Defects formed in boron-doped Si diodes after high energy electron irradiation

EP-DT-DD
Detector Technologies
Detector Development

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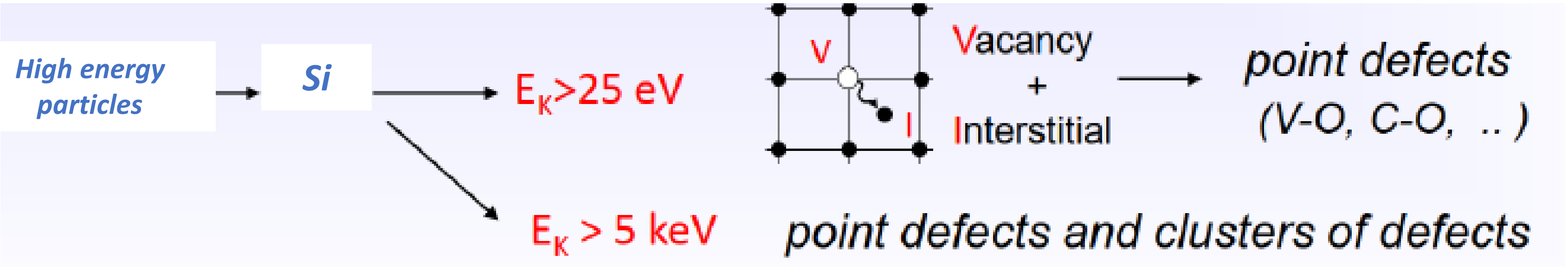
Motivation


High energy particles → *Si* → E_K>25 eV → Vacancy + Interstitial → *point defects (V-O, C-O, ..)*

E_K > 5 keV *point defects and clusters of defects*

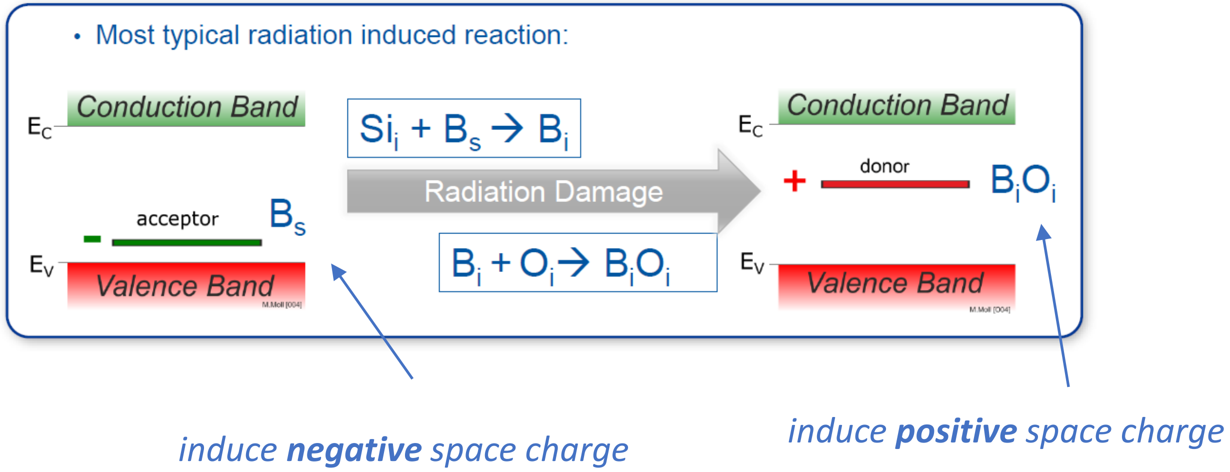
Defect Characterization:

- Identify defects responsible for changes of macroscopic sensors properties/ **sensor degradation**
- Adapt this knowledge to mitigate radiation damage (e.g. defect engineering)
- Deliver input for device simulations to predict detector performance under various conditions

High energy particles leading to radiation damage: e.g. neutrons, protons, **electrons** …

Acceptor Removal Effect in p-type Si:

- de-activation of B as shallow dopant


- Most typical radiation induced reaction:

$Si_i + B_s \rightarrow B_i$

Radiation Damage

$B_i + O_i \rightarrow B_iO_i$

*induce **negative** space charge*

*induce **positive** space charge*

Sample overview

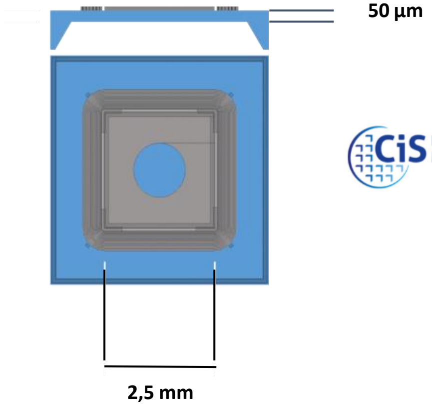
200 MeV

Details on the radiation:
A. Himmerlich et al.
37th RD50 Workshop 2020

	sample	resistivity [Ωcm]	Fluence (coll.) [e/cm-2]	fluence (coll.) [neq/cm-2]
2	EPI-02-103	10	4.72E+14	3.87E+13
4	EPI-06-105	50	8.70E+13	7.14E+12
6	EPI-08-78	250	2.88E+13	2.36E+12
7	EPI-12-69	1000	1.46E+13	1.19E+12

Hardness factor* (200 MeV) κ = 0.082

characterization
before & after
annealing
(10 min @ 60°C)



5.5 MeV (annealed)

	sample	Resistivity (Ω cm)	Fluence (e/cm^2)	Fluence (n_{eq}/cm^2)
	EPI-02-100	10	5.00E+14	1.90E+13
	EPI-02-105	10	5.00E+14	1.90E+13
	EPI-06-88	50	2.00E+14	7.60E+12
	EPI-08-88	250	1.00E+14	3.80E+12
	EPI-06-97	50	5.00E+13	1.90E+12

Hardness factor*
(5.5 MeV) κ = 0.038

Material:
Standard EPI diodes (EPI layer 50 µm)
p-type Si pad diodes produced by CiS (Erfurt, Germany):
area = (2.632 x 2.632) µm^2
nominal active thickness = 50 µm
guard rings
passivation with openings for connection
on back and front side openings for light injection

Characterization methodes:
CV/IV
DLTS: Deep Level Transient Spectroscopy
TSC: Thermally Stimulated Current

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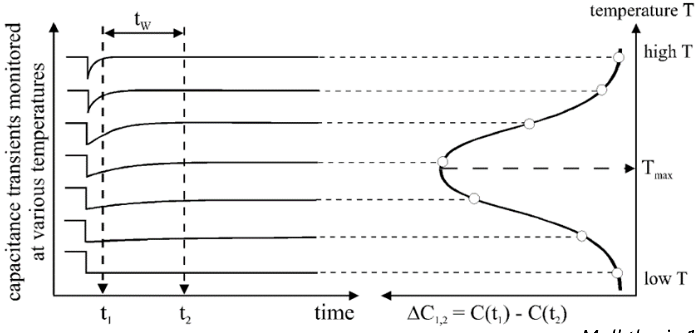
* IEEE-TS Nucl. Sci. Vol. 56, No 6, Dec 2009, pp 3229-3235

DLTS & TSC

DLTS: Deep Level Transient Spectroscopy

(1) Junction under reverse bias @ different temperatures→ defect states unoccupied
(2) Injection pulse (electrical or optical) → injection of minority and/or majority carriers → occupation of defect levels
(3) Junction under reverse bias → charge carriers thermally emitted → change in capacitance



Moll thesis 1999

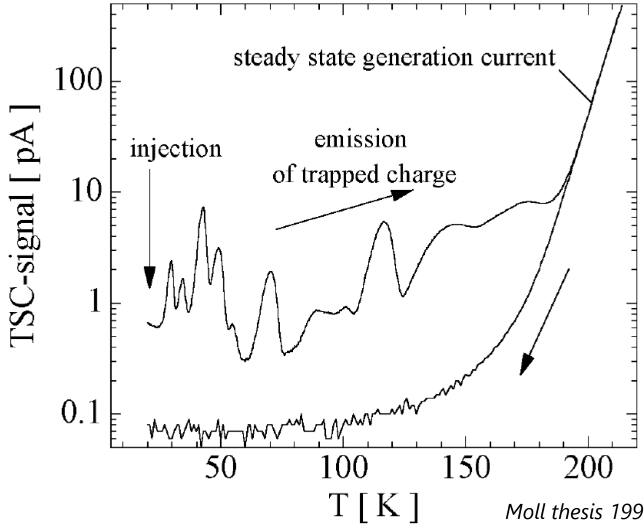
Defect parameters:

activation energy
capture cross section
defect concentrations

DLTS limited to defect concentrations $N_t \approx 0.1\text{-}0.3 * N_{doping}$

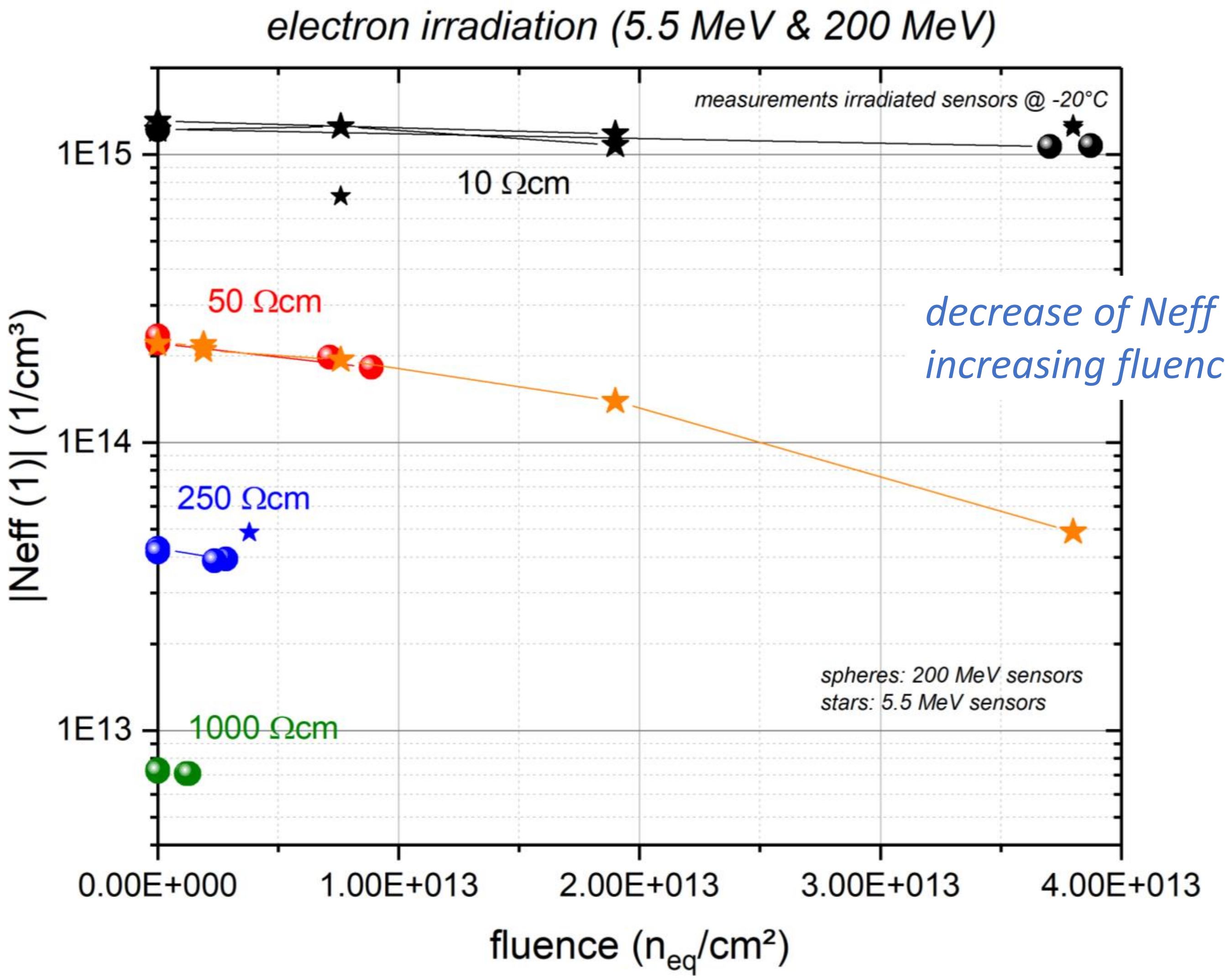
TSC: Thermally Stimulated Current

(1) Junction under reverse bias during cooling down of the sample to T_{Fill}
→ defect states unoccupied
(2) Injection pulse (electrical or optical) → injection of minority and/or majority carriers
→ occupation of defect levels
(3) Junction under reverse bias & Temperature raised
→ monitoring the discharging current due to thermal emission from the defect levels

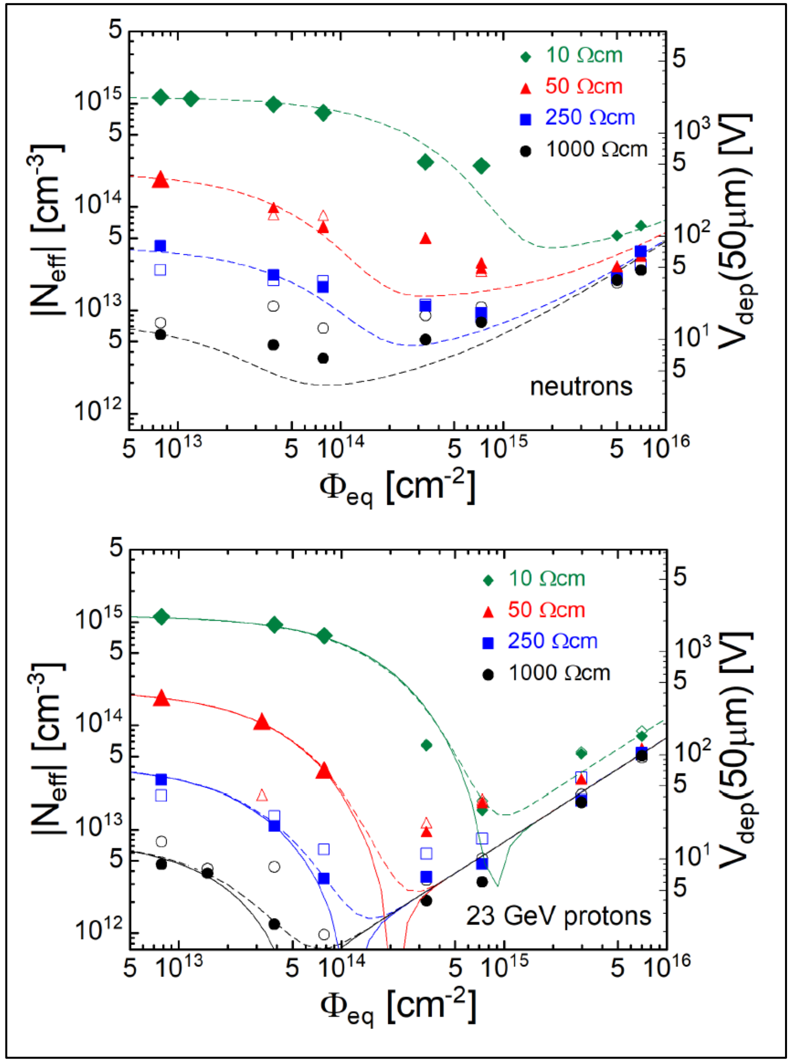


Moll thesis 1999

Results of cv/iv measurements



decrease of Neff with increasing fluence



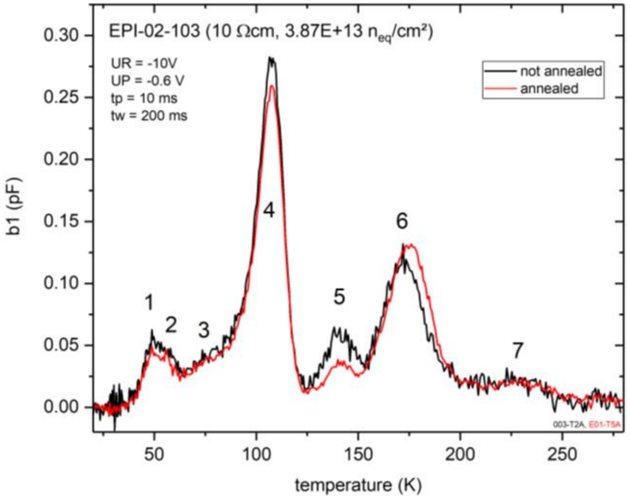
P. Almeida et al. „Characterization of radiation induced acceptor removal in boron doped epitaxial silicon pad diodes" (in preparation)

P. Almeida et al. 31th RD50 Workshop 2017

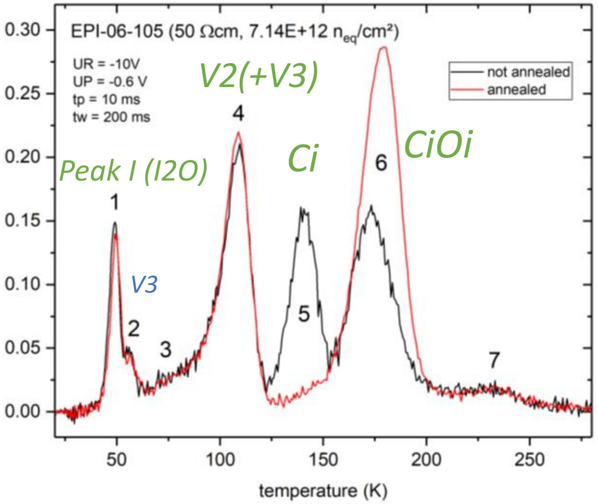
DLTS (200 MeV electron irrad., before & after annealing 10 min @ 60°C)

maj. carrier injection:

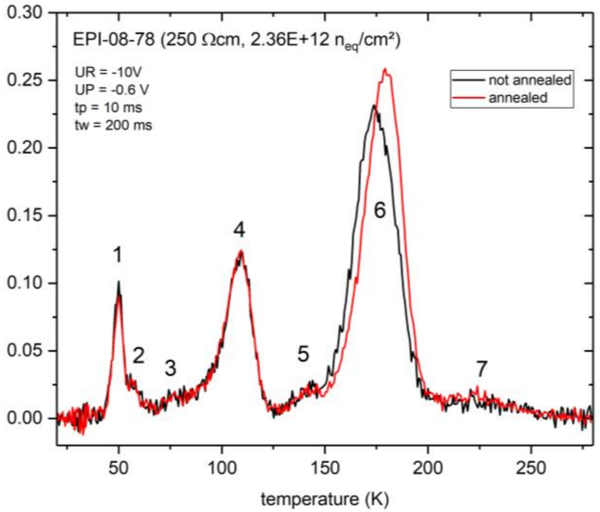
10 Ωcm



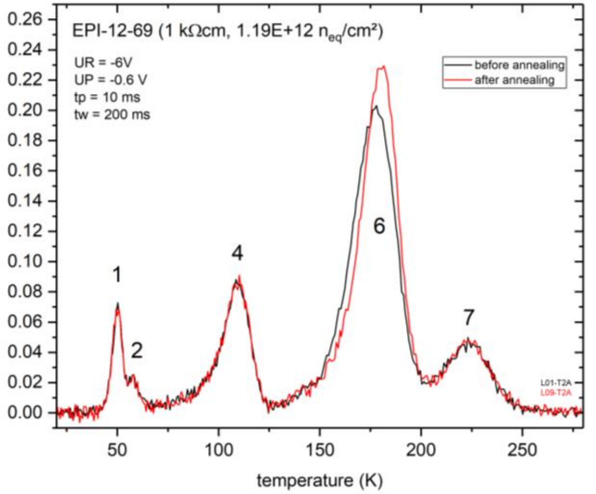
50 Ωcm



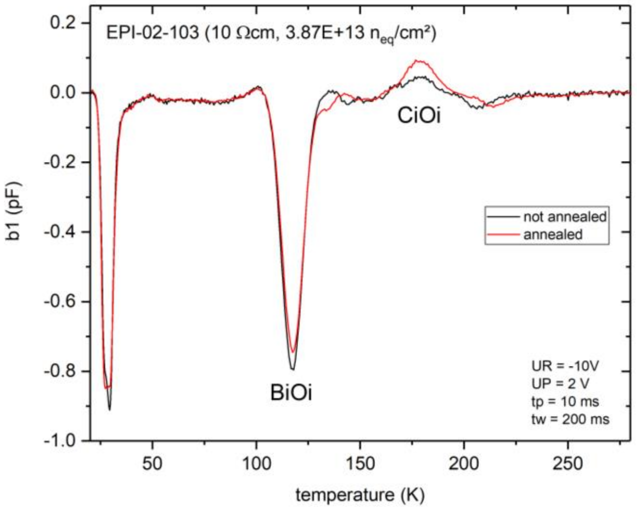
250 Ωcm

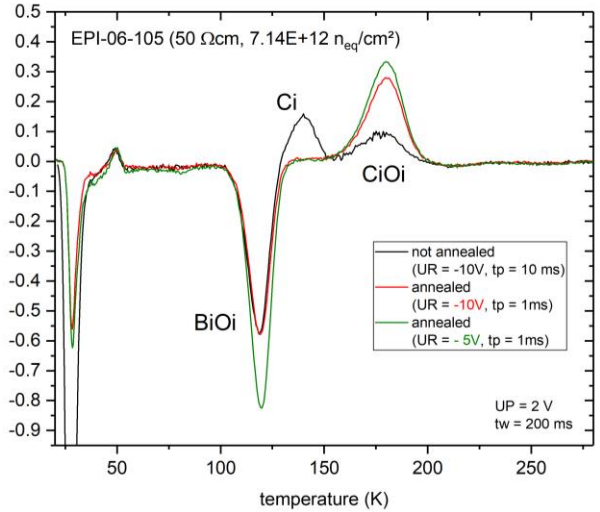


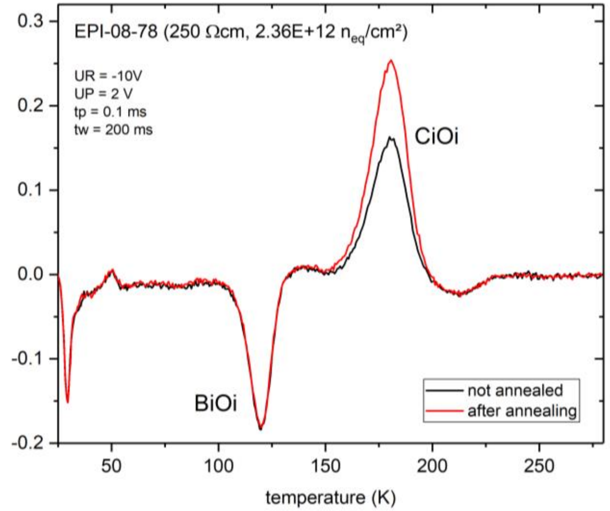
1 kΩcm

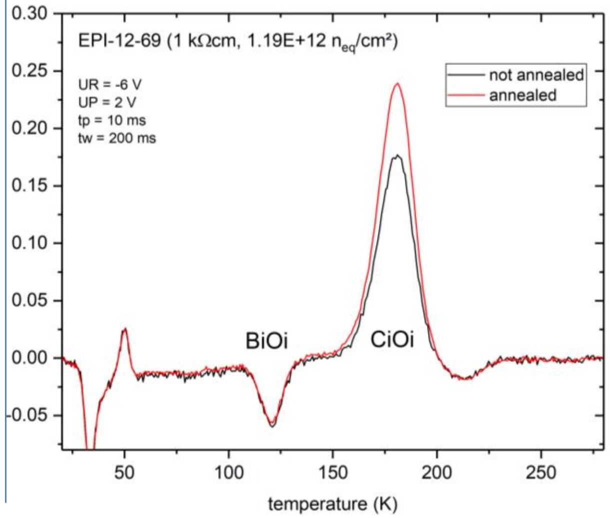


maj. & min. carrier injection:









- at least 8 defect levels detected (e.g. I2O, V2(+V3), Ci, CiOi, BiOi ...)

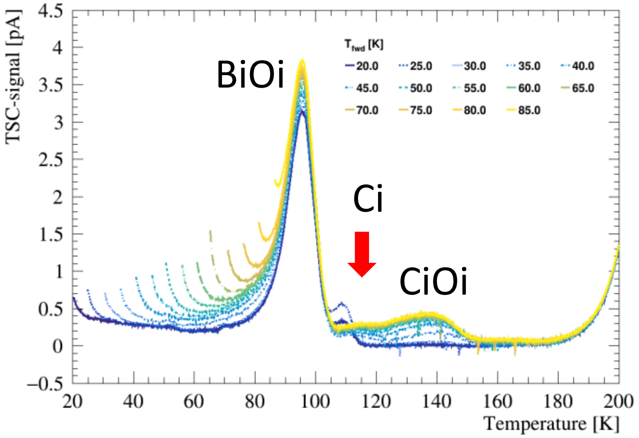
Comparable to 5.5. MeV sensors -> see:
Y. Gurimskaya et al. 35th RD50 Workshop 2019

TSC (before & after annealing 10 min @ 60°C)

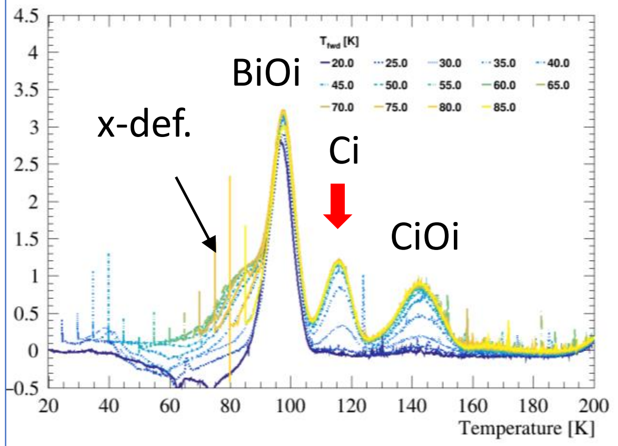
10 Ωcm | *50 Ωcm* | *250 Ωcm* | *1 kΩcm*

before annealing:

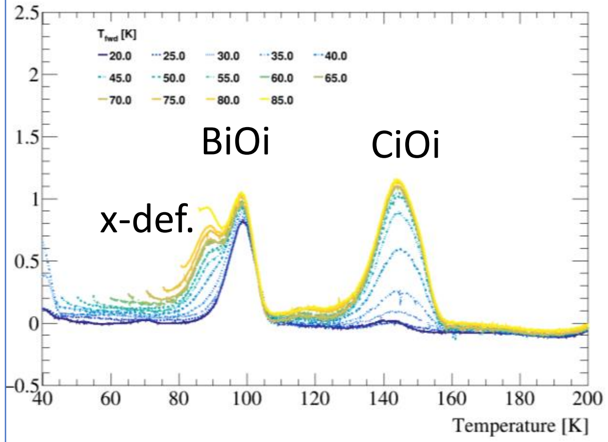
CIS16-EPI-02-50-DS-103_10Ohmcm: before annealing, Vbias: -75V



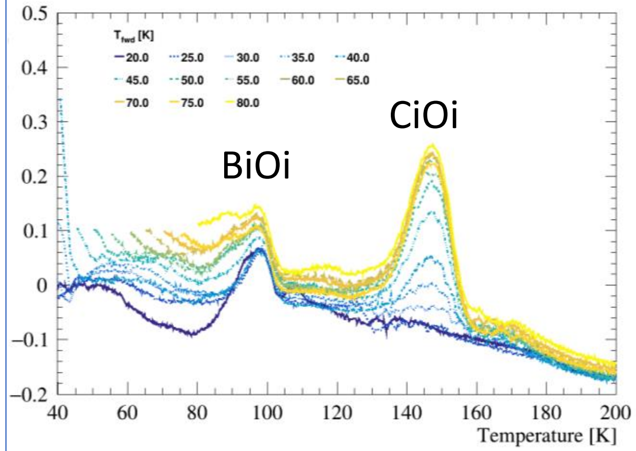
CIS16-EPI-06-50-DS-105_50Ohmcm: before annealing, Vbias: -100V



CIS16-EPI-08-50-DS-78_250Ohmcm: before annealing, Vbias: -100V

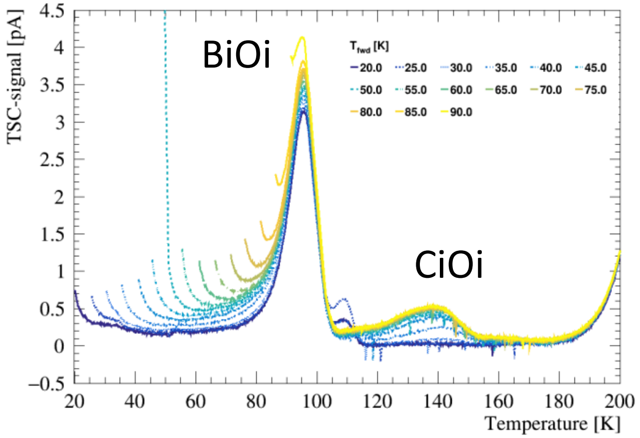


CIS16-EPI-12-50-DS-69_1kOhmcm: before annealing, Vbias: -100V

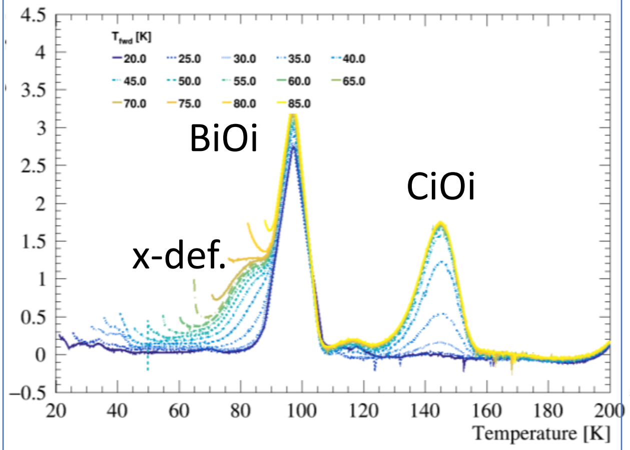


after annealing:

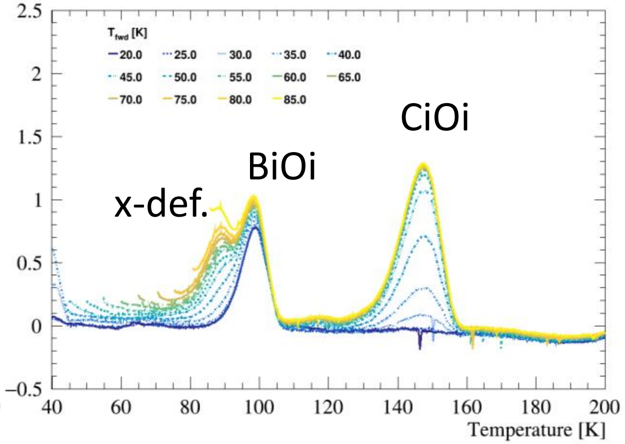
CIS16-EPI-02-50-DS-103_10Ohmcm: after annealing, Vbias: -75V



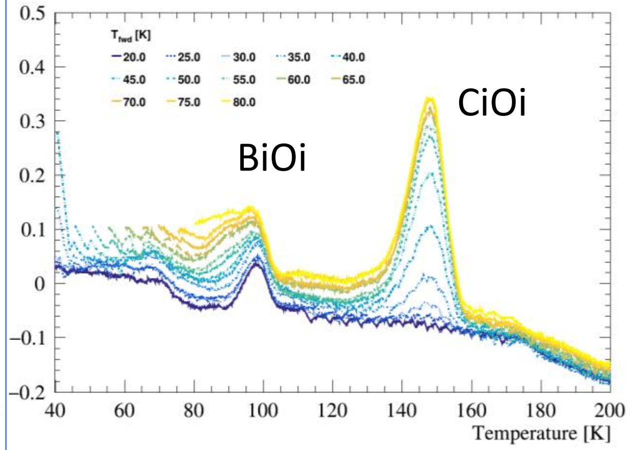
CIS16-EPI-06-50-DS-105_50Ohmcm: after annealing, Vbias: -100V



CIS16-EPI-08-50-DS-78_250Ohmcm: after annealing, Vbias: -100V



CIS16-EPI-12-50-DS-69_1kOhmcm: after annealing, Vbias: -100V



TSC spectra of 5.5 MeV electron irradiated samples – see: A. Himmerlich et al. 37th RD50 Workshop 2020

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TSC defect concentrations (200 MeV before & after annealing 10 min @ 60°C)

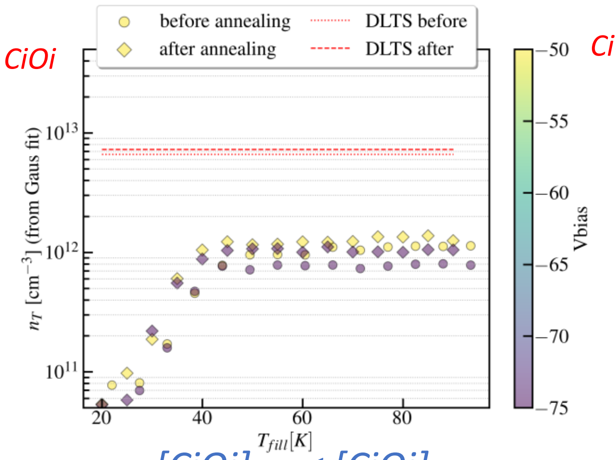
10 Ωcm

50 Ωcm

250 Ωcm

1 kΩcm

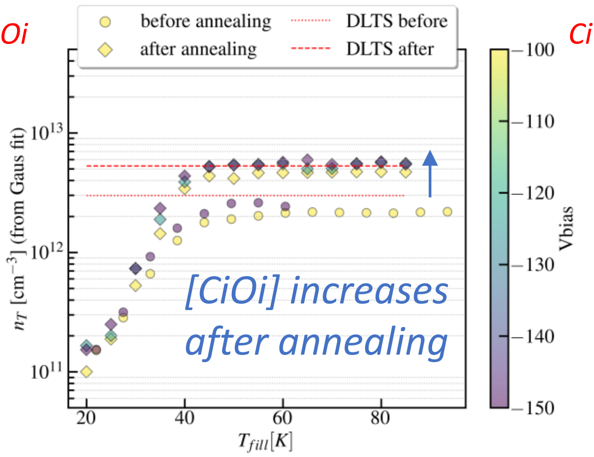
CiOi



$[CiOi]_{TSC} < [CiOi]_{DLTS}$

sensor not fully depleted!

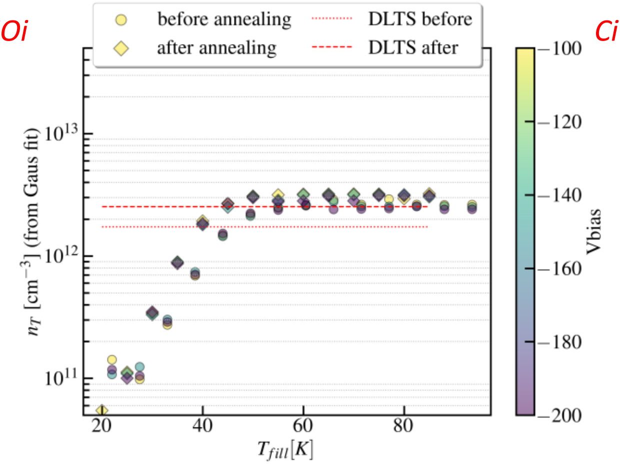
CiOi



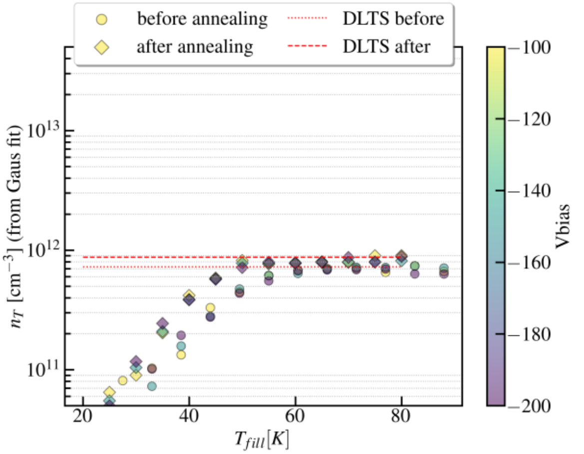
[CiOi] increases after annealing

$[CiOi]_{TSC} \approx [CiOi]_{DLTS}$

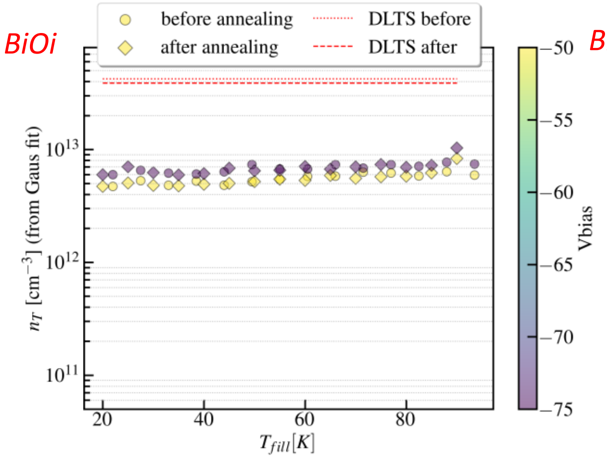
CiOi



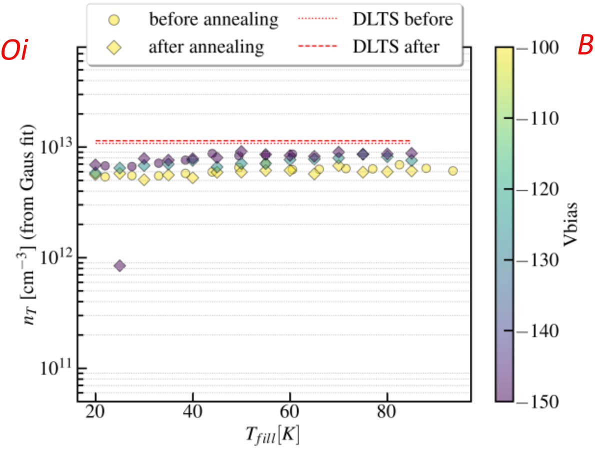
CiOi



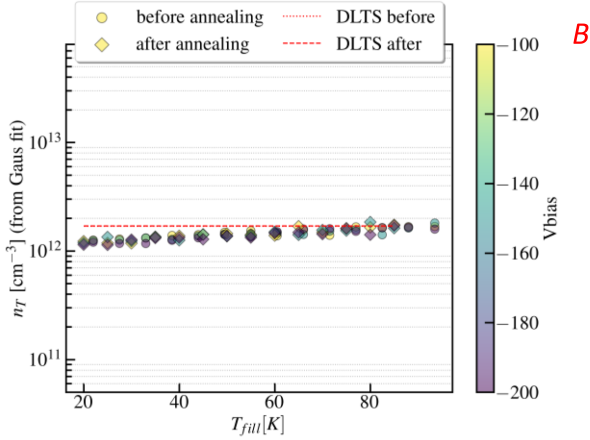
BiOi



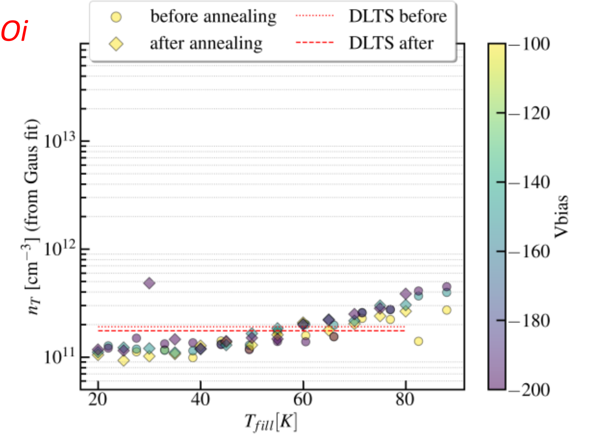
BiOi



BiOi



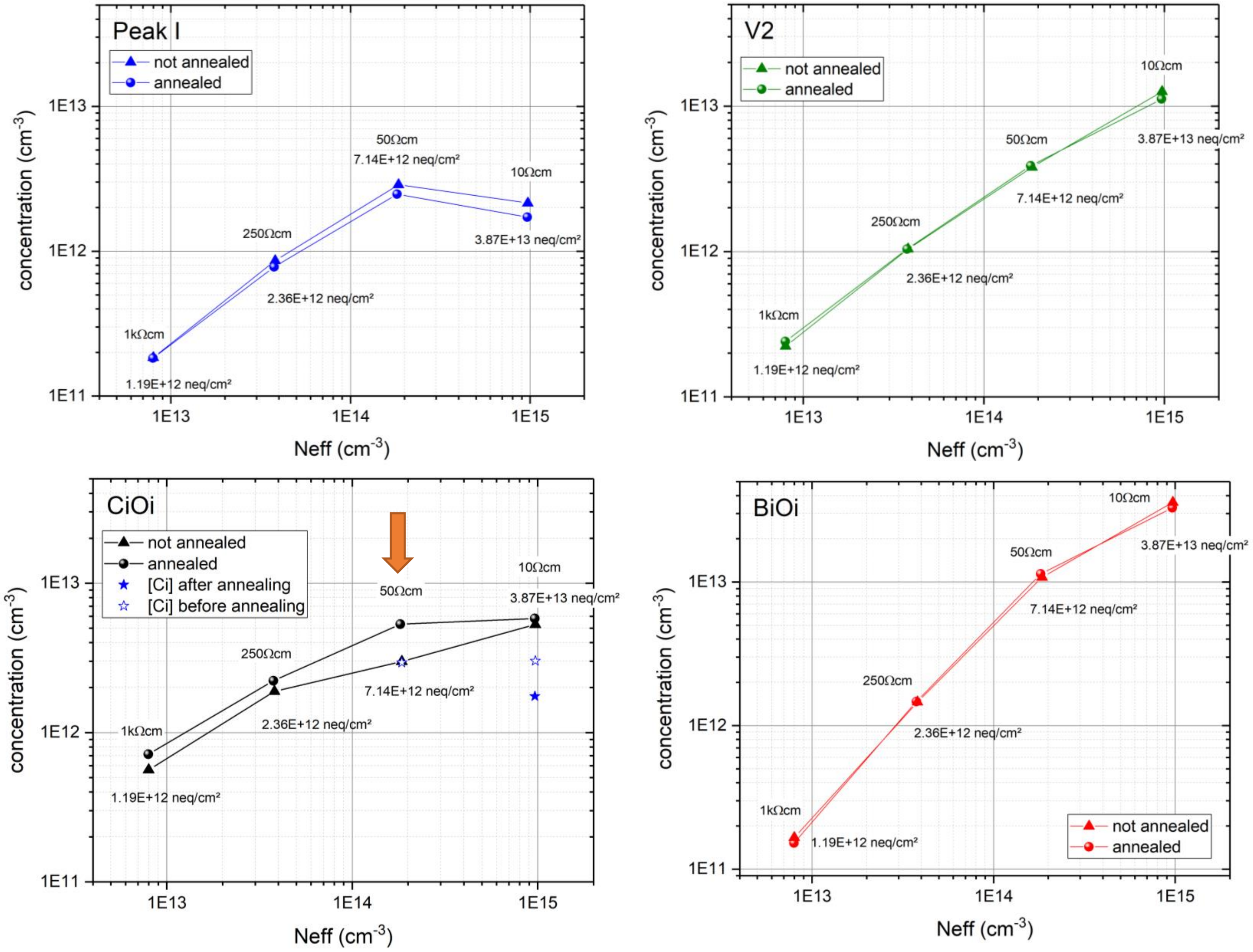
BiOi



$[BiOi]_{TSC} < [BiOi]_{DLTS}$

BiOi peak overlapps with X-defect!

Defect concentrations vs. Neff (200 MeV - before & after annealing 10 min @ 60°C)



- N_{eff} almost no change after annealing

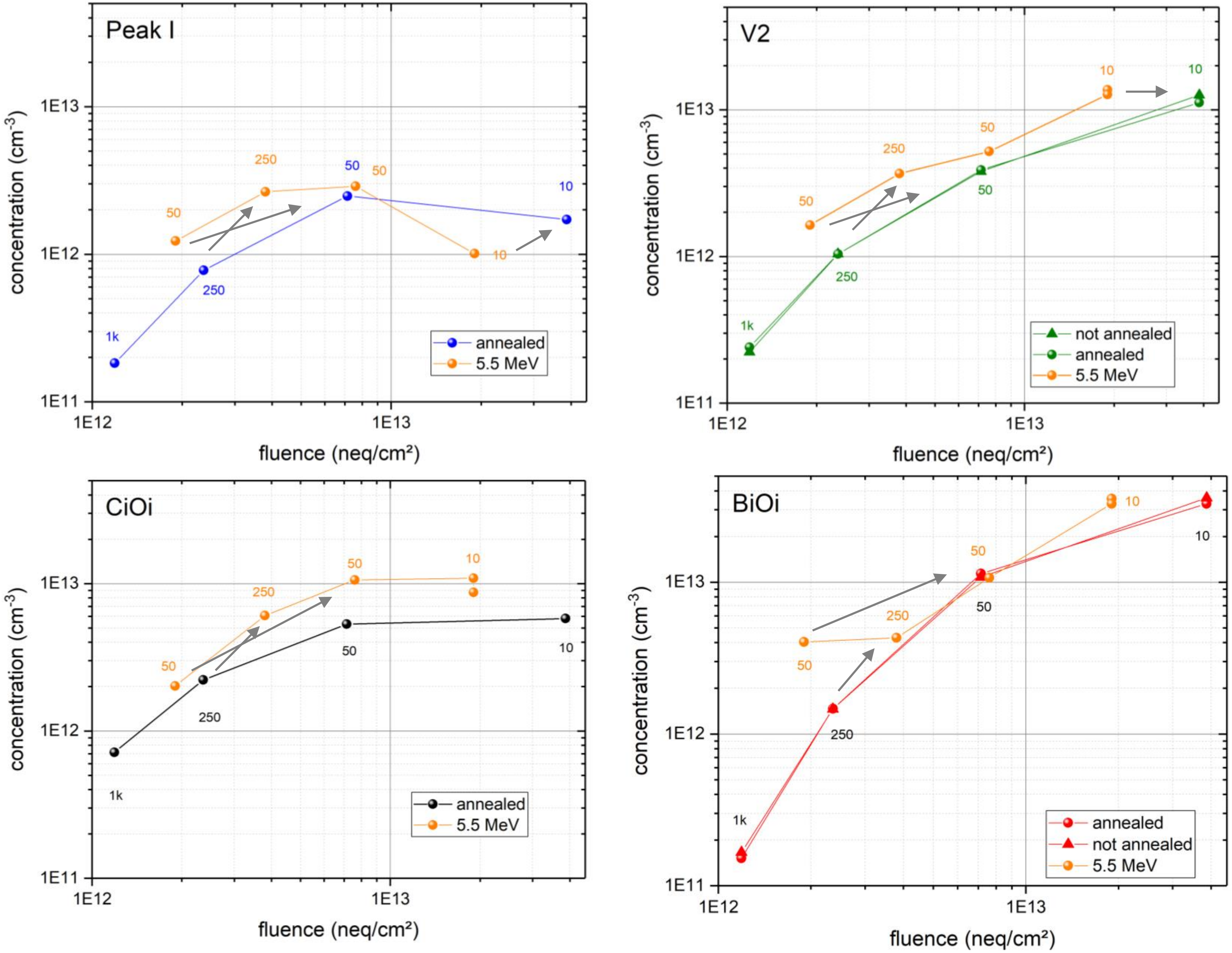
- CiOi defect concentration affected by annealing
(accompagnied with the decrease of Ci concentration)
Ci + Oi → CiOi

- „no“ effect on BiOi

- highest defect concentrations when N_{eff} highest
(but irradiation fluence also higher)

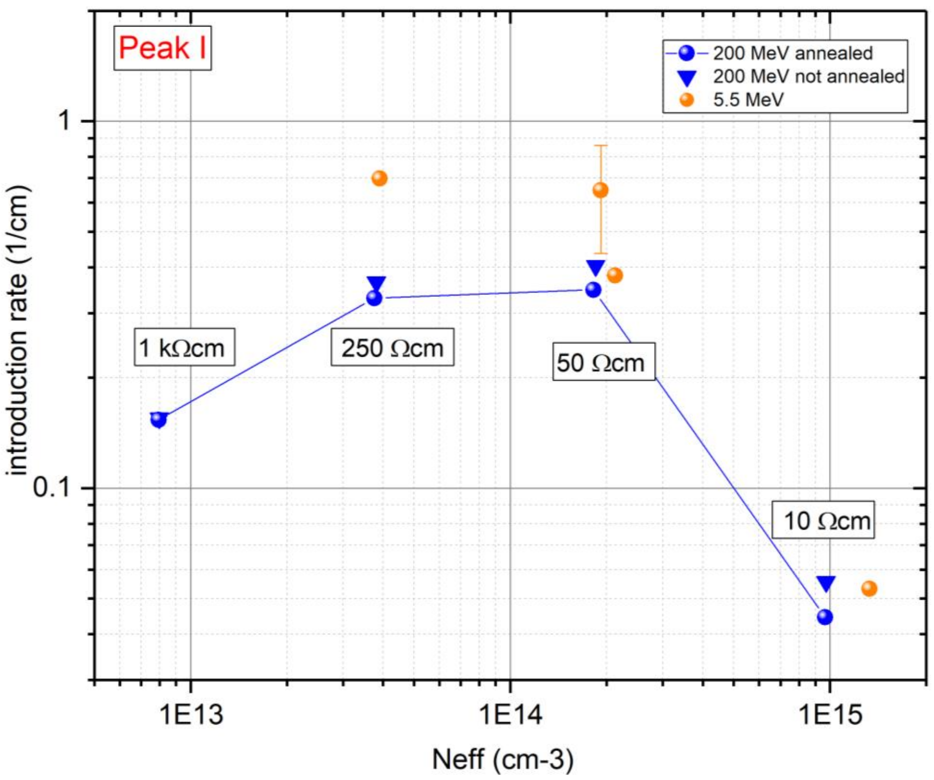
- Peak I concentration lowered for 10 Ωcm sensors

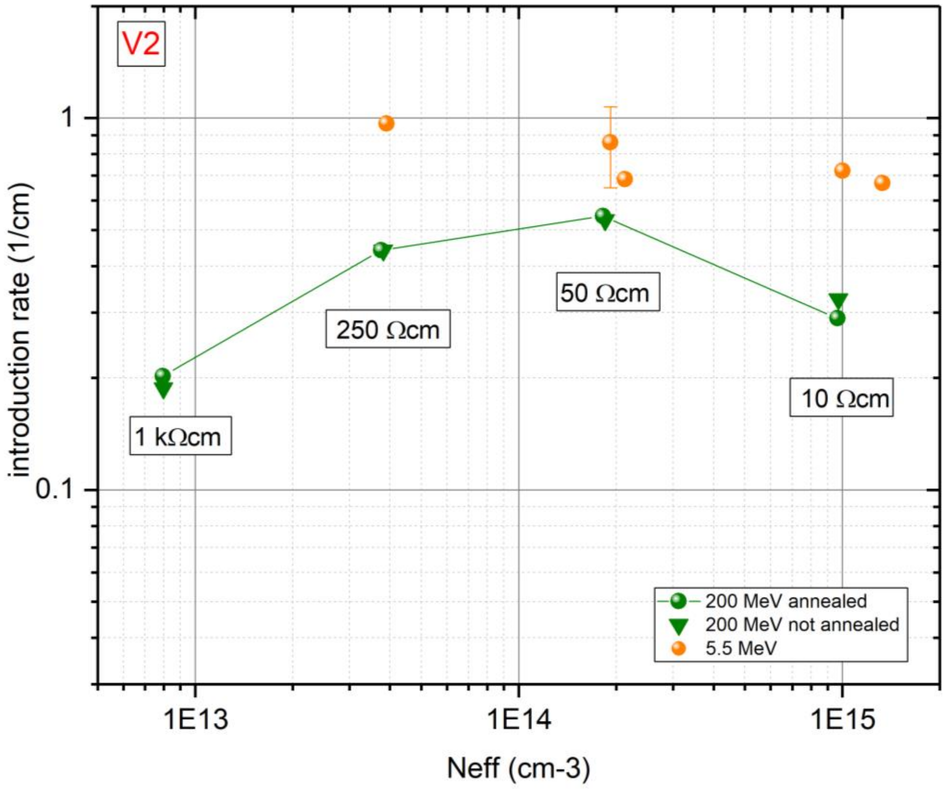
Defect concentrations vs. fluence (200 MeV & 5.5 MeV)



- defect concentrations increase with increasing fluence

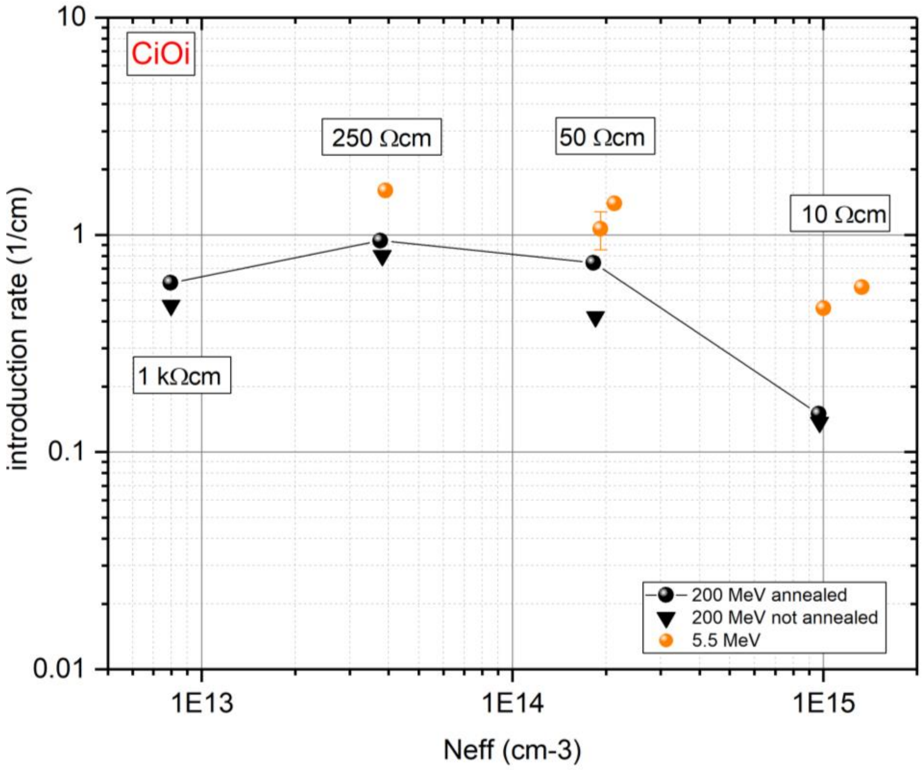
Introduction rates (200 MeV & 5.5 MeV)

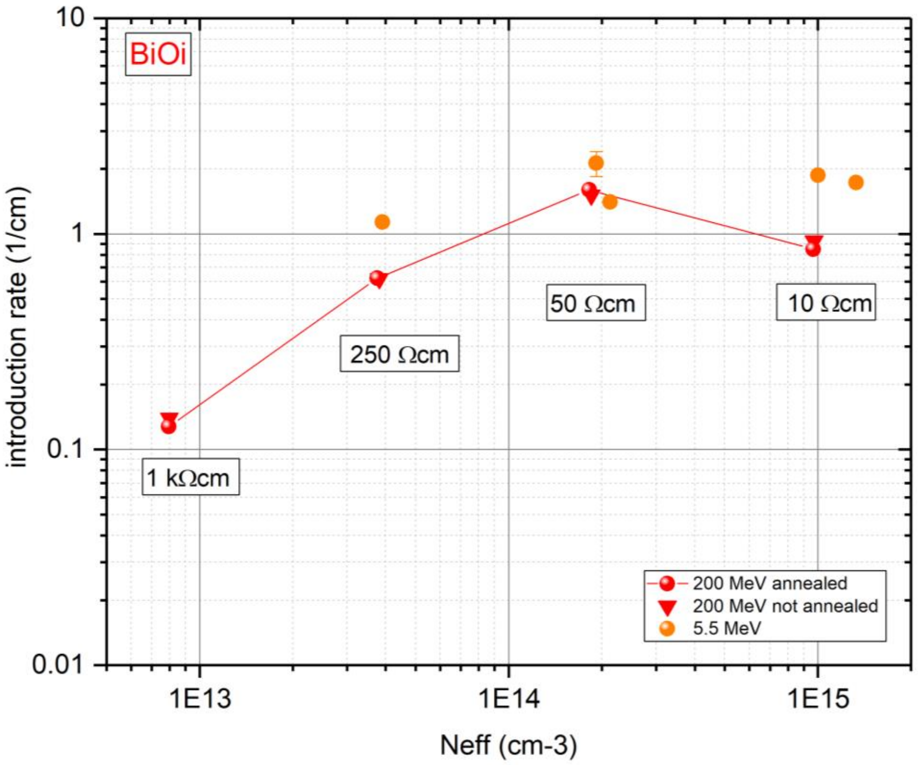




- Introduction rates of the defects decrease/saturate with Neff > 1E+14 cm-3
- strongest decrease for Peak I (I2O)

Inttroduction rates (200 MeV & 5.5 MeV)





- Introduction rates of the CiOi & BiOi decrease with Neff > 1E+14 cm-3

- 1kΩcm-sensor: CiOi introduction rate > BiOi introduction rate
- the higher the B-concentration, the higher the BiOi/CiOi ratio

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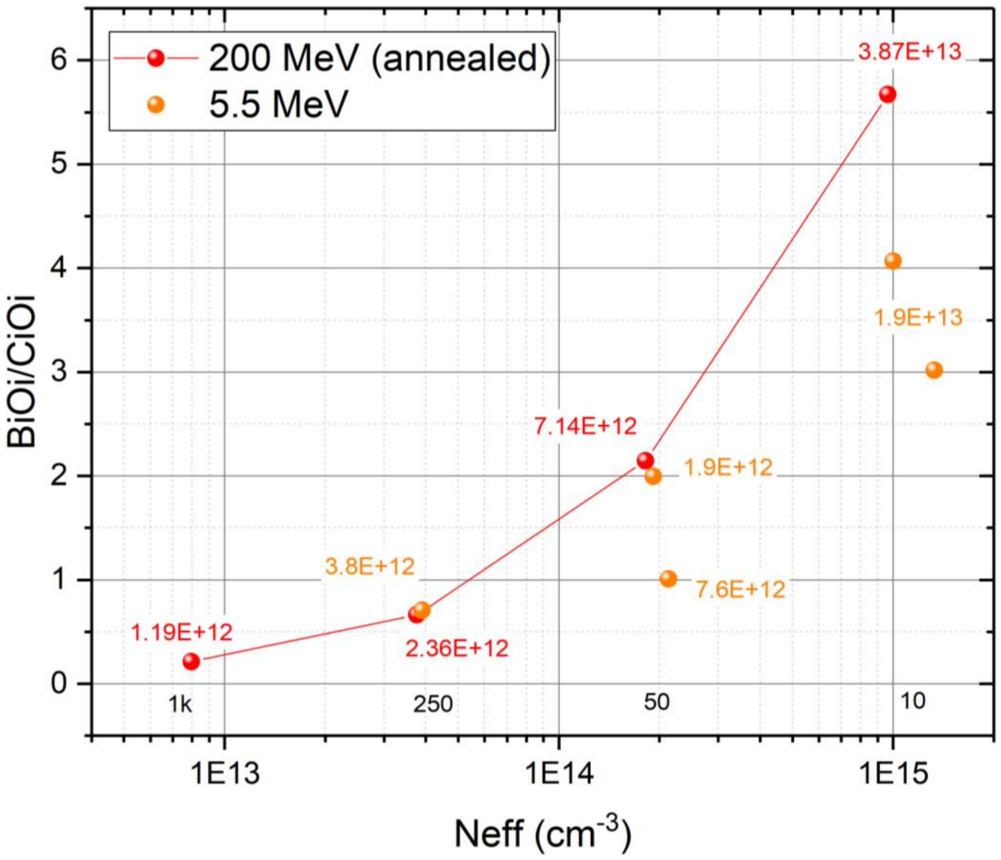
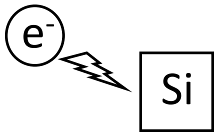
BiOi to CiOi ratio (200 MeV & 5.5 MeV)





$I + B_s \rightarrow B_i$

$I + C_s \rightarrow C_i$

$B_i + O_i \rightarrow B_iO_i$

$C_i + O_i \rightarrow C_iO_i$

⇩

more B –> more Bi: less C_i that can create the C_iO_i defect

BiOi introduction rate higher

- 5.5 MeV BiOi/CiOi ratio is lower -> less BiOi formation at lower electron irradiation energy
- the higher the B-concentration, the higher the BiOi/CiOi ratio → less CiOi produced

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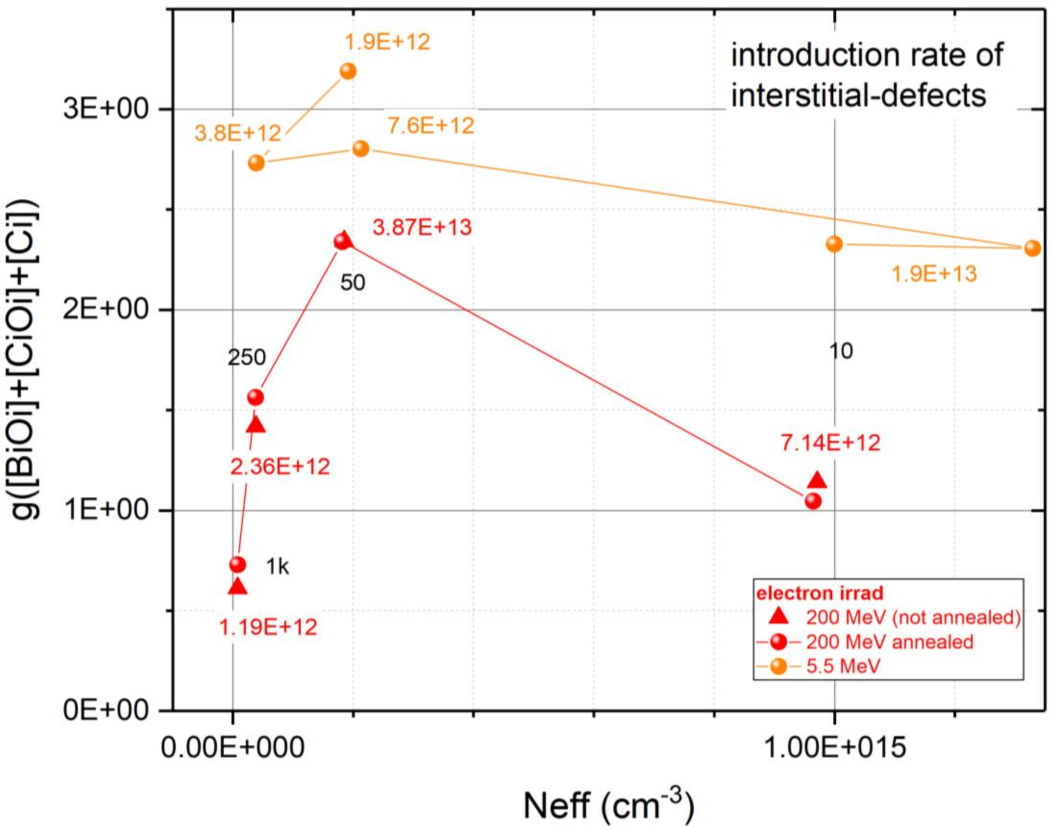
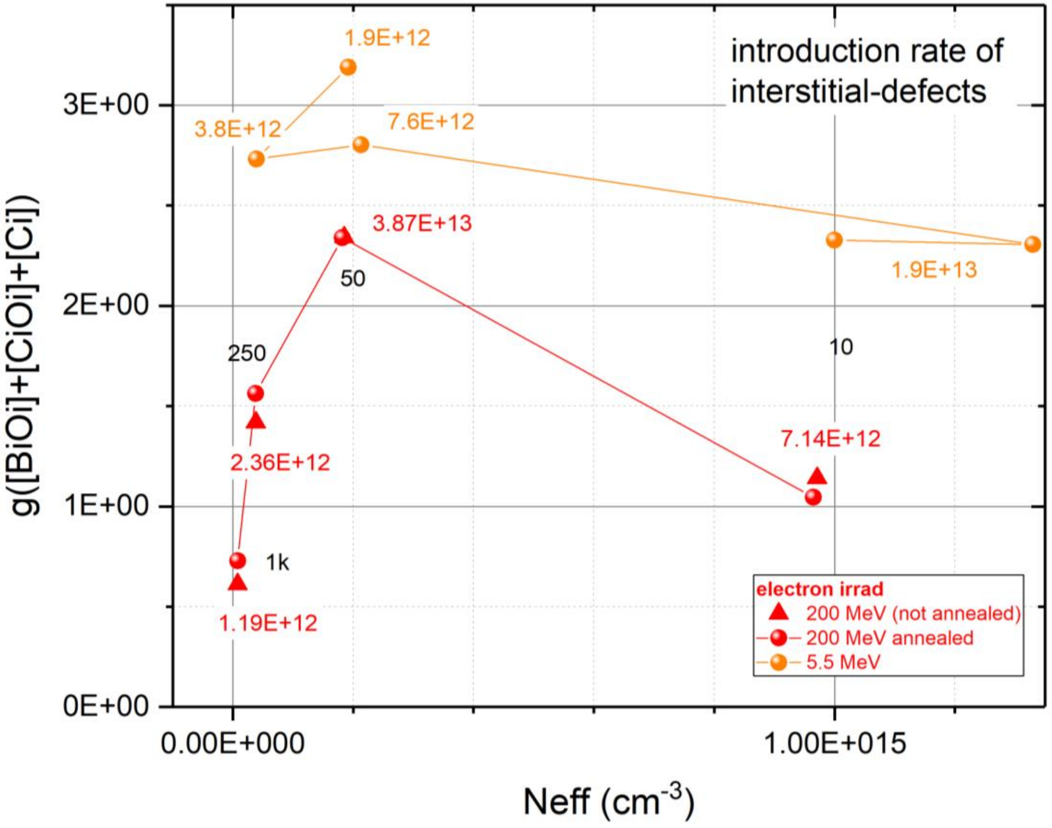
Introduction rate: Interstitial related defects (200 MeV & 5.5 MeV)



- high B-doped samples:

⟹ formation of interstital related defects (BiOi + CiOi + Ci) reduced

Introduction rate: Interstitial related defects (200 MeV & 5.5 MeV)



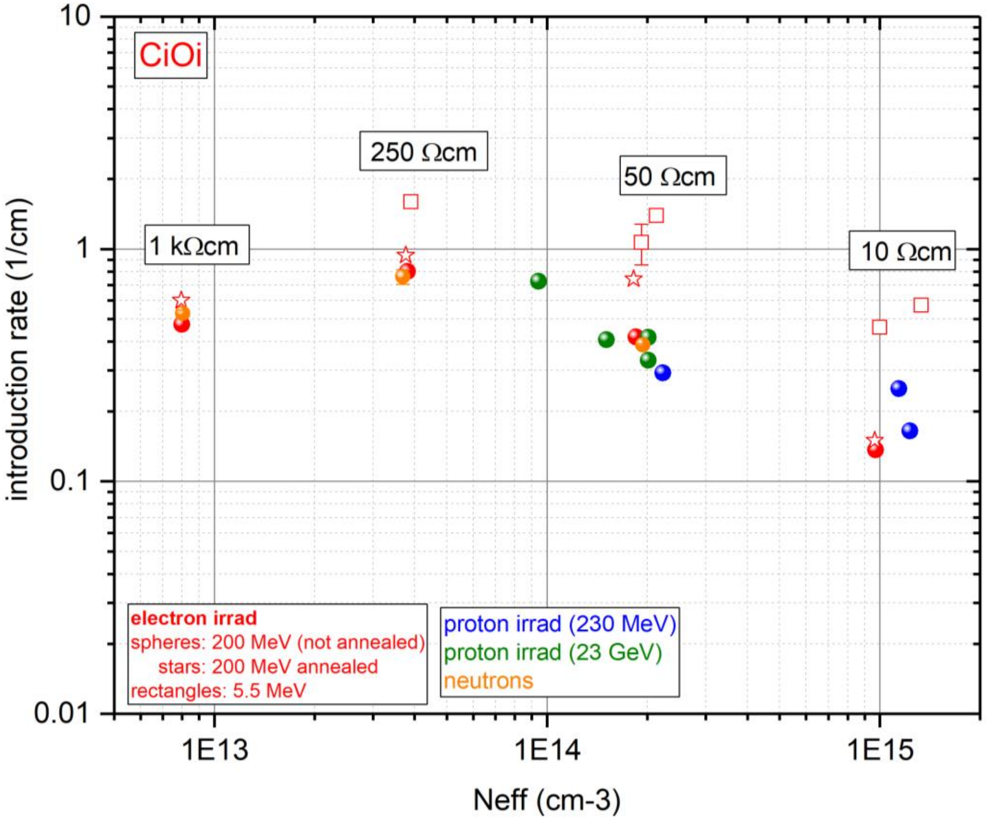
- high B-doped samples:

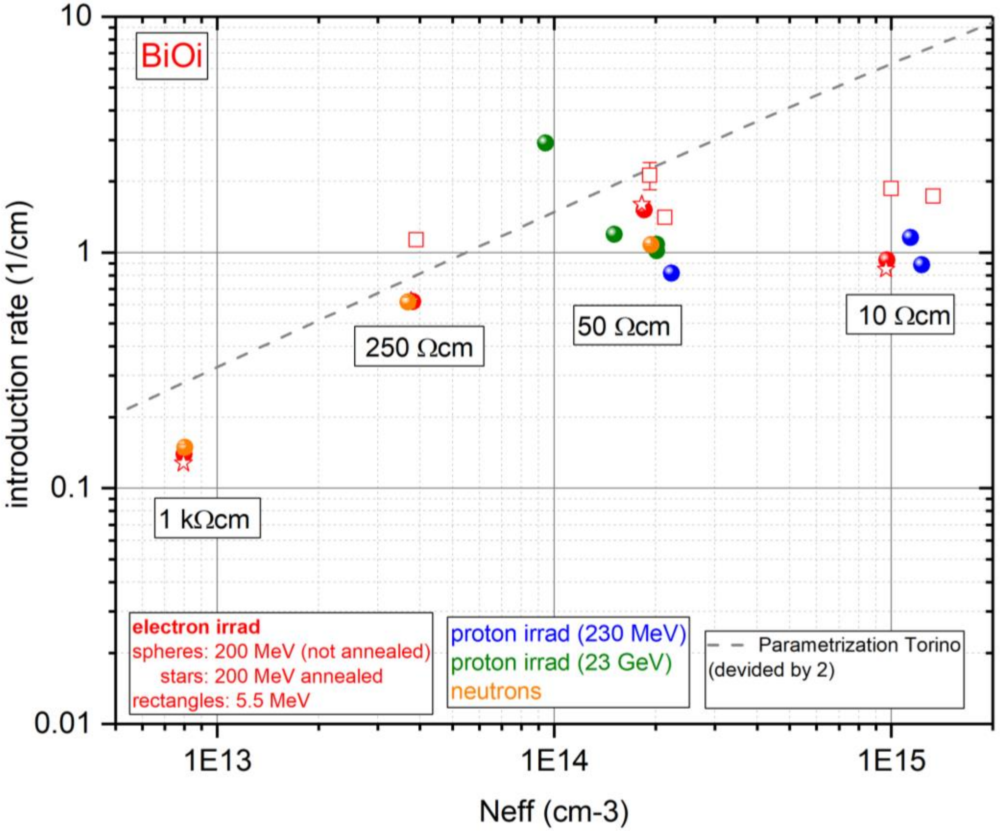
⟹ formation of interstital related defects
(BiOi + CiOi + Ci) reduced

additional defect reactions of Bi:
⟹ BiBs
⟹ boron-carbon or
boron-hydrogen
related defects
(probably electrical inactive)

Vienes et al. PRB 78, 085205 (2008): numerical simulation of the generation rates as function of B-concentration -> at high [B]: formation of BiBs dominates -> BiOi concentration reduced

Introduction rates (from DLTS) for electron, proton & neutron irradiated sensors





- Introduction rates of the defects decrease/ saturate with Neff > 1E+14 cm-3

Summary & Outlook

- Investigation p-type Si diodes with different resistivity (10, 50, 250 & 1000 Ω cm) irradiated with 5.5 MeV and 200 MeV electrons (fluence: 4.1E+11 – 3.8E+13 n_{eq}/cm^2)

- Characterisation of the defect levels using DLTS & TSC:
  - ⟹ up to 8 defect levels detected with DLTS
  - ⟹ most dominant: Peak I (I2O), V2(+V3), Ci, CiOi, BiOi
  - ⟹ TSC & DLTS defect concentrations comparable if sensors can be fully depleted
  - ⟹ for sensors ≥ 50 Ωcm: X-defect peak overlapps with BiOi peak in TSC

- defect concentrations & introduction rates:
  - ⟹ defect concentrations increase with increasing fluence
  - ⟹ Introduction rates of the defects decrease/saturate for highly B-doped Si (Neff > 1E+14 cm-3) *(formation of electrical inactive or not detectable B-related defect clusters)*
  - ⟹ in highly B-doped sensors the introduction rate of CiOi is smaller than the introduction rate for BiOi *(Bi formation dominated over Ci formation)*

See the next talk from Yana Gurimskaya

… ongoing investigations to identify defects:
*annealing studies, optical filling, additional defect characterization methodes, like **I-DLTS** …)*

Thank you for your attention!