Defect level identification of ATLAS ITk Strip Sensors using DLTS

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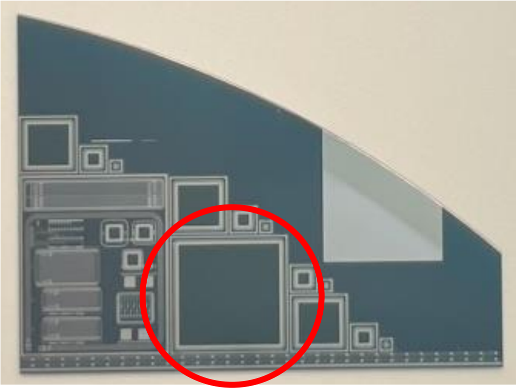
Introduction

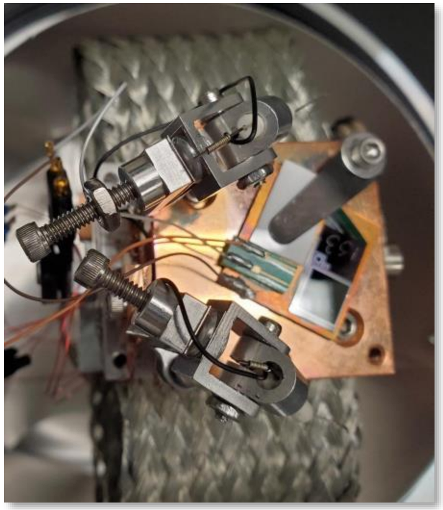
Motivation:

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



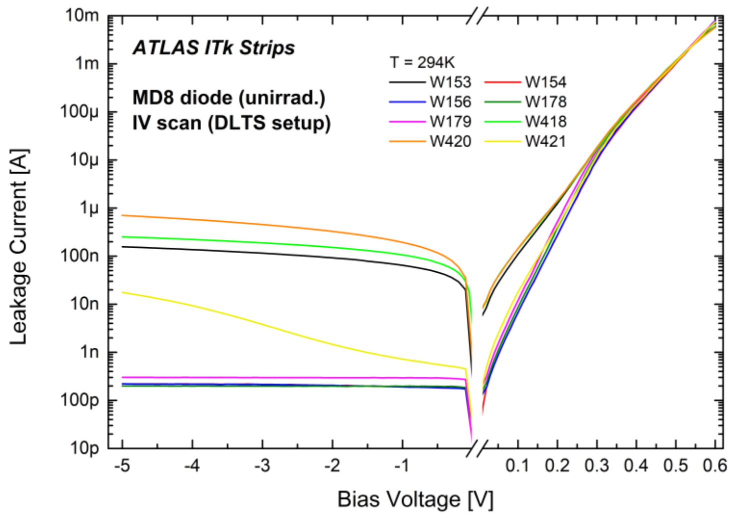
- measurements on MD8 diodes
  - square 8mm x 8mm n^+-in-p diodes
  - produced as test structure on same wafers as main ITk Strip Sensors
- tests performed on unirradiated and irradiated devices
  - unirradiated halfmoons from batch with high current main sensors + reference samples from 'normal' batch
  - 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

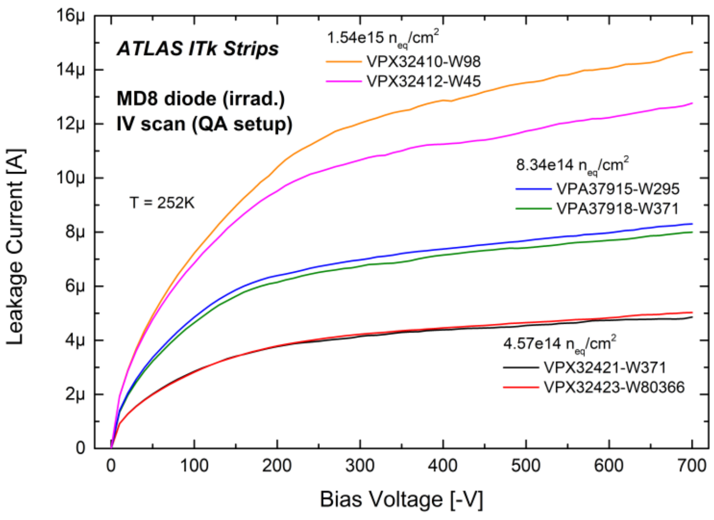


IV scans

UNIRRADIATED



IRRADIATED

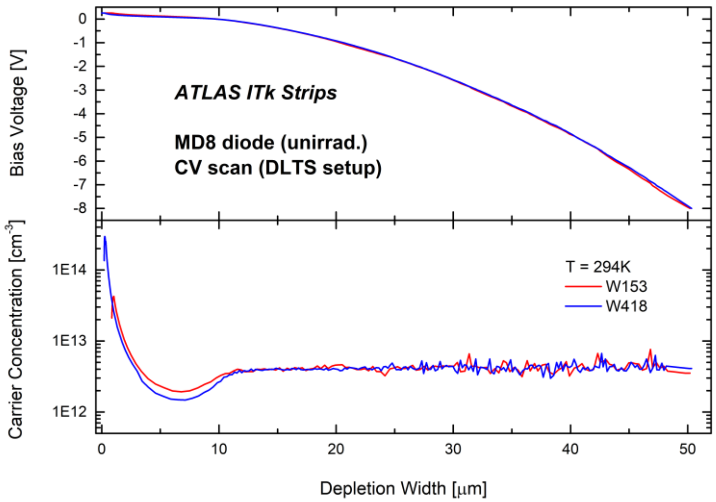


- IV curves taken at room temperature on DLTS setup
- W153-179 from a batch with high current main sensors; W418-421 for reference
- incidentally W153, W418, W420 with highest current

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

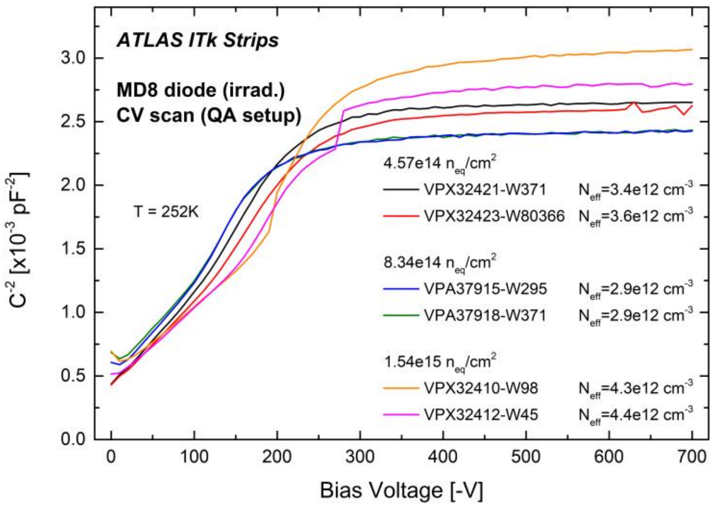
CV scans

UNIRRADIATED



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

IRRADIATED

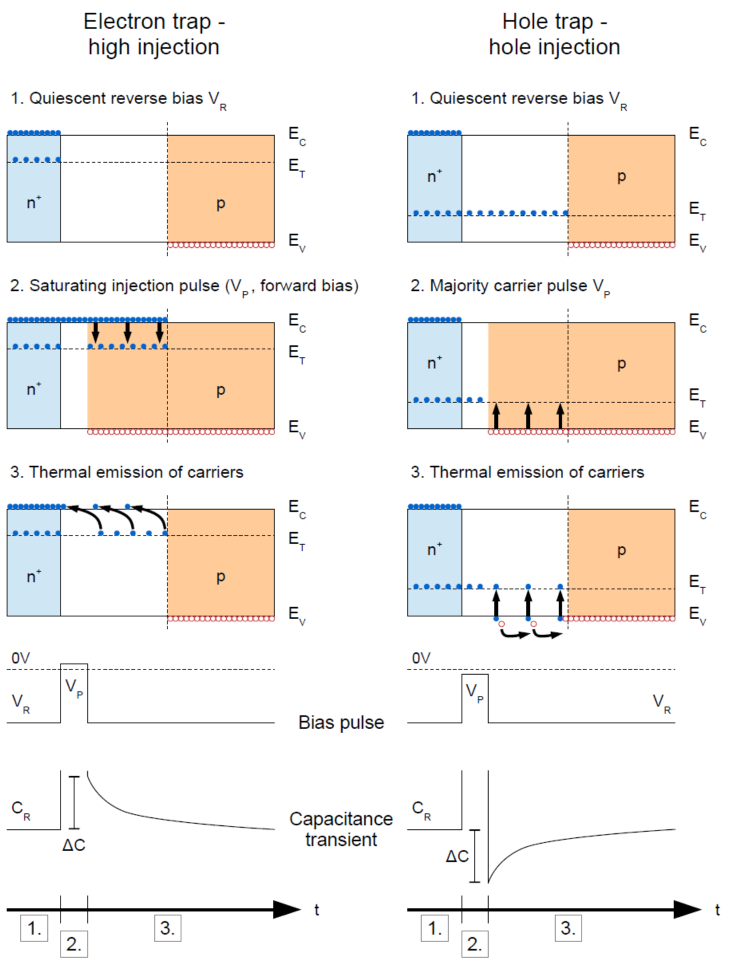


- full depletion still present at highest irradiation level
  - limited acceptor removal, N_{eff} similar to before irradiation
- DLTS setup can only bias up to 10V,
  - low bias readings of irradiated samples not useful for calculation of depletion width and carrier concentration

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



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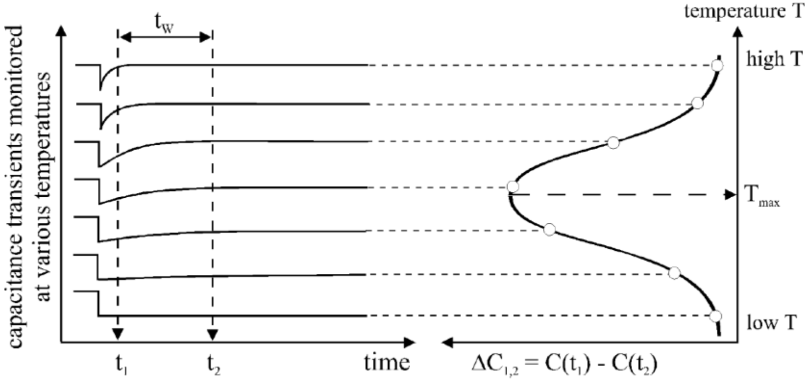
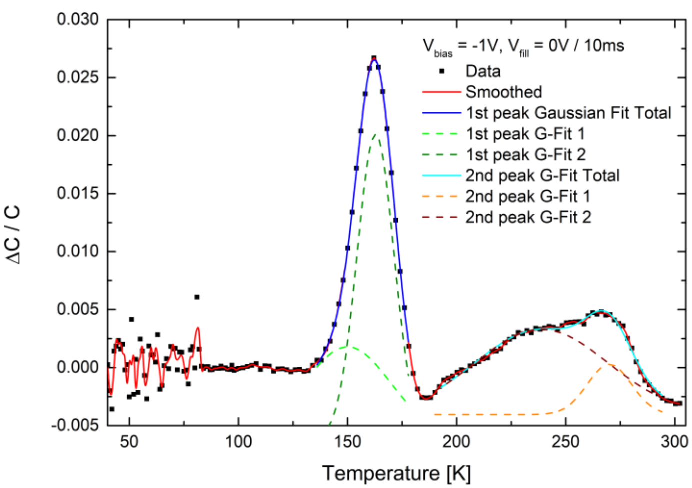


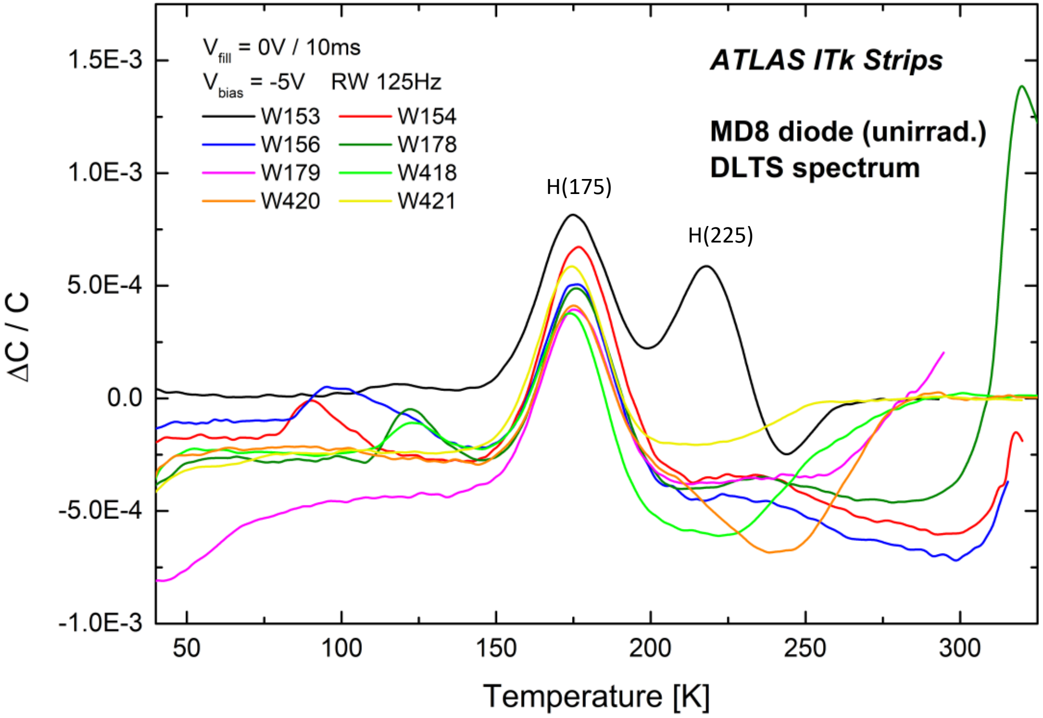
D. V. Lang, Deep-level transient spectroscopy



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



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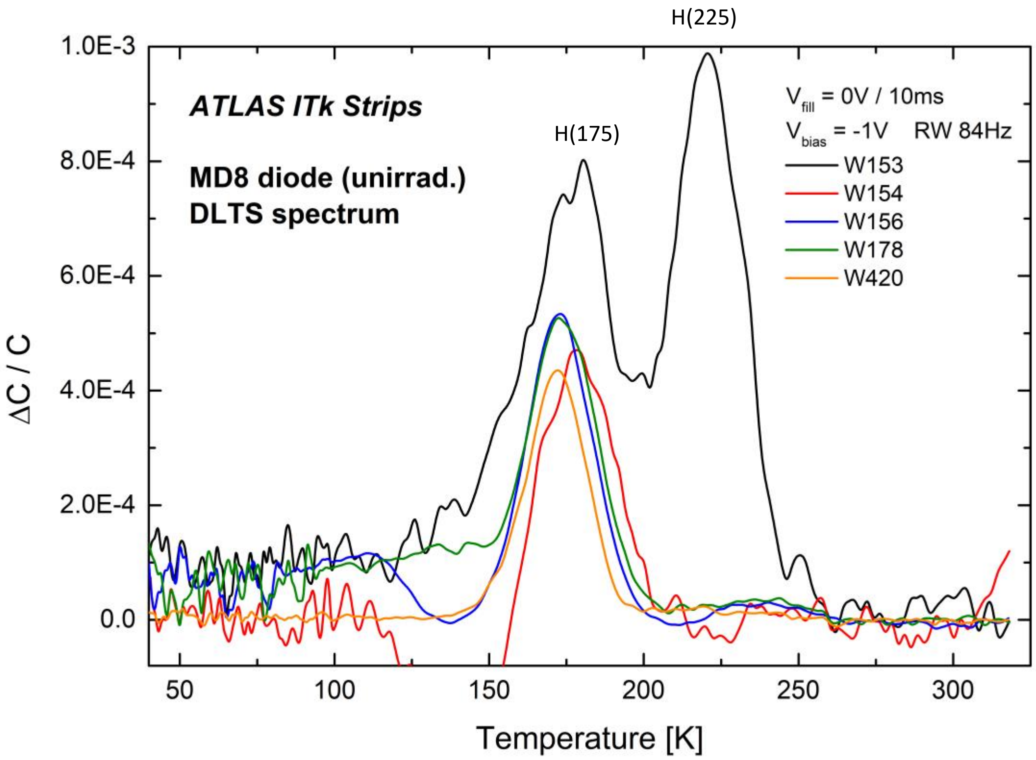
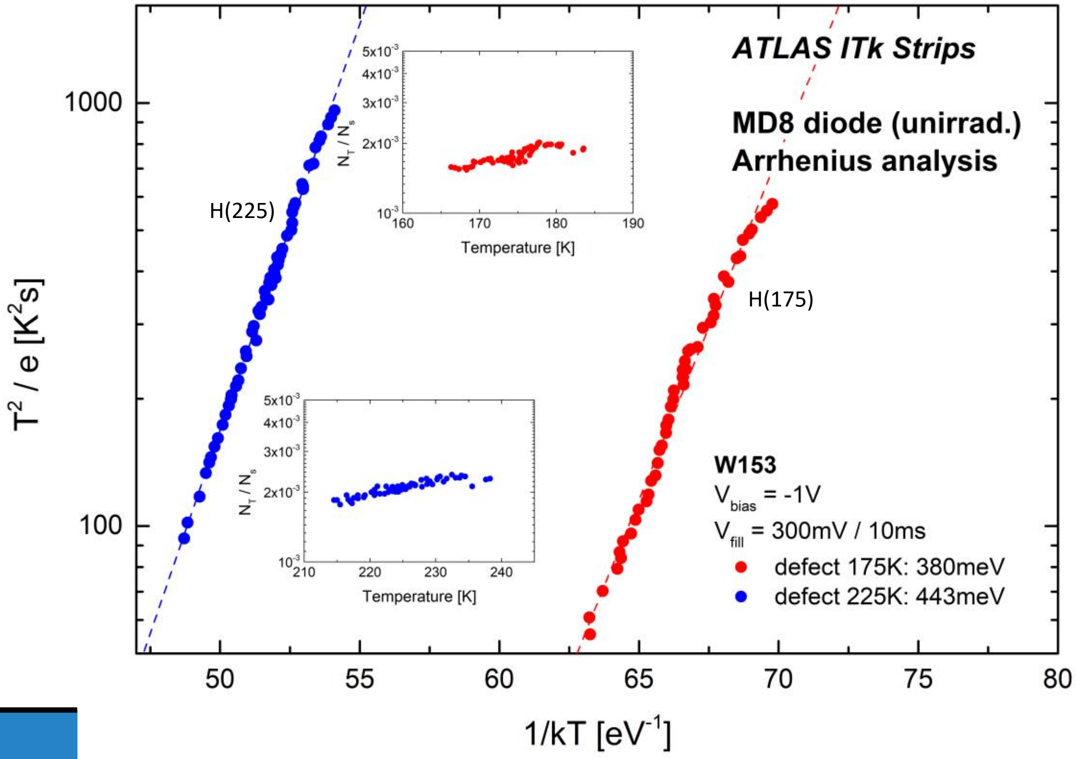


Unirradiated diodes: Arrhenius analysis

- 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



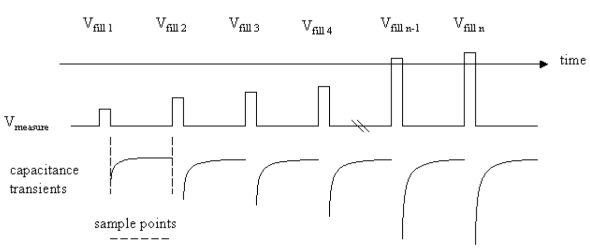
T_{median} [K]	E_T [meV]	σ [cm²]
175 (common)	310 – 390	$10^{-14} – 10^{-13}$
225 (W153 only)	443 ± 6	$7.5 \times 10^{-15} \pm 1.4X$

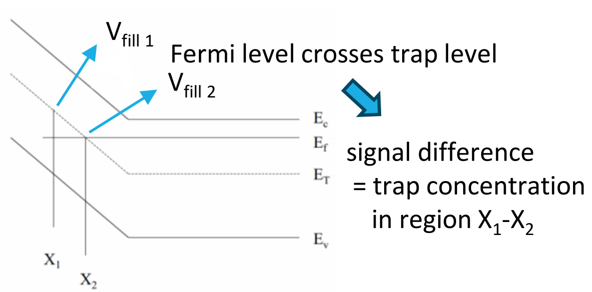
$$\ln(\tau_e T^2) = -\ln\left(\sigma_{n,p}^{\text{eff}}\,\Gamma_{n,p}\right) + \frac{E_A}{k_B T}$$

Measurement methods: DDLTS, Capture Kinematics

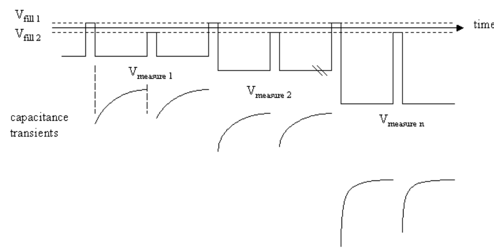
- Double-Pulse DLTS (DDLTS) measured at temperature of observed trap

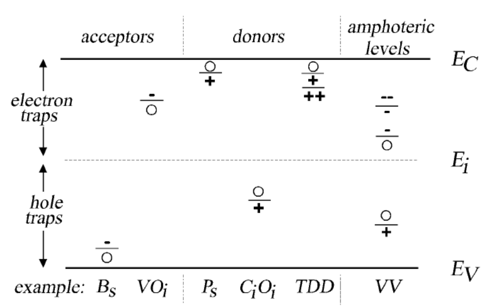
- progressively increasing filling pulse at fixed bias
  ⇒ **deep level trap profile**





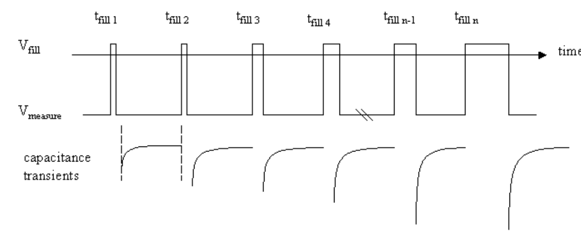
- fixed pair of filling pulses at increasing measurement bias
  ⇒ **field strength dependence**;
  indicates acceptor/donor state

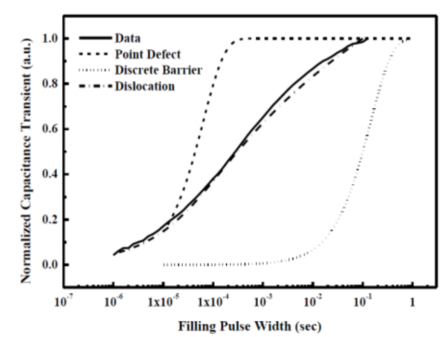




M. Moll, Ph.D. thesis

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

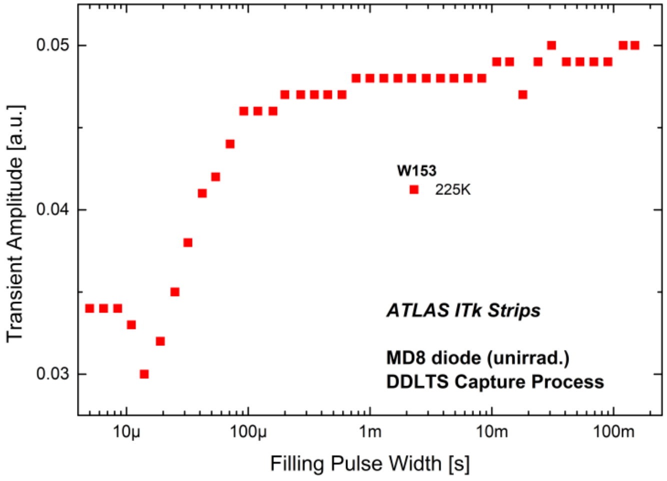


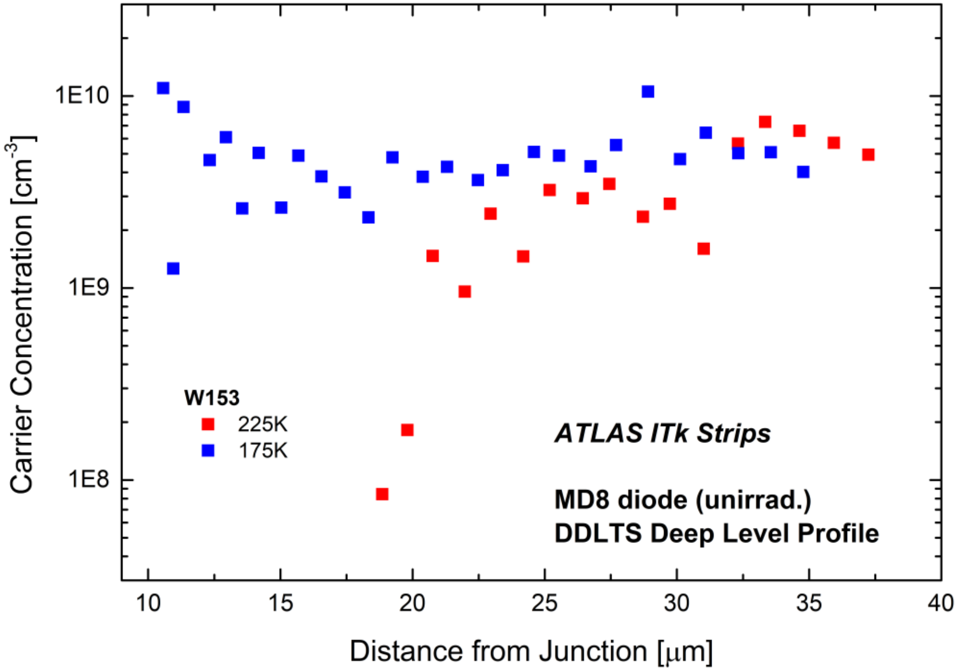


all other figures:
Semetrol DLTS Manual

Unirradiated diodes: deep level profile & capture process

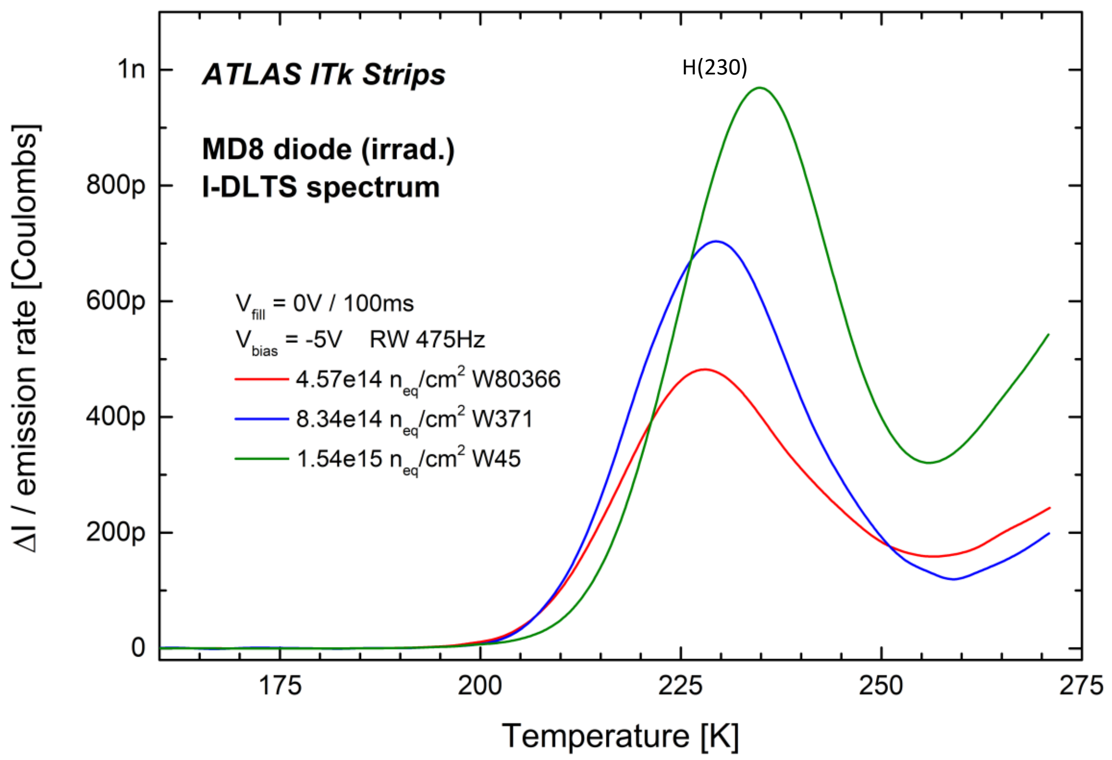
- 175K trap has constant concentration throughout depletion width
- 225K trap has decreased concentration close to junction
- trap saturation plateaus for filling pulse ≳1ms
  - observed dependence indicates point defect





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



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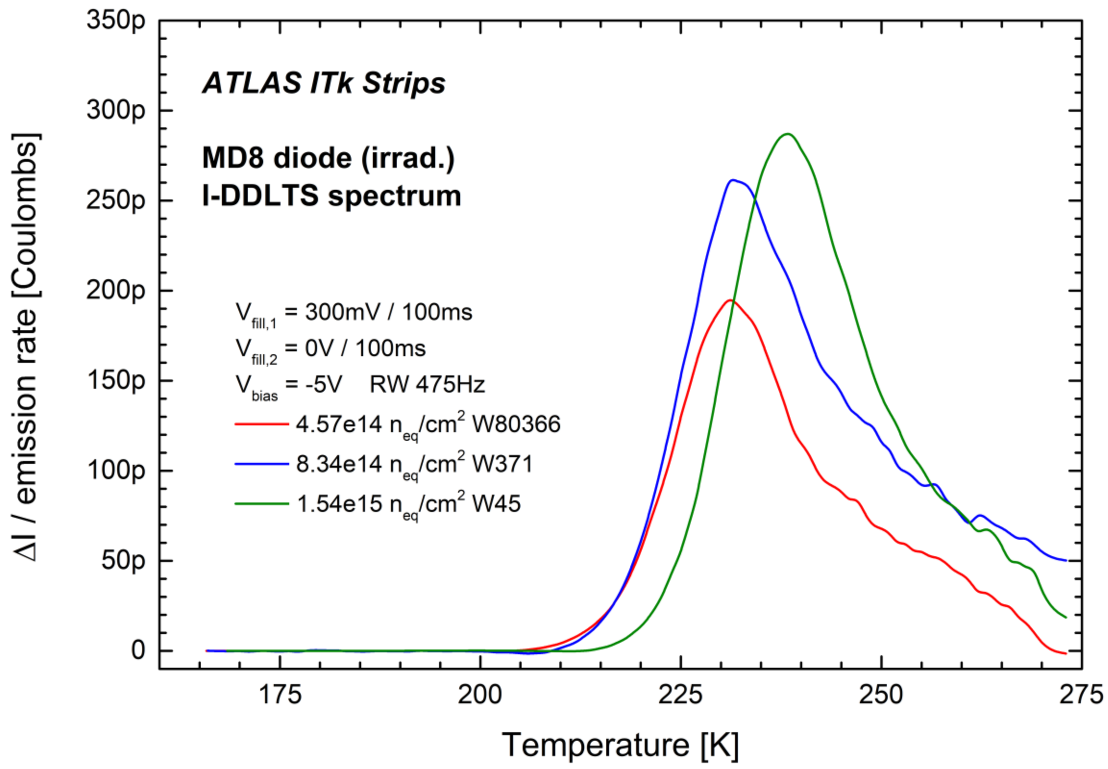
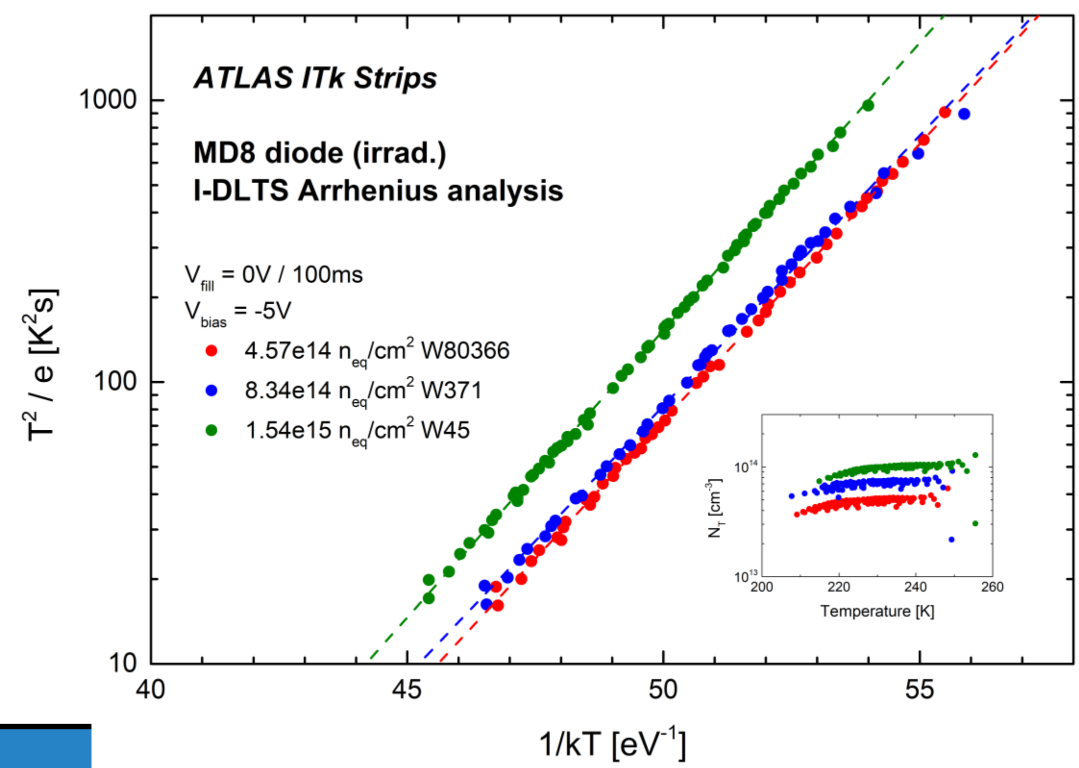


Unirradiated diodes: Arrhenius analysis

- 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

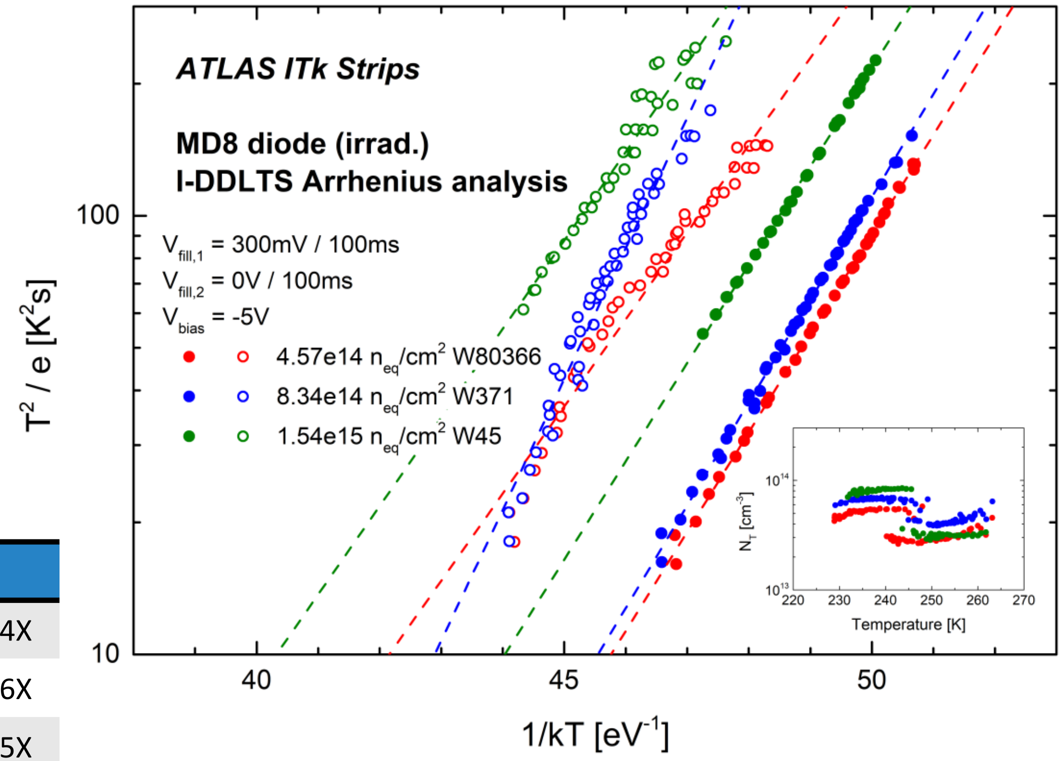


Φ [n_{eq}/cm^2]	T_{peak} [K]	E_T [meV]	σ [cm^2]
4.57e14	229	452 ± 4	2.7 x 10^{-14} ± 1.2X
8.34e14	228	442 ± 7	1.5 x 10^{-14} ± 1.5X
1.54e15	233	469 ± 3	3.2 x 10^{-14} ± 1.2X

Irradiated diodes: I-DLTS Arrhenius analysis

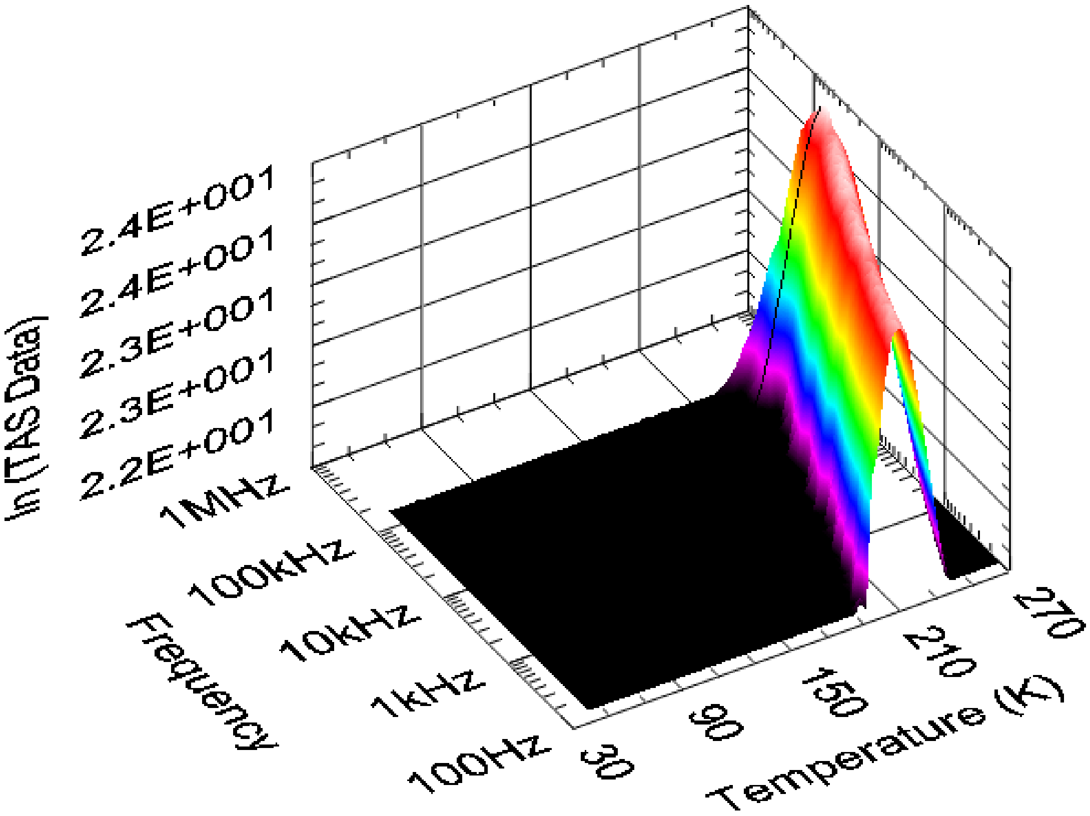
- forward injection pulse
  - remove large signal with double-pulse measurement
- 2-Gaussian deconvolution yields second trap contribution in peak flank
  - larger uncertainties on fit results of secondary peak component

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



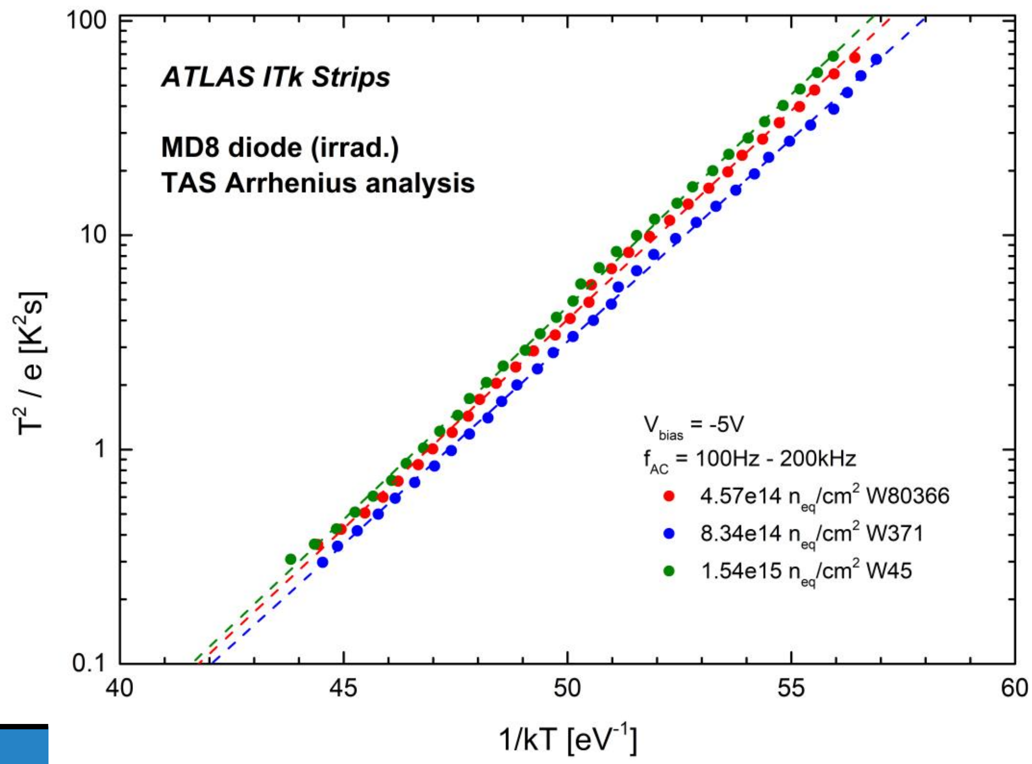
Measurement methods: TAS

- 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

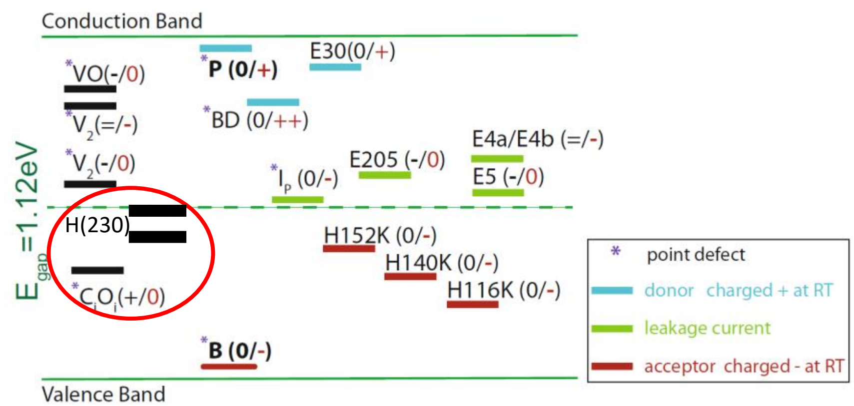


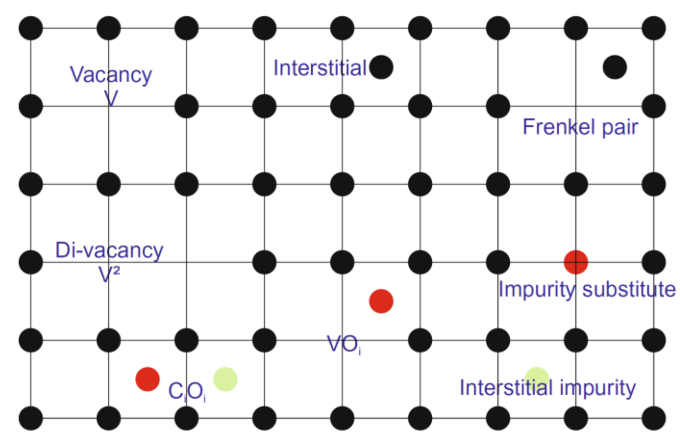
Φ [n_{eq}/cm^2]	T_{median} [K]	E_T [meV]	σ [cm^2]
4.57e14	230	449 ± 6	4.2 x 10^{-13} ± 1.3X
8.34e14	228	435 ± 4	2.7 x 10^{-13} ± 1.2X
1.54e15	232	456 ± 5	5.4 x 10^{-13} ± 1.3X

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





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

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

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Backup

Double-Pulse DLTS (DDLTS): capture process

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