# Defect level identification of ATLAS ITk Strip Sensors using DLTS

**Christoph Klein**

J. Dandoy, D. Duvnjak, C. Jessiman, J. Keller, T. Koffas, E. Staats, R. Vandusen,
V. Fadeyev, Y. Unno, M. Ullan

13th Hiroshima Symposium, Vancouver, 3-8 December 2023

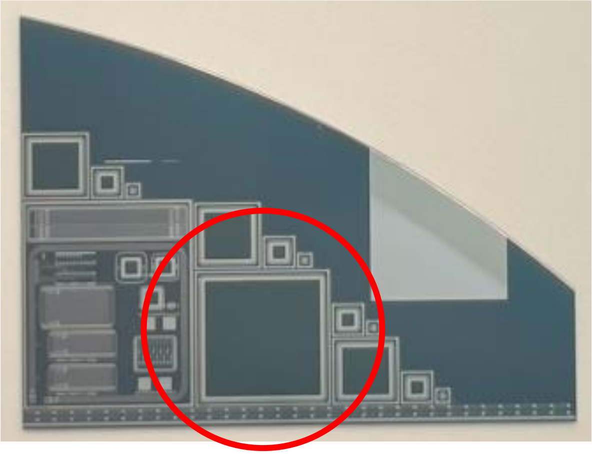
# Introduction

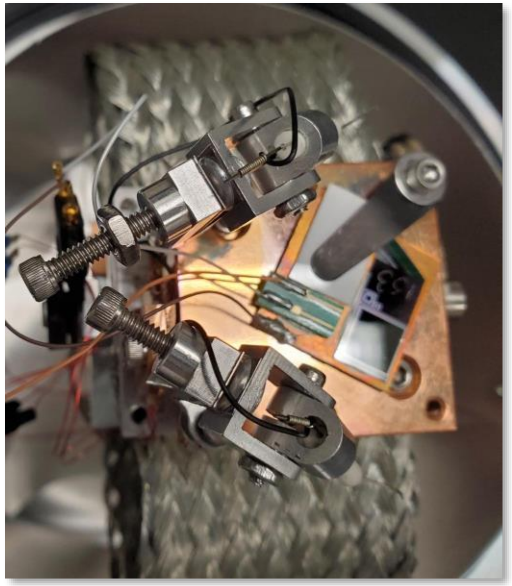
**Motivation:**

- implement trap parameters in TCAD (see poster contribution by C. Jessiman)
  - precise simulations of irradiated ITk sensors

- measurements on MD8 diodes
  - square 8mm x 8mm $n^+$-in-p diodes
  - produced as test structure on same wafers as main ITk Strip Sensors
- 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:

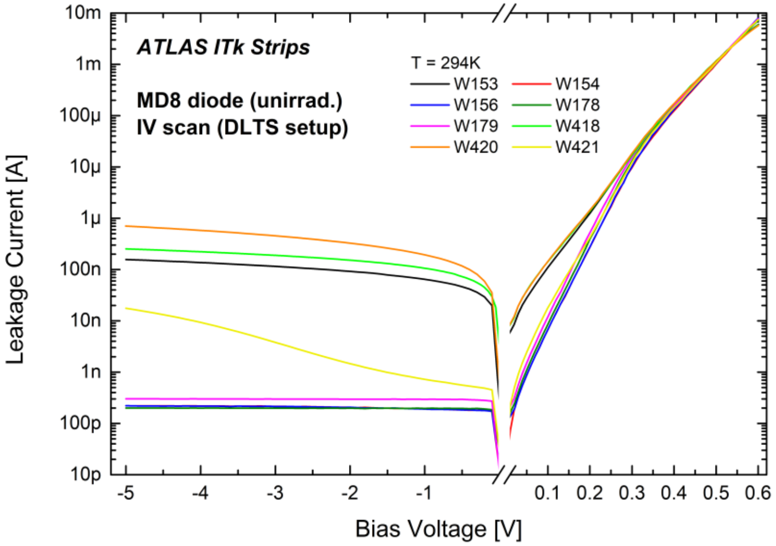
    **4.57e14 $n_{eq}/cm^2$** **8.34e14 $n_{eq}/cm^2$** **1.54e15 $n_{eq}/cm^2$**
- samples mounted on heatsinks and wire bonded contacts for implant and GR





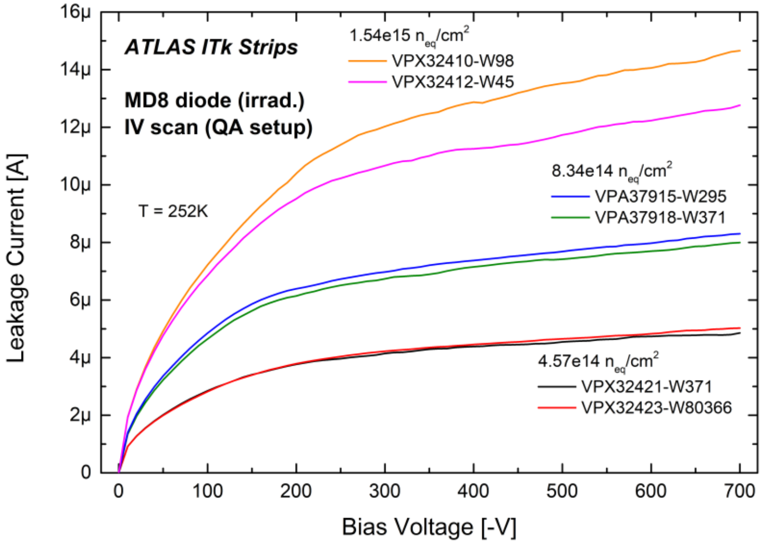
# IV scans

## UNIRRADIATED



- IV curves taken at room temperature on DLTS setup
- W153-179 from a batch with high current main sensors; W418-421 for reference
- incidentally W153, W418, W420 with highest current

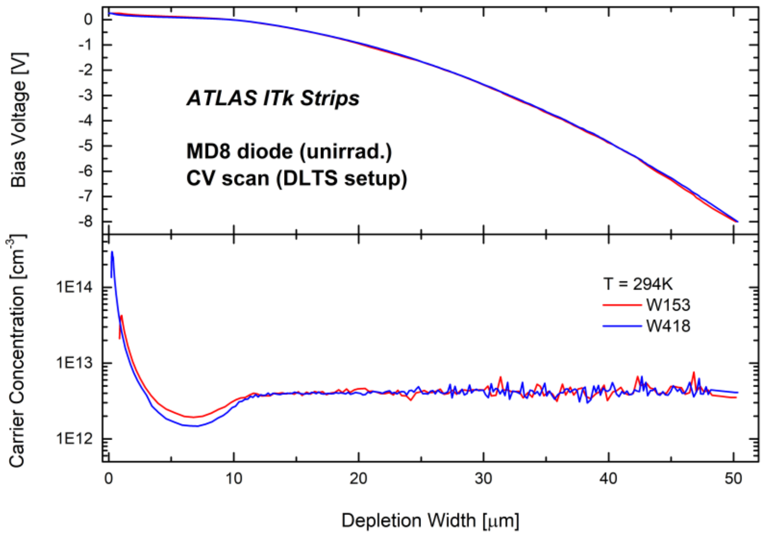
## IRRADIATED



- QA results
- leakage current shows clear scaling with fluence
- higher currents allow for use of I-DLTS, but can limit usefulness of capacitance transients

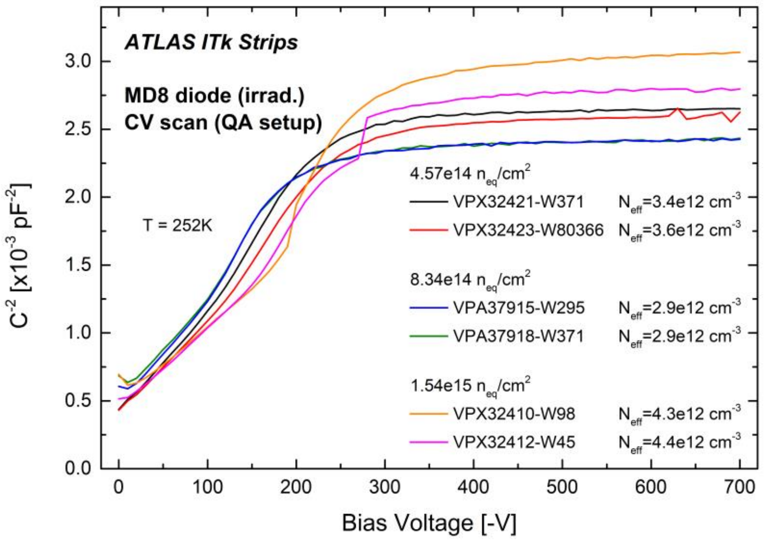
# CV scans

## UNIRRADIATED



- CV scans did not show significant differences between samples
- depletion width and doping concentration can be derived from CV curves

## IRRADIATED

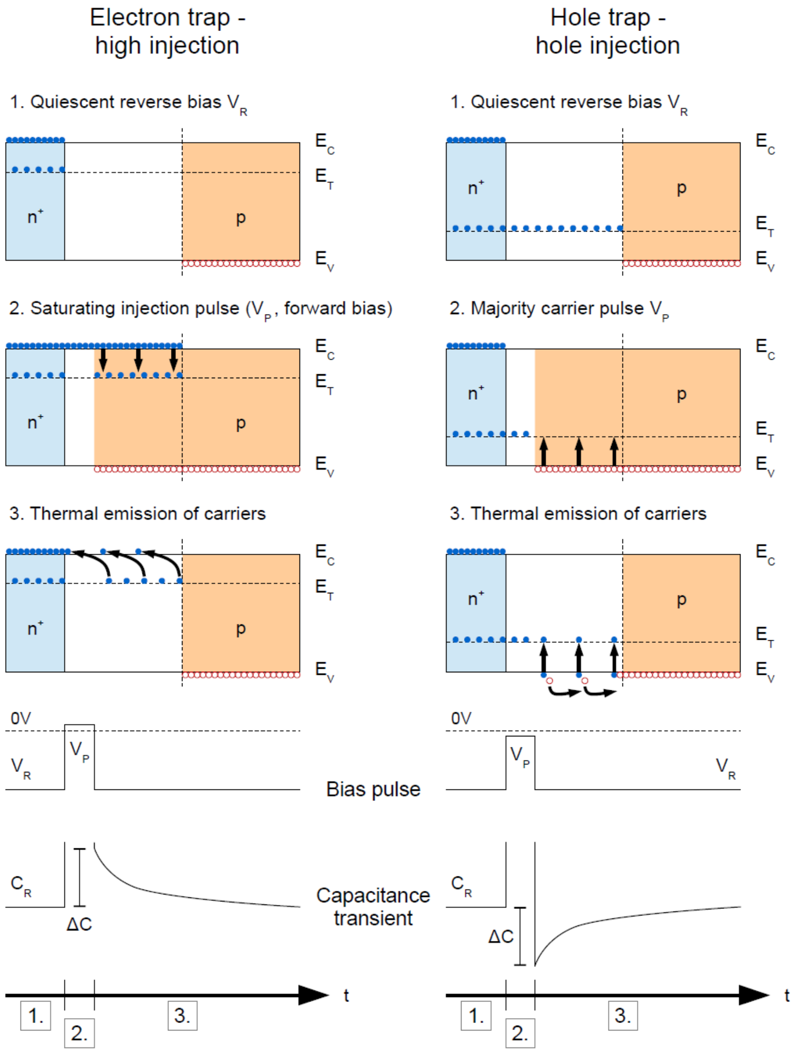


- full depletion still present at highest irradiation level
  - limited acceptor removal, $N_{eff}$ similar to before irradiation
- DLTS setup can only bias up to 10V,
  - low bias readings of irradiated samples not useful for calculation of depletion width and carrier concentration

# 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

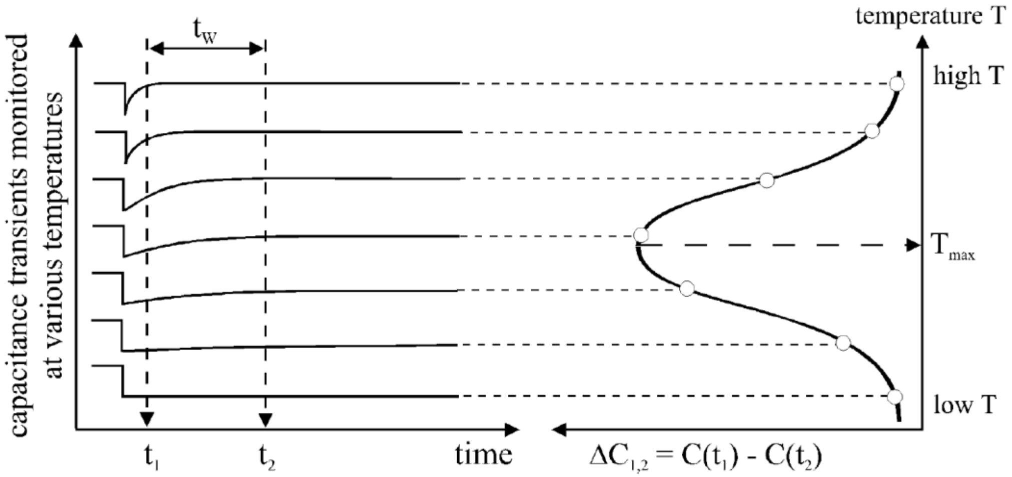
- usually average O(100) transients per temperature point
- plot ΔC or ΔI vs. temperature for fixed rate window corresponding to emission rate
- analysing spectrum for varying rate window [$t_1$; $t_2$] yields Arrhenius plot of trap levels



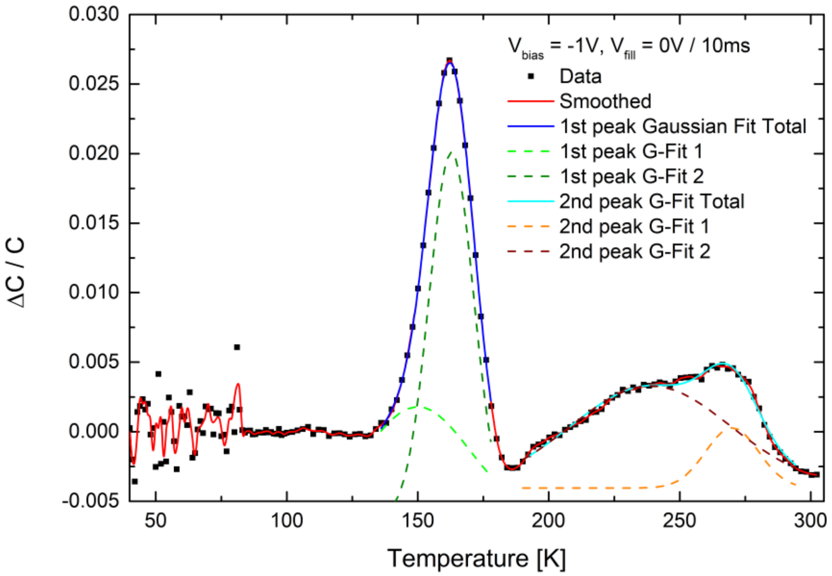
# Measurement methods: DLTS/I-DLTS

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



D. V. Lang, Deep-level transient spectroscopy

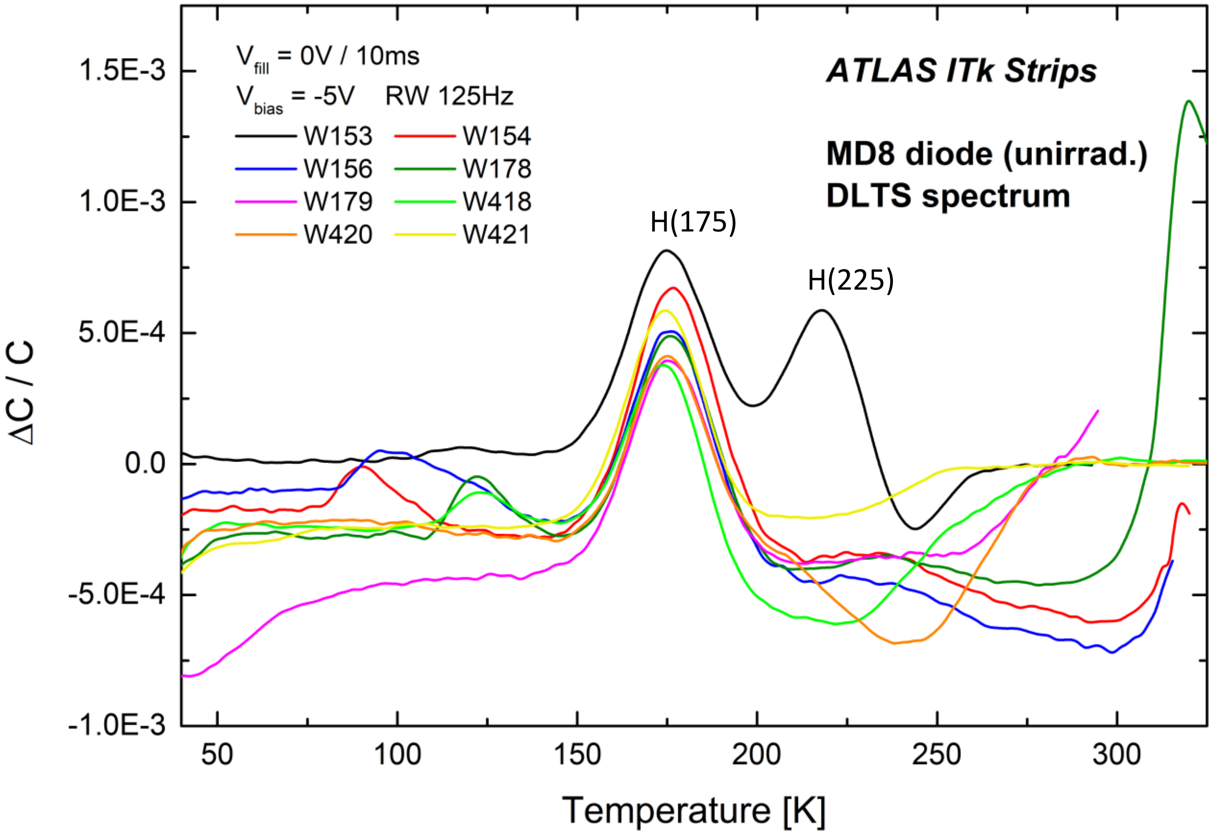


# Unirradiated diodes: DLTS spectra

- 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 and 2 diode samples

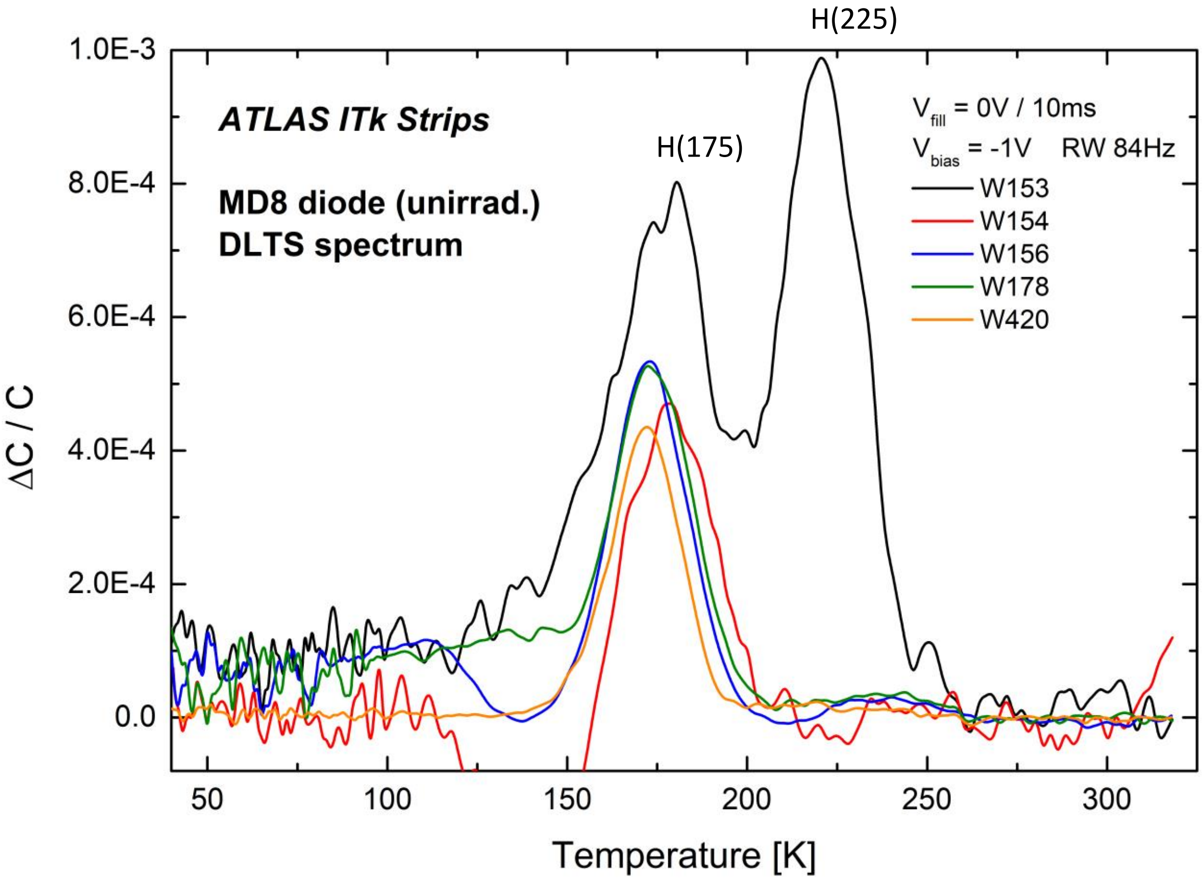


# Unirradiated diodes: DLTS spectra

- 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**

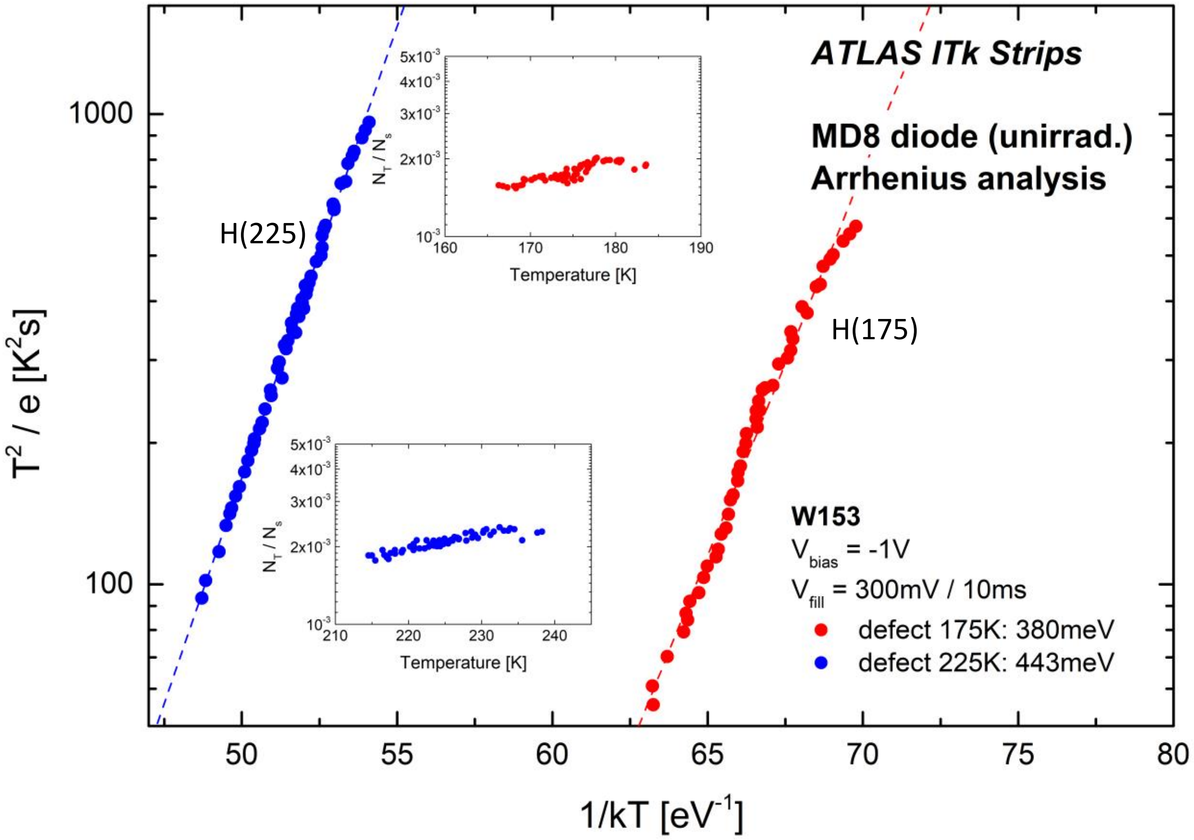
  ➢ confirmed over multiple runs and 2 diode samples



# 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 | $7.5 \times 10^{-15}$ ± 1.4X |

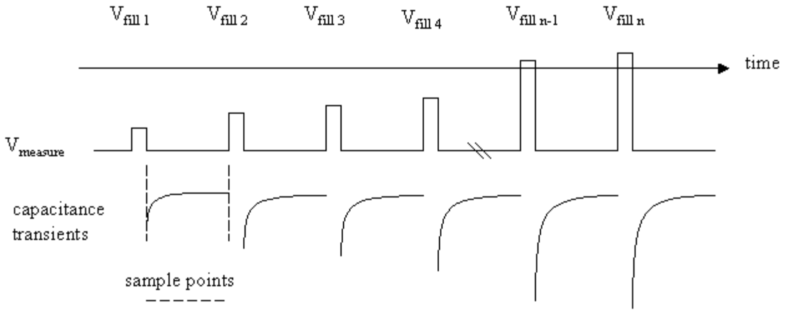


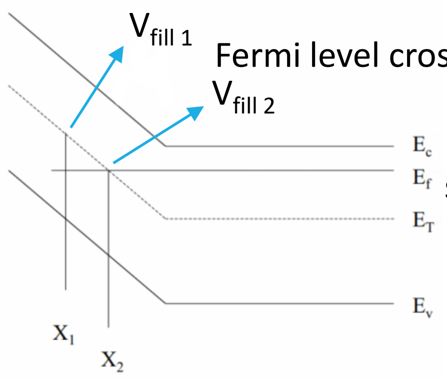
$$\ln(\tau_e T^2) = -\ln\left(\sigma_{n,p}^{\text{eff}}\, \Gamma_{n,p}\right) + \frac{E_A}{k_B T}$$

# Measurement methods: DDLTS, Capture Kinematics

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

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

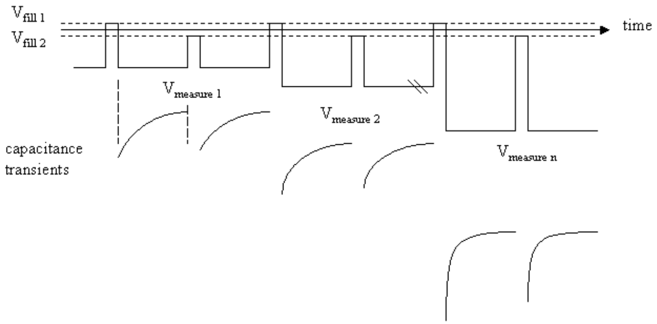


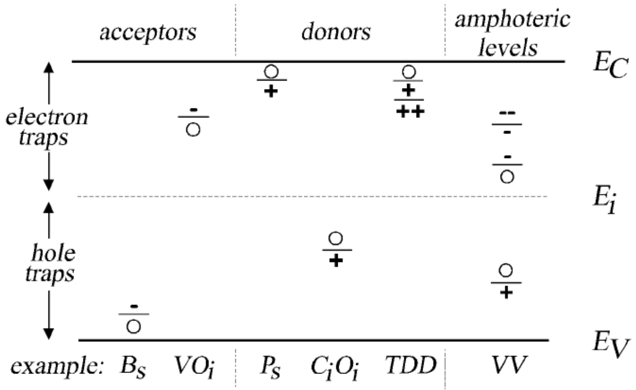


Fermi level crosses trap level

signal difference
= trap concentration
in region $X_1$-$X_2$

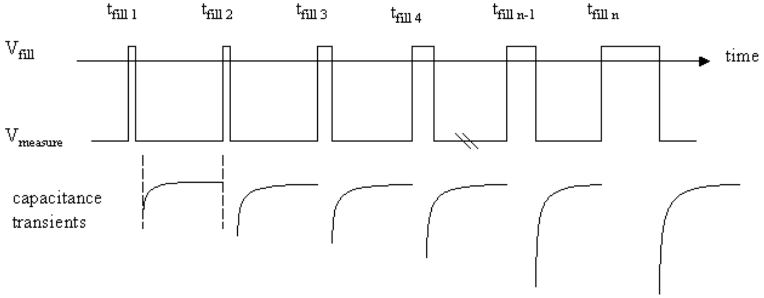
- fixed pair of filling pulses at increasing measurement bias
  ⇒ **field strength dependence**;
  indicates acceptor/donor state

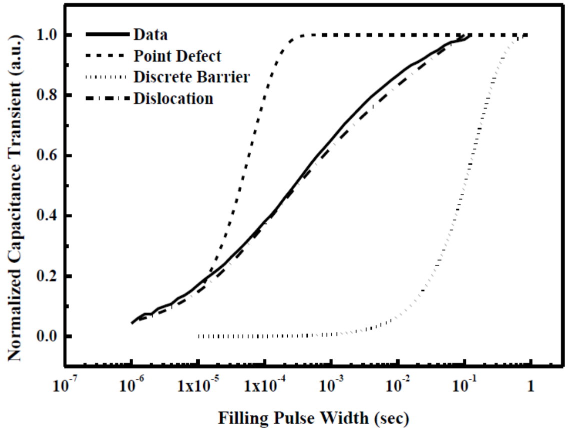




M. Moll, Ph.D. thesis

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

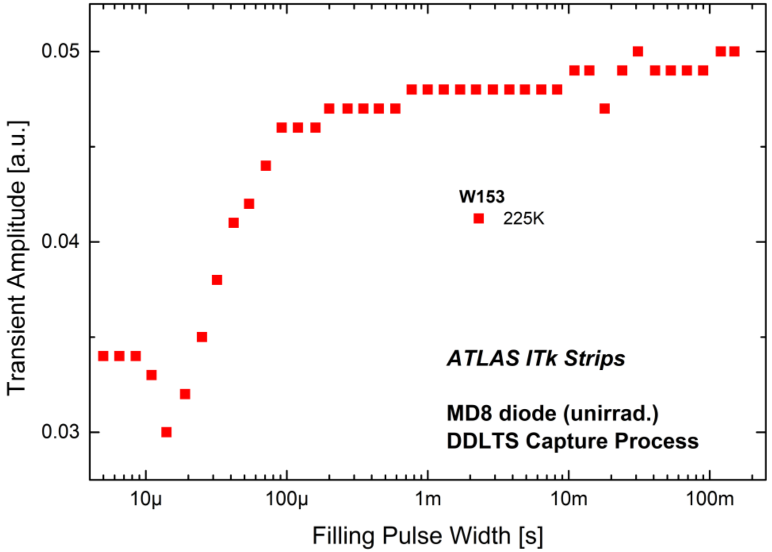


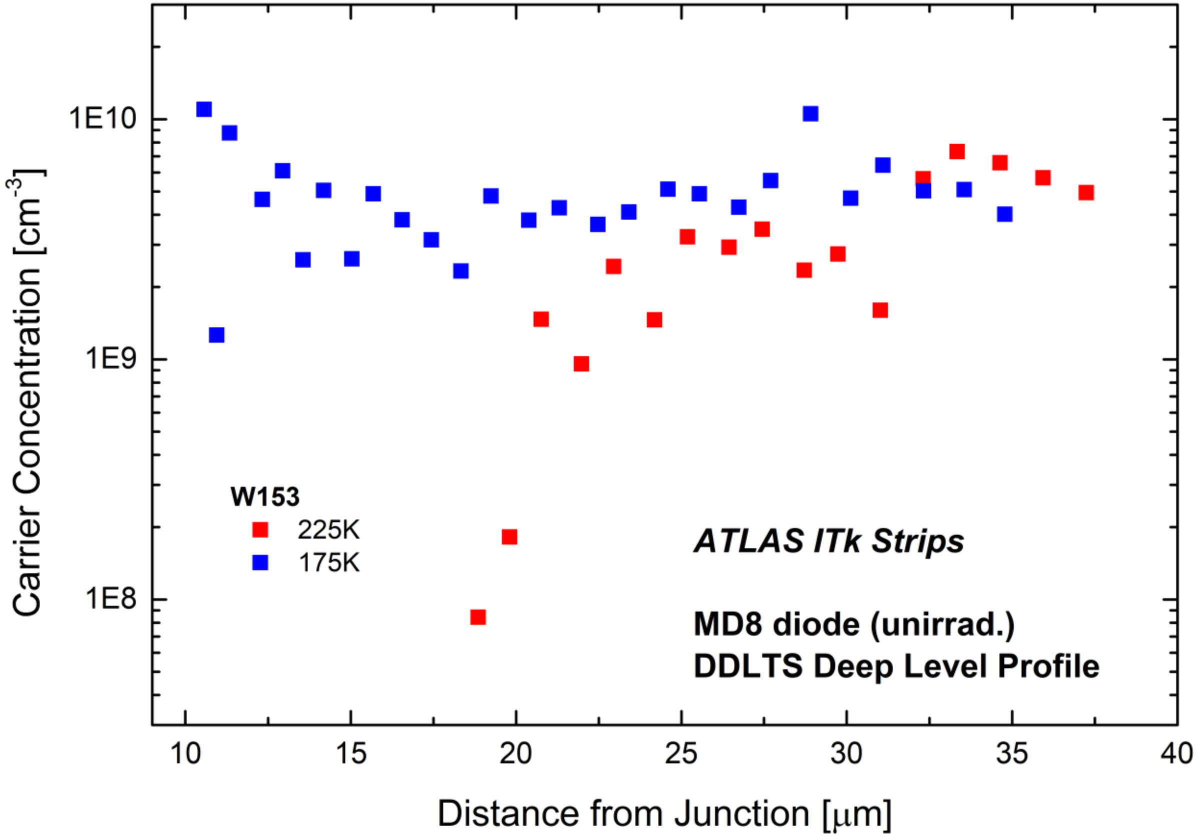


all other figures:
Semetrol DLTS Manual

# Unirradiated diodes: deep level profile & capture process

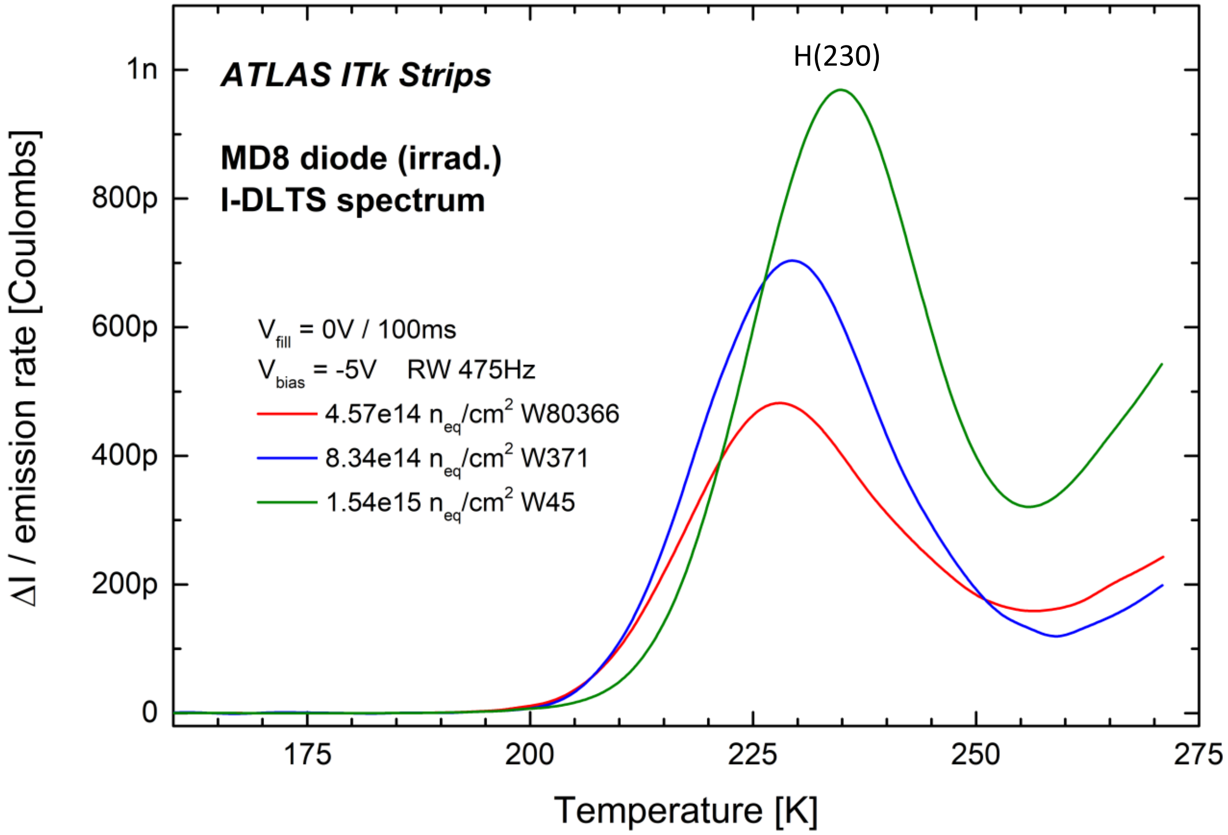
- 175K trap has constant concentration throughout depletion width
- 225K trap has decreased concentration close to junction
- trap saturation plateaus for filling pulse ≳1ms
  - observed dependence indicates point defect





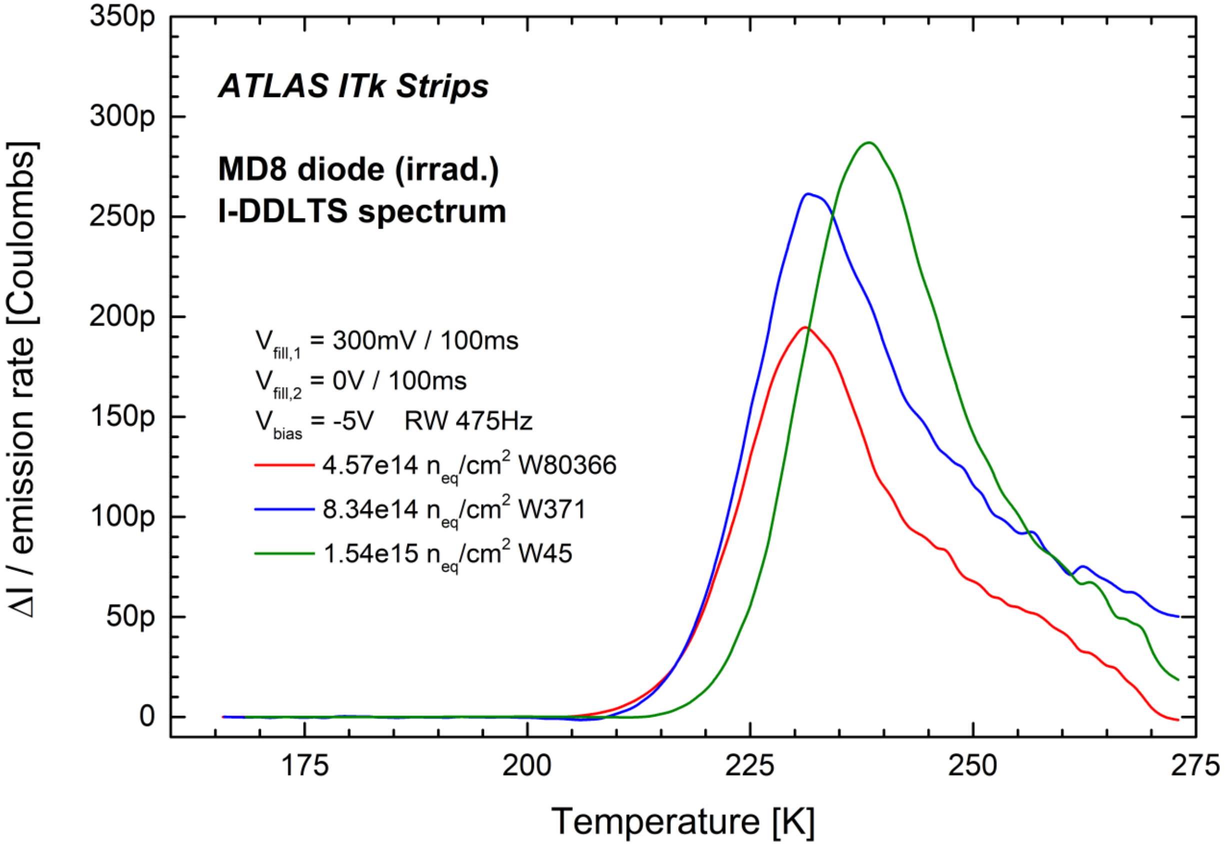
# Irradiated diodes: I-DLTS spectra

- capacitance transients did not yield reliable results
  - insufficient trap saturation, high trap concentration
  - exponential increase in capacitance for T > 260K
- I-DLTS spectra very clean
  - peak >270K could not be fully explored due to high current
- slight shift of median peak temperature
- additional traps observed using injection pulse in double-pulse setting



# Irradiated diodes: I-DLTS spectra

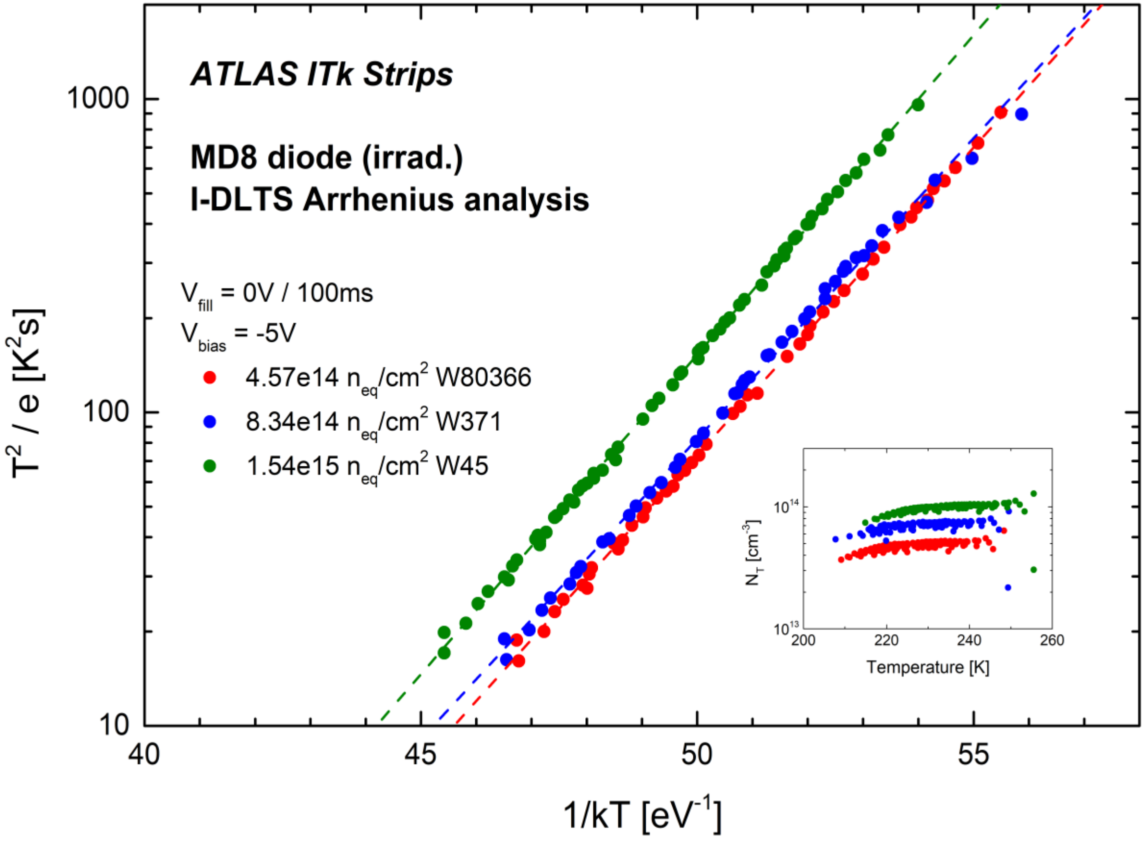
- capacitance transients did not yield reliable results
  - insufficient trap saturation, high trap concentration
  - exponential increase in capacitance for T > 260K
- I-DLTS spectra very clean
  - peak >270K could not be fully explored due to high current
- slight shift of median peak temperature
- additional traps observed using injection pulse in double-pulse setting



# 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

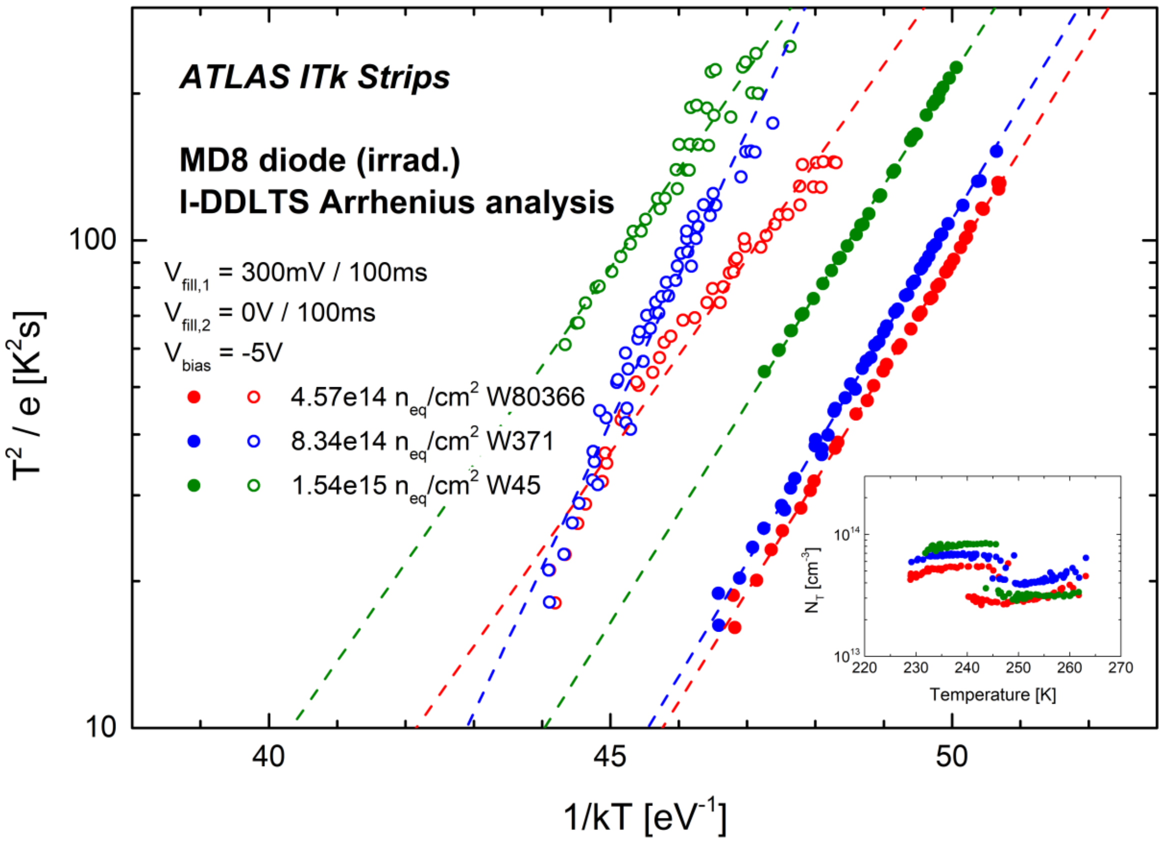
| $\Phi$ [$n_{eq}/cm^2$] | $T_{peak}$ [K] | $E_T$ [meV] | $\sigma$ [$cm^2$] |
|---|---|---|---|
| 4.57e14 | 229 | 452 ± 4 | $2.7 \times 10^{-14} \pm 1.2$X |
| 8.34e14 | 228 | 442 ± 7 | $1.5 \times 10^{-14} \pm 1.5$X |
| 1.54e15 | 233 | 469 ± 3 | $3.2 \times 10^{-14} \pm 1.2$X |



# Irradiated diodes: I-DLTS Arrhenius analysis

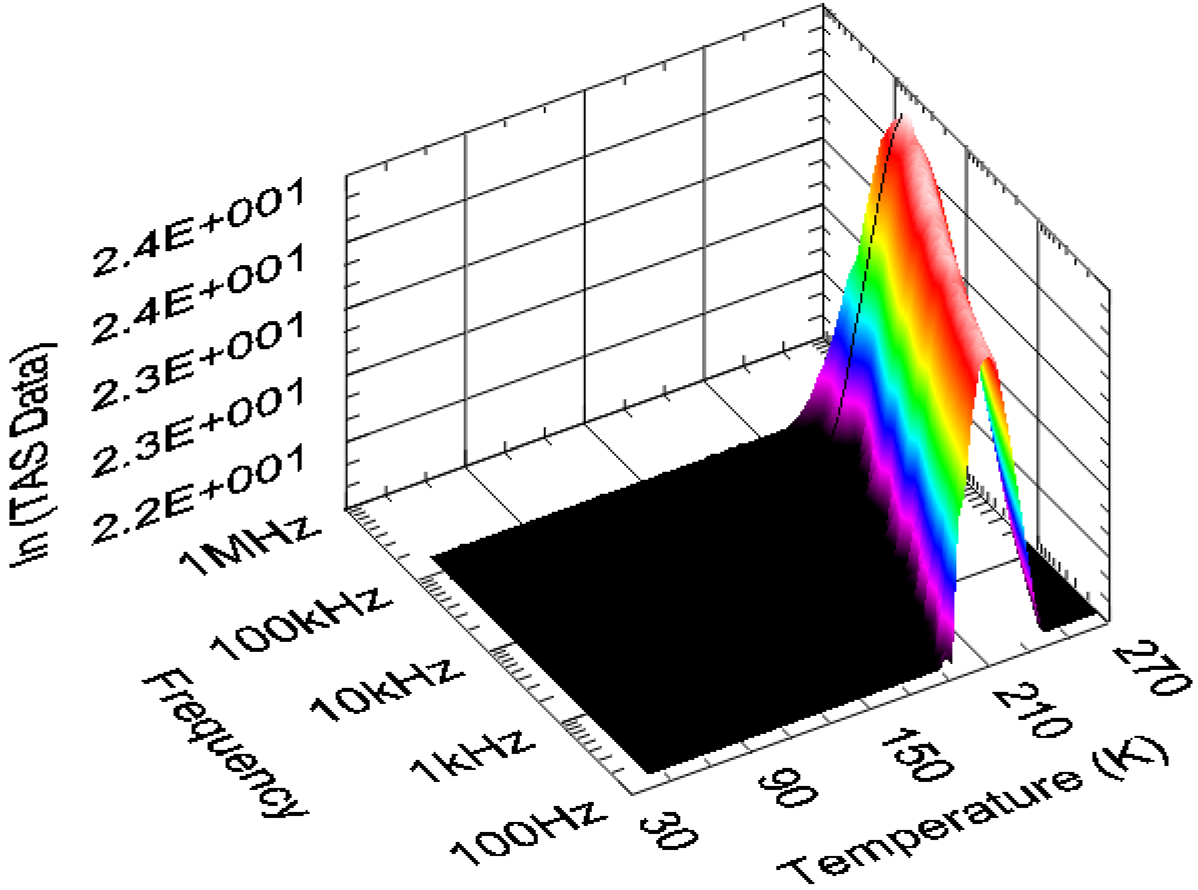
- forward injection pulse
  - remove large signal with double-pulse measurement
- 2-Gaussian deconvolution yields second trap contribution in peak flank
  - larger uncertainties on fit results of secondary peak component

| $\Phi$ [$n_{eq}/cm^2$] | $T_{peak}$ [K] | $E_T$ [meV] | $\sigma$ [$cm^2$] |
|---|---|---|---|
| 4.57e14 | 234 | 521 ± 7 | $6.9 \times 10^{-13}$ ± 1.4X |
| | 248 | 457 ± 28 | $7.3 \times 10^{-15}$ ± 3.6X |
| 8.34e14 | 237 | 539 ± 9 | $1.4 \times 10^{-12}$ ± 1.5X |
| | 254 | 686 ± 42 | $1.9 \times 10^{-10}$ ± 6.8X |
| 1.54e15 | 238 | 516 ± 6 | $2.3 \times 10^{-13}$ ± 1.4X |
| | 251 | 465 ± 41 | $4.2 \times 10^{-15}$ ± 6.5X |



# Measurement methods: TAS

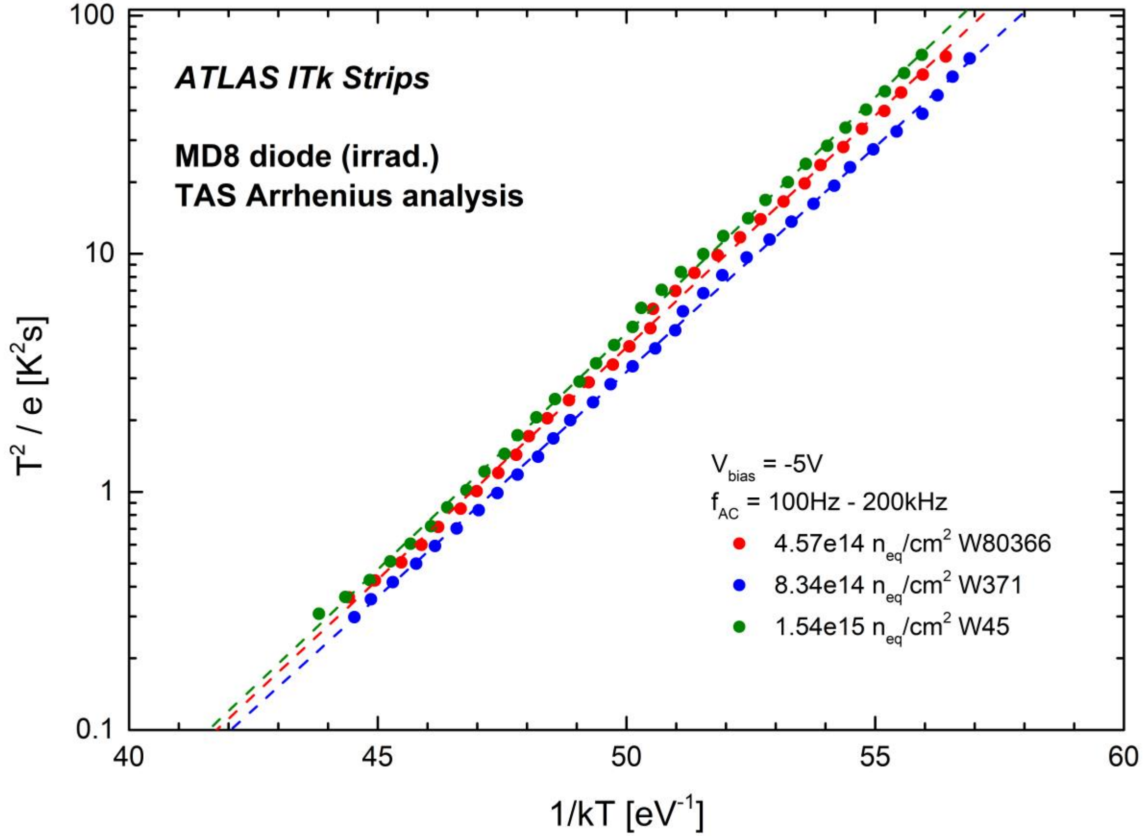
- Thermal Admittance Spectroscopy (TAS)
- measure C/R/G/Phase as a function of temperature and frequency
  - steady-state measurement
  - defect contribution depending on test signal frequency and temperature
- steps in C or peak in G/R temperature dependence indicate thresholds for new traps contributing
  - steps/peaks yield Arrhenius plots of corresponding trap states



# Irradiated diodes: TAS

- TAS yielded good results for irradiated diodes
  - no need to optimize filling pulse parameters for trap saturation
- trap parameters consistent with results from I-DLTS
  - no changes at different levels of irradiation

| $\Phi$ [$n_{eq}$/cm$^2$] | $T_{median}$ [K] | $E_T$ [meV] | $\sigma$ [cm$^2$] |
|---|---|---|---|
| 4.57e14 | 230 | 449 ± 6 | $4.2 \times 10^{-13} \pm 1.3$X |
| 8.34e14 | 228 | 435 ± 4 | $2.7 \times 10^{-13} \pm 1.2$X |
| 1.54e15 | 232 | 456 ± 5 | $5.4 \times 10^{-13} \pm 1.3$X |



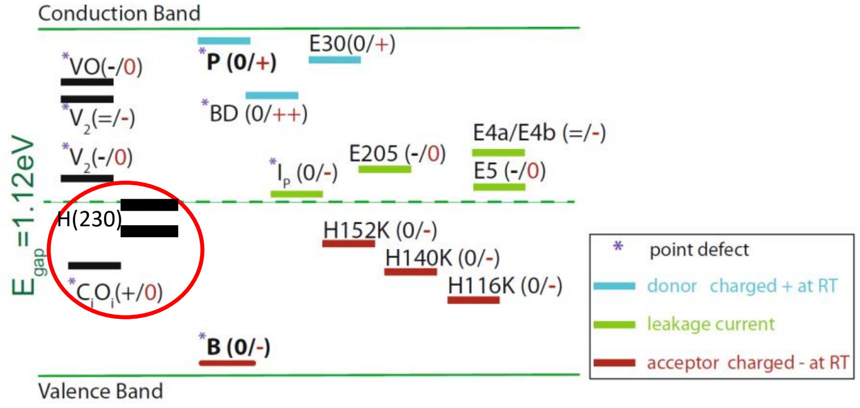
# Discussion and Conclusion

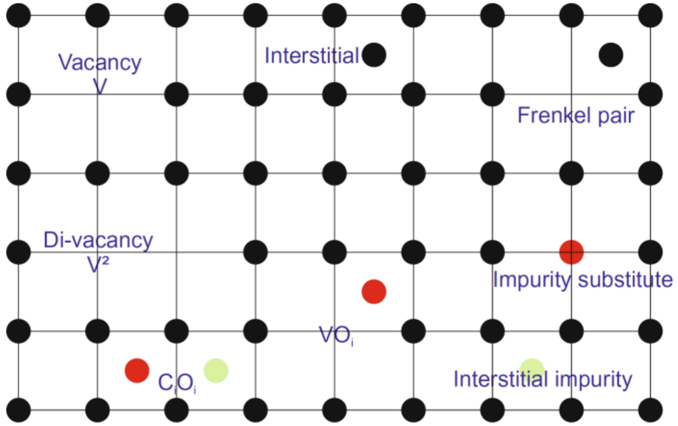
## Discussion

- $T_{peak}$ and $E_T$ of common H(175) defect in unirrad. diodes consistent with **interstitial carbon - interstitial oxygen ($C_iO_i$) complex** and other carbon-related defects (e.g. K-centre/*VOC* complex)
- common H(230) defect in irradiated diodes consistent with reported **vacancy-clusters**
  - H(225) defect in unirrad. W153 has similar parameters
  - also found in CMS test structures with major contribution to high leakage current **A. Junkes, Ph.D. thesis**

## Conclusion

- multiple trap parameters obtained for both unirradiated and irradiated diode samples of ITk Strip Sensors
- DLTS setup proven effective
  - standard C-DLTS and double-pulse variants yield precise results for unirradiated devices
  - I-DLTS and TAS more effective in highly irradiated samples due to significant trap concentration





F. Hartmann, Evolution of Silicon Sensor Technology in Particle Physics

**Acknowledgements:**
This work was supported by the Canada Foundation for Innovation and the Natural Sciences and Engineering Research Council of Canada. This work is part of the Spanish R&D grant PID2021-126327OB-C22, funded by MCIN/ AEI/10.13039/501100011033 / FEDER, UE. The work at SCIPP was supported by the US Department of Energy, grant DE-SC0010107.

# Backup

# Double-Pulse DLTS (DDLTS): capture process

- transients with filling pulse from 5us to 200ms
- trap saturation for filling pulse ≳1ms