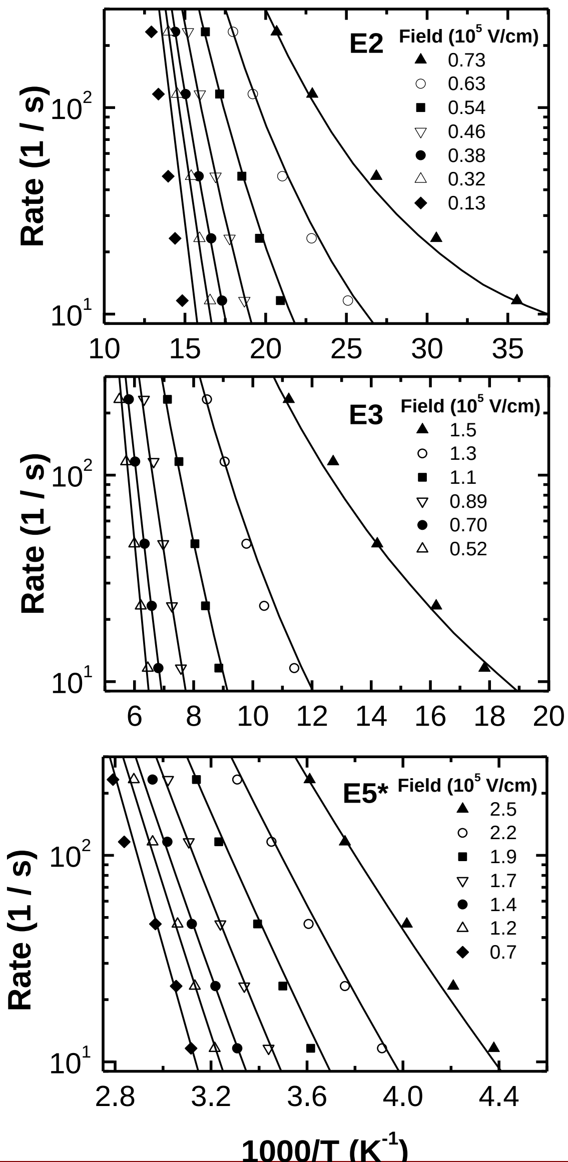
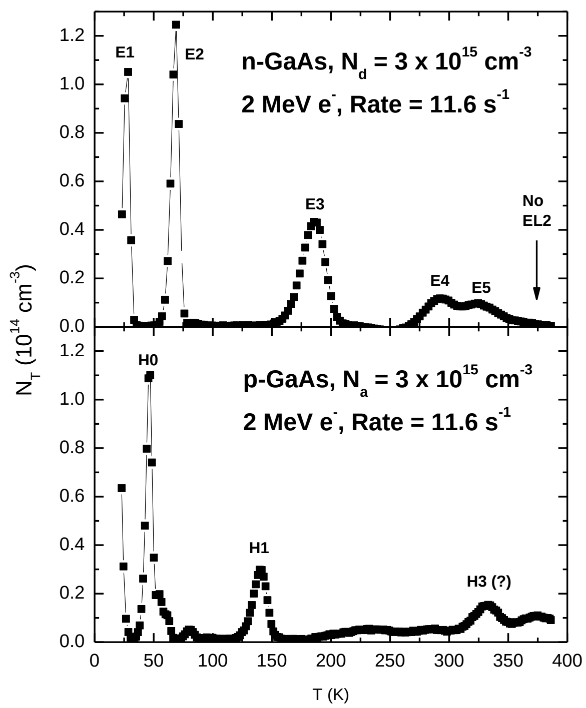
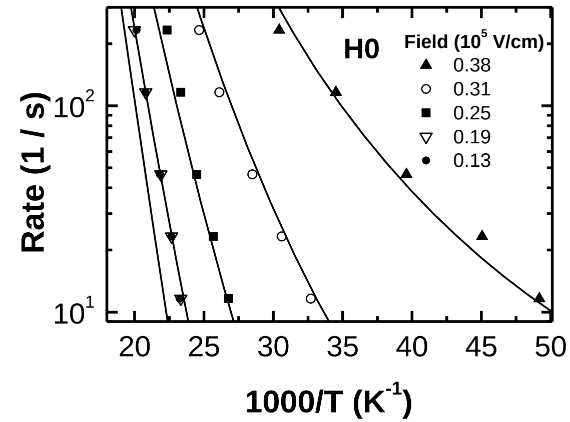
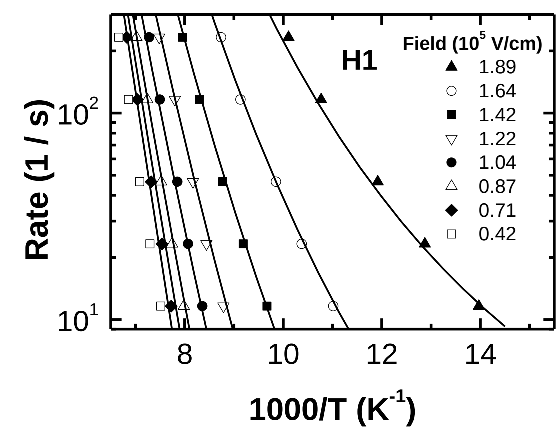



R. M. Fleming, et al., J. Appl. Phys. **116**, 013710 (2014)

# MEASUREMENTS OF THE CAPTURE RATE

- ❖ Modeling of recombination current requires knowledge of four rates
  - Electron emission – Electron capture
  - Hole emission – Hole capture
- ❖ Emission rates are easily measured by DLTS
- ❖ Capture rates are more difficult and data in the literature are sparse

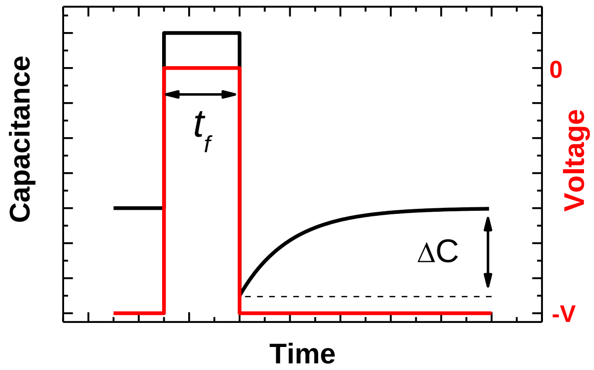
# MEASUREMENTS OF THE CAPTURE RATE

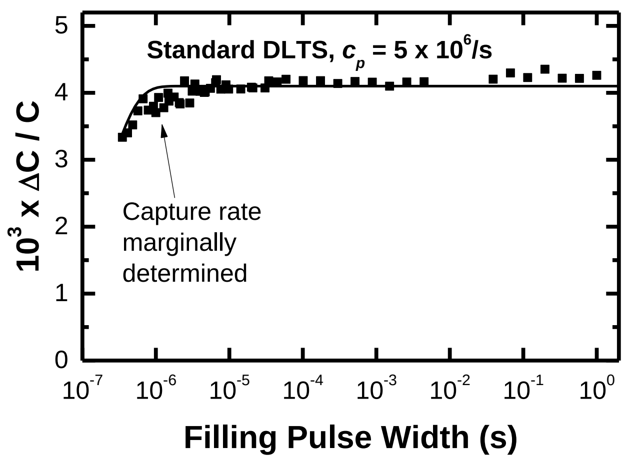
## Injection DLTS (inj-DLTS)

- A new method to measure capture rates in transistor structures
- Standard DLTS: Fill traps by pulsing the bias across the diode
  - Large density of carriers available to fill traps
  - Fast capture rates
- Injection DLTS: Fill traps by pulsing adjacent diode
  - Control the number of carriers available to fill the traps
  - Slower capture rates

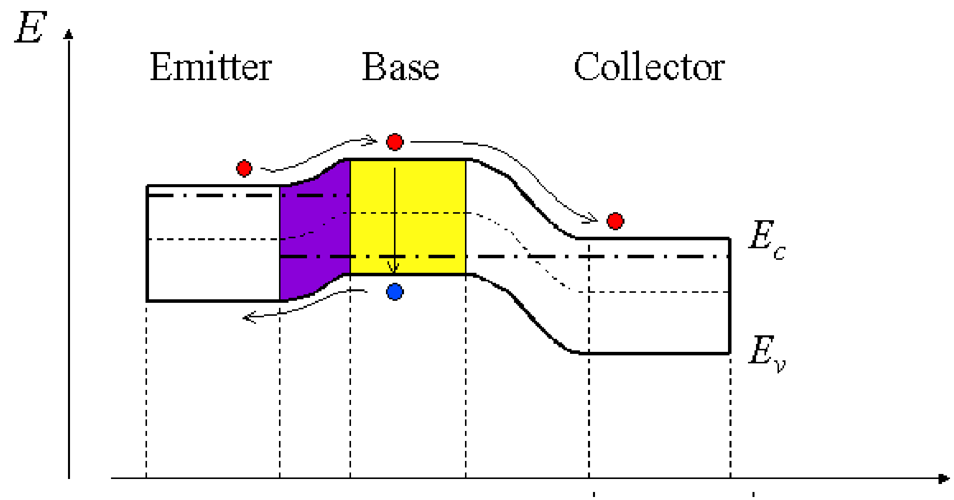
# Carrier Capture Using Standard DLTS

- Capture cross section is calculated from the capture rate
  - $c_n = \sigma_n \langle v \rangle n$
- Capture rate is determined by measuring $\Delta C$ as a function of filling pulse width
- Using standard DLTS, capture rate is too fast
  - With standard DLTS, the only solution is to decrease doping (thereby decreasing the capture rate)



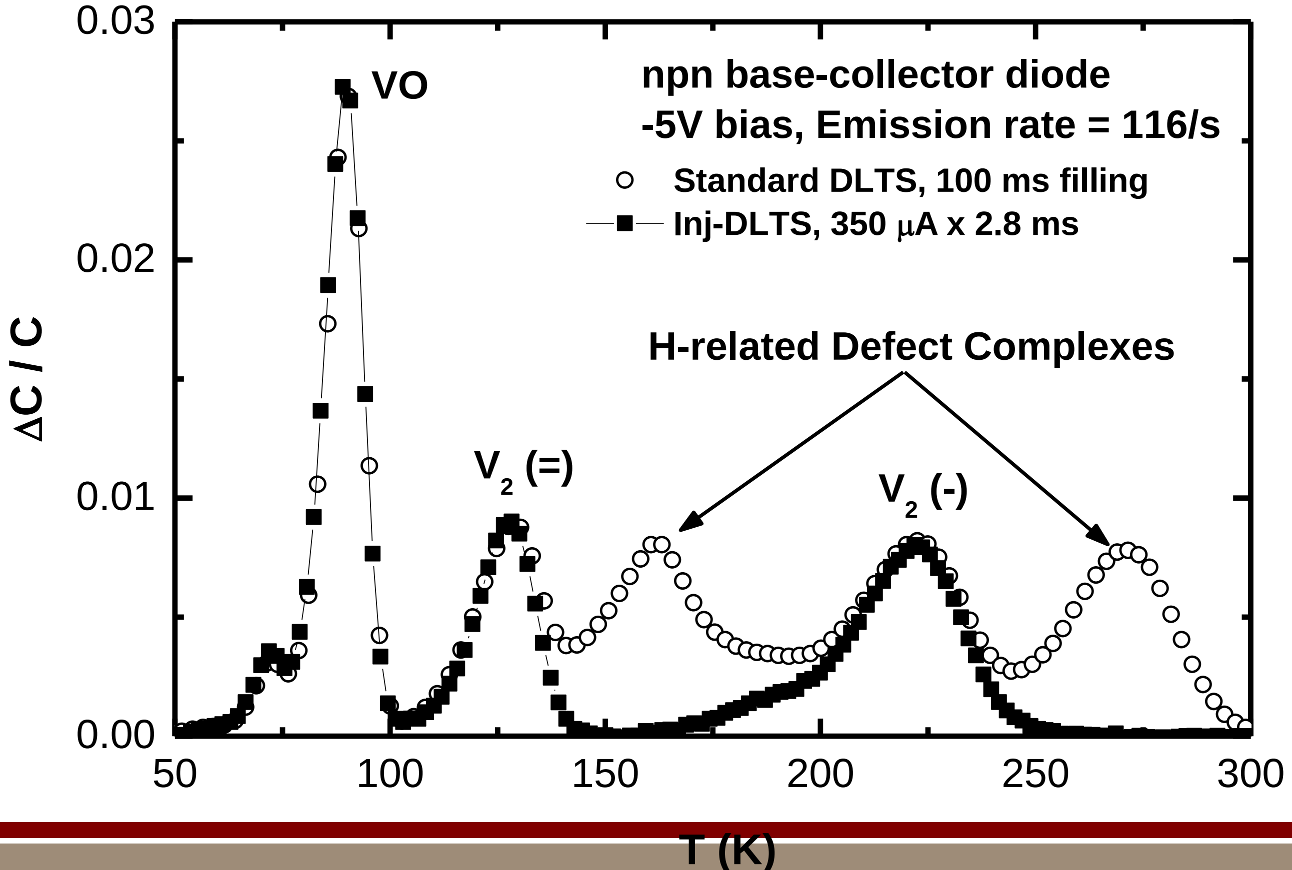
# Solution: Injection DLTS

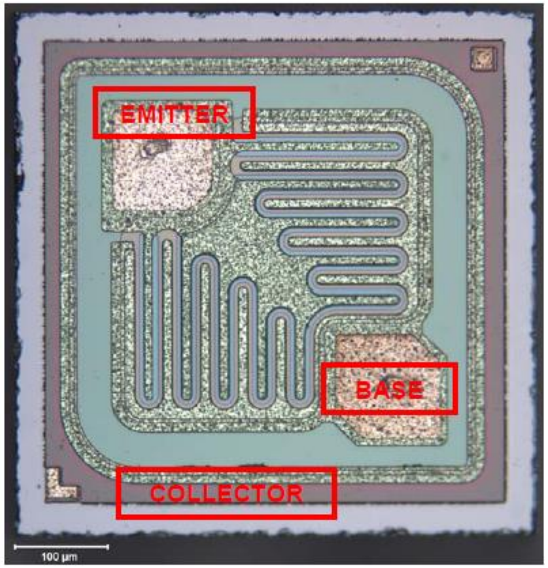



- DLTS in a bipolar transistor collector
- Pulse emitter-base into forward bias (collec. at fixed rev. bias)
  - Use injected carriers to fill traps
  - Control capture rate by amplitude of forward-bias current pulse
- Also allows measurement of capture versus electric field

# Inj-DLTS: Si npn BJT Collector

- Electron damage Si npn LMTF linac ~25 Mrad
- Use current limiting diode to provide constant b/e current
- Scale inj-DLTS C by 1/2.5 to match ΔC/C of standard DLTS
  - Consistent with emitter versus collector area – Filled traps are under emitter



# Inj-DLTS: npn Collector

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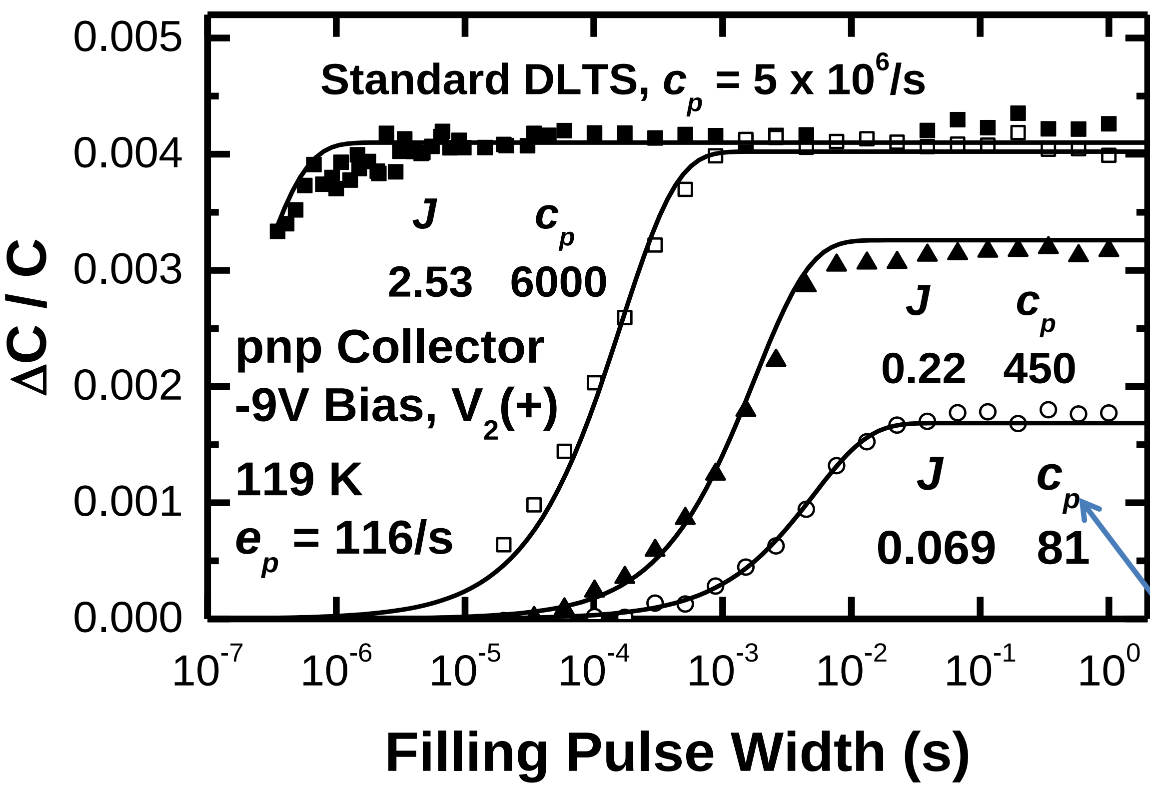
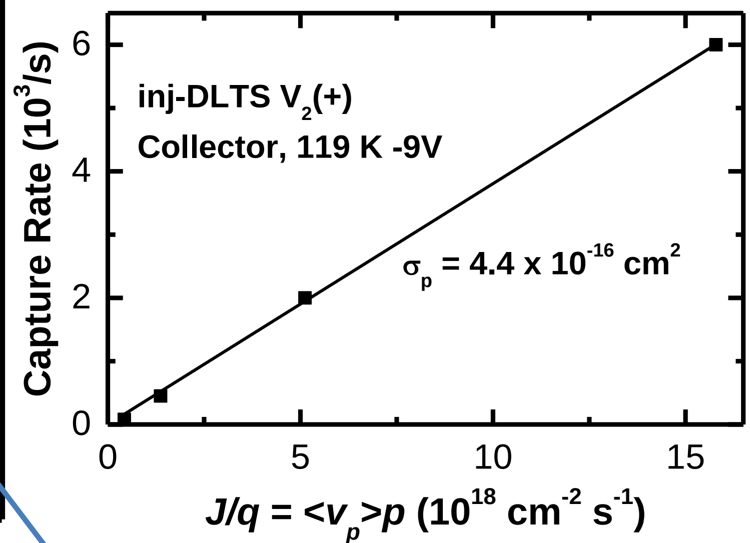
- pnp collector: $V_2(+)$ -9V 119K, $e$ = 116/s
- Fit capture rate
- Calculate capture cross section using current density $J/q =< v_{sat} > n$

$$\Delta C(t_f) = \Delta C_{max}\left[\frac{c}{(c+e)}\right] * \left[1 - \exp(-t_f(c+e))\right]$$

$$c_p = \sigma_p \langle v \rangle p$$

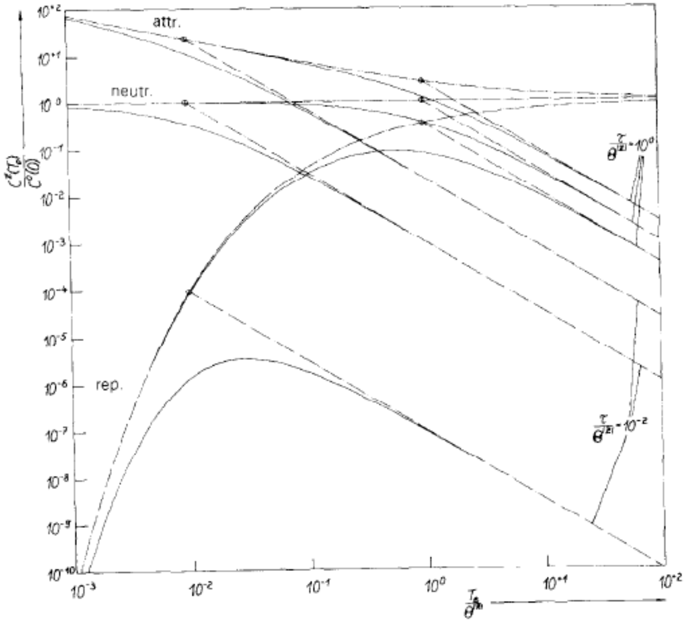
$$c_p = \sigma_p (J/q)$$

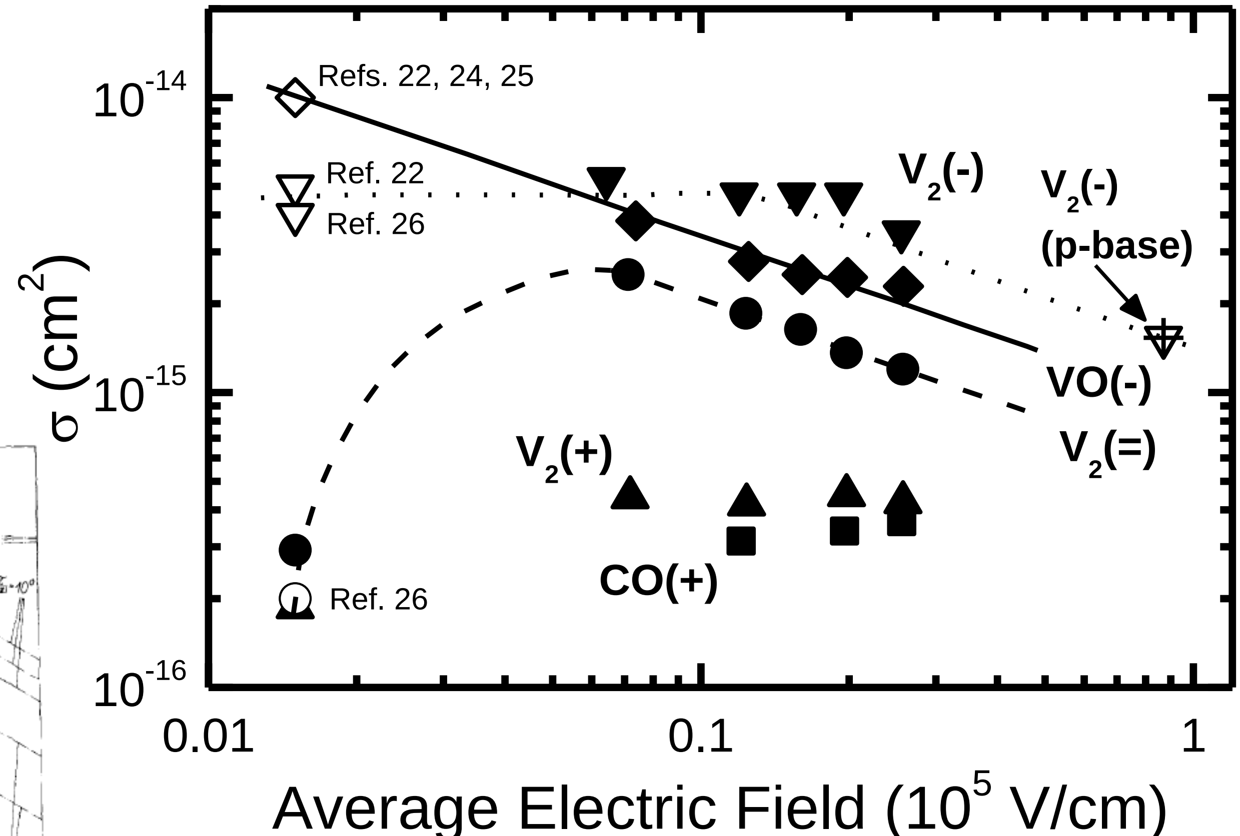



Roll-off off of $\Delta C$ at small $J$ is a consequence of $c \approx e$

# Capture Cross Sections: Si Traps

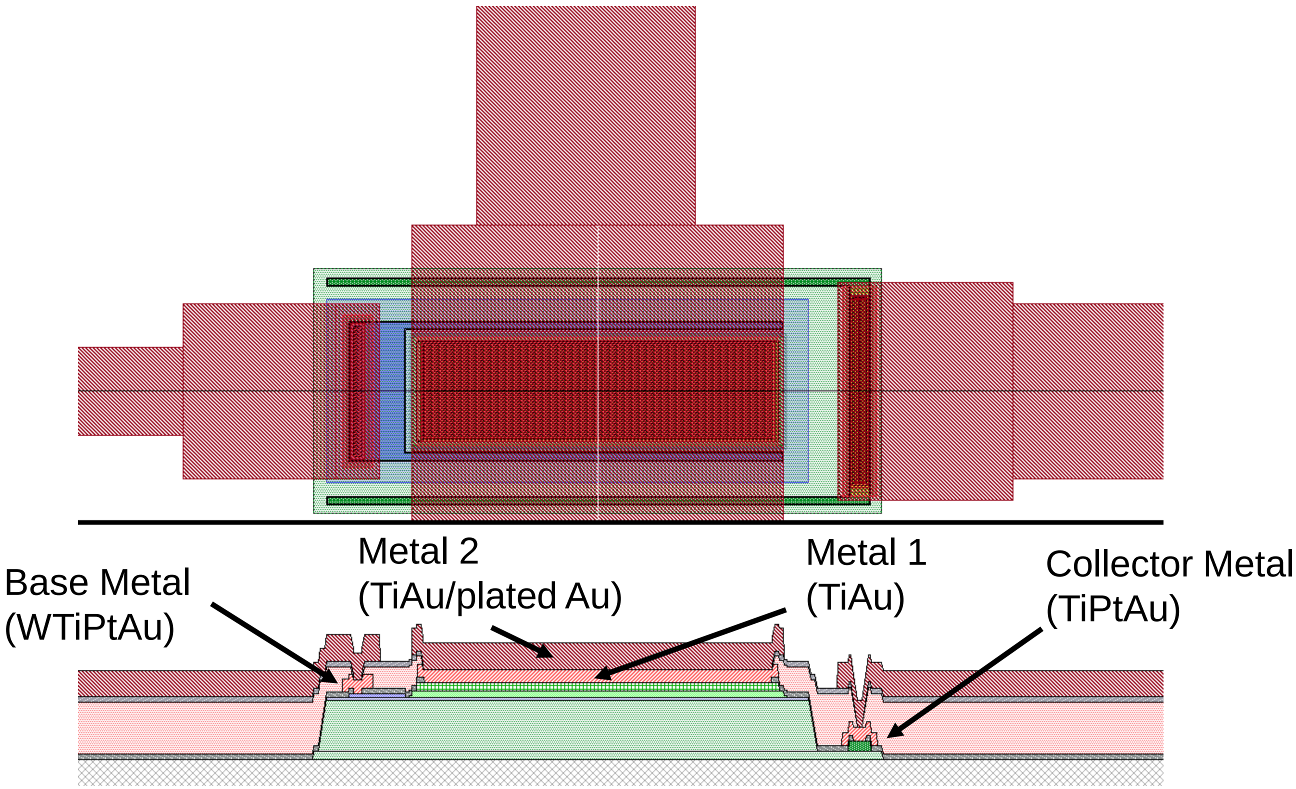


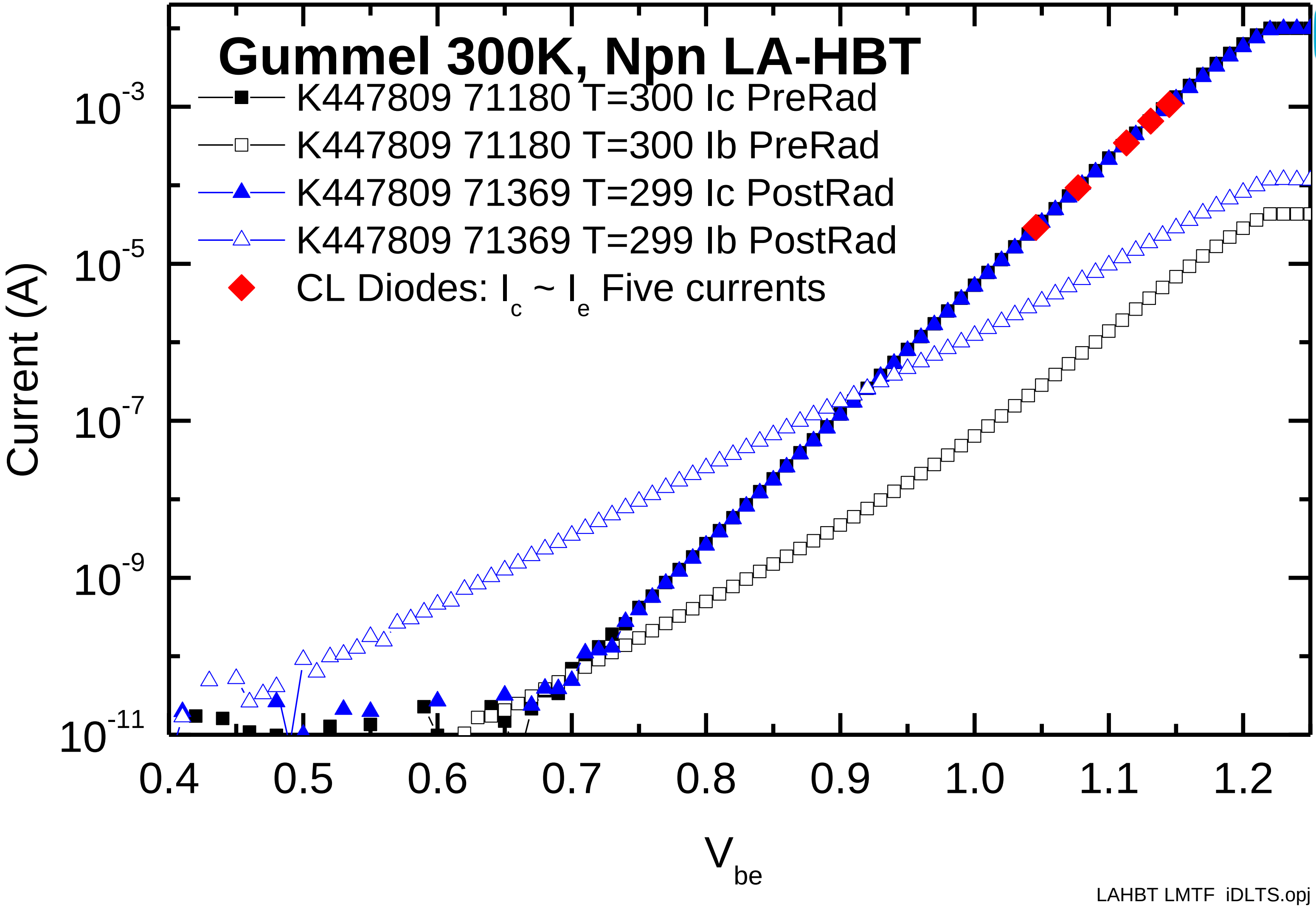




R. Pässler, *Solid-State Electronics,* vol. 27, pp. 155-166, 1984.

R. M. Fleming, et al., J. Appl. Phys. **118**, 015703 (2015)

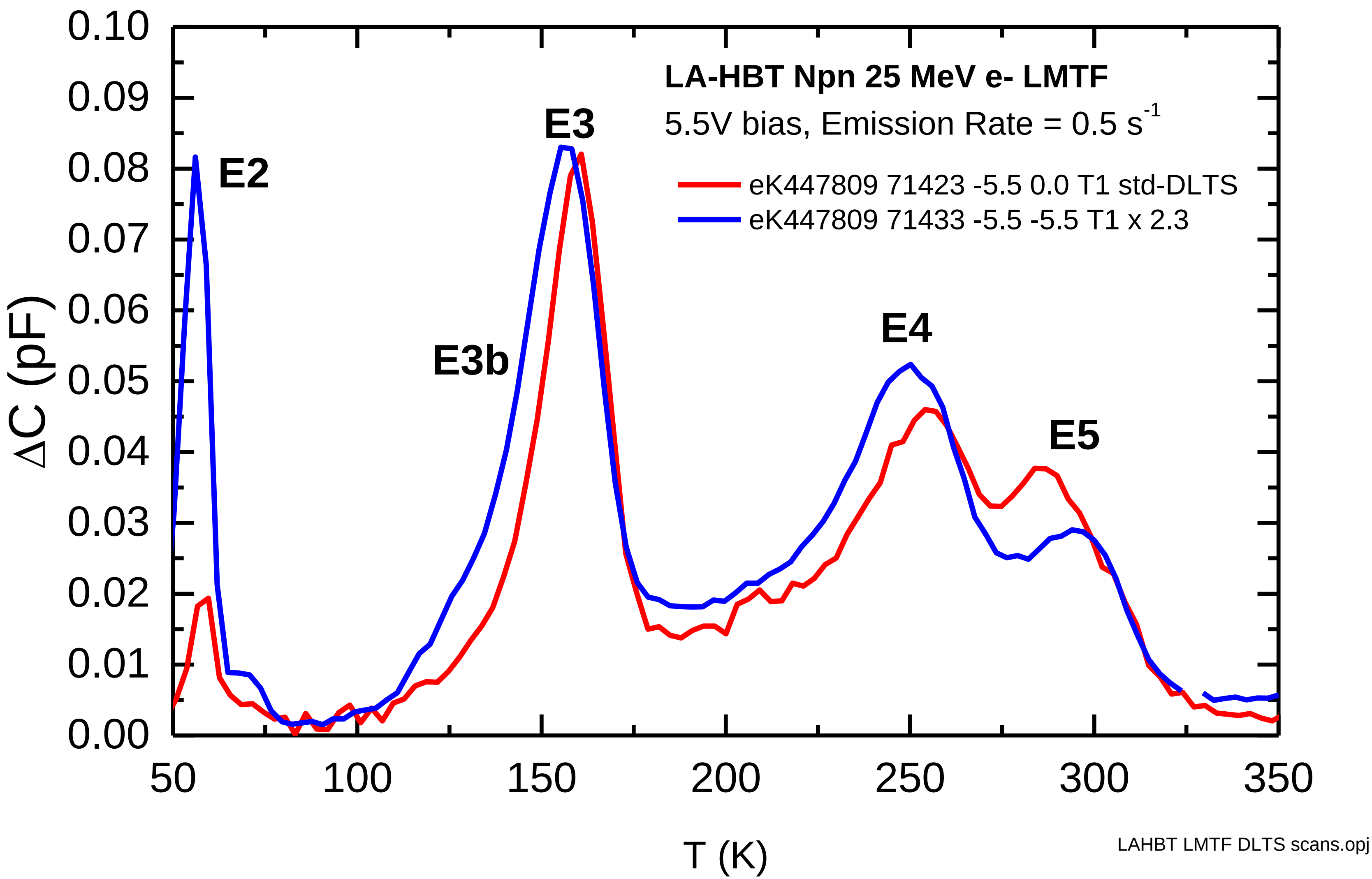
# MEASUREMENTS OF CAPTURE RATE IN LARGE-AREA GaAs HBT's





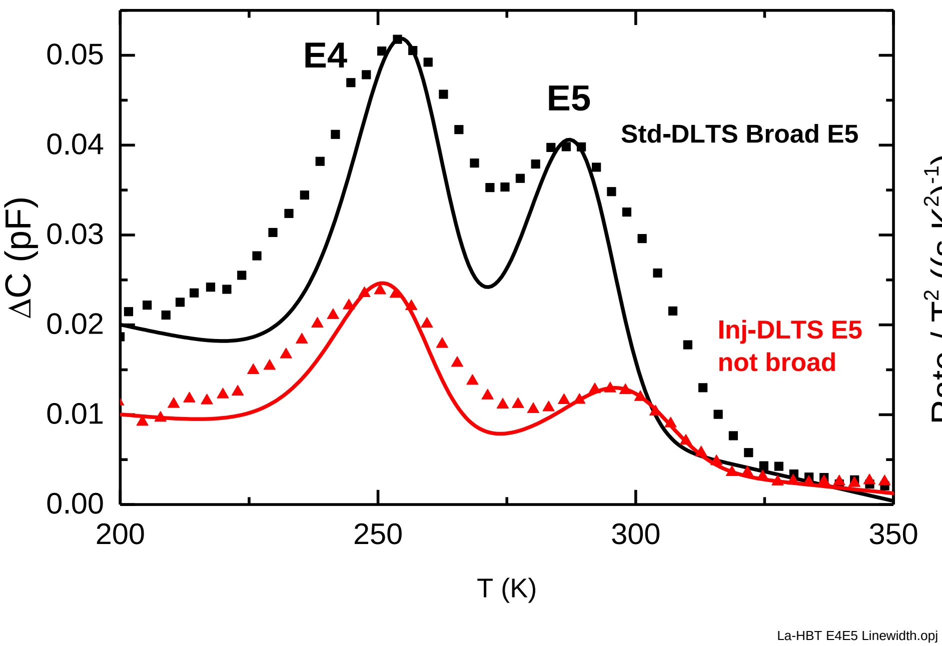

300K Gummel before/after damage showing biases for five current-limiting diodes.
Diode currents = 30, 100, 350, 650, 1000 $\mu A$.
For injected current density, take Ie = Ic & use emitter area 1e-4 $cm^2$

# Compare std- and inj-DLTS

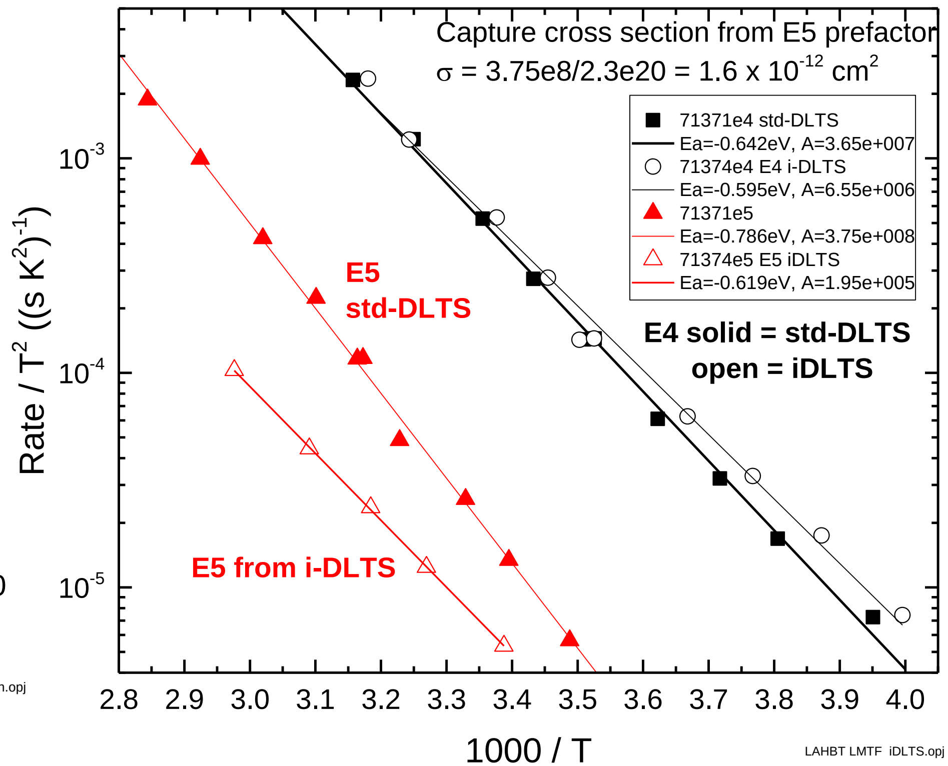



Have measured capture from inj-DLTS from E3, E4 and E5

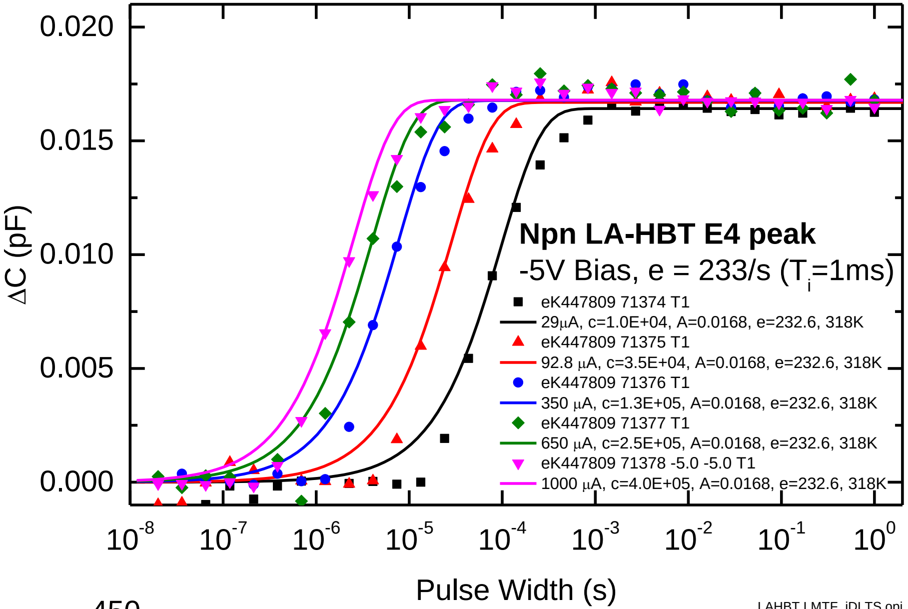
# E5 peak under emitter (i-DLTS) has lower Arrhenius slope

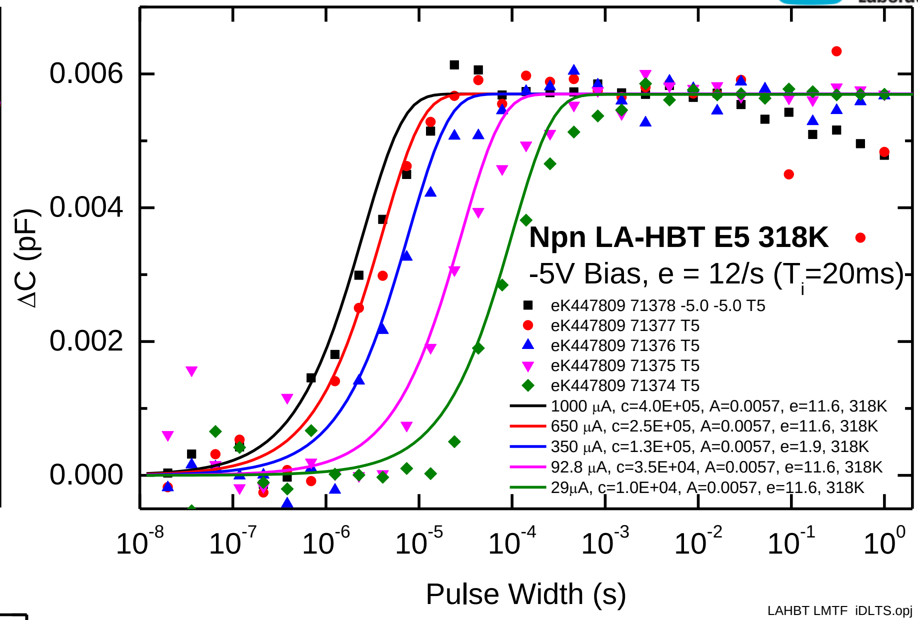


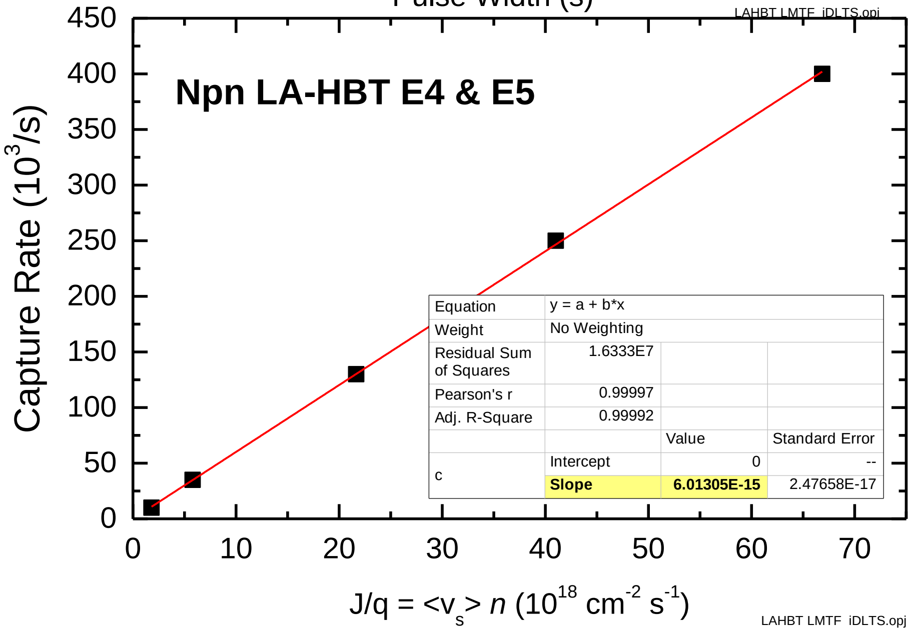

**Solid lines are the calculated DLTS linewidth.**



# Capture into E4 & E5



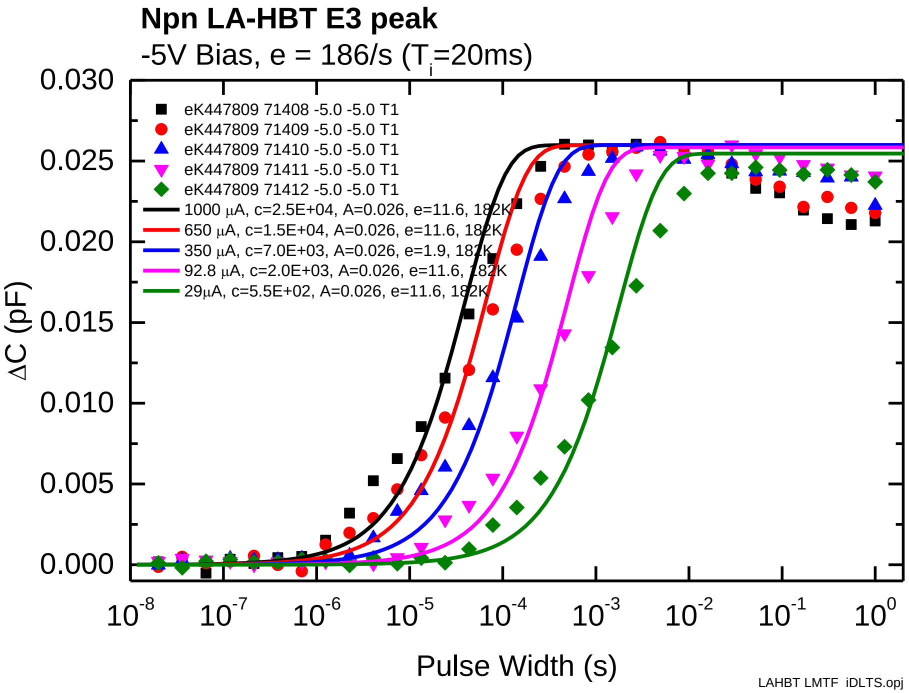

| Equation | y = a + b*x | | |
|---|---|---|---|
| Weight | No Weighting | | |
| Residual Sum of Squares | 1.6333E7 | | |
| Pearson's r | 0.99997 | | |
| Adj. R-Square | 0.99992 | | |
| | | Value | Standard Error |
| c | Intercept | 0 | -- |
| | **Slope** | **6.01305E-15** | 2.47658E-17 |

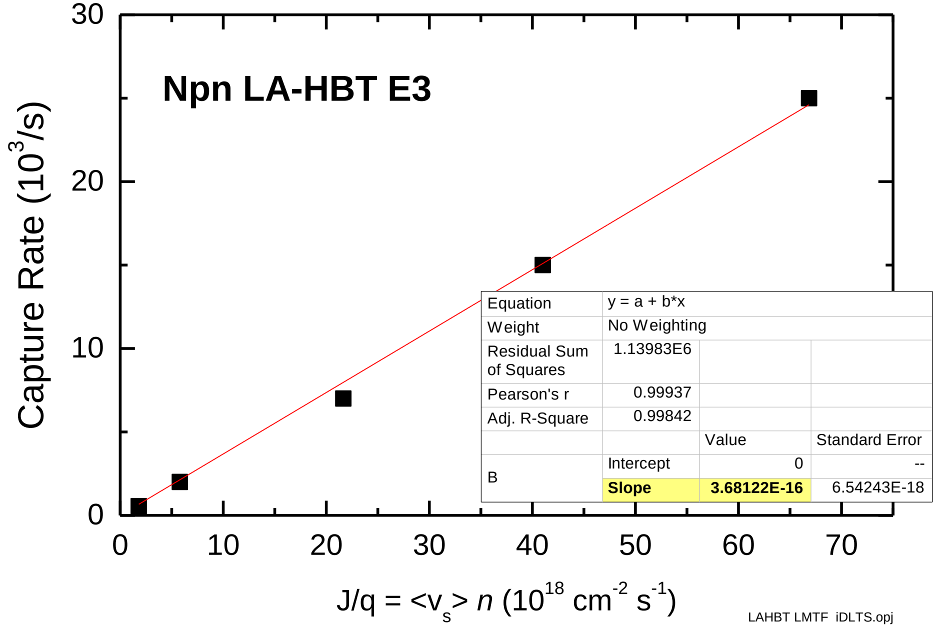
Fits to capture rates (solid lines) in these plots are all the same for both E4 and E5.

The capture rates are not influenced by the emission rate (temperature of the measurement) or the electric field.

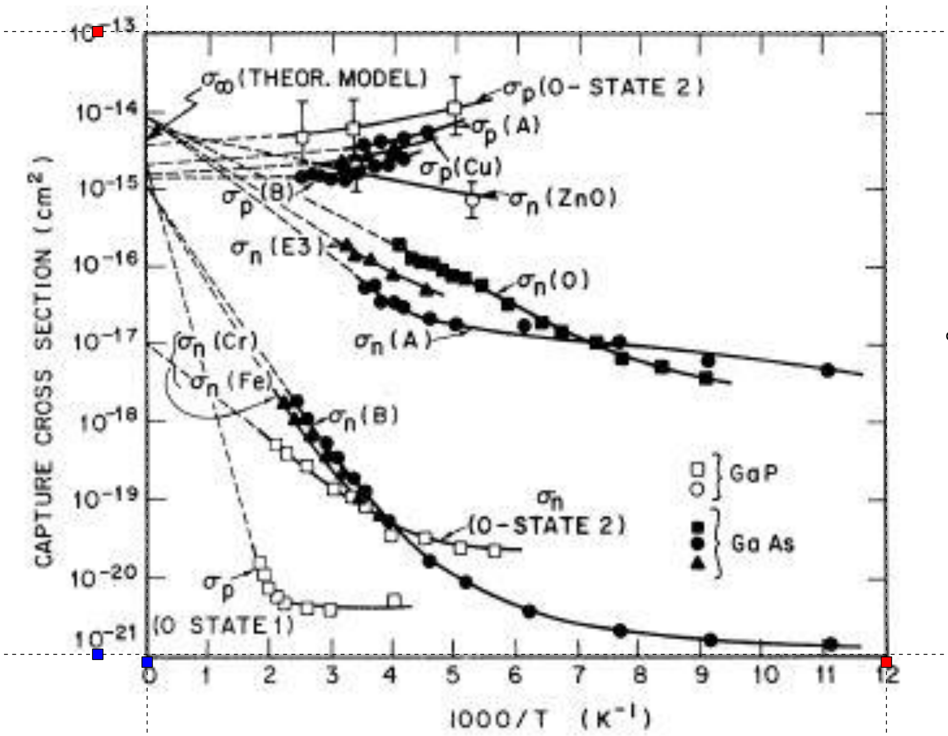
E5 prefactor from MPE fits to field dep. emission (JAP paper) give $\sigma = 7 - 11 \times 10^{-15} cm^2$

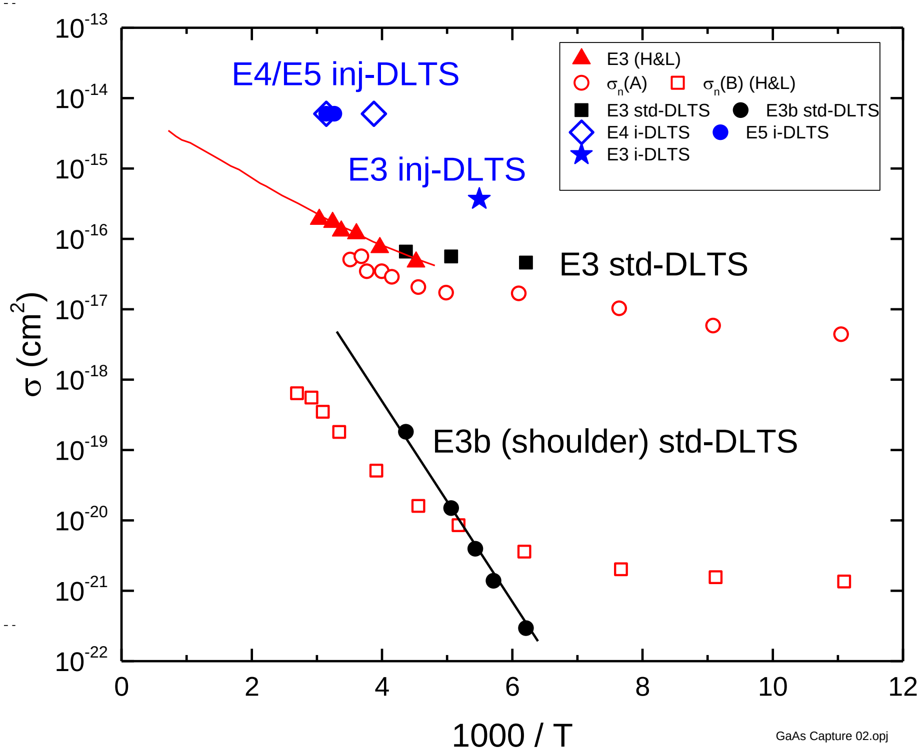
# E3 Capture Rates are Lower



# Compare with Lang’s 1977 Data




C. H. Henry and D. V. Lang, "Nonradiative capture and recombination by multiphonon emission in GaAs and GaP," *Physical Review B,* vol. 15, p. 989, 1977

# Summary:

- **DLTS reveals fundamental properties of GaAs defects**
  - **Emission from clustered defects indicates broad density of defect states**
  - **Recombination currents in GaAs diodes scale with number of defects**
    - **Independent of degree of clustering (mass of implanted ion)**
  - **GaAs field-dependent emission can be fit by theories of phonon assisted tunneling**
- **Carrier capture in transistor structures can be quantified using injection-DLTS**
  - **Validated the technique using silicon BJT's**
  - **Find large & equal capture cross sections of GaAs E4 and E5**
  - **Smaller values of $\sigma$ for E3**

# Acknowledgements

**Contributors & Collaborators:** D. V. Lang, C.H. Seager, S. M. Myers, W. R. Wampler, D. B. King, E. Bielejec, G. Vizkelethy, J. M Campbell

**QASPR-related Publications**

R. M. Fleming et al., Appl. Phys. Lett. **90**, 172105 (2007)
R. M. Fleming, et al., J. Appl. Phys. **104**, 083702 (2008)
R. M. Fleming, et al., J. Appl. Phys. **107**, 053712 (2010)
R. M. Fleming, et al., J. Appl. Phys. **107**, 123710 (2010)
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R. M. Fleming, et al., J. Appl. Phys. **111**, 023715 (2012)
R. M. Fleming, et al., J. Appl. Phys. **116**, 013710 (2014)
R. M. Fleming, et al., J. Appl. Phys. **118**, 015703 (2015)
D.B. King, et al., NIMB, in press (2015), http://dx.doi.org/10.1016/j.nimb.2015.08.026