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

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Abstract

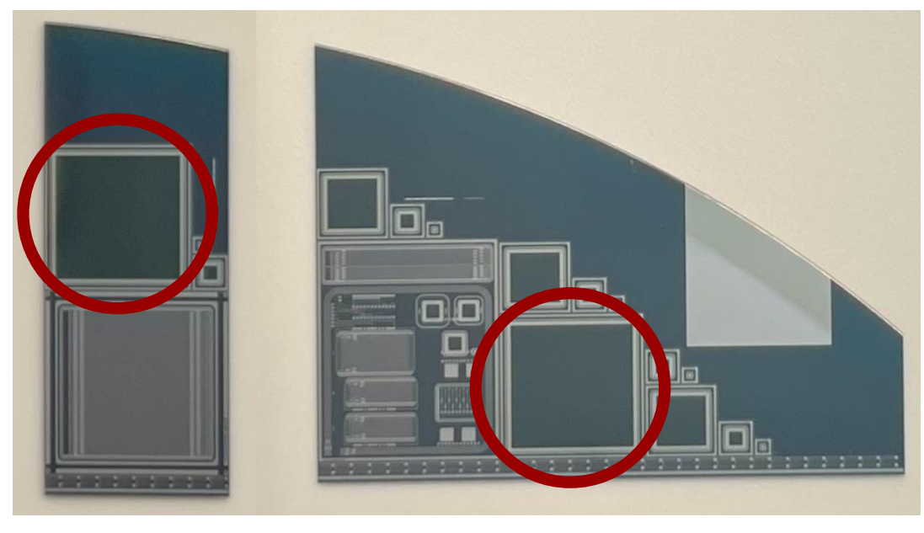
With the upgrade of the LHC to the High-Luminosity LHC (HL-LHC), the Inner Detector will be replaced with the new all-silicon ATLAS Inner Tracker (ITk). Comprising an active area of 165m², the outer detector layers will host strip modules, built with single-sided micro-strip sensors. The ATLAS18 main sensors were tested at different institutes in the collaboration for mechanical and electrical compliance with technical specifications, while technological parameters were verified on test structures from the same wafers before and after irradiation.

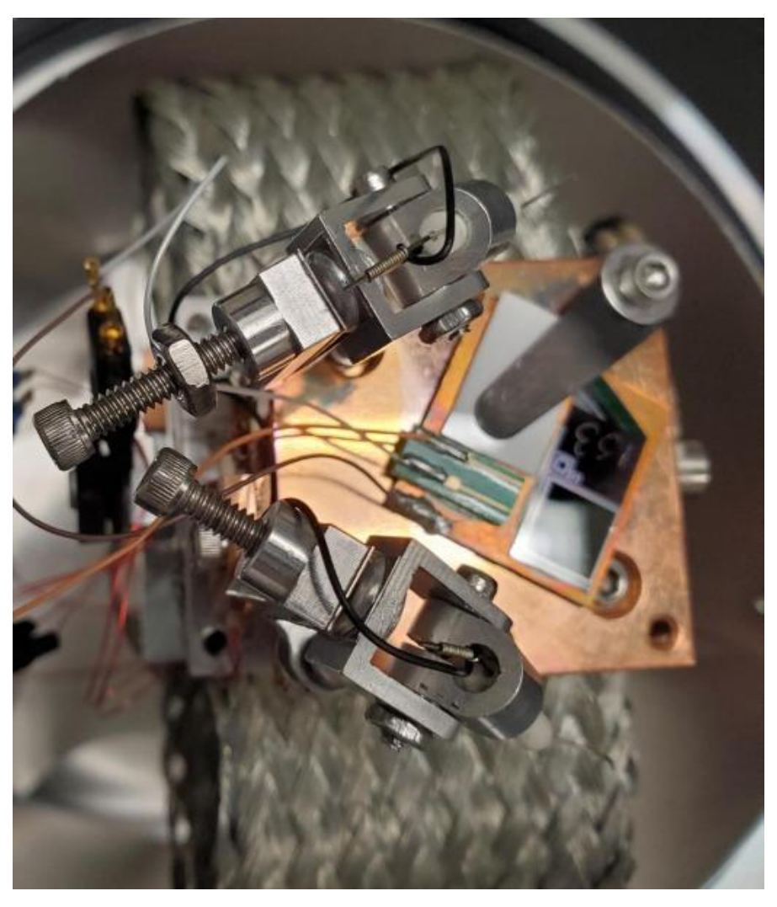
Diodes fabricated as test structures were studied using variants of Deep-Level Transient Spectroscopy (DLTS). Irradiated diode samples were measured with Current-DLTS, using both electrical and photo-induced injection. Utilising DLTS spectra with varying test parameters, trap energy levels and cross-sections associated with defects were obtained. This was done to improve the precision of sensor simulations as well as to compile a more complete model of radiation damage in ITk Strip Sensors. Moreover, previously observed features such as an increasing trend in the full depletion voltage after irradiation and little beneficial annealing in charge collection after high fluence irradiation of high energy protons were also investigated. This poster will present a summary of the defect parameters observed in the samples and will compare results obtained for samples with radiation damage from different sources at various fluences.

Samples

- ☐ diced MD8 diodes (8mm × 8mm) from irradiated QA pieces
- ☐ samples mounted on heatsinks, biased through backplane and wire-bonded implant; additional wire-bonded GR contact
- ☐ all samples were annealed for 80min @60°C
- ☐ previously observed unusual annealing effects of samples from IRRAD (see I. Mandic's talk at VCI2025)

Source	Fluence [1 MeV n_{eq}/cm^2]
CYRIC 70 MeV/c protons	4.57e14
	8.34e14
	1.54e15
IRRAD (CERN PS) 24 GeV/c protons	3.6e14
	4.2e14
	7.6e14
	1.2e15



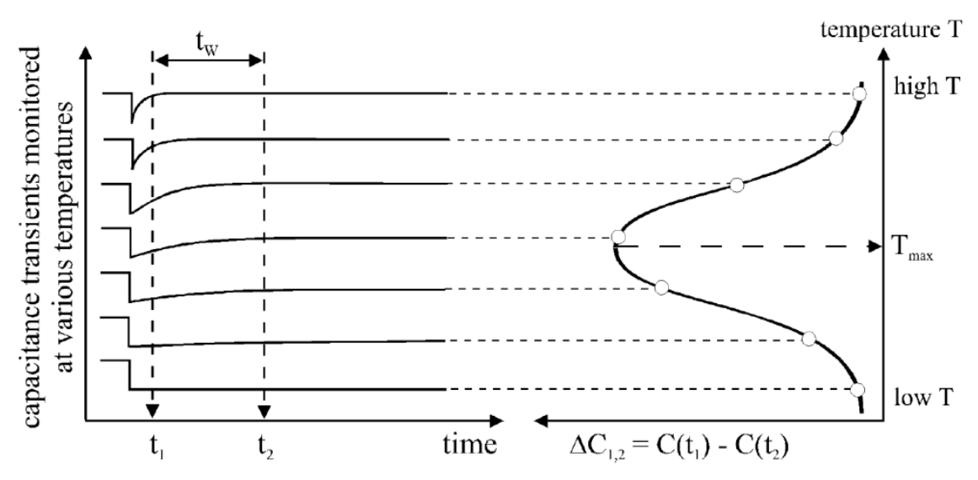


Deep-Level Transient Spectroscopy (DLTS)

Principles of DLTS measurements:

1. DUT is under constant reverse bias
2. filling pulse with specific voltage V_P and duration is applied
   - V_P 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



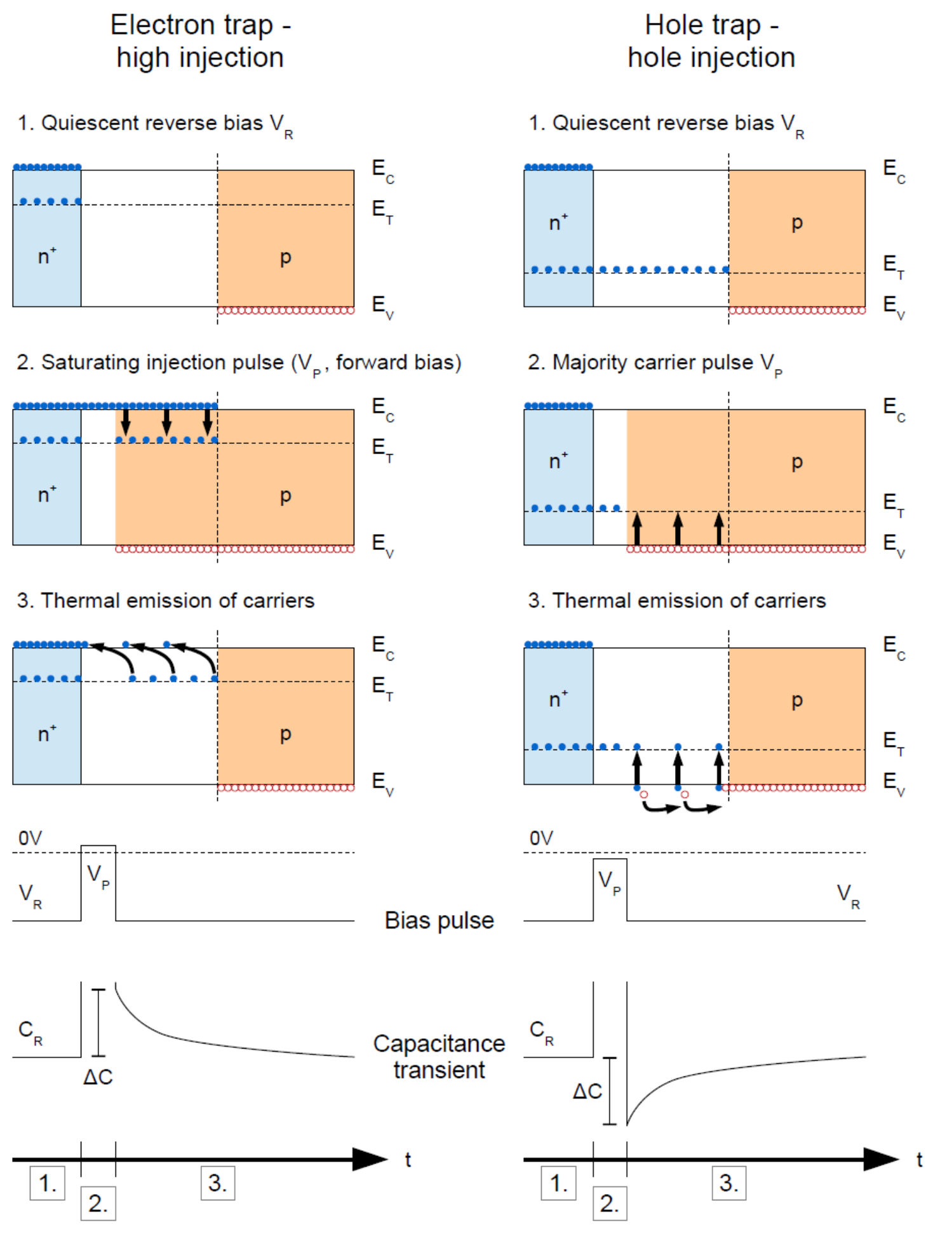
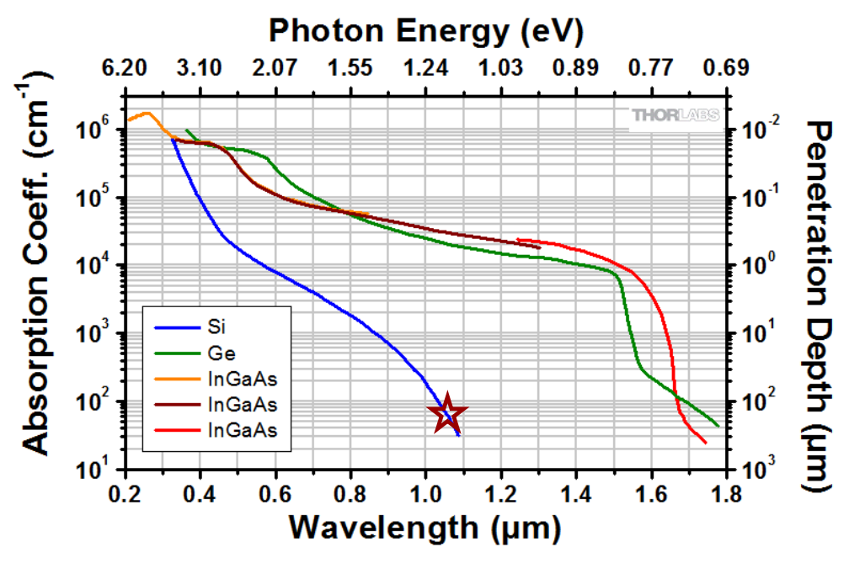
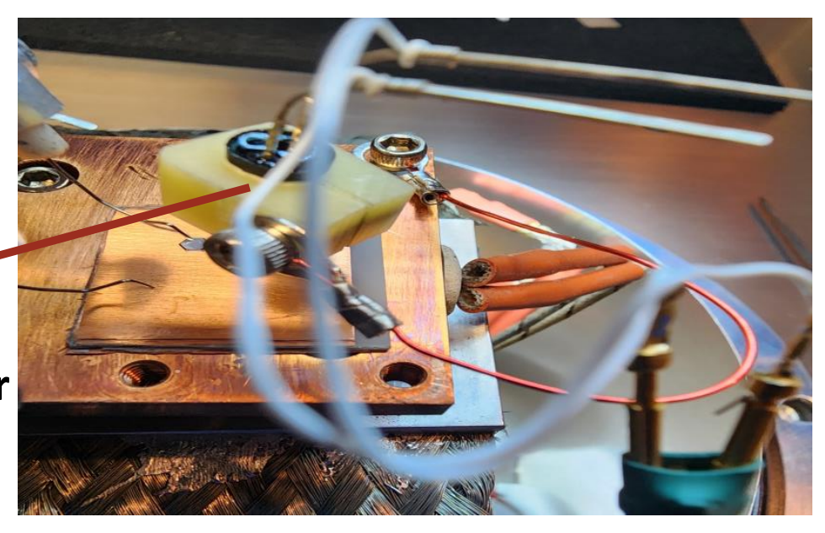


Photo-Induced Current Transient Spectroscopy (PICTS):

- ☐ Photo-Induced Current Transient Spectroscopy variant of basic DLTS/I-DLTS
  - trap concentration in irradiated diodes too high for electrical filling and capacitance DLTS
- ☐ 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 mode to subtract baseline current



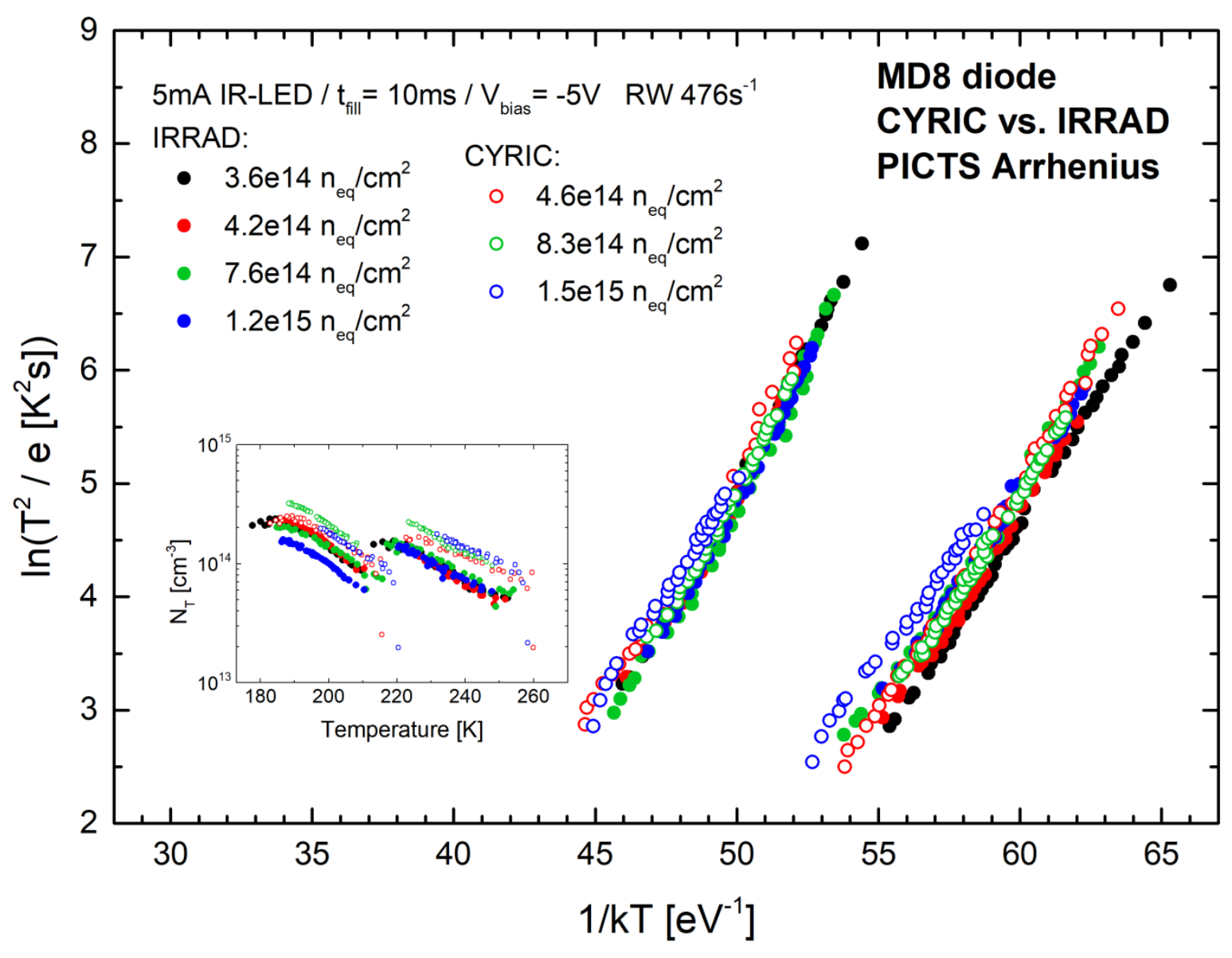
LED mount above sample holder



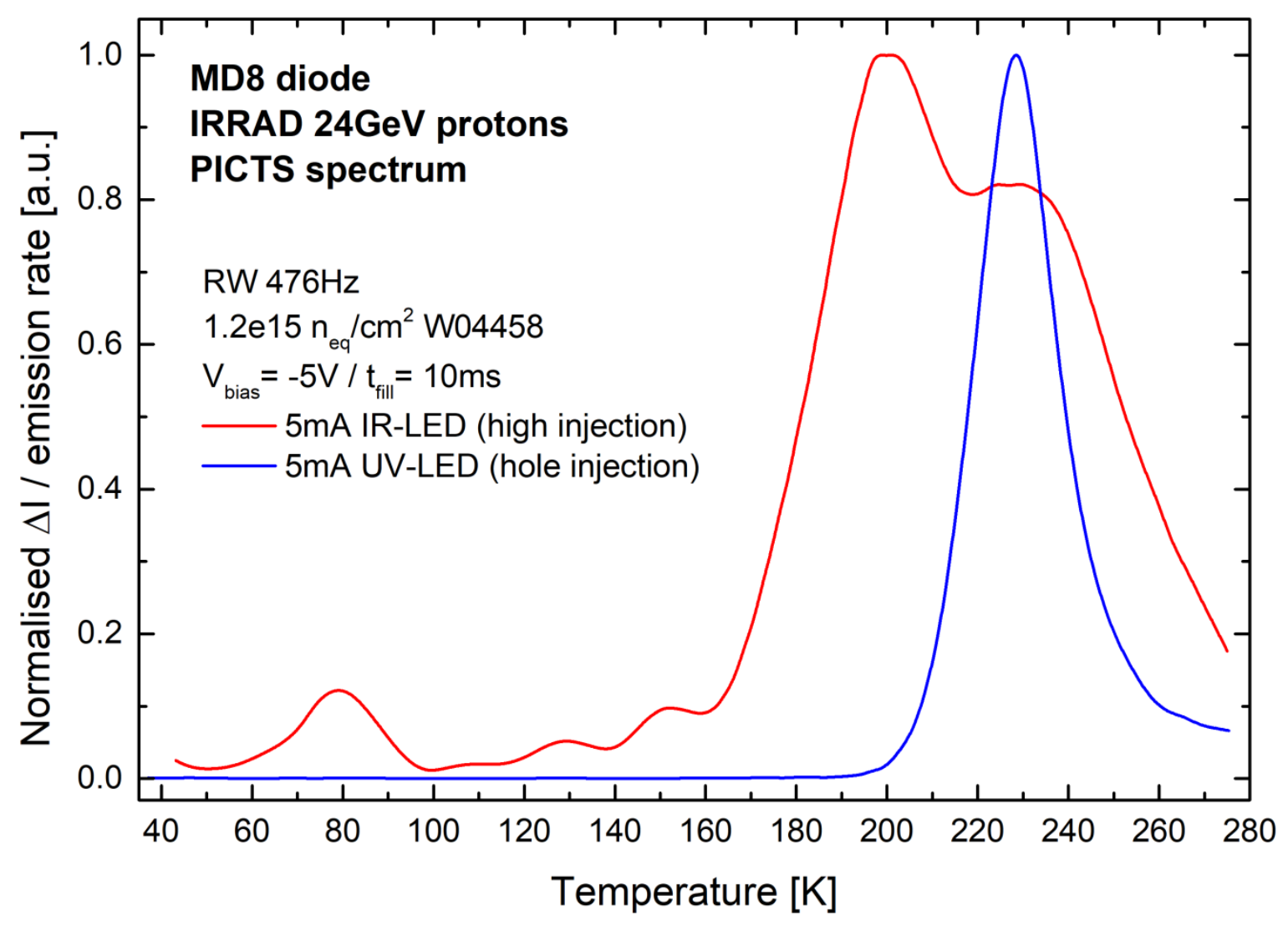
DLTS spectra and Arrhenius plots

- ☐ trap filling purely through LED
  - second transient without LED to subtract baseline current
- ☐ observable defects even at low temperatures
  - not seen in without LED filling pulses
- ☐ convolution of two trap states in large peak
  - same large double-peak 200K/240K for all samples, irrespective of fluence or source
  - minor differences in low-temperature peaks

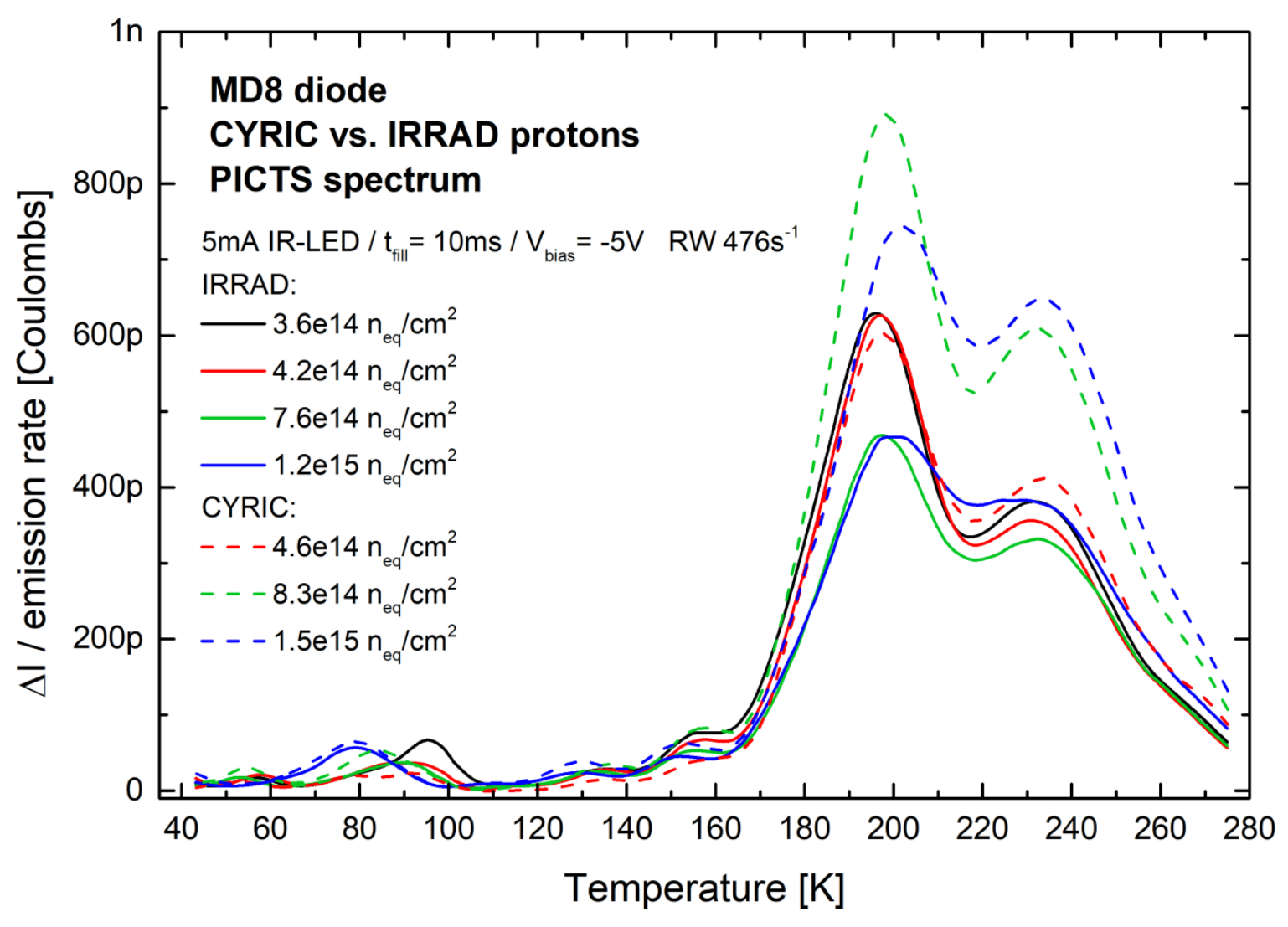
Arrhenius plots of large double-peak



- ☐ 240K peak corresponds to both electron and hole trap, all other traps are electron traps
  - electron capture coefficient much higher in 240K peak
  - complimentary energy levels add up to Si bandgap



spectrum for specific rate window [t_1; t_2] corresponding to trap emission rate (Rate Window plot)



- ☐ double-peak 200K/240K has highest trap concentration and energy closest to mid-bandgap
  - traps closer to midgap have most significant effect on behaviour
- ☐ CYRIC samples have higher trap concentration
- ☐ PICTS does not inherently differentiate between electron and hole traps, unlike capacitance transients in DLTS
  - check whether electron/hole trap using UV-LED

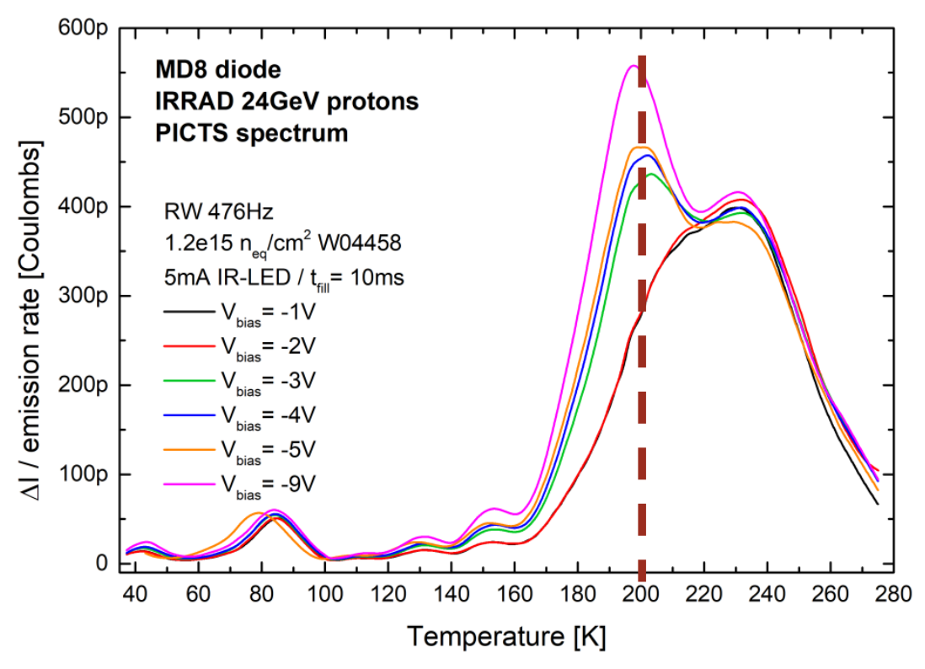
  ⇒ charge generation at surface, only holes fill traps in depleted region

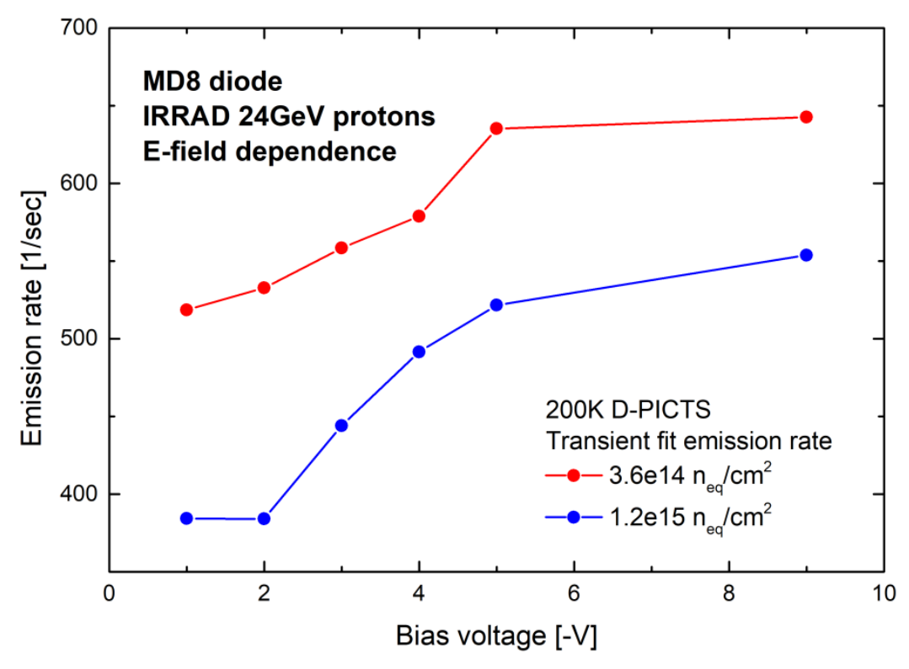
	Φ [n_{eq}/cm^2]	T_{peak} [K]	E_T [meV]	σ [cm^2]
CYRIC	4.57e14	200	413 ± 9	2.3×10^{-13} ± 1.7X
		240	427 ± 19	6.7×10^{-15} ± 2.5X
	8.34e14	200	400 ± 9	1.1×10^{-13} ± 1.7X
		240	459 ± 13	3.8×10^{-14} ± 1.9X
	1.54e15	200	340 ± 11	2.6×10^{-15} ± 1.8X
		240	396 ± 15	1.5×10^{-15} ± 2.0X
IRRAD	3.6e14	200	403 ± 5	1.8×10^{-13} ± 1.3X
		240	475 ± 10	8.8×10^{-14} ± 1.6X
	4.2e14	200	395 ± 9	1.0×10^{-13} ± 1.7X
		240	454 ± 14	3.1×10^{-14} ± 2.0X
	7.6e14	200	385 ± 14	4.1×10^{-14} ± 2.3X
		240	460 ± 23	4.5×10^{-14} ± 3.1X
	1.2e15	200	388 ± 9	5.4×10^{-14} ± 1.7X
		240	469 ± 13	6.8×10^{-14} ± 1.9X

Field strength and filling pulse width dependence

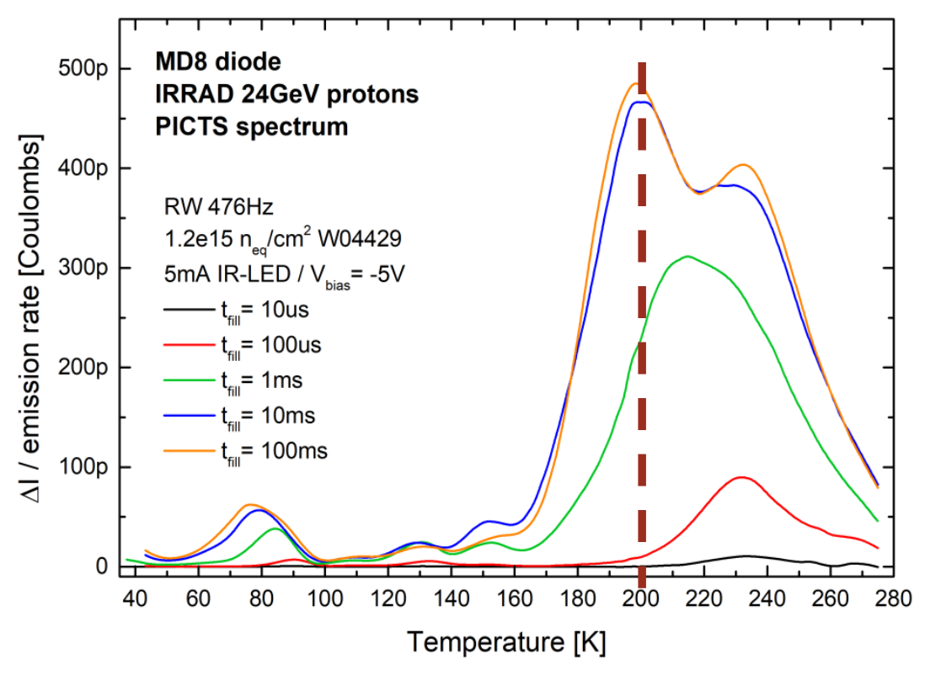
- ☐ derive emission rate and transient amplitude from direct fit of transient at peak in spectrum
- ☐ field strength dependence of emission rate indicates whether defect acquires net charge upon emission

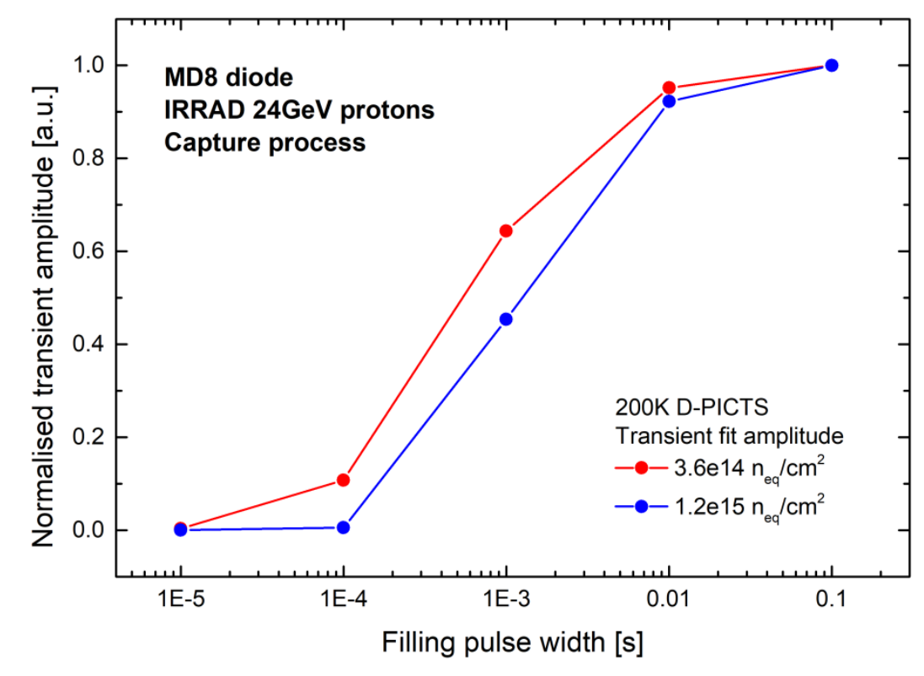
  ⇒ evidence of Poole-Frenkel effect, defect is electron-donor





- ☐ measurement of transient amplitude with increasing filling pulse width allows for fitting of various capture processes ⇒ indicates nature of defect in crystal lattice, e.g. point defect or dislocation





Conclusions

- ☐ multiple microscopic defects were observed in ITk Strip Sensor diode samples after irradiation with low and high energy protons
  - trap parameters were determined, and most traps were found to be electron traps in the upper half of the bandgap
  - no clear dependence on fluence and proton source were observed for the investigated samples
- ☐ investigation will continue with neutron/gamma-irradiated samples and different levels of annealing

Acknowledgments

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References

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