Defect investigation in irradiated ATLAS18 ITk Strip Sensors using transient spectroscopy techniques

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on behalf of the ATLAS ITk Strip Sensors community

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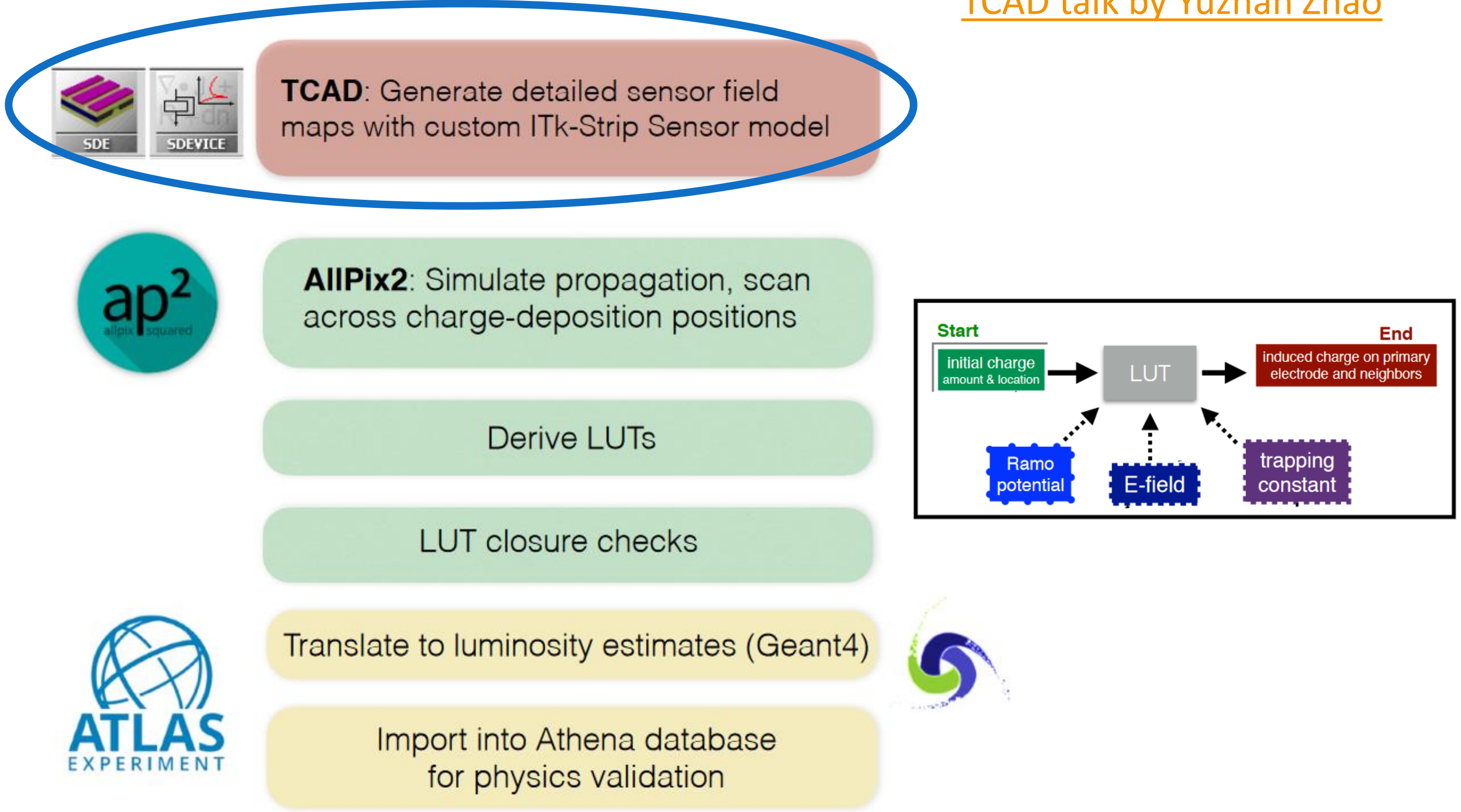
Motivation

- ITk Strip Sensors will degrade with increasing radiation damage
- necessity to reliably predict behaviour and adapt operational parameters e.g. bias voltage
- modelling of radiation damage effects in digitization for detector readout
  - currently, simulation methods too slow
  - look-up table (LUT) method for fast and accurate predictions

➢ **custom ITk Strips model of radiation damage in silicon sensors informed by direct measurements**

TCAD talk by Yuzhan Zhao



TCAD: Generate detailed sensor field maps with custom ITk-Strip Sensor model

AllPix2: Simulate propagation, scan across charge-deposition positions

Derive LUTs

LUT closure checks

Translate to luminosity estimates (Geant4)

Import into Athena database for physics validation

TCAD + AllPix2 pipeline talk by Jeff Dandoy

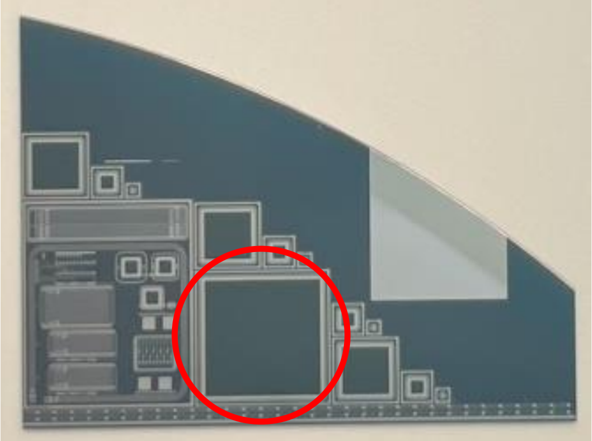
Introduction

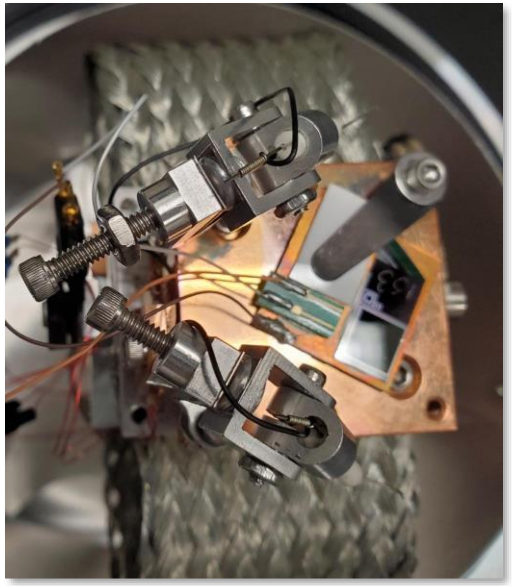
- measurements on MD8 diodes
- samples mounted on heatsinks and wire-bonded contacts for implant and GR
- previous tests performed on unirradiated and irradiated devices
  - unirradiated halfmoons from batch with high current main sensors + reference samples from 'normal' batch
  - irradiated samples with irradiation done at CYRIC with 70 MeV protons
    - 3 different fluences (10% uncertainty) and annealed 80min@60°C:

4.57e14 n_{eq}/cm^2 8.34e14 n_{eq}/cm^2 1.54e15 n_{eq}/cm^2

⇒ presented during 'Hiroshima' Symposium 2023

- neutron/gamma-irradiated samples not yet tested
- recently received CERN-PS 24GeV proton-irradiated samples

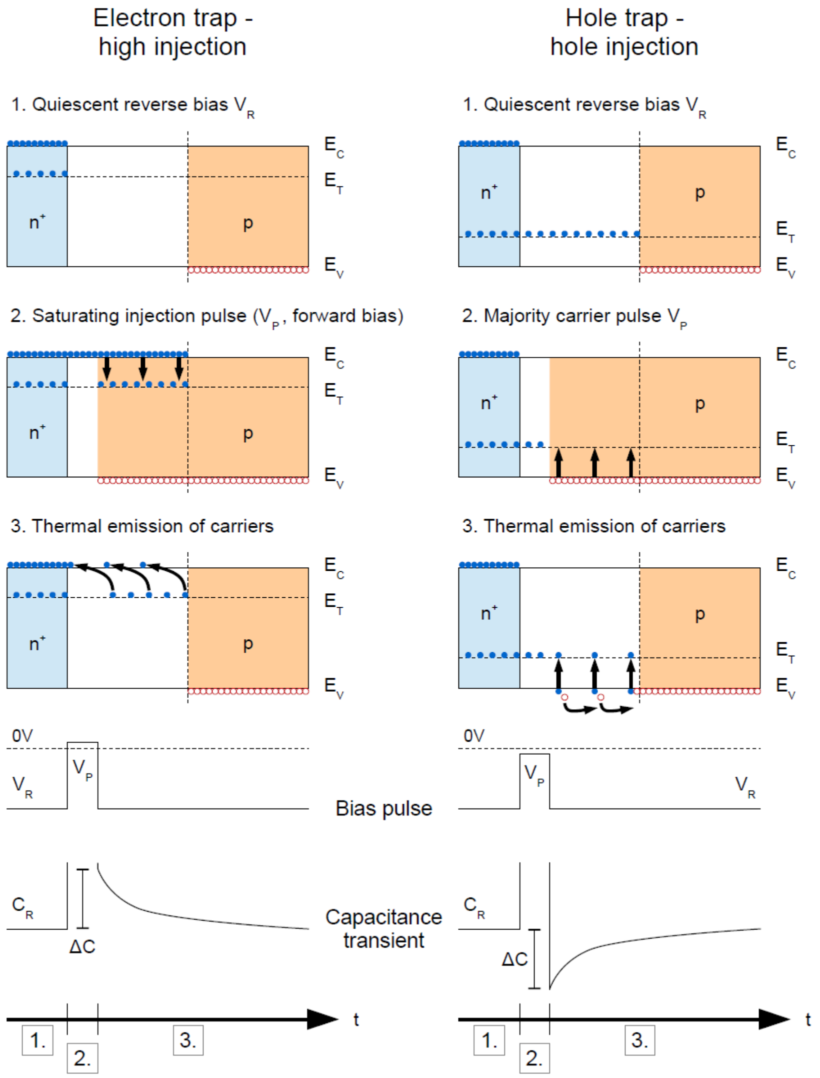




Measurement methods: DLTS/I-DLTS

1. DUT is under constant reverse bias
2. filling pulse with specific voltage V_P and duration is applied, adjusted to trap states of interest
   - V_P as reduced reverse bias → majority carrier traps (holes)
   - V_P slight forward bias → minority carrier traps (electrons), if capture rate much larger than competing majority traps
3. bias back to prior level, measure transients
   - capacitance or current transients, depending on sample

- usually average O(100) transients per temperature point
- plot ΔC or ΔI vs. temperature for fixed rate window corresponding to emission rate
- analysing spectrum for varying rate window $[t_1; t_2]$ yields Arrhenius plot of trap levels



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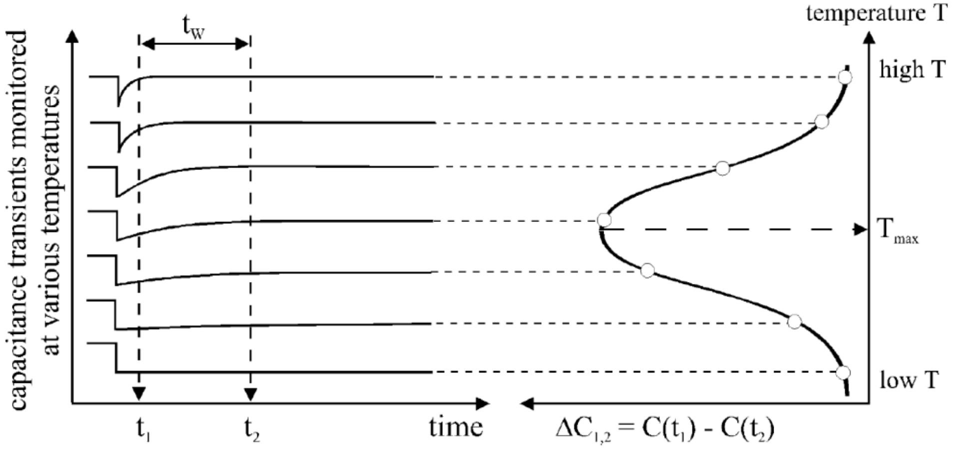
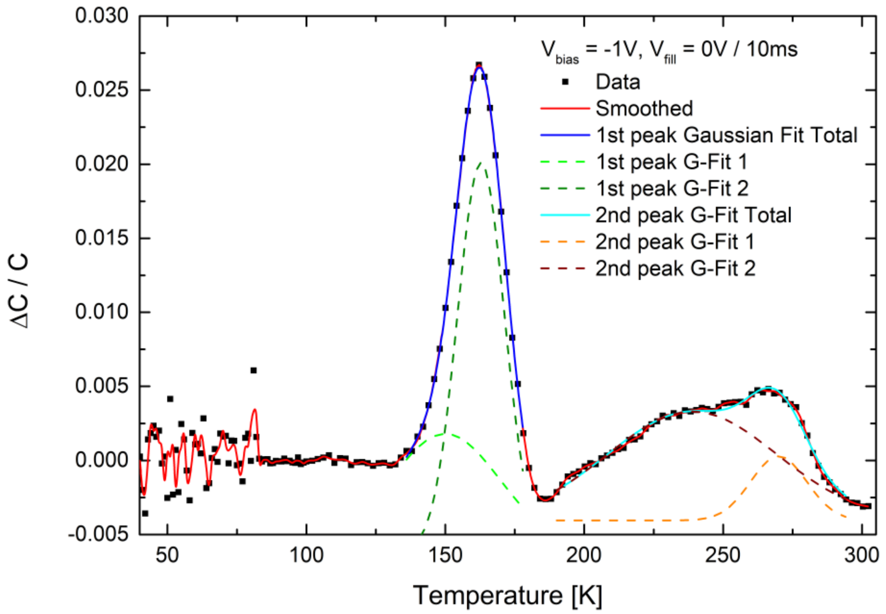
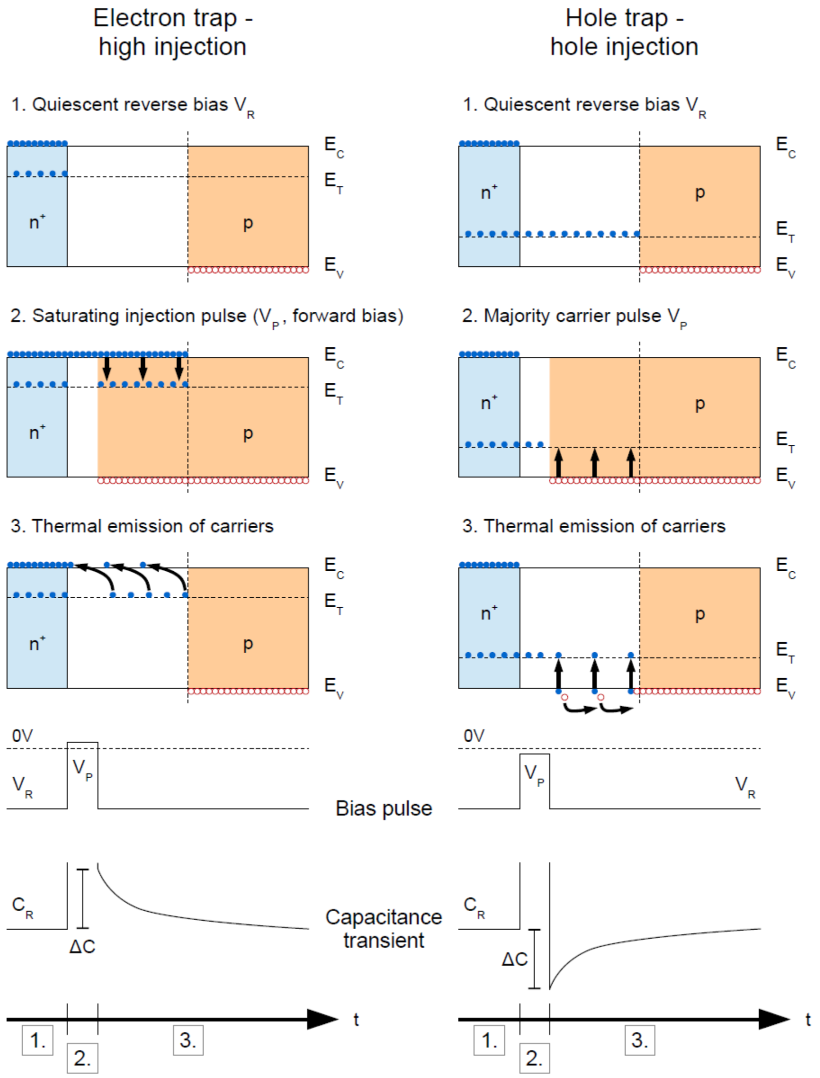


D. V. Lang, Deep-level transient spectroscopy



Measurement methods: O-DLTS/PICTS

- Optical-DLTS and Photo-Induced Current Transient Spectroscopy variants of basic DLTS/I-DLTS
- difference: use LED for injection and trap filling
- IR-LED (1050nm) has high penetration depth, energy slightly above Si bandgap
- LED pulse allows charge injection above what is possible with (forward) electrical filling pulse; more/different traps can be saturated
- can also use differential modes for measurements to subtract baseline current



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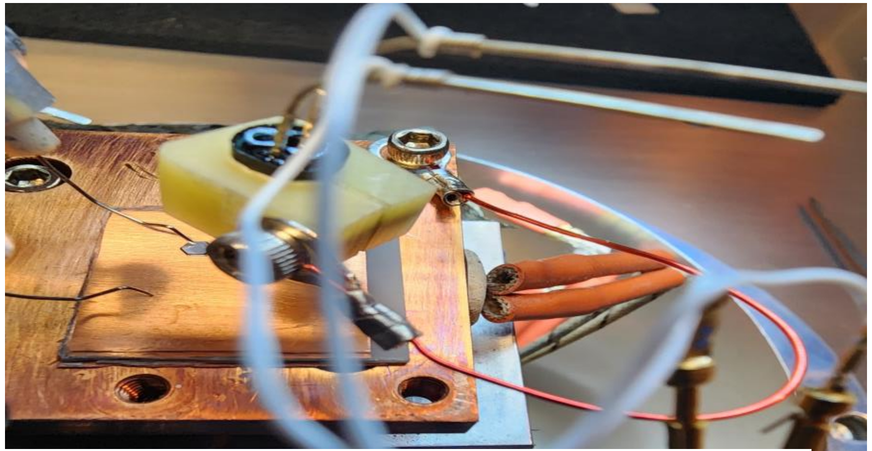
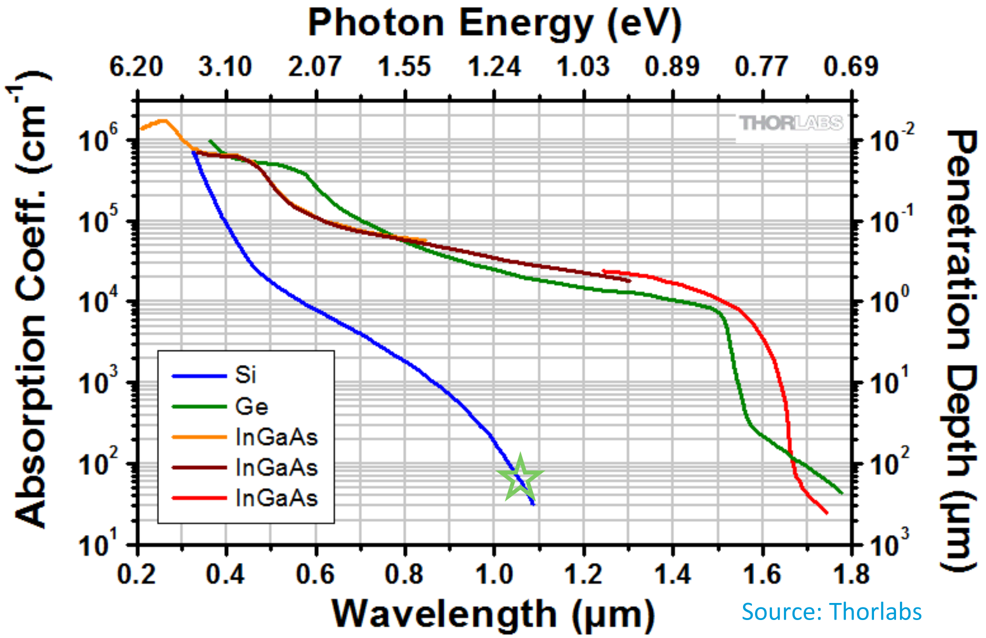
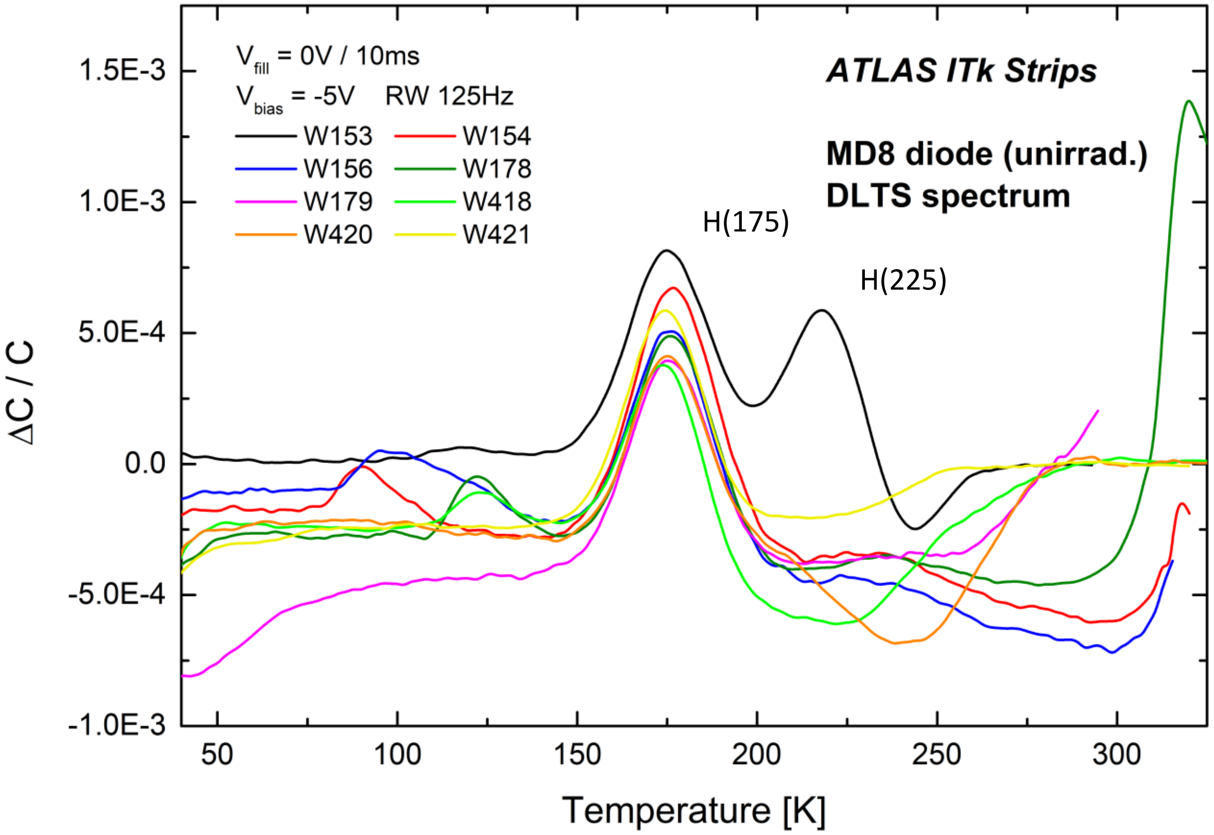




Source: Thorlabs

Unirradiated diodes: DLTS spectra

- DLTS measurements performed for different bias voltage and filling pulse settings
  - common trap at ~175K seen in all diodes
  - negative offset observed, mitigated with GR at GND
  - peaks at ~100K not consistent between different scan parameters no clear Arrhenius plot

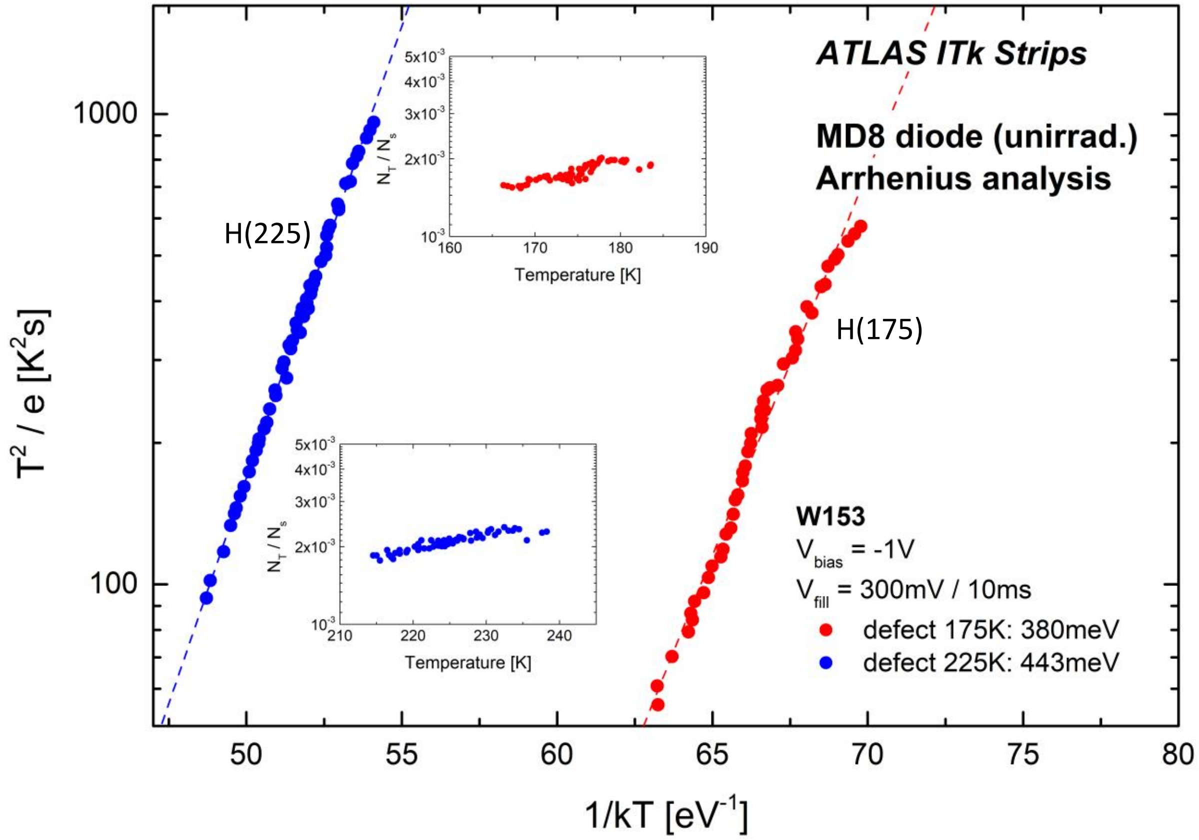


- ➢ **only true additional defect observed for W153 at ~225K**
  - ➢ confirmed over multiple runs anc 2 diode samples

Unirradiated diodes: Arrhenius analysis

- good trap saturation for 10ms filling pulse
  - flat relative trap concentration as indicator
- increased transient amplitude for larger bias
  - no changes to overall spectrum
- Arrhenius plots from rate window analysis
  - derive trap parameters from linear fits

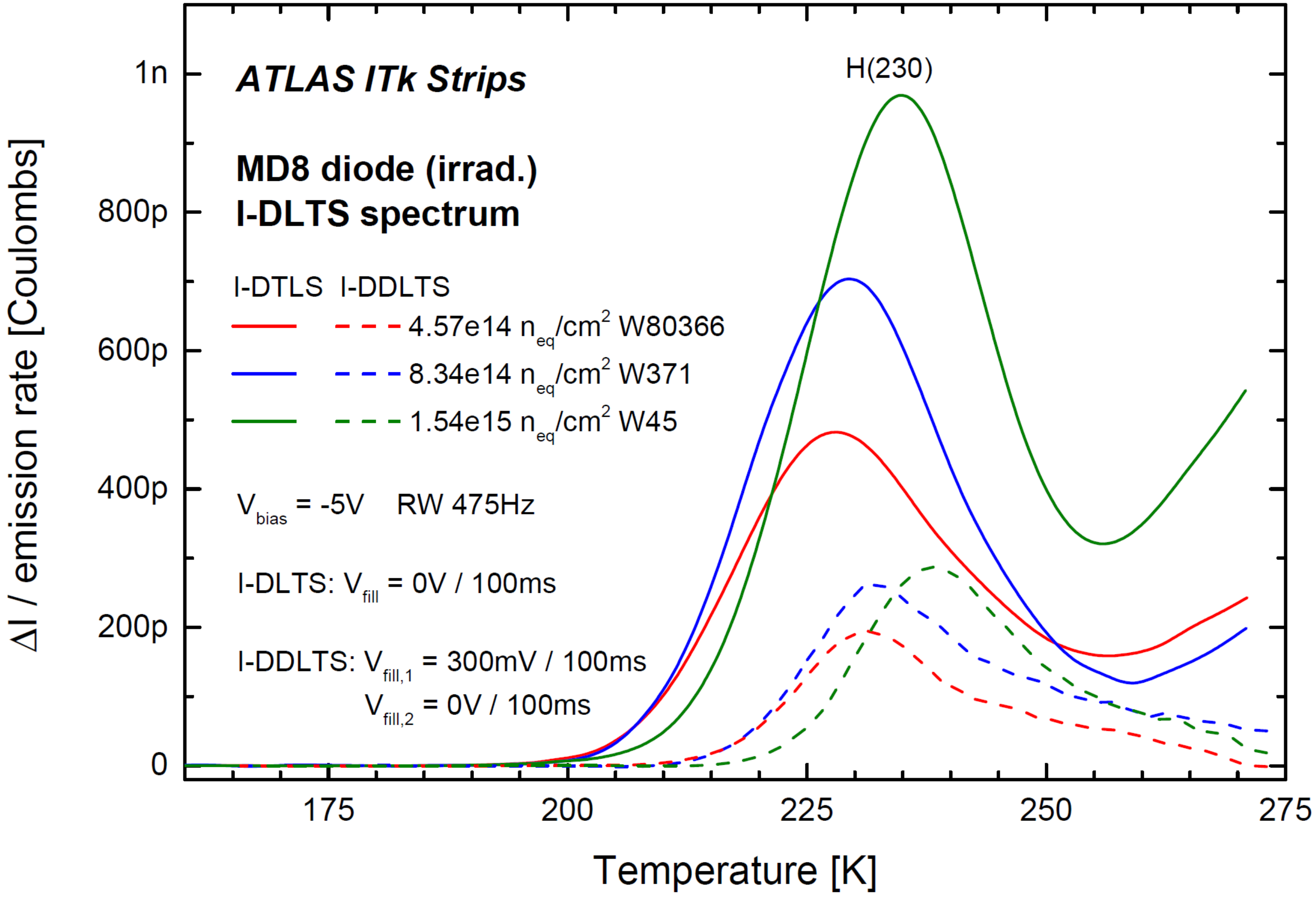
T_{median} [K]	E_T [meV]	σ [cm²]
175 (common)	310 – 390	$10^{-14} – 10^{-13}$
225 (W153 only)	443 ± 6	7.5×10^{-15} ± 1.4X



$$\ln(\tau_e T^2) = -\ln\left(\sigma_{n,p}^{\text{eff}}\,\Gamma_{n,p}\right) + \frac{E_A}{k_B T}$$

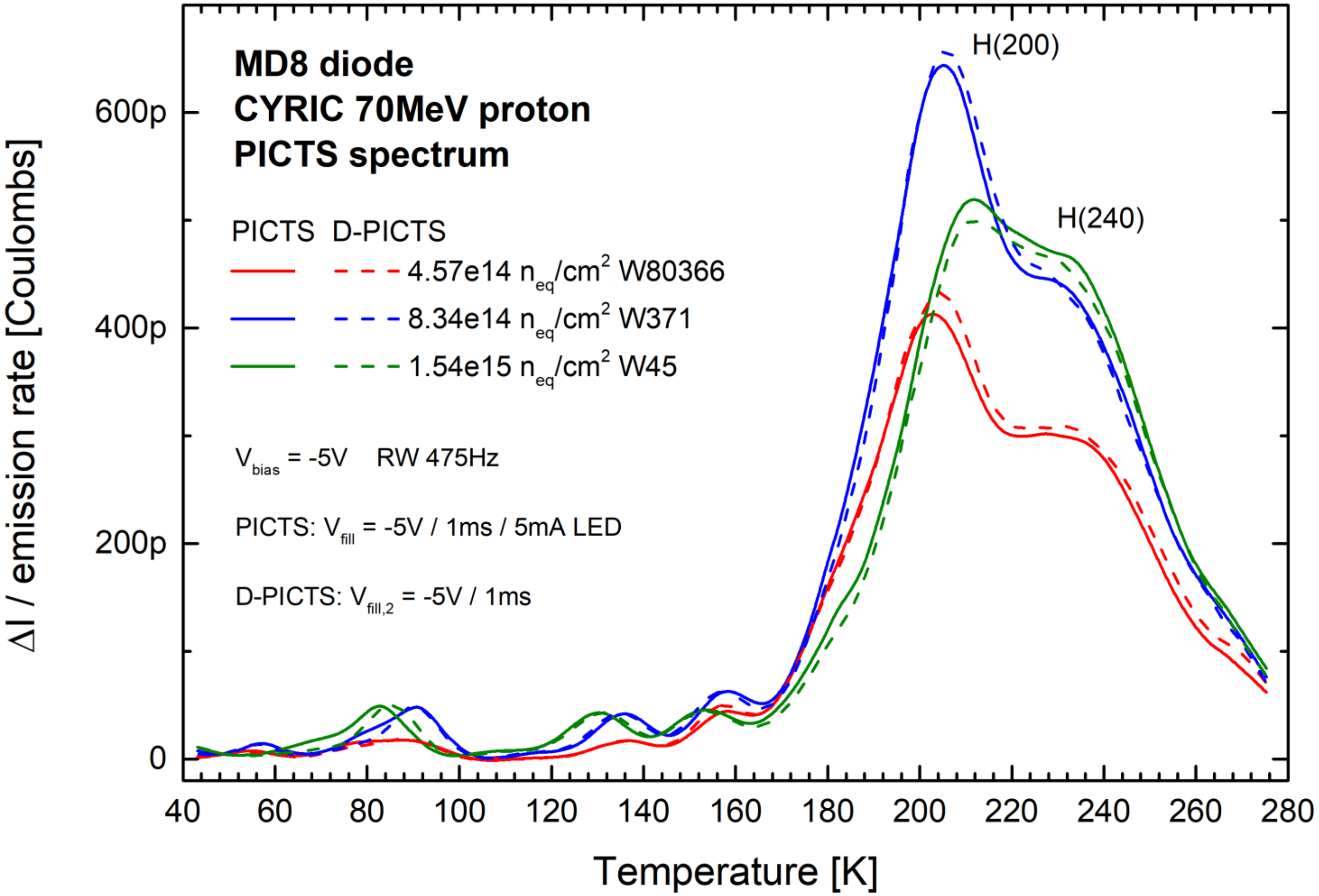
Irradiated diodes: I-DLTS spectra

- capacitance transients did not yield reliable results
  - high trap concentration
- I-DLTS spectra very clean
  - >270K could not be fully explored due to high current
- additional traps observed using forward injection pulse in double-pulse setting
- **observable traps limited to those with largest capture cross-section**



Irradiated diodes: PICTS spectra

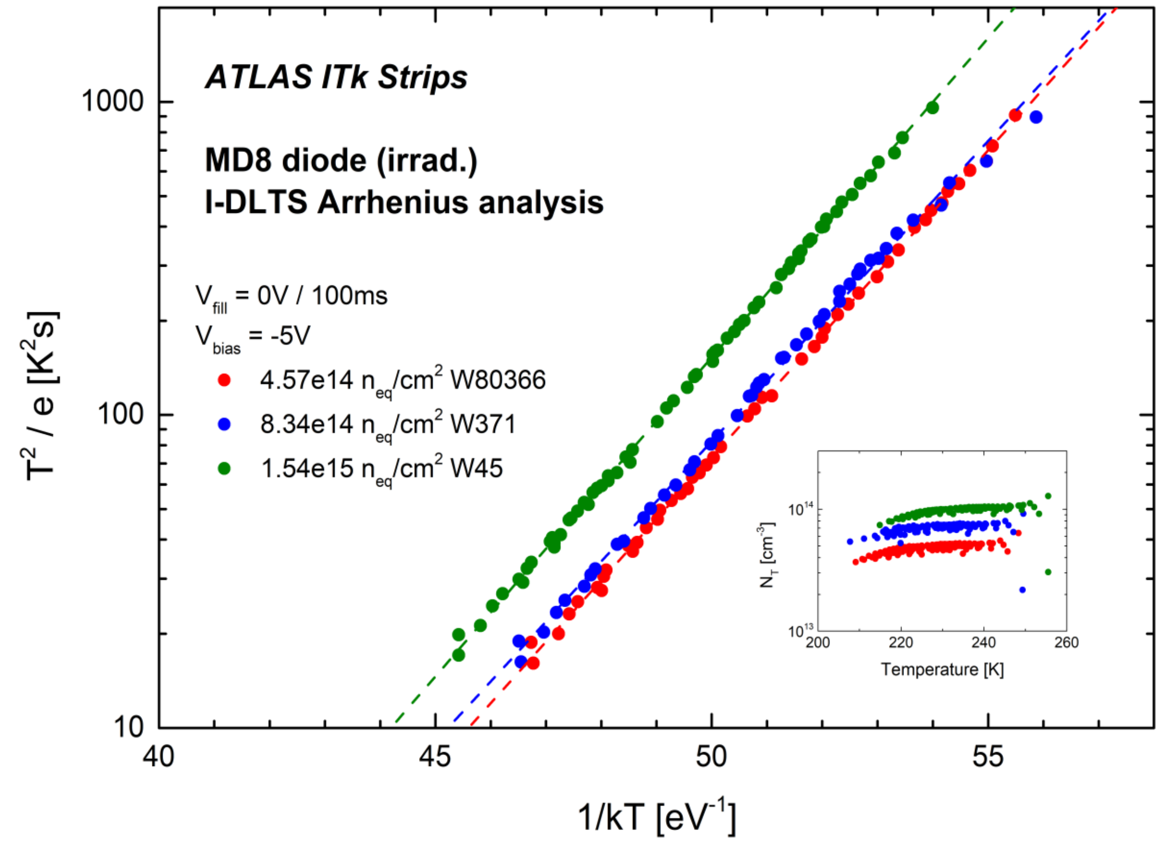
- observable defects even at low temperatures
  - not seen in I-DLTS
- convolution of (at least) two trap states in large peak
- trap filling purely through LED (could be combined with electrical pulse)
  - D-PICTS to subtract baseline current without LED
- shorter 1ms filling pulses give stable trap saturation



Irradiated diodes: I-DLTS Arrhenius analysis

- good trap saturation for 100ms filling pulse
- higher trap concentrations in devices irradiated to higher fluences
- no significant variation in trap parameters with higher fluence
- **observed trap parameter precision limited due to high trap concentration**

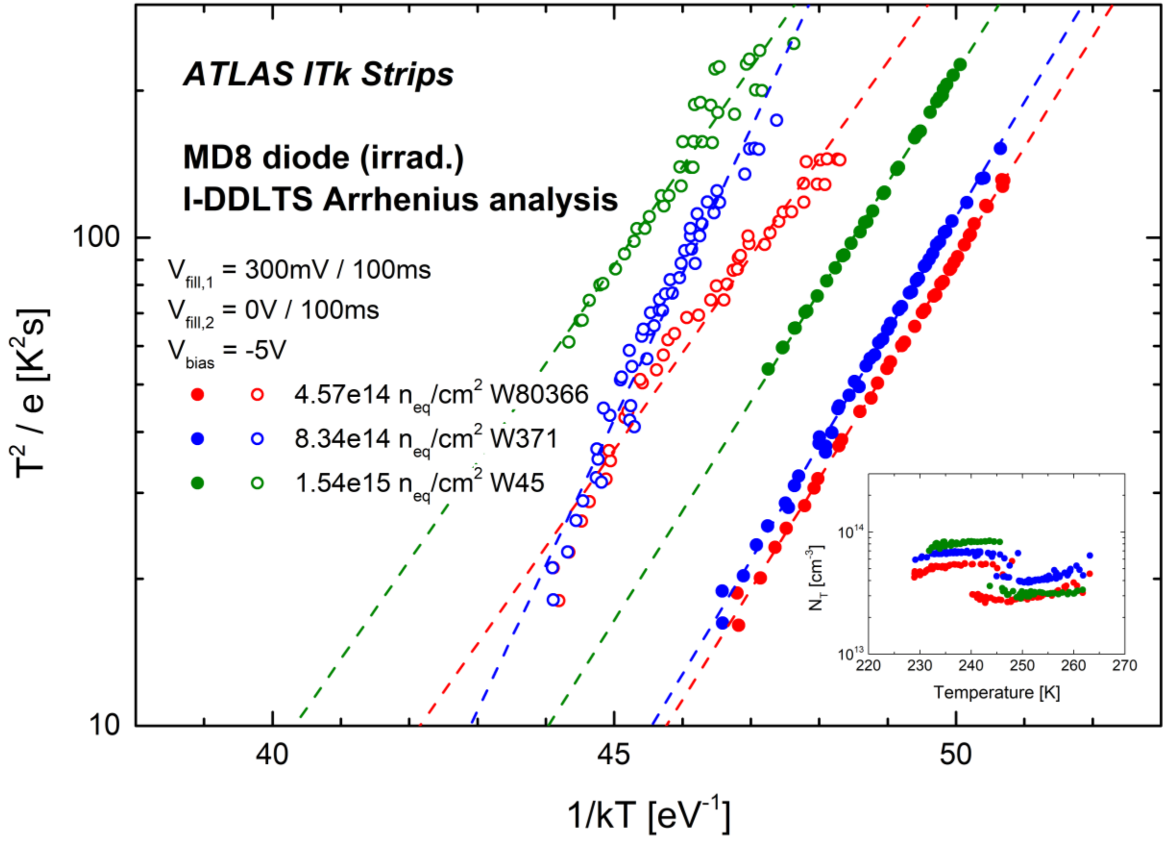
Φ [n_{eq}/cm^2]	E_T [meV]	σ [cm^2]
4.57e14	452 ± 4	2.7 x 10^{-14} ± 1.2X
8.34e14	442 ± 7	1.5 x 10^{-14} ± 1.5X
1.54e15	469 ± 3	3.2 x 10^{-14} ± 1.2X



Irradiated diodes: I-DDLTS Arrhenius analysis

- forward injection pulse
  - remove large signal with double-pulse measurement
- 2-Gaussian deconvolution yields second trap contribution in peak flank
  - larger uncertainties on fit results of secondary peak component

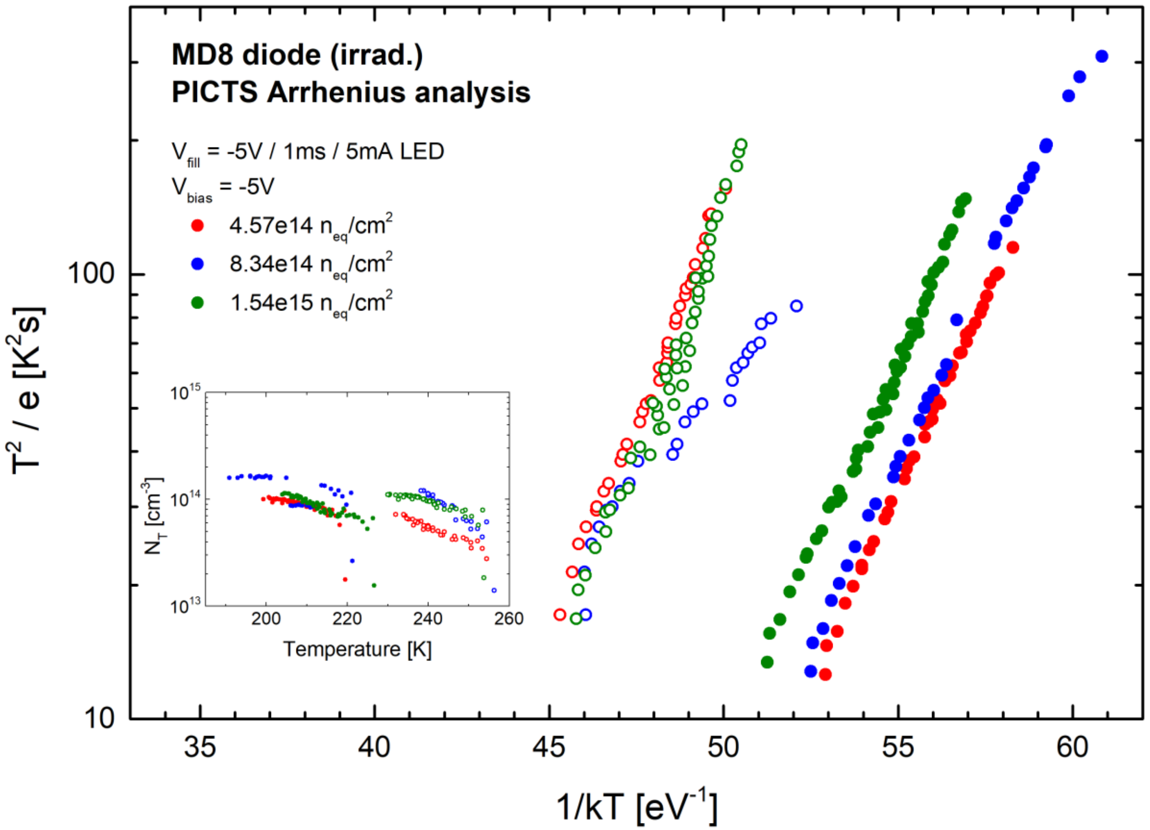
Φ [n_{eq}/cm^2]	E_T [meV]	σ [cm^2]
4.57e14	521 ± 7	$6.9 \times 10^{-13} \pm 1.4X$
	457 ± 28	$7.3 \times 10^{-15} \pm 3.6X$
8.34e14	539 ± 9	$1.4 \times 10^{-12} \pm 1.5X$
	686 ± 42	$1.9 \times 10^{-10} \pm 6.8X$
1.54e15	516 ± 6	$2.3 \times 10^{-13} \pm 1.4X$
	465 ± 41	$4.2 \times 10^{-15} \pm 6.5X$



Irradiated diodes: PICTS Arrhenius analysis

- observed trap concentration much higher than for electrical injection
- shift in trap energy compared to I-DLTS

Φ [n_{eq}/cm^2]	T_{peak} [K]	E_T [meV]	σ [cm^2]
4.57e14	200	399 ± 6	$3.2 \times 10^{-14} \pm 1.5$X
	240	452 ± 16	$1.3 \times 10^{-14} \pm 2.2$X
8.34e14	200	387 ± 7	$1.4 \times 10^{-14} \pm 1.5$X
	240	513 ± 13	$3.0 \times 10^{-13} \pm 1.9$X
1.54e15	200	405 ± 10	$2.3 \times 10^{-14} \pm 1.8$X
	240	487 ± 29	$8.8 \times 10^{-14} \pm 4.1$X



Summary and Outlook

- started collecting trap parameters for unirradiated + irradiated MD8 diodes
  - create custom radiation damage model in TCAD with DLTS-measured defects
- established pipeline to build LUTs from ITk Strip Sensor simulations

Outlook

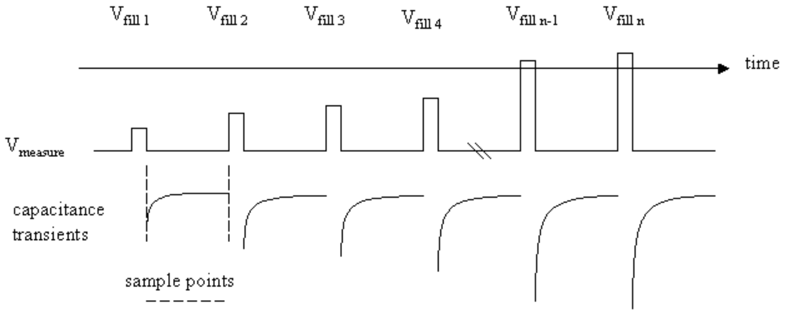
- measure other irradiated diode samples
  - mainly use PICTS
  - currently ongoing
- compare observed traps for different sources of irradiation + fluence
  - CYRIC 60MeV vs. CERN-PS 24 GeV protons
  - comparison between proton/neutron/gamma samples

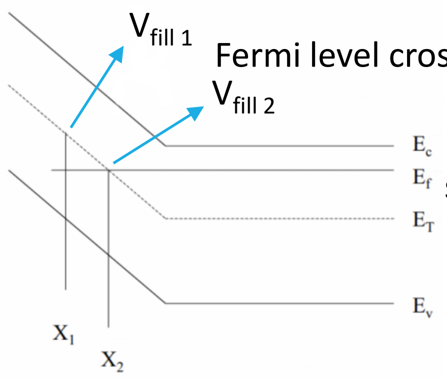
Backup

Measurement methods: DDLTS, Capture Kinematics

- Capacitance Double-Pulse DLTS (DDLTS) measured at temperature of observed trap

- progressively increasing filling pulse at fixed bias ⇒ **deep level trap profile**





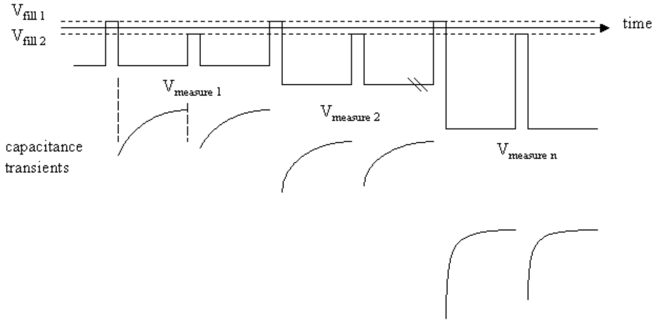
$V_{fill\ 1}$

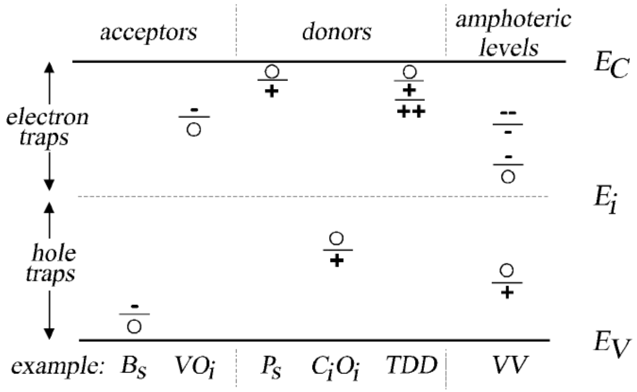
Fermi level crosses trap level

$V_{fill\ 2}$

signal difference = trap concentration in region X_1-X_2

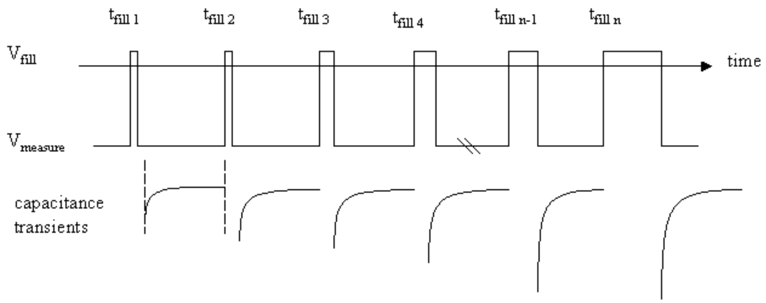
- fixed pair of filling pulses at increasing measurement bias ⇒ **field strength dependence**; indicates acceptor/donor state

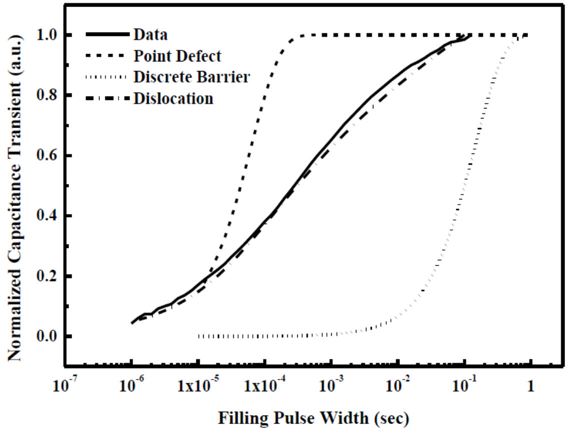




M. Moll, Ph.D. thesis

- increasing filling pulse duration ⇒ **capture kinematics**; defect type





all other figures: Semetrol DLTS Manual

PICTS: 1.54e15 n_{eq}/cm^2 sample – all traps