Defect Spectroscopy on 23 GeV Proton-Irradiated CZ Pad Diodes

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Acceptor Removal Team

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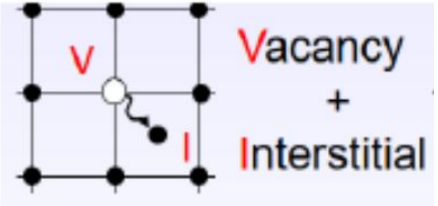
Motivation for Defect Characterisation

High Energy Particles → Si Lattice → E>21eV →



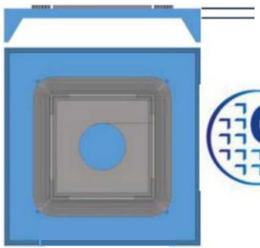
→ Recombination

→ Migration & Formation of Point & Cluster Defects

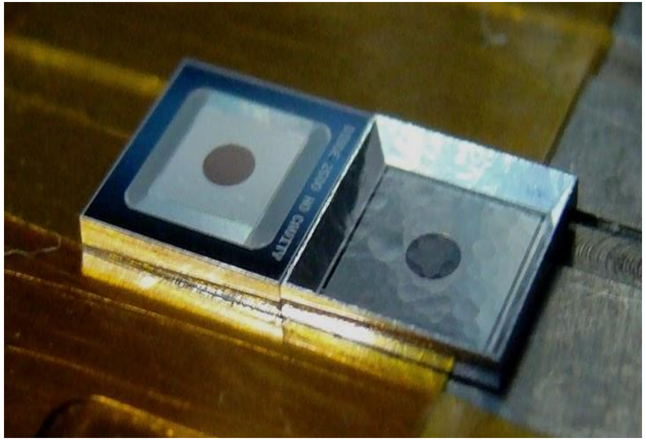
- Identify defects in silicon lattice responsible for macroscopic changes / degradation of sensor properties
  - Increase of full depletion voltage and noise, decrease of charge collection
- Specific defects are responsible for specific macroscopic changes
- Use this knowledge in defect engineering to mitigate radiation damage
- Use characterised defect parameters as input for device simulations to improve them

Devices Studied

- Produced by CIS
- p-type CZ
- 100 Ωcm
- 0.06927 cm² area
- 50 µm or 350 µm thickness
- 23 GeV proton irradiation
  @ PS-IRRAD Proton Facility (hardness factor 0.62)
- Not annealed after irradiation

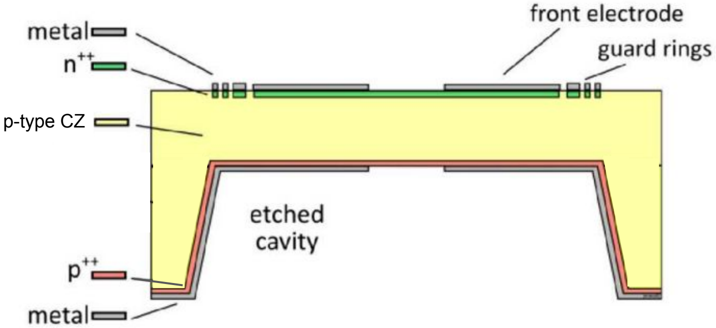


CiS Forschungsinstitut für Mikrosensorik GmbH

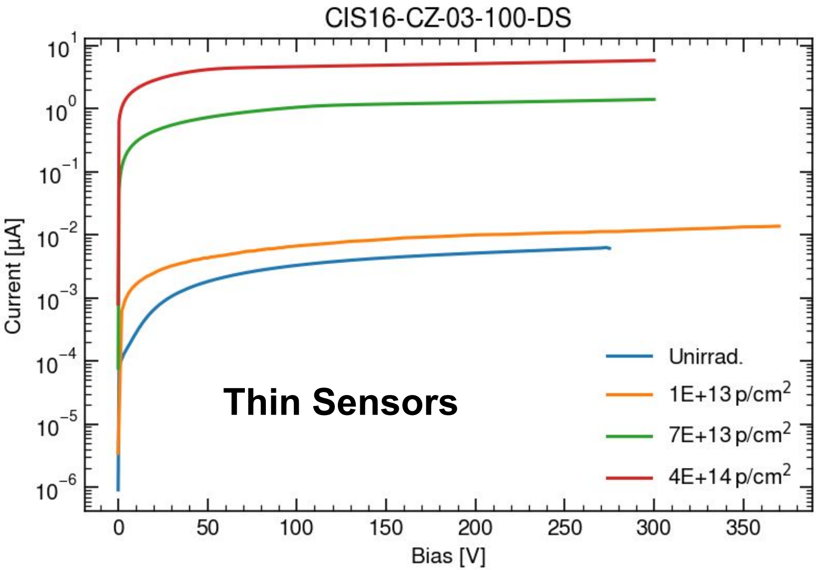


Proton Fluence [p/cm²]	Samples	Nominal Thickness
1E+13	CIS-16-CZ-03-100-DS-66	50 µm
7E+13	CIS-16-CZ-03-100-DS-67	
4E+14	CIS-16-CZ-03-100-DS-69	
1E+13	CIS-16-CZ-05-350-DS-63	350 µm
7E+13	CIS-16-CZ-05-350-DS-64	
4E+14	CIS-16-CZ-05-350-DS-77	

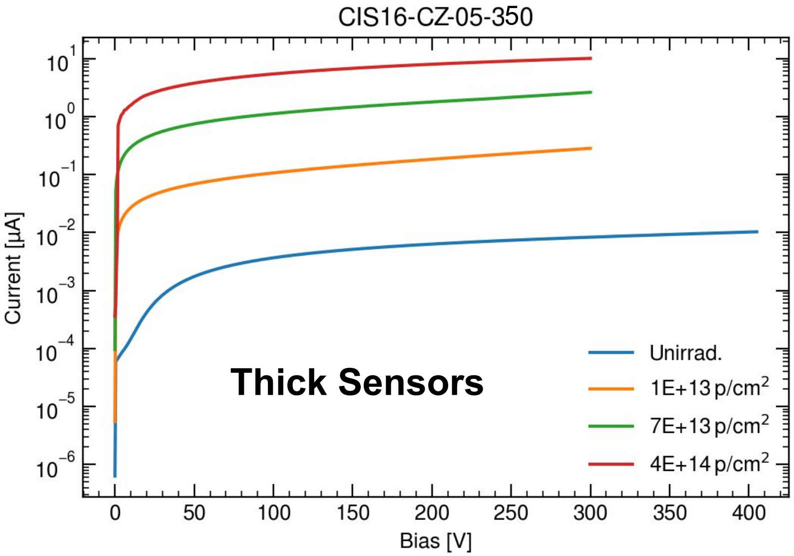
Confirmed by TPA-TCT measurements!



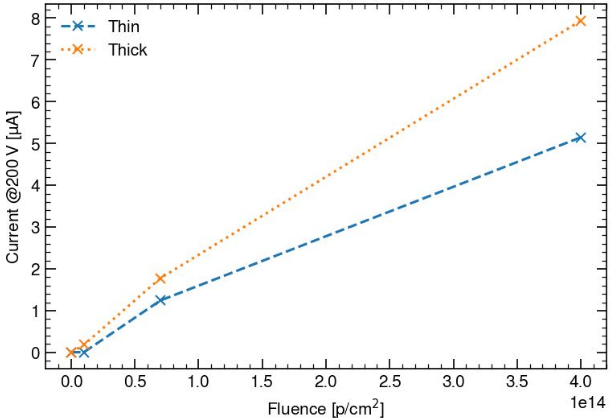
IV Measurements



Thin Sensors

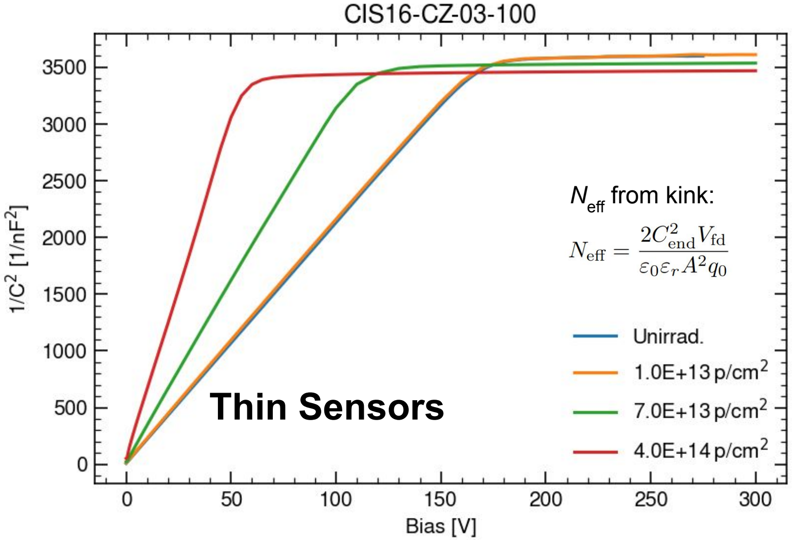


Thick Sensors



- Shielded probe station, flooded with dry air
- HV from chuck
- Guard ring grounded
- Room temp. (unirrad.) or -20°C (irrad.)

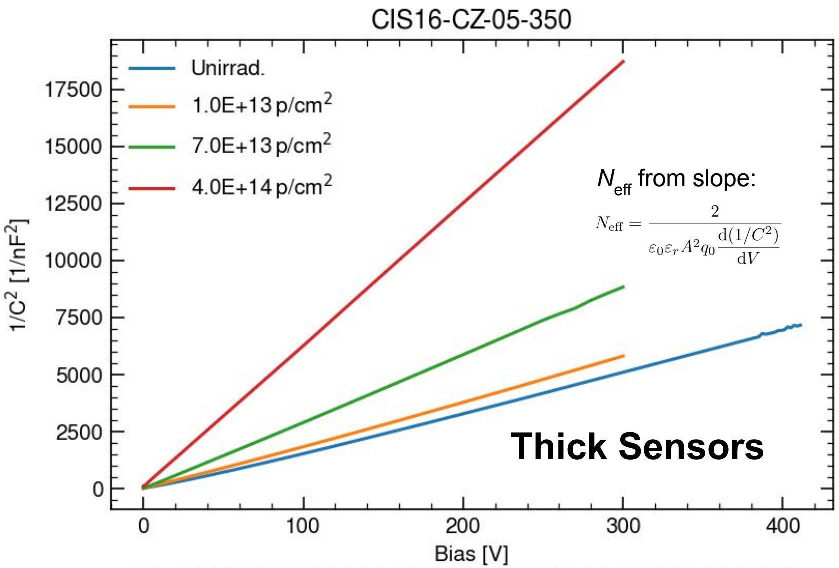
CV Measurements



N_{eff} from kink:

$$N_{\mathrm{eff}} = \frac{2C_{\mathrm{end}}^2 V_{\mathrm{fd}}}{\varepsilon_0 \varepsilon_r A^2 q_0}$$

Thin Sensors

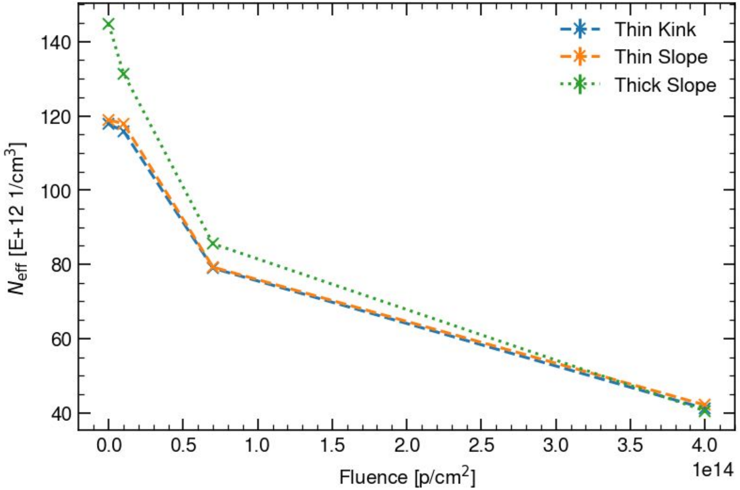


N_{eff} from slope:

$$N_{\mathrm{eff}} = \frac{2}{\varepsilon_0 \varepsilon_r A^2 q_0 \frac{\mathrm{d}(1/C^2)}{\mathrm{d}V}}$$

Thick Sensors

- All measured @10 kHz
- Room temp. (unirrad.) or -20 °C (irrad.)
- V_{fd} from intersection of lin. fits (only thin sensors)
- N_{eff} from kink or slope of CVs

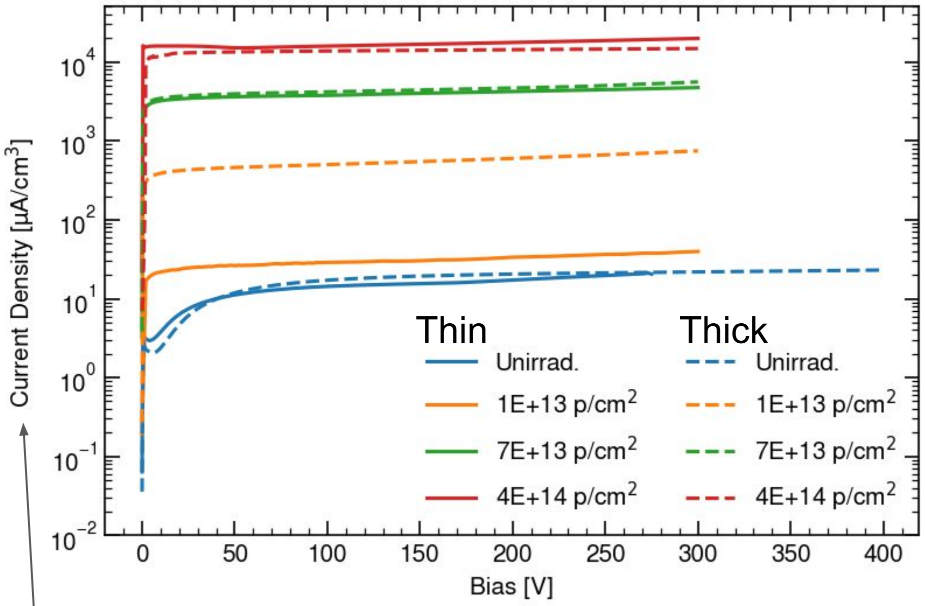


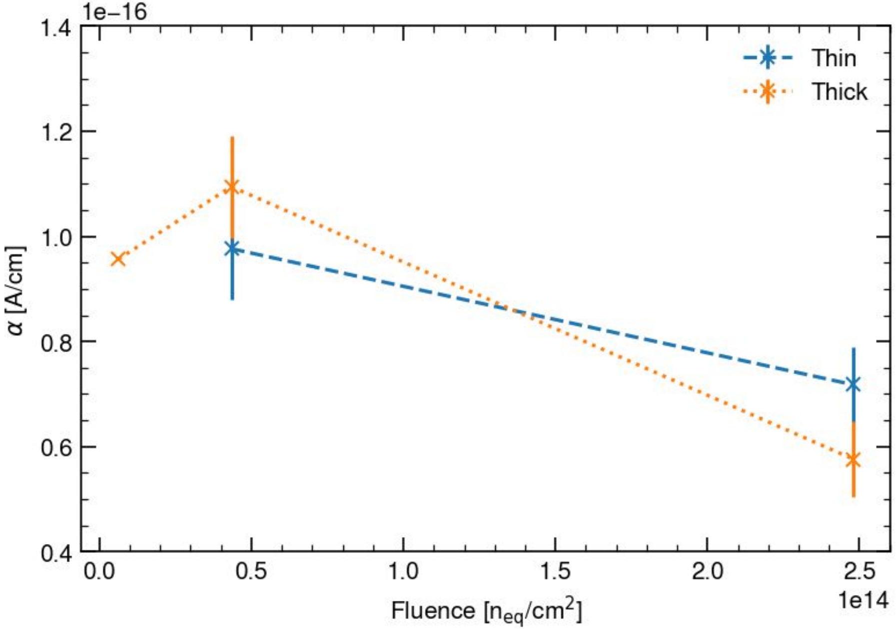
Resistivity estimated† from N_{eff}:
- Thin: 114 Ωcm
- Thick: 92 Ωcm

Manufacturer: 100 Ωcm

† https://www.pvlighthouse.com.au/resistivity

Current Density & Current Related Damage Parameter α





$$j_d(V) = \frac{I(V)}{Aw(V)}$$

$$w(V) = \frac{\varepsilon_0 \varepsilon_r A}{C(V)}$$

Thin, 1E13 sensor was assigned wrong fluence!

- Lit. value 0.4E-16 A/cm (after 80 min @60°C)
- Here: non-annealed devices

$$\alpha = \frac{j_d(\Phi) - j_d(\Phi = 0)}{\Phi}$$

Thermally Stimulated Current (TSC)

1. **Cool down sensor** under reverse bias (to not fill traps with majority carriers)
2. **Inject charge** carriers
    - ○ Forward bias for e & h
    - ○ 0V for majority carriers (h)
    - ○ Optical injection
3. **Heat up sensor** at constant heating rate under reverse bias
    - ○ Measure current due to detrapping of charges at specific temperatures
    - ○ Obtain defect concentration, activation energy, …

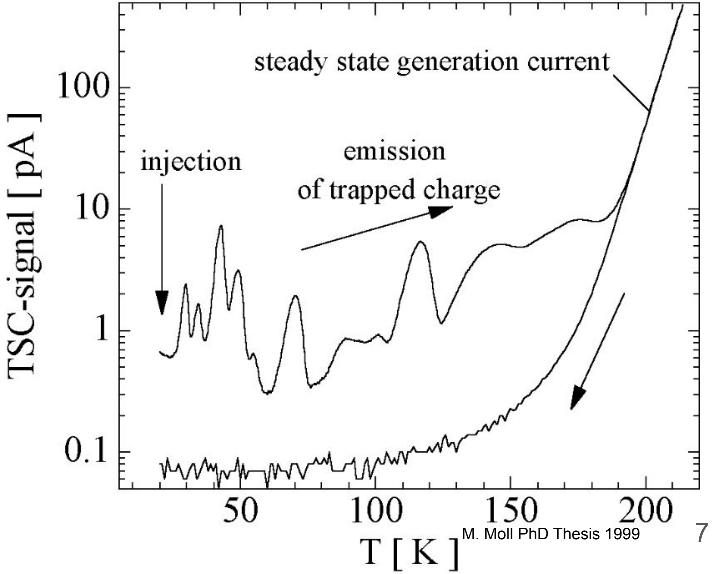
$$n = \frac{2Q}{q_0 A w}$$

Obtain from integration over peak

Defect concentration

Standard parameters used for electrical filling:

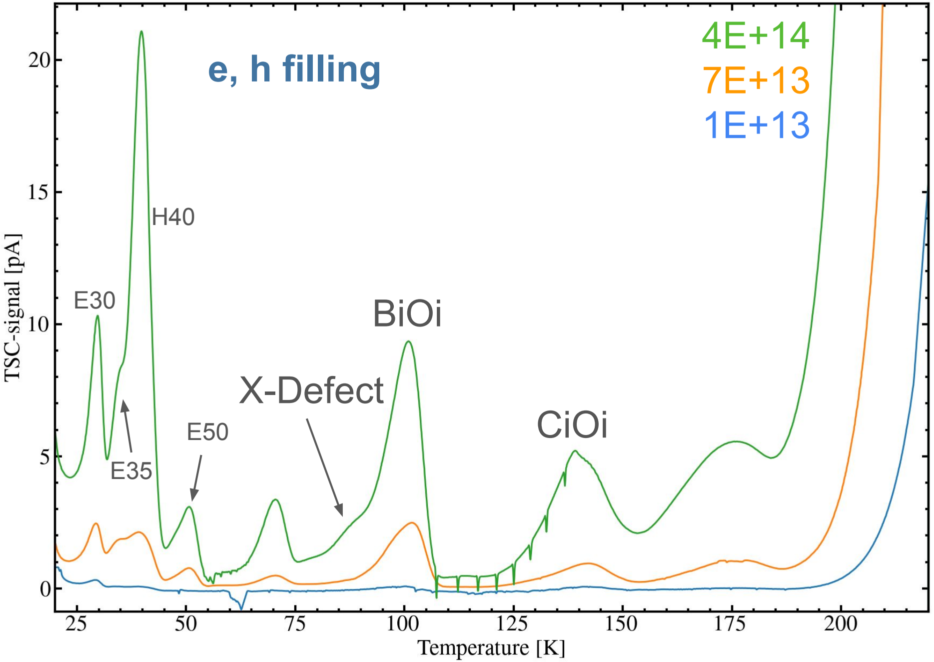
- -200V cool down bias
- 11K/min heating rate
- 60s filling time + 60s wait after filling



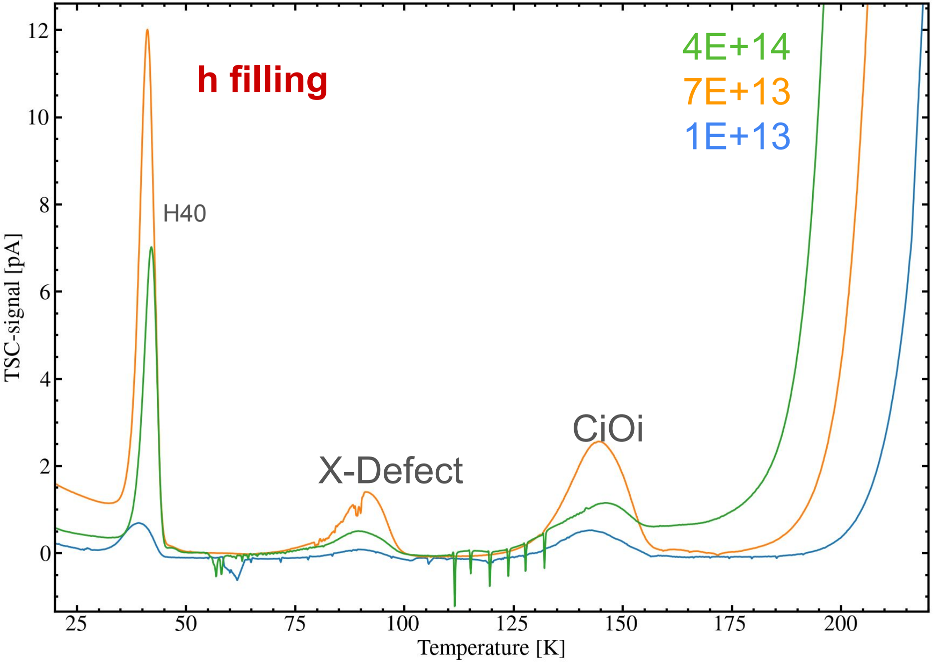
M. Moll PhD Thesis 1999

TSC Measurements of Thin Sensors (Electrical Filling)

1. Cooling down @-200V
2. **Forward bias filling (20V, 1mA)** @20K for 60s
3. Warming up @-50V



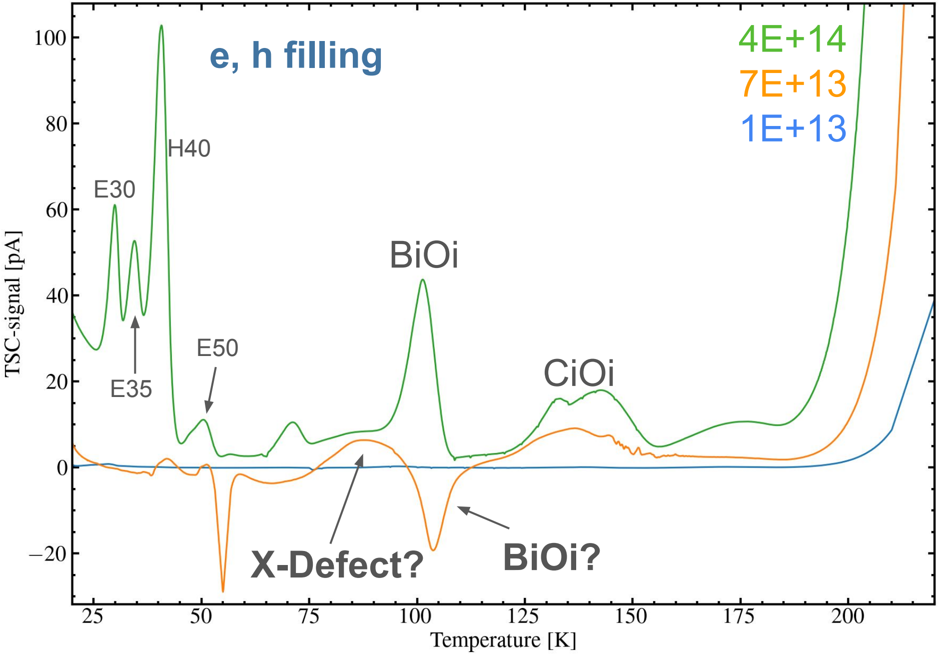
1. Cooling down @-200V
2. **0V filling** (majority carriers) @20K for 60s
3. Warming up @-50V



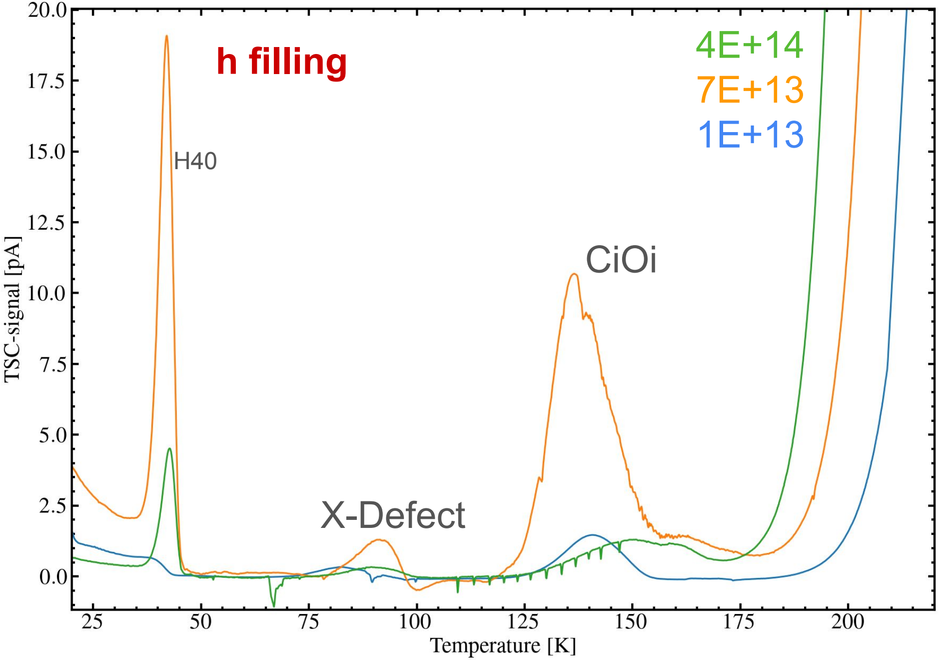
- From difference between forward bias and 0V filling infer which kind of trap (e or h)
  - E.g.: E30 visible in e/h filling, but not in h filling plot → electron trap
- Disentangle overlapping peaks
  - X-Defect (h trap) and BiOi (e trap)

TSC Measurements of Thick Sensors (Electrical Filling)

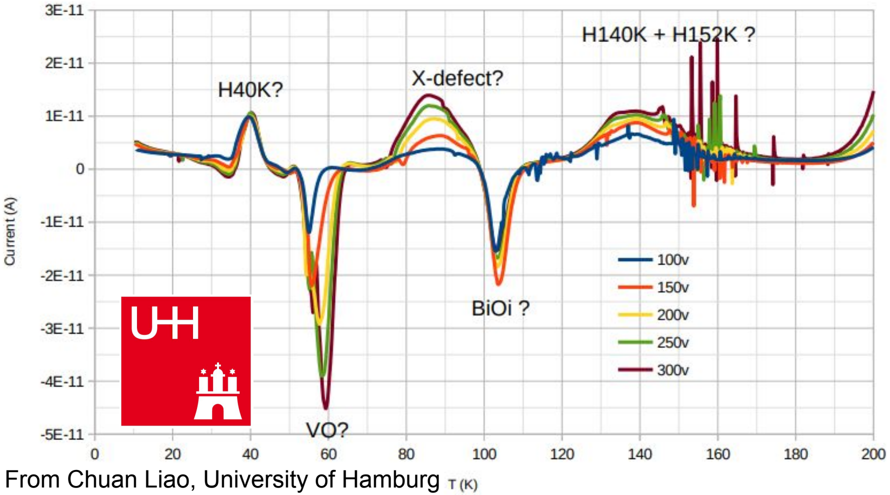
1. Cooling down @-200V
2. **Forward bias filling (300V, 1mA)** @20K for 60s
3. Warming up @-200V



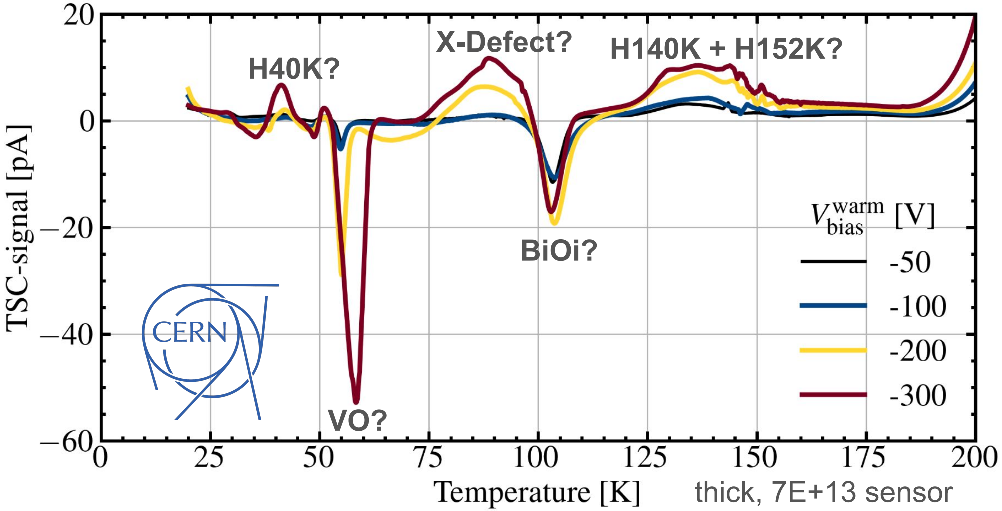
1. Cooling down @-200V
2. **0V filling** (majority carriers) @20K for 60s
3. Warming up @-200V



Negative TSC Peaks



From Chuan Liao, University of Hamburg

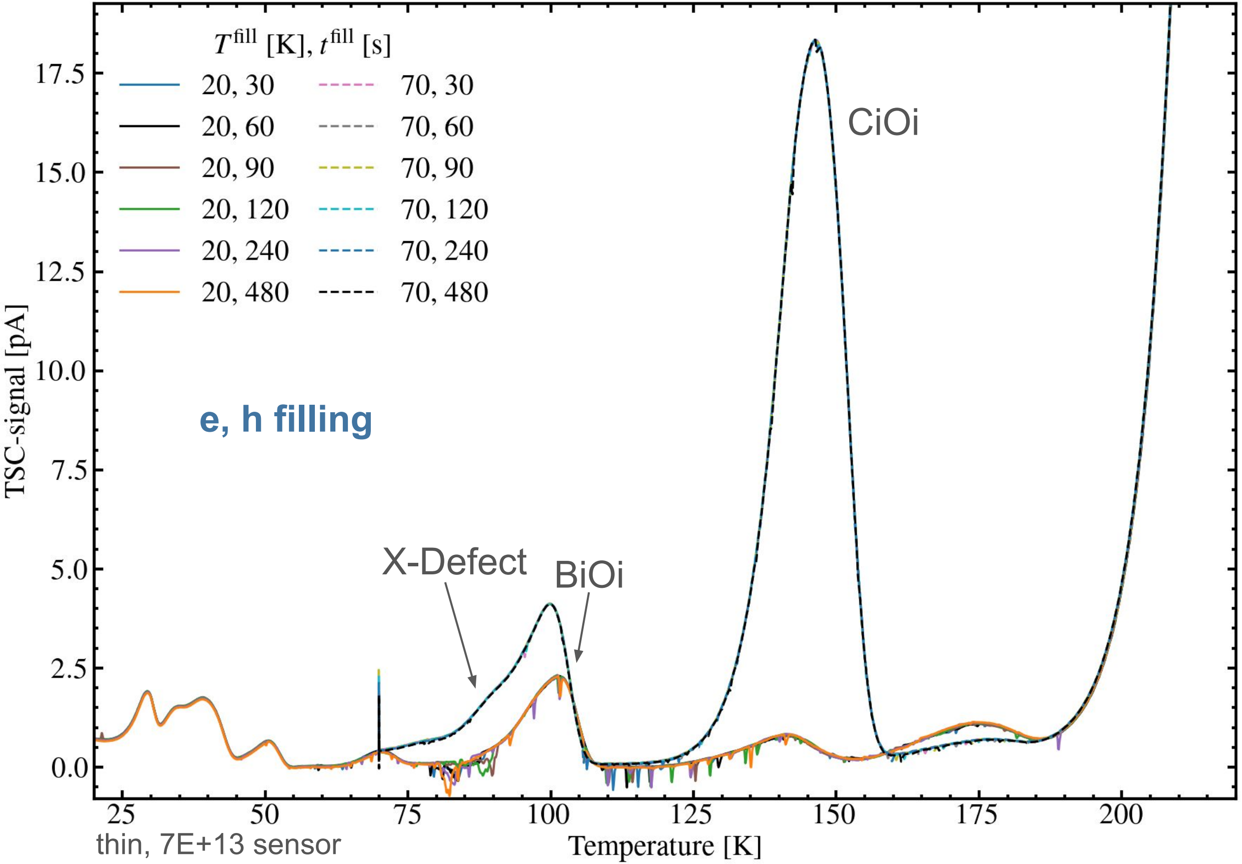


thick, 7E+13 sensor
300V filling @20K

- **Measured twice** in the Acceptor Removal Team (Hamburg & CERN) on **two** identical **devices** (same fluence, thickness, wafer)
- Negative peaks only observed for
  - Thick sensor
  - 7E+13 (middle fluence)
- Negative current → charges flow in opposite direction
  - **Polarisation** inside sensor?
  - **Intrinsic E-field** stronger than externally applied?

Still under investigation!

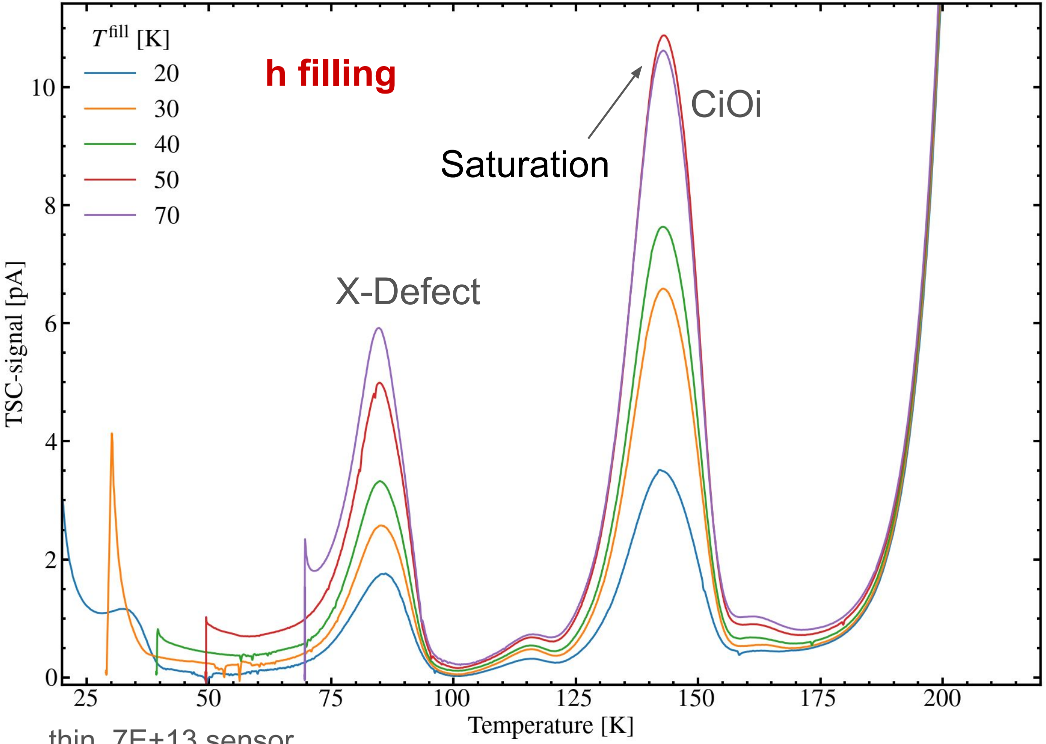
Dependence on Filling Time (tfill) and Filling Temperature (Tfill)



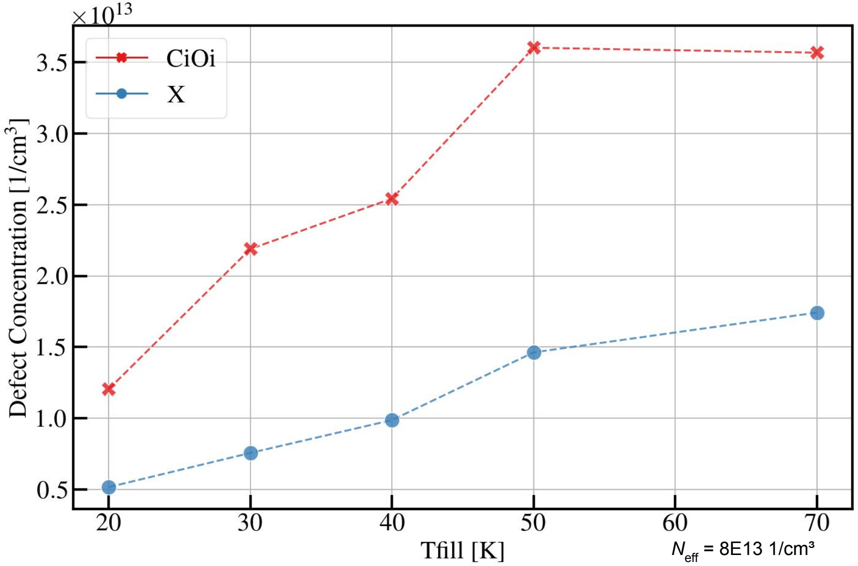
thin, 7E+13 sensor
20V filling, -50V up

- **No dependence on filling time** for electrical filling
- Reliable repeatability of measurements
- **Strong dependence on filling temperature**

Dependence on Filling Temperature (Tfill)

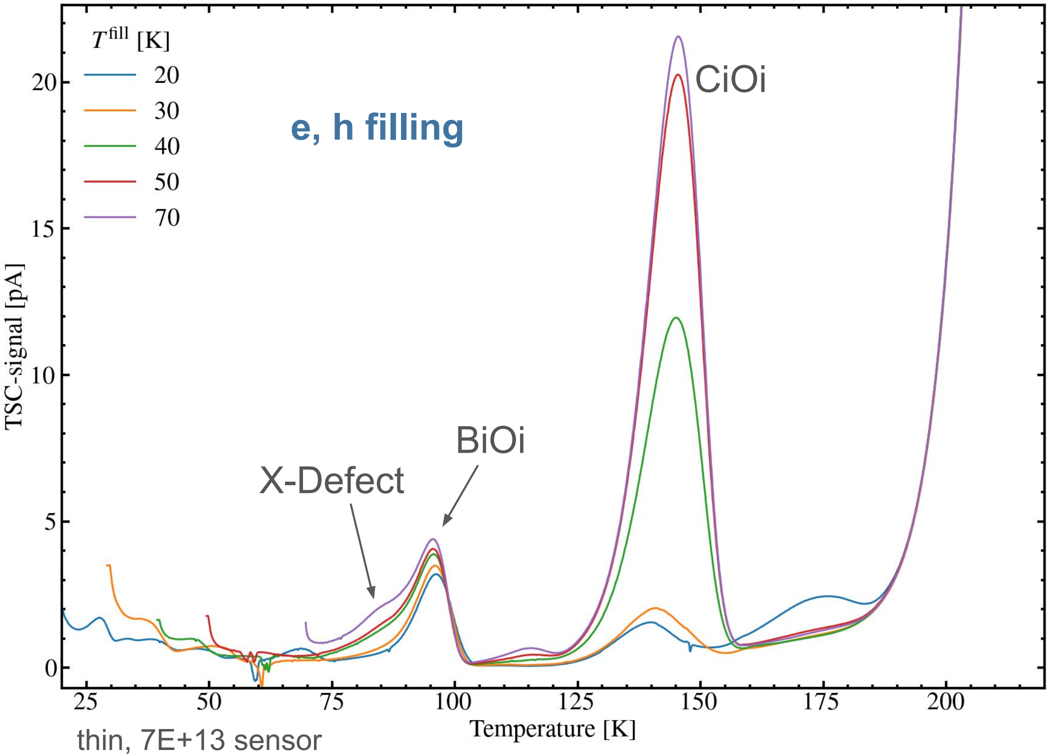


thin, 7E+13 sensor
0V filling, -200V up

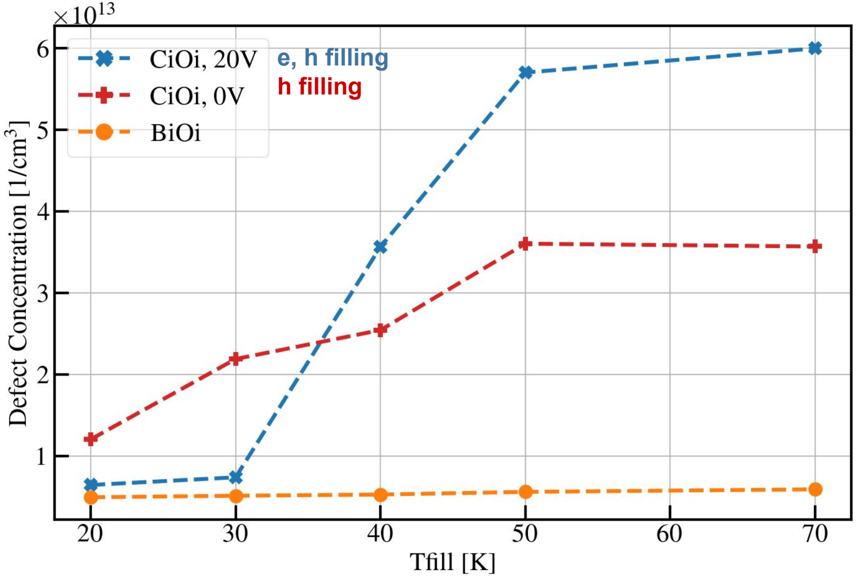


- **Filling** of X-Defect and CiOi **strongly dependent** on **Tfill**
  → Strong dependence in calculated defect concentration
- Calculated defect conc. dependent on amount of h available in 0V filling (related to N_{eff}, fluence dependent)

Dependence on Filling Temperature (Tfill)

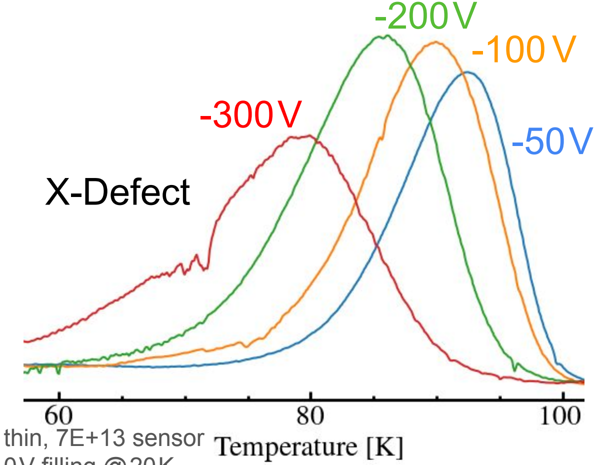


thin, 7E+13 sensor
20V filling, -200V up

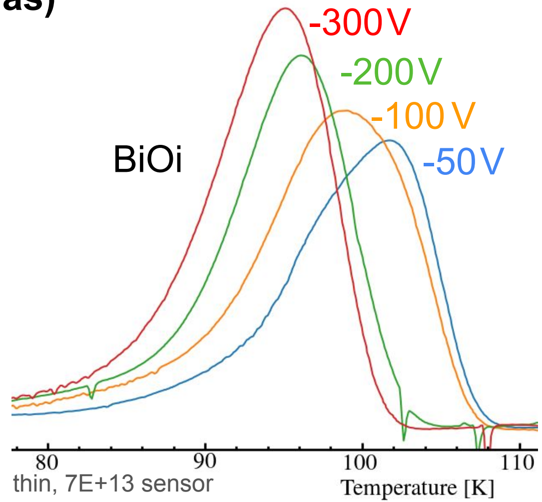


- CiOi filled more than with 0V filling
- BiOi only weakly dependent on Tfill
- X-Defect overlapped with BiOi
    - Difficult to extract accurate defect concentration

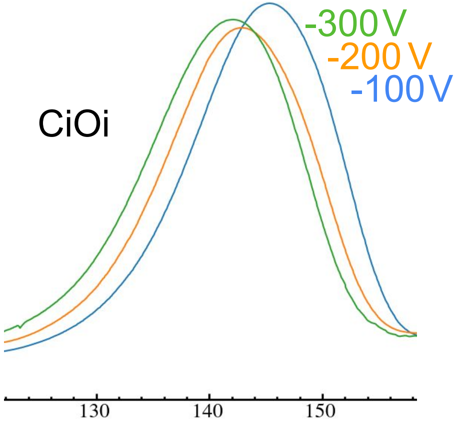
Dependence on Warm-Up Bias (Vbias)



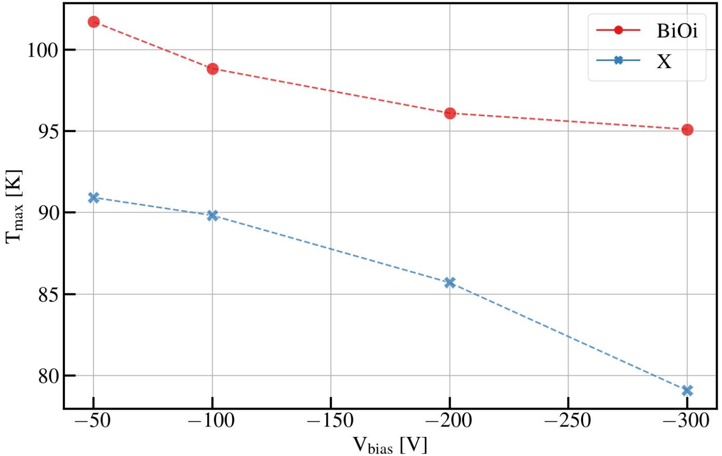
thin, 7E+13 sensor
0V filling @20K

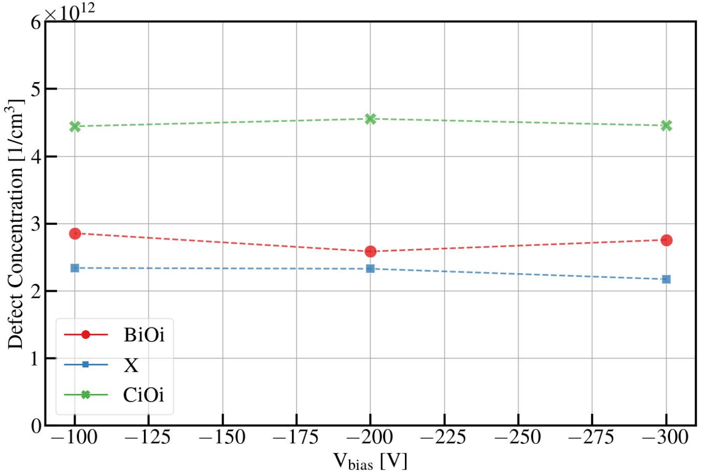


thin, 7E+13 sensor
20V filling @20K



thin, 7E+13 sensor
0V filling @70K



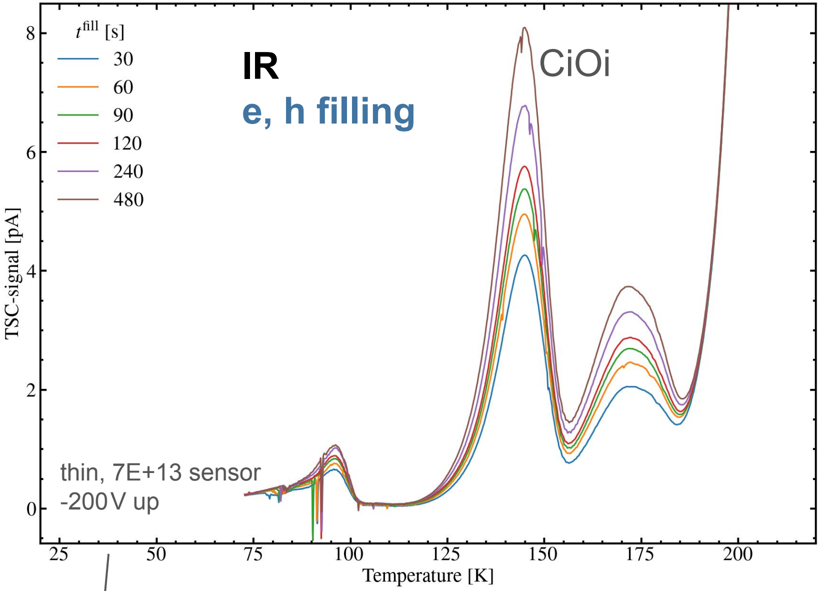


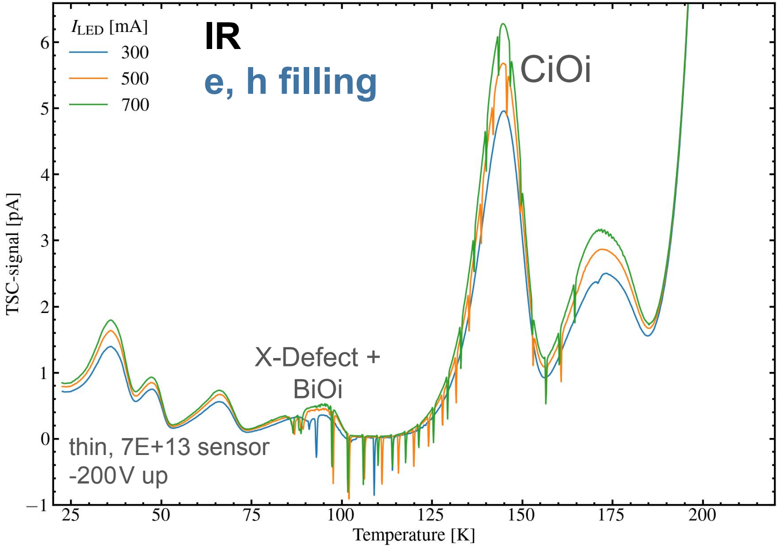
- Position of X-Defect, BiOi and CiOi dependent on bias applied during heating → **Poole-Frenkel Effect**
- Defect concentration does not depend on Vbias

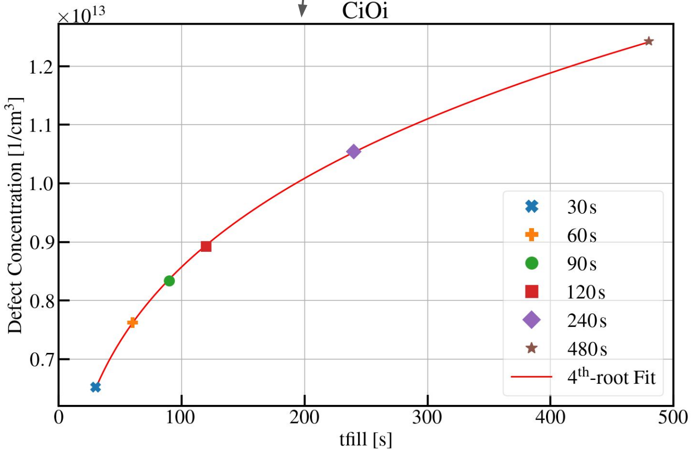
Light Injection & Dependence on Intensity and tfill

Shine light on sensor to fill traps:

- Infrared (IR) goes through sensor: creates e & h
- Green absorbed after few microns in Si (1-3 µm)
  - Green on Front: h
  - Green on Back: e







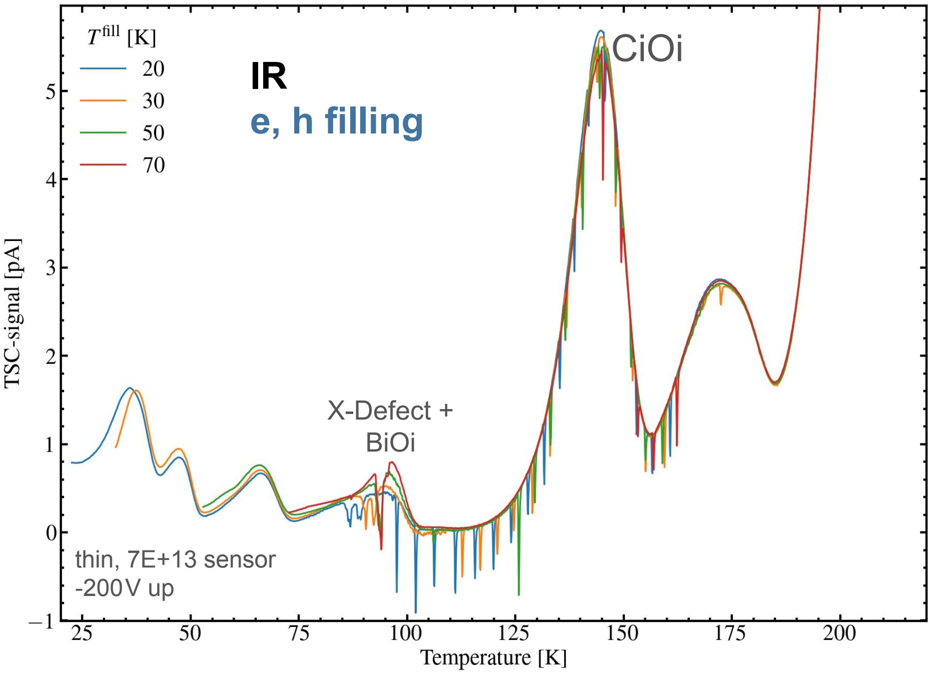
Defect concentration follows 4th-root function

$$\text{Def. Conc.} = a\sqrt[4]{t_{\text{fill}}} + b$$

From fit:
a = 2.5 E12 $s^{3/4}/cm^3$
b = 5.9 E11 $1/cm^3$

- **Filling** of defects **depends** on **light intensity** and **filling time**

Dependence on Tfill for IR and Green Light



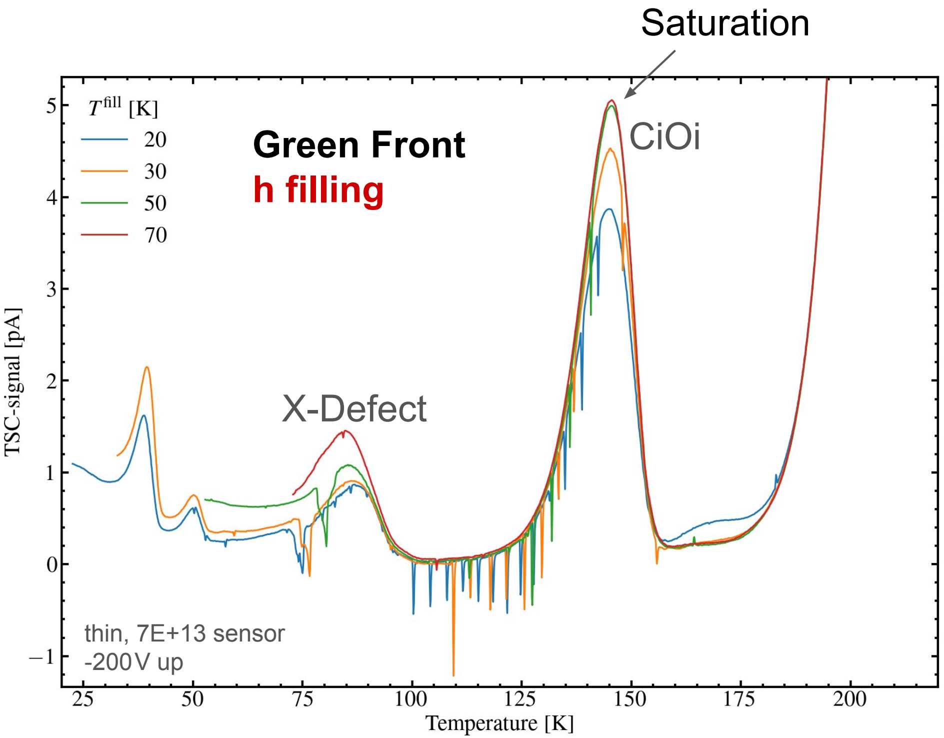
IR

e, h filling

CiOi

X-Defect +
BiOi

thin, 7E+13 sensor
-200V up



Saturation

Green Front

h filling

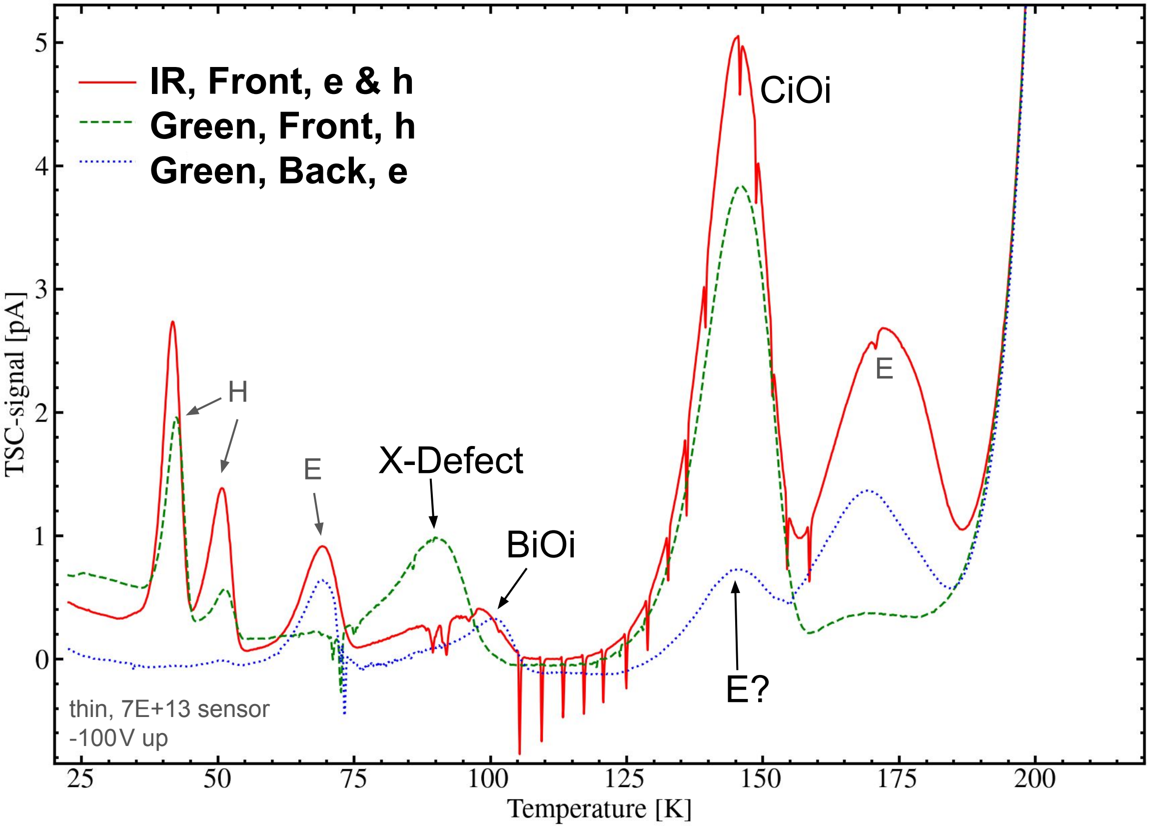
CiOi

X-Defect

thin, 7E+13 sensor
-200V up

- **IR** filling does **not dependent** on **Tfill**
- **Green** filling does **dependent** on **Tfill**

IR vs Green Front/Back

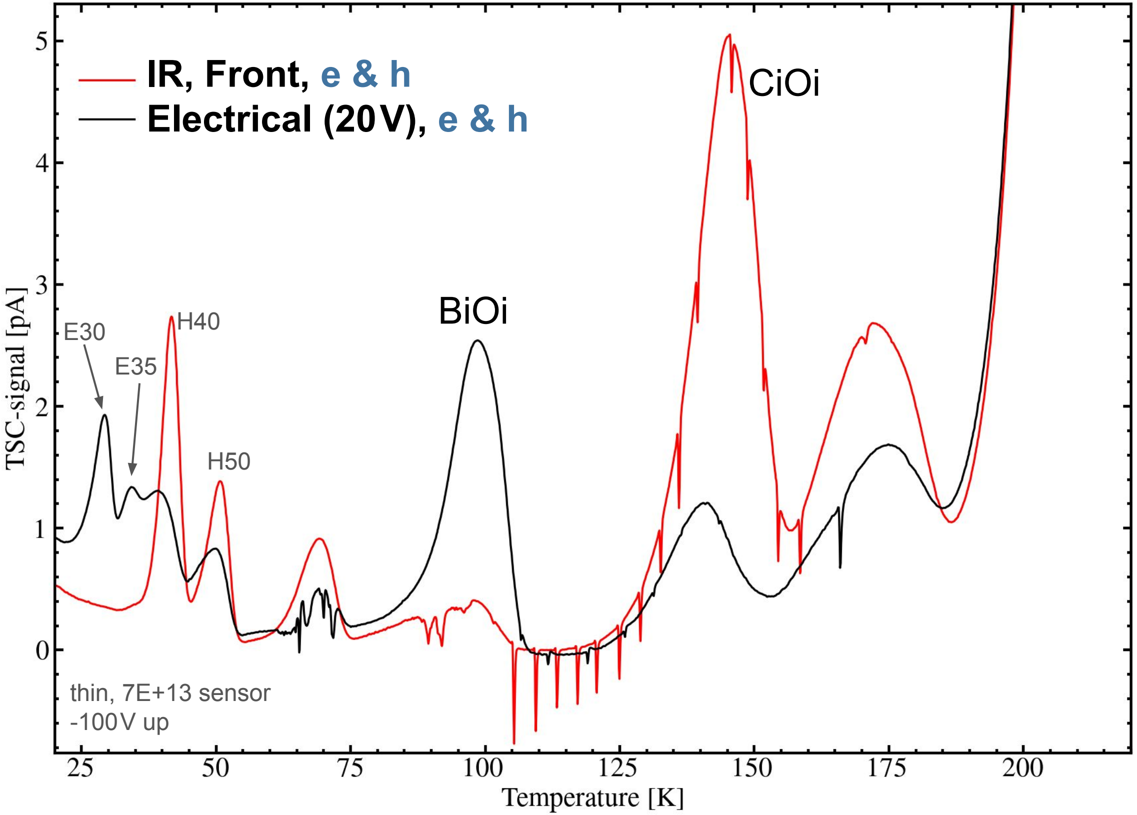


- **Can choose between e and h traps with Green light**

- Integral of peaks differ for IR and Green
  - ○ Light diodes have different intensities
  - ○ Green depends on Tfill,
    IR does not
  - ➢ Filling not saturated!

- X-Defect not filled with IR?
- Unknown electron trap concealed by CiOi
  - ○ Not observable with electrical filling
  - ○ Always overshadowed by CiOi

IR vs Electrical Filling



- Overall similar picture, but some differences observed
- Data shown as measured:
  - Not normalised to illuminated area
  - Need to normalise according to number of e and h injected?

- Small temp. defects (E30, E35) only filled by electrical pulse?

→ More work to be done!

Conclusion

- Results shown for p-type CZ pad diodes, 50/350 µm thickness, 3 proton fluences (1E+13, 7E+13, 4E+14)

- Light injection with IR and Green can be used for e & h, h or e filling!
- Negative TSC spectrum observed by two independent setups → **Must be physics!**

Open Questions

- Negative peaks caused by polarisation?
- Negative peaks only observed for thick sensors at that fluence?

- IR filling not dependent on Tfill, but Green filling depends on Tfill?
- IR filling dependent on 4th-root of tfill?
- X-Defect and low temp. electron traps not filled with IR?
- How to saturate IR and Green filling?

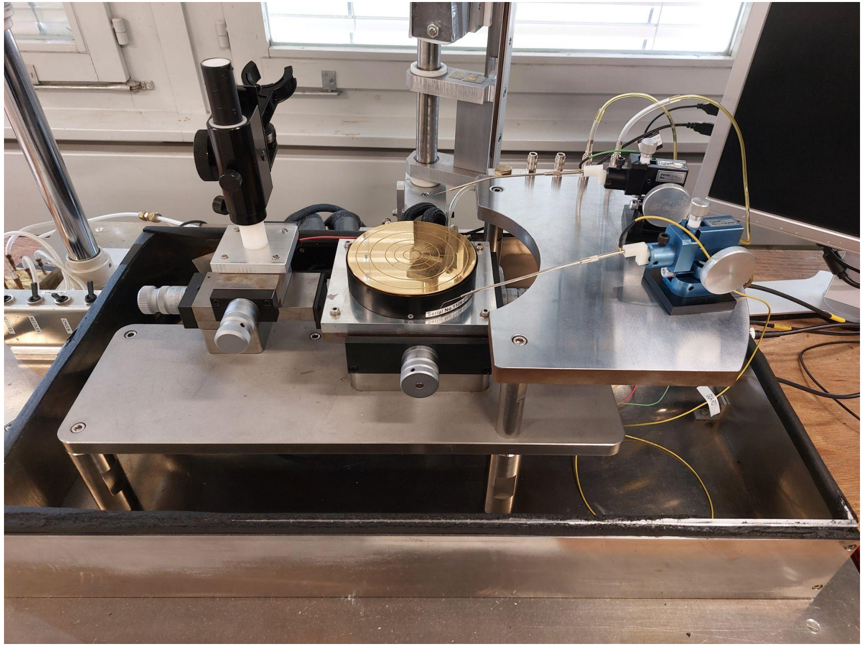
Outlook

- Extract defect concentrations and calculate introduction rates
- Annealing study
- Study electron trap hidden under the CiOi peak

This work has received funding by the Wolfgang Gentner Programme of the German Federal Ministry of Education and Research (grant no. 13E18CHA).

Backup

Used IV/CV Setup @ CERN



CV Measurement Data

50 µm	V_fd [V]	C_end [pF]	N_eff [E+12 1/cm³] Kink	N_eff [E+12 1/cm³] Slope
Unirrad.	168.1 ± 0.2	16.68 ± 0.01	117.7 ± 0.2	118.88 ± 0.04
1E13	163.9 ± 0.3	16.61 ± 0.02	113.7 ± 0.3	117.92 ± 0.14
7E13	110.7 ± 0.3	16.84 ± 0.02	78.9 ± 0.3	79.2 ± 0.2
4E14	56.4 ± 0.2	17.02 ± 0.04	41.1 ± 0.2	42.1 ± 0.2

350 µm	N_eff [E+12 1/cm³] Slope
Unirrad.	144.8 ± 0.4
1E13	131.4 ± 0.4
7E13	85.5 ± 0.1
4E14	40.5 ± 0.01

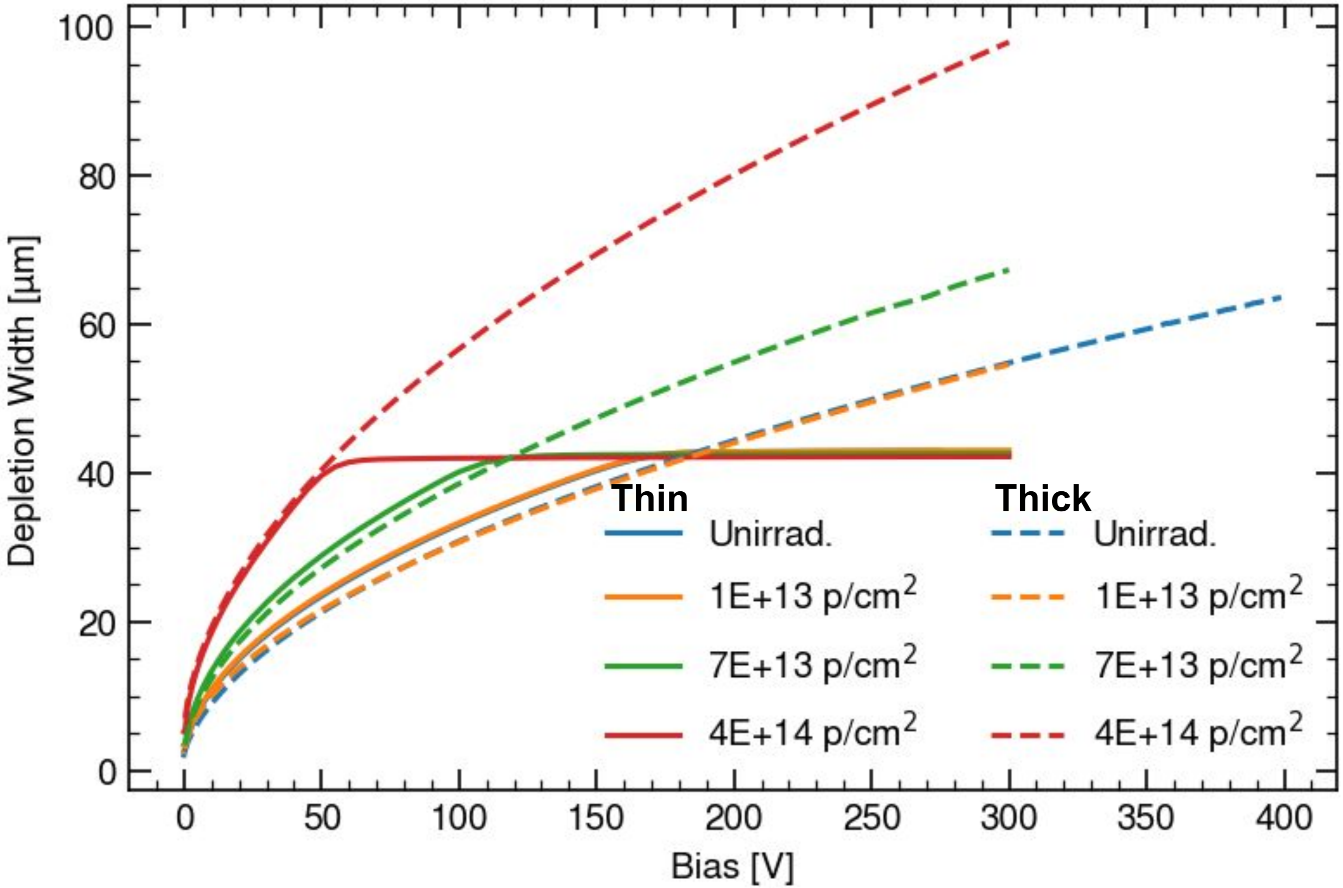
N_{eff} from kink:

$$N_{\text{eff}} = \frac{2C_{\text{end}}^2 V_{\text{fd}}}{\varepsilon_0 \varepsilon_r A^2 q_0}$$

N_{eff} from slope:

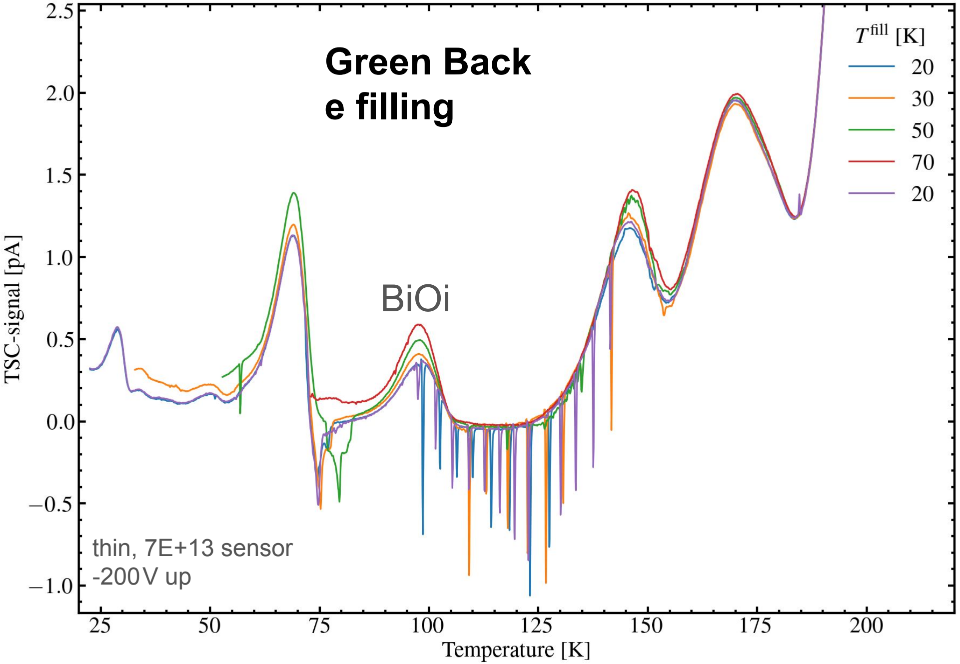
$$N_{\text{eff}} = \frac{2}{\varepsilon_0 \varepsilon_r A^2 q_0 \frac{\mathrm{d}(1/C^2)}{\mathrm{d}V}}$$

Depletion Width

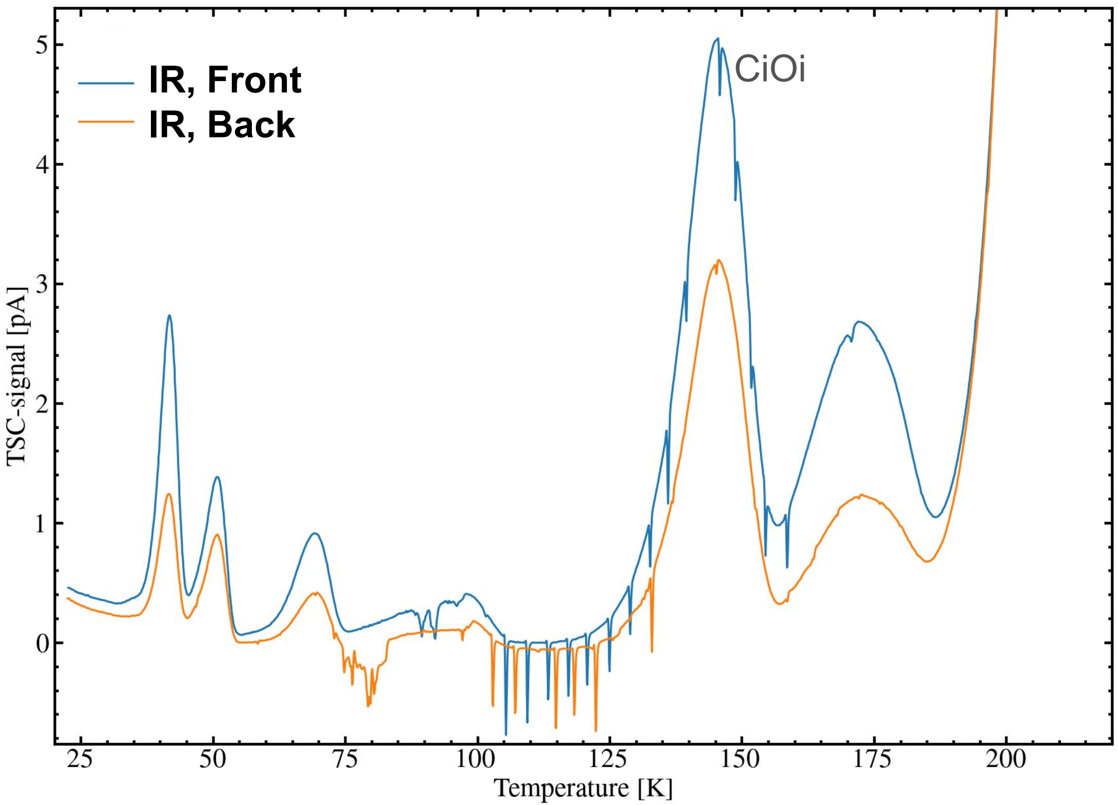


$$w(V) = \frac{\varepsilon_0 \varepsilon_r A}{C(V)}$$

Tfill Dependence of Green Back Filling



IR Front vs Back Illumination



- Should yield no difference
- No difference in amount and shape of observed defects
- Back has smaller opening in cryostat shield
  → Less light intensity
  → Less filling