Defect investigation of electron irradiated p-type Si sensors

EP-DT-DD
Detector Technologies
Detector Development

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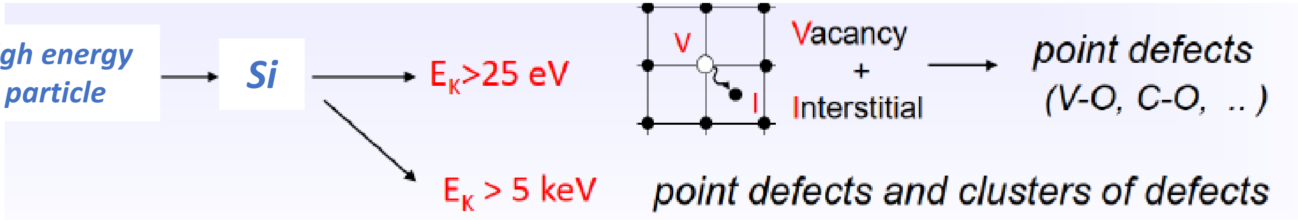
Motivation



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

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

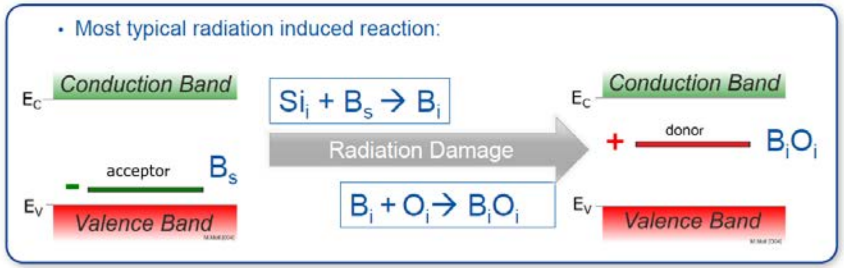
Defect Characterization:

- 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

$B_i + O_i \rightarrow B_iO_i$

Sensors: *Standard EPI diodes (50 µm thickness)*

Resistivity: ***10, 50, 250, 1000 Ωcm***

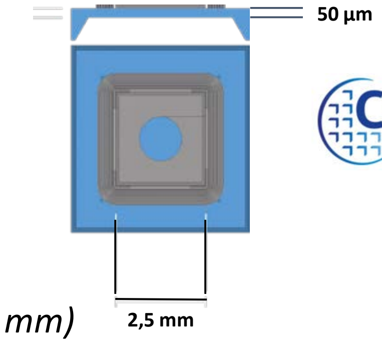
p-type Si pad diodes produced by CiS (Erfurt, Germany):

area = (2.632 x 2.632) mm² = 6.927E-2 cm²

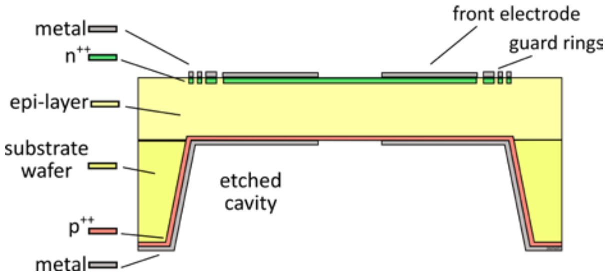
guard rings

on back and front side openings for light injection

area (hole / optical injection) = 1.13E-2 cm² (r ~ 0.6 mm)



CiS Forschungsinstitut für Mikrosensorik GmbH



Outline

- Electron irradiation
  - 200 MeV electrons @ clear
  - 5.5 MeV electrons @ Belarusian State University, Minsk

- Changes of Macroscopic sensor properties (Neff):
  - C(V) measurements

- DLTS (Deep Level Transient Spectroscopy) & TSC (Thermally Stimulated current) measurements @ CERN

  → Experimental Details
  → Defect characterization: Results

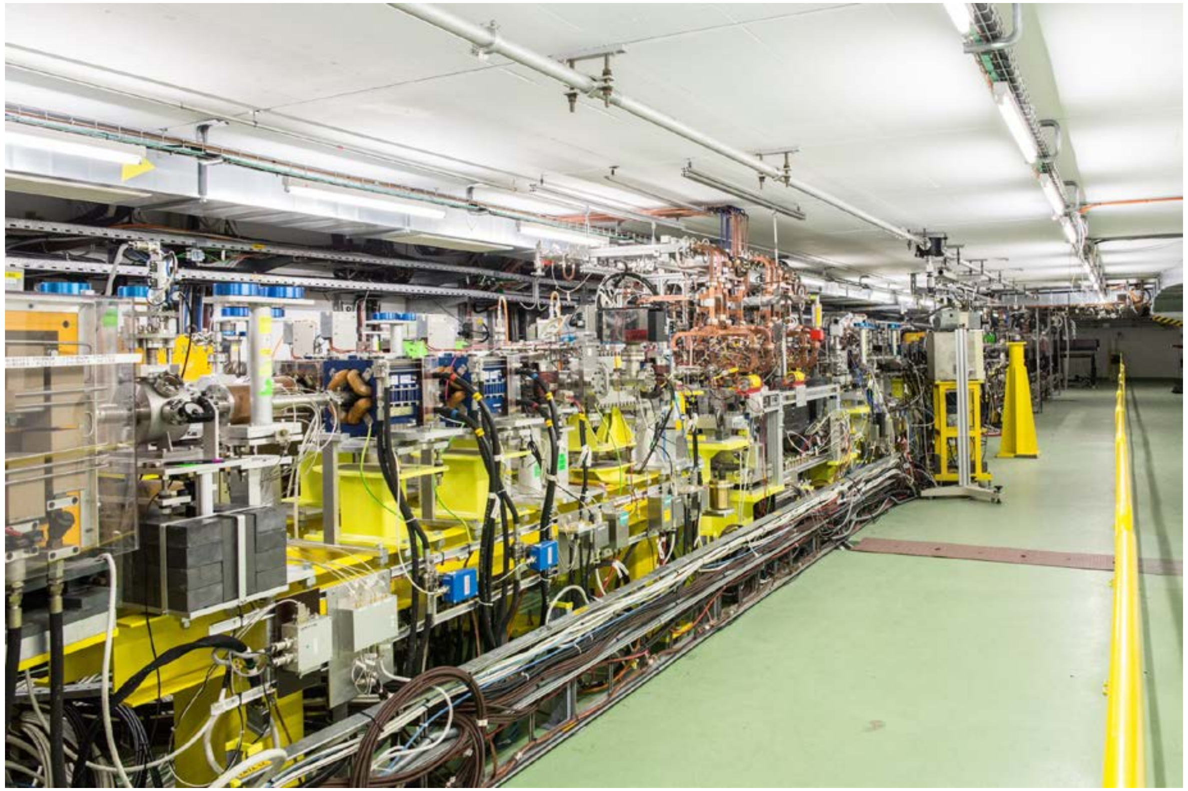
- Summary & Outlook

clear

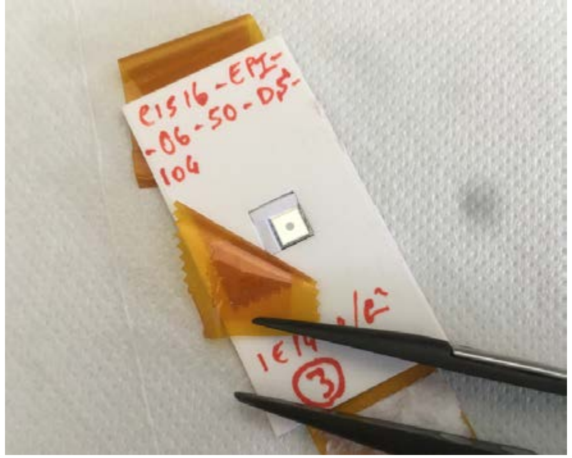
experimental linear electron accelerator at CERN

Thanks to…

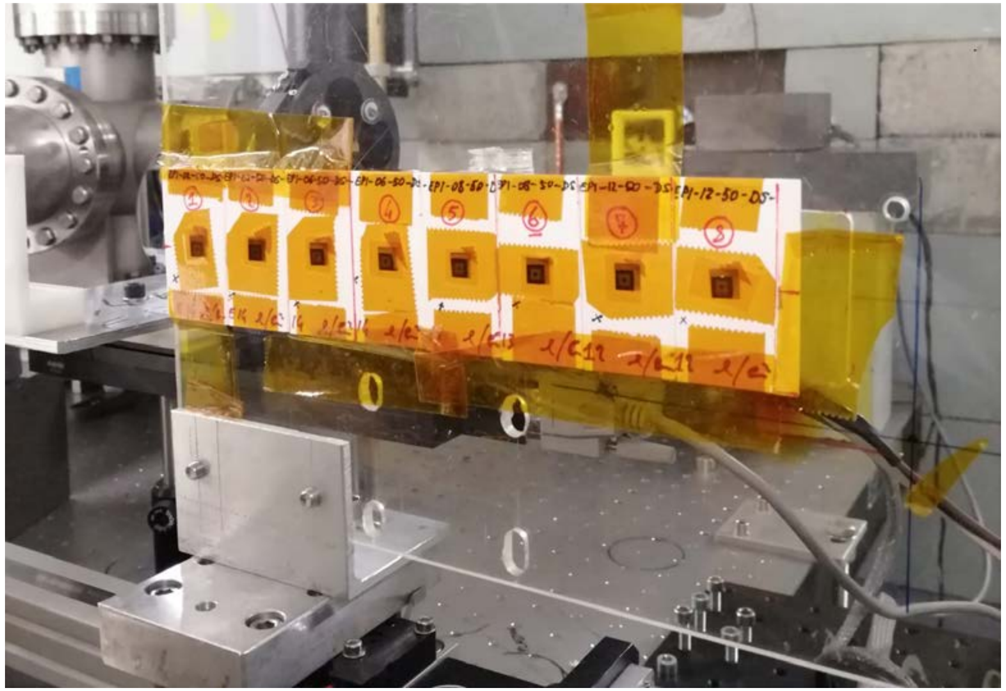
Giuseppe Pezzullo, Davide Gamba,
Antonio Gilardi, Luke Dyks & Federico Ravotti

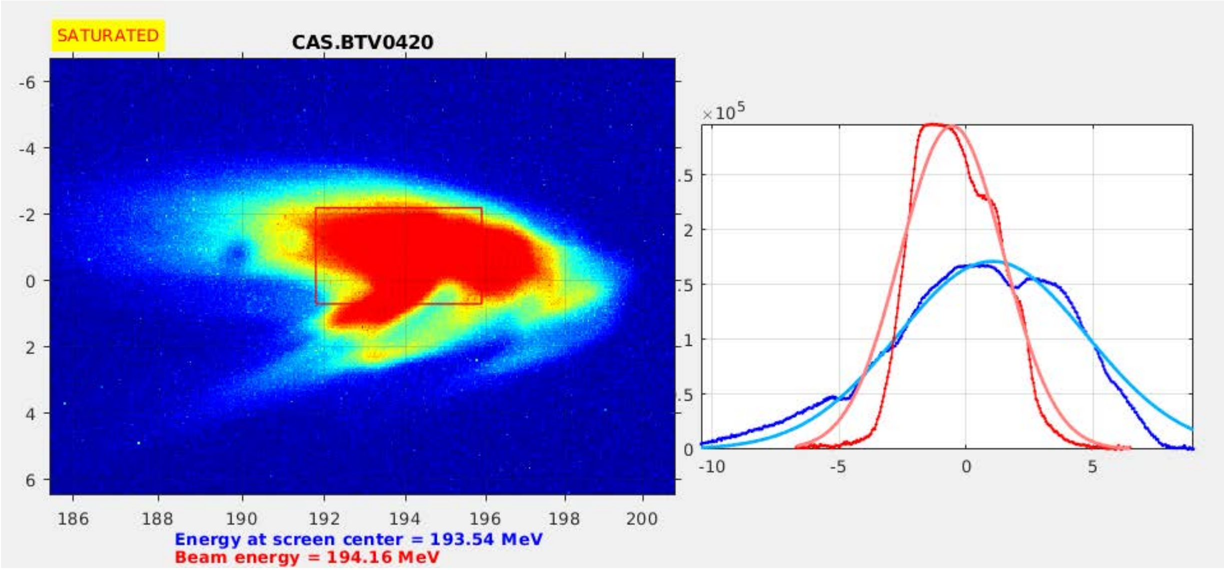


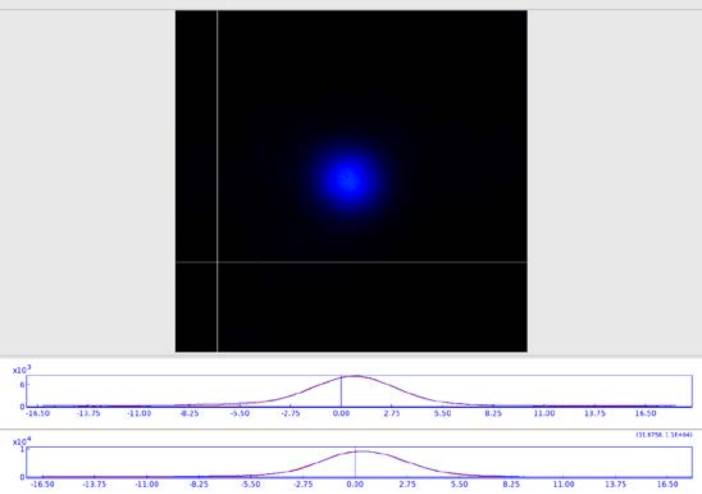
- upgrade of the facility in 2017
- energy range **60 MeV to 200 MeV**
- http://vesper.web.cern.ch/

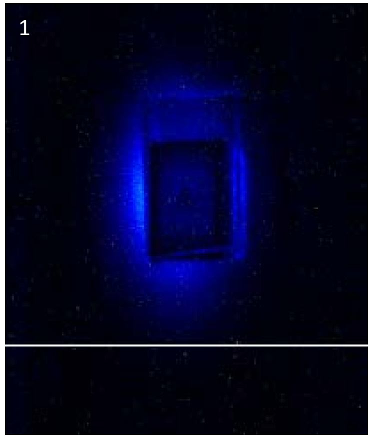


200 MeV electron irradiation @ CLEAR









- Irradiation at RT
- Electron beam energy (194 ± 2) MeV
- Beam spot size ≈ 5 mm diameter

200 MeV electron irradiation @ CLEAR

200 MeV electron irradiation @ clear

	sample	Resistivity (Ω cm)	Neff (cm^{-3})* (nonirradiated)	Vdepl (V)* (nonirradiated)	Fluence (e/cm^2)	Fluence (n_{eq}/cm^2)	Neff (cm^{-3})* (irradiated)
1	CIS16-EPI-02-50-DS-78	**10**	1.2E+15		2.5E+14	**2.1E+13**	1.07E+15
2	CIS16-EPI-02-50-DS-103	**10**	1.2E+15		2.5E+14	**2.1E+13**	1.07E+15
3	CIS16-EPI-06-50-DS-104	**50**	2.2E+14		1E+14	**8.2E+12**	1.82E+14
4	**CIS16-EPI-06-50-DS-105**	**50**	2.3E+14		1E+14	**8.2E+12**	1.98E+14
5	CIS16-EPI-08-50-DS-65	**250**	4.3E+13	-80.6 V	2E+13	**1.6E+12**	3.88E+13
6	CIS16-EPI-08-50-DS-78	**250**	4.2E+13	-80.6 V	2E+13	**1.6E+12**	3.88E+13
7	CIS16-EPI-12-50-DS-69	**1000**	7.3E+12	-14.5 V	5E+12	**4.1E+11**	7.08E+12
8	CIS16-EPI-12-50-DS-70	**1000**	7.2E+12	-14.5 V	5E+12	**4.1E+11**	7.07E+12

* from cv measurements

Hardness factor
(200 MeV) $\kappa = 0.082$

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

5.5 MeV electron irradiation @ Minsk

5.5 MeV electron irradiation @ Minsk

BELARUSIAN STATE UNIVERSITY

	sample	Resistivity (Ω cm)	Neff (cm^{-3})* (nonirrad)	Fluence (e/cm²)	Fluence (n_{eq}/cm²)	Neff (cm^{-3})* (irrad)
	CIS16-EPI-06-50-DS-103	**50**	2.18E+14	1.00E+15	3.80E+13	4.90E+13
	CIS16-EPI-02-50-DS-100	**10**	1.22E+15	5.00E+14	1.90E+13	1.08E+15
	CIS16-EPI-02-50-DS-105	**10**	1.31E+15	5.00E+14	1.90E+13	1.18E+15
	CIS16-EPI-06-50-DS-88	**50**	2.22E+14	2.00E+14	7.60E+12	1.93E+14

* from cv measurements

Hardness factor
(5.5 MeV) κ = 0.038

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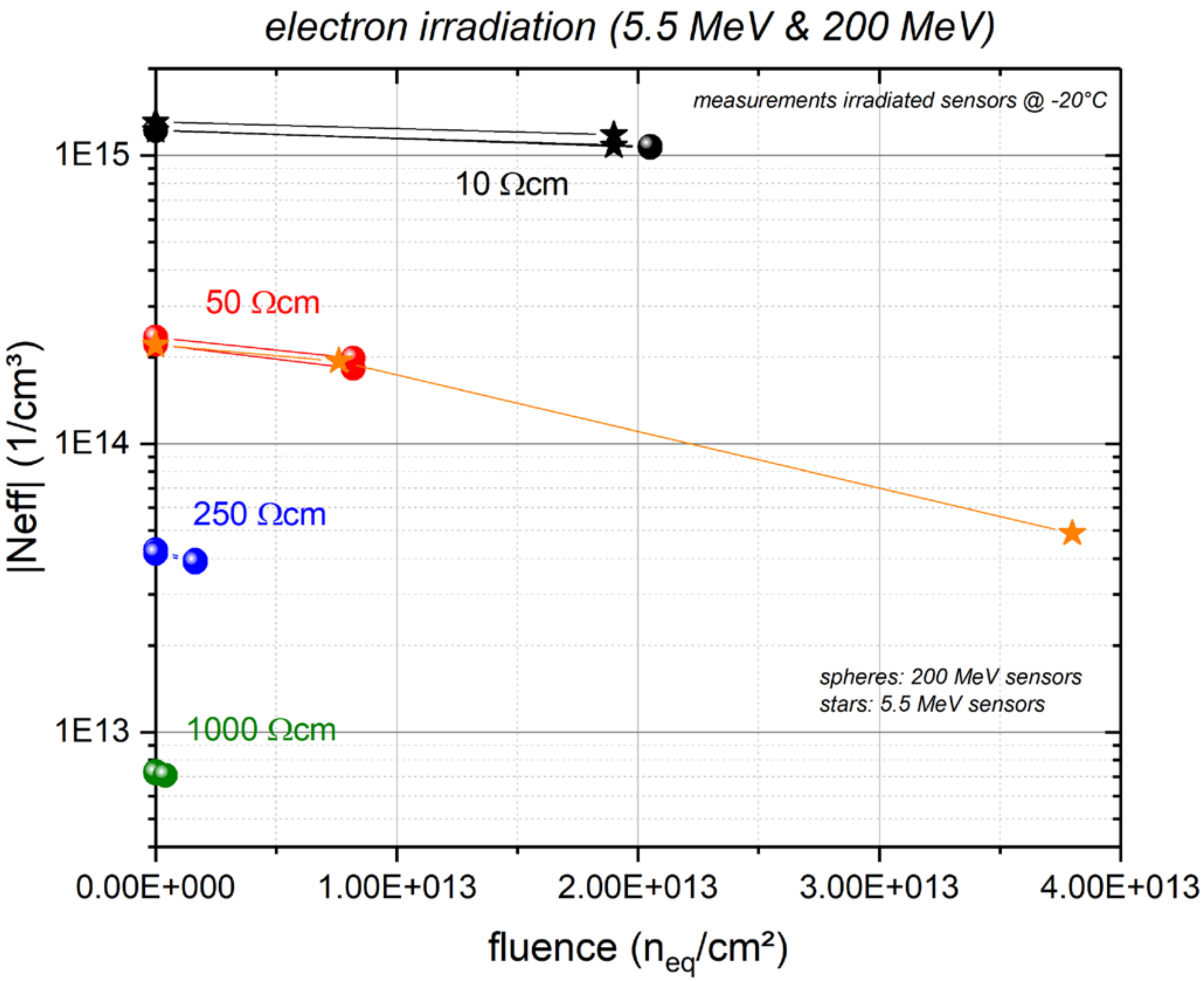
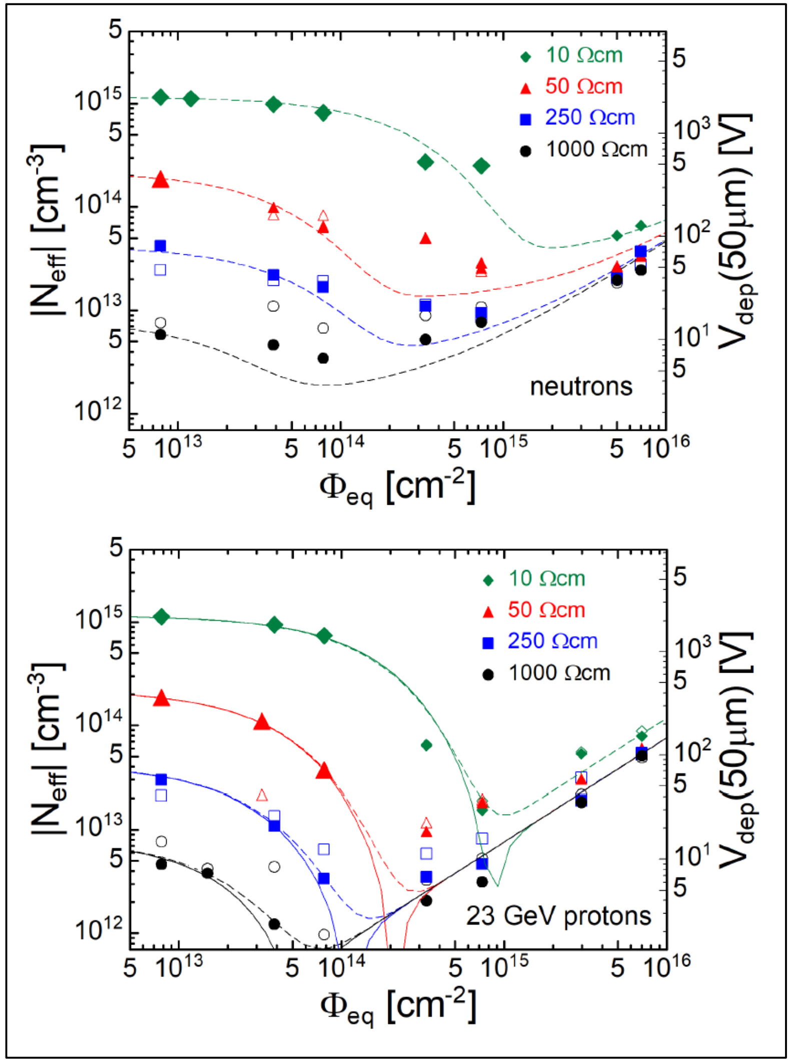
Neff vs. fluence





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

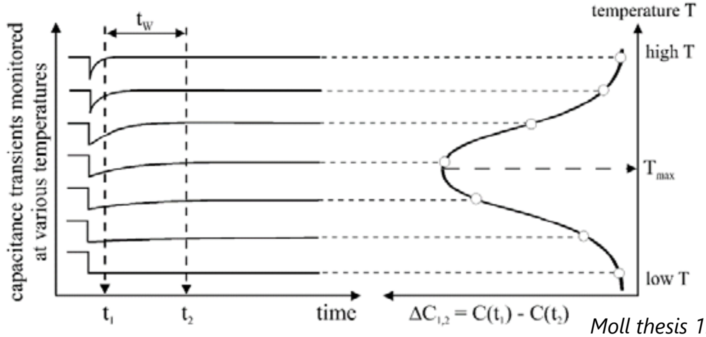
P. Almeida et al. 31th RD50 Workshop 2017

decrease in N_{eff} - biggest change for highest fluence

DLTS and TSC measurements (fundamentals)

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



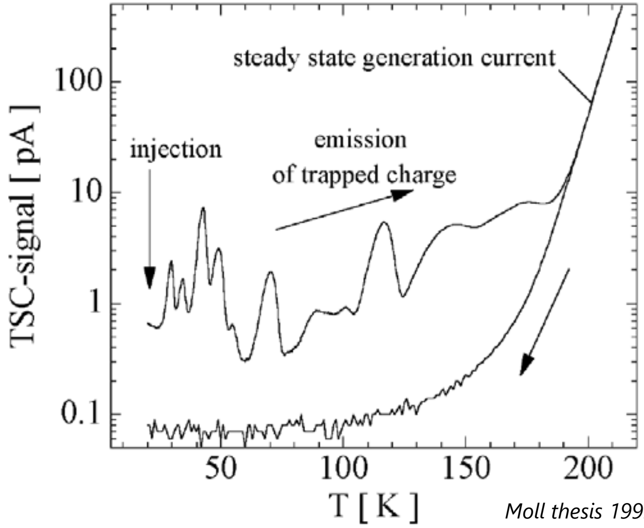
Moll thesis 1999

Defect parameters:
activation energy
capture cross section
defect concentrations

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

TSC: Thermally Stimulated Current

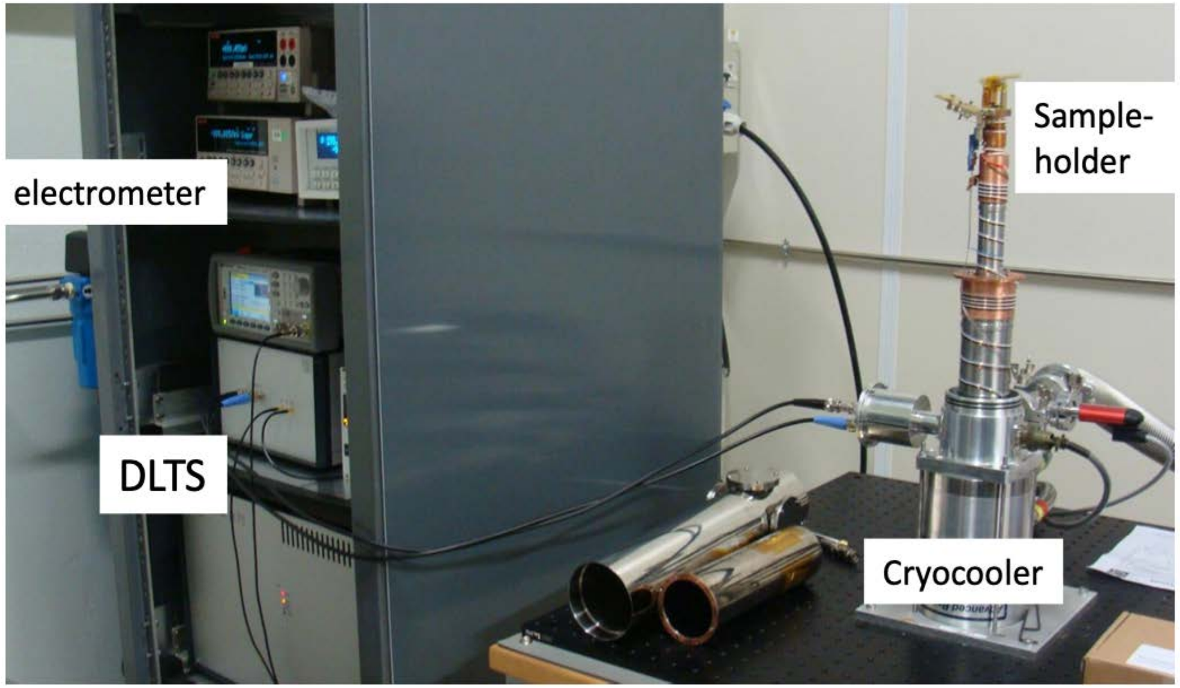
(1) Junction under reverse bias during cooling down of the sample to T_{Fill}
→ defect states unoccupied
(2) Injection pulse (electrical or optical) → injection of minority and/or majority carriers
→ occupation of defect levels
(3) Junction under reverse bias & Temperature raised
→ monitoring the discharging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

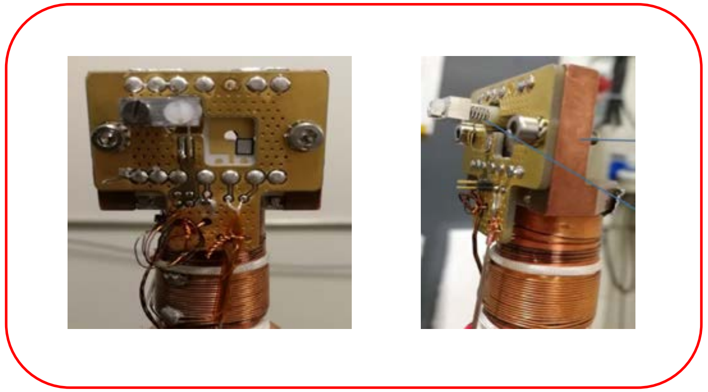


Moll thesis 1999

DLTS and TSC measurements @ CERN (set-up)

- Closed cycle liquid Helium Cryocooler with cold head down to 8K
- Vacuum ~10^{-6} mbar
- Heating coil with temperature regulation for controlled warm-up
- TSC ⟹ electrometer + Custom LabView DAQ
- DLTS ⟹ PhysTech commercial system (hardware, DAQ, analysis software)





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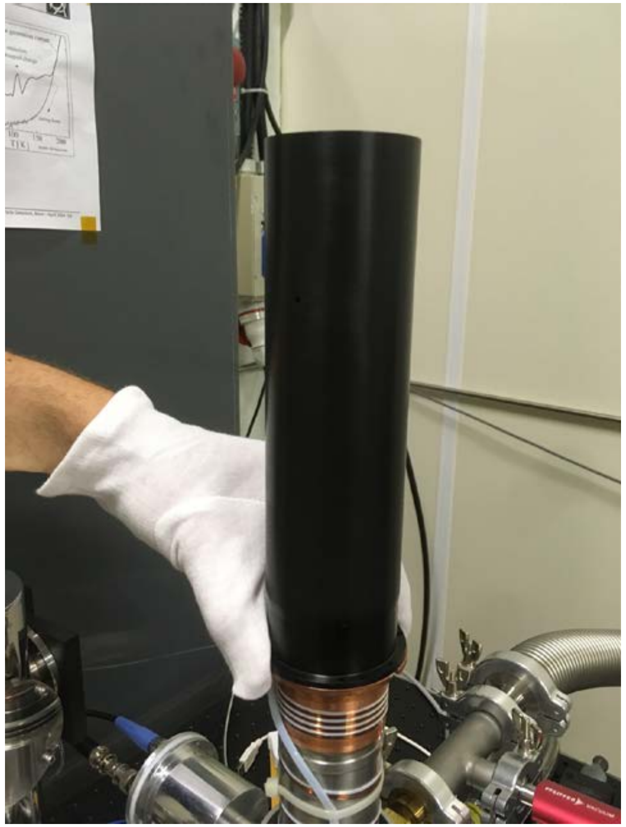
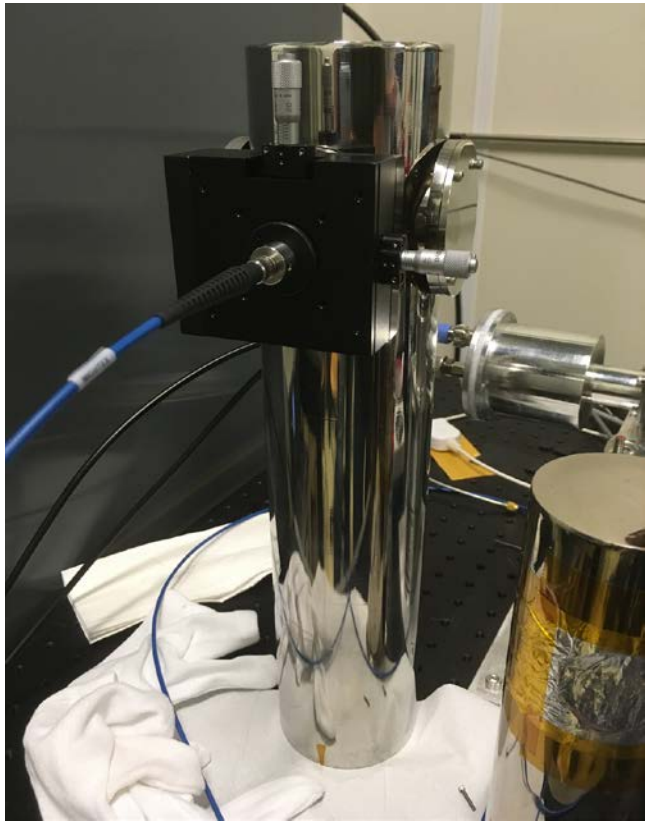
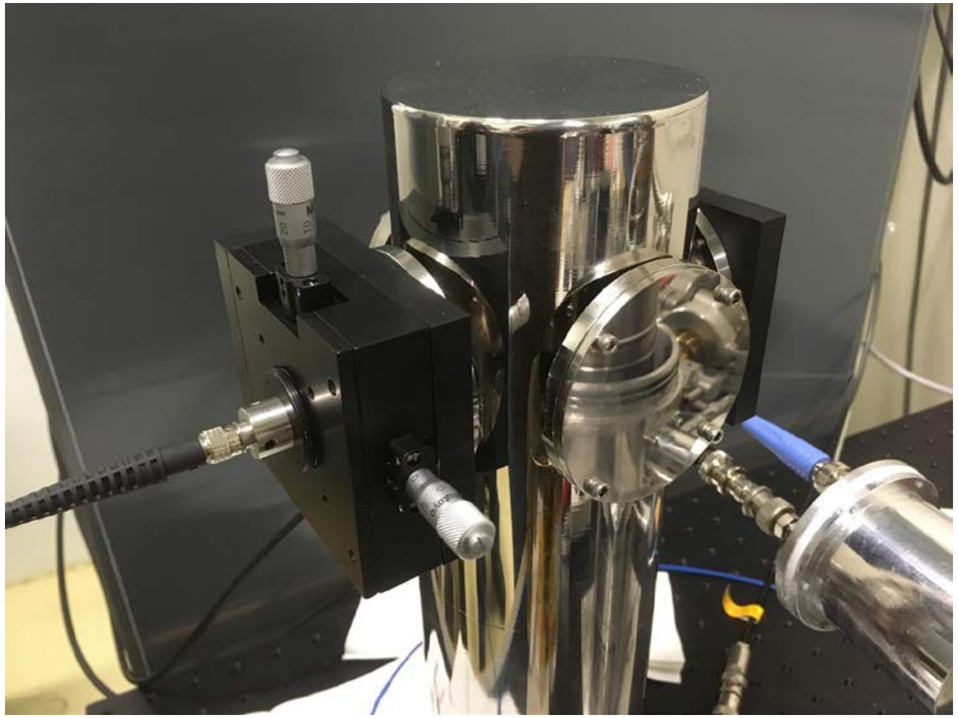
electrical filling pulse
or ***light injection (front & back)***
940 nm (1.32 eV)
740 nm (1.68 eV)
625 nm (1.98 eV)
530 nm (2.34 eV)

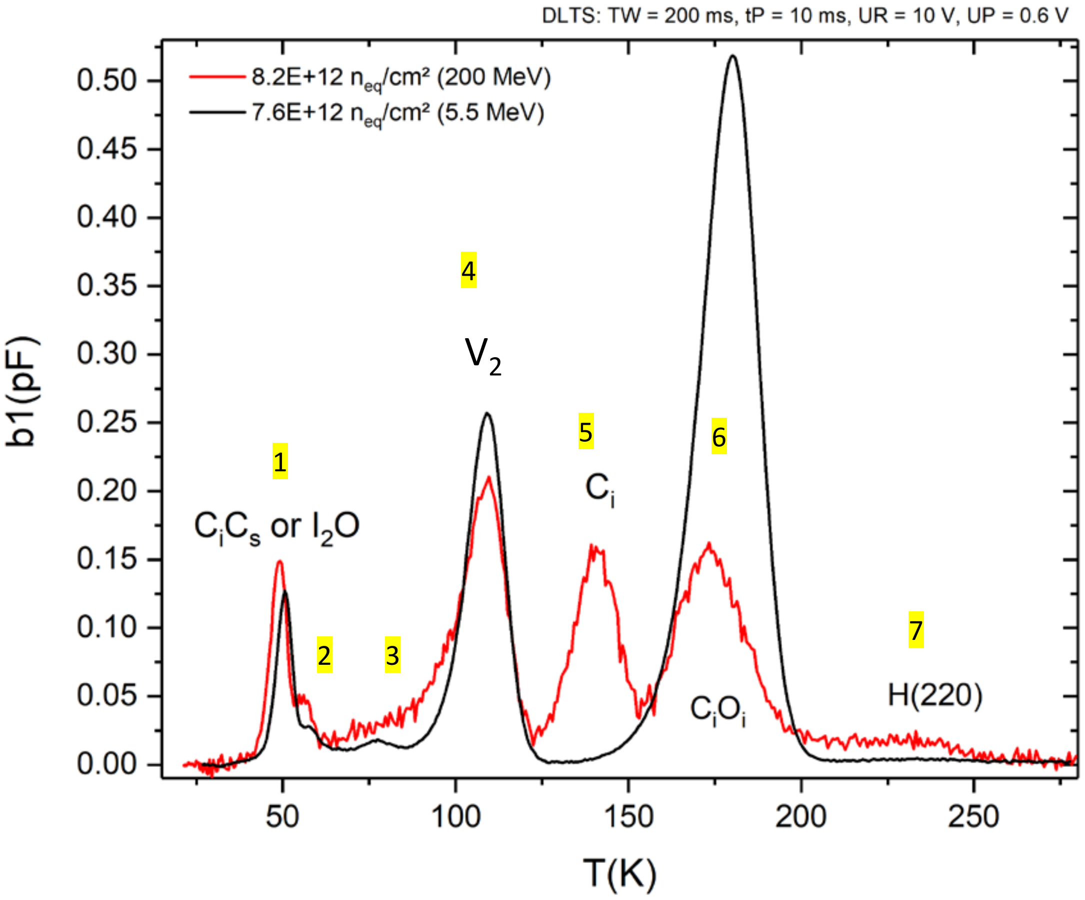




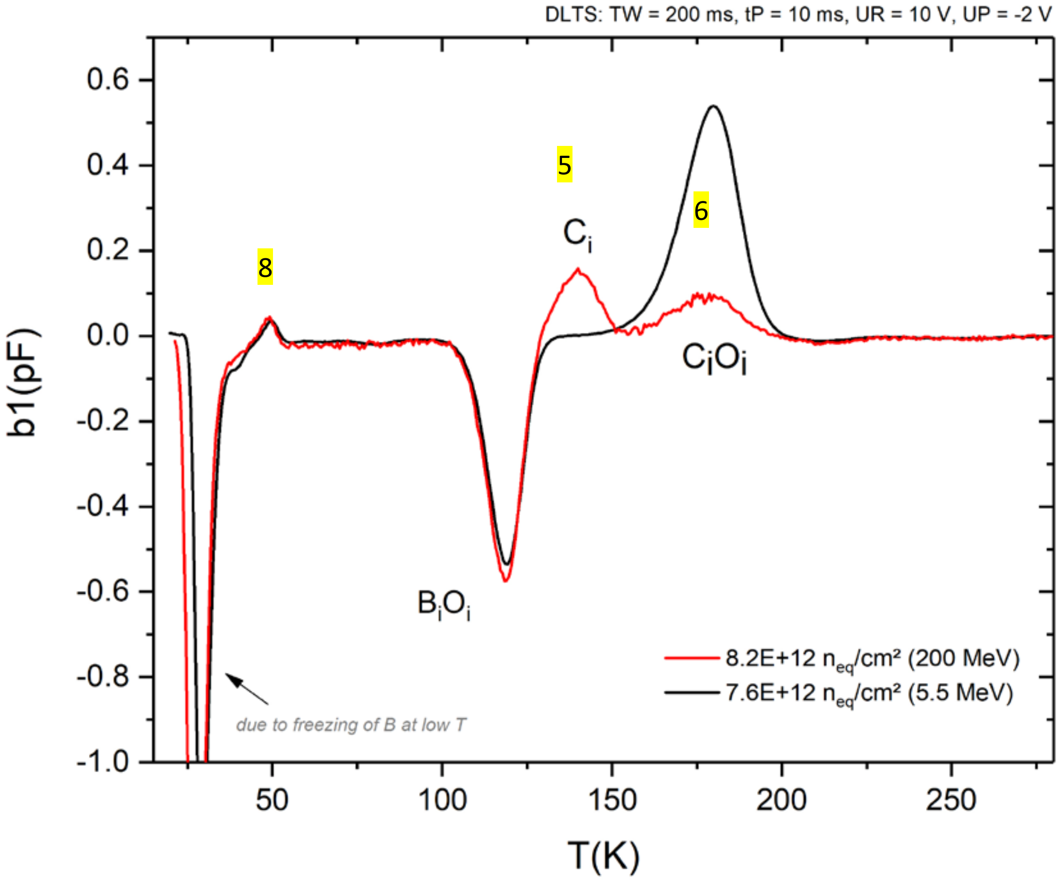


DLTS – Results: comparison of different electron irradiated samples

Majority carrier injection



Minority & majority carrier injection



C_i detected in non-annealed sample: in this case reduced [C_iO_i]

B_iO_i comparable concentrations

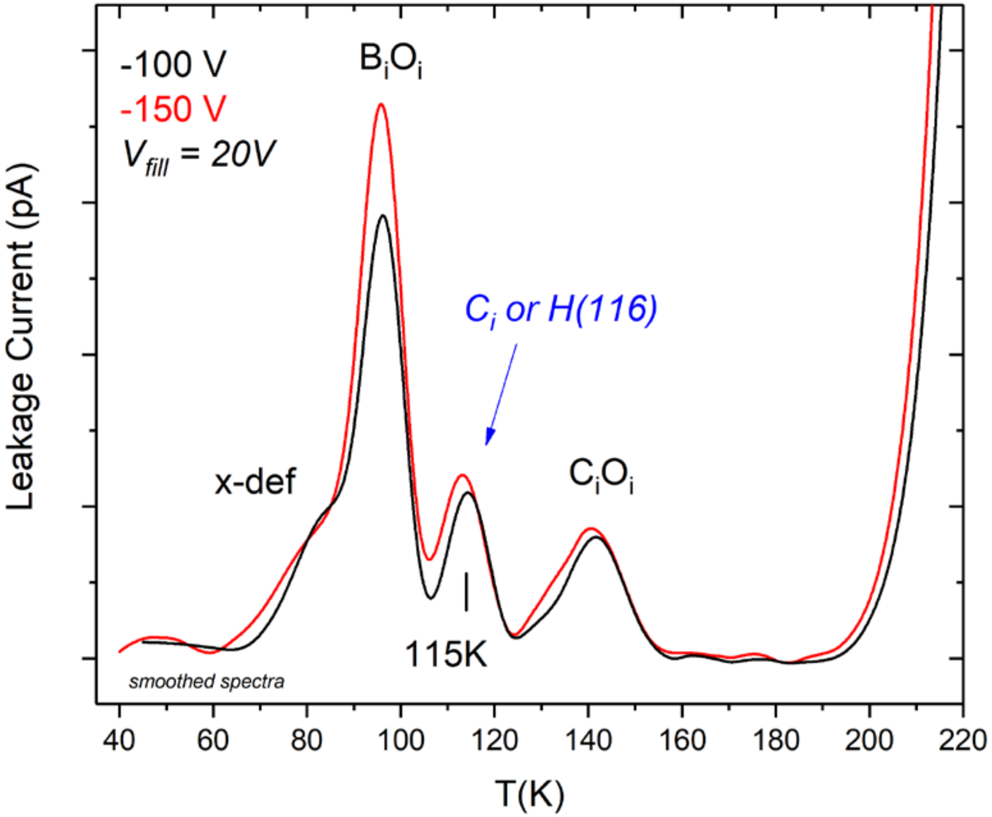
DLTS – Results: comparison of different electron irradiated samples

			EPI-06-88: 7.6E+12 neq/cm²				EPI-06-105: 8.2E+12 neq/cm²				EPI-02-100: 1.9E+13 neq/cm²	
			minority carrier inj.	min.+maj. carrier inj.	TSC (-200 V)		minority carrier inj.	min.+maj. carrier inj.	TSC (-100 V)		minority carrier inj.	min.+maj. carrier inj.
BiOi	Energy (eV)		/	0.248			/	0.244			/	0.229
	sigma		/	1.24E-14			/	8.829E-15			/	2.75E-15
	NT'		/	1.08E+13	1.30E+13		/	1.09E+13	5.70E+12		/	3.53E+13
Level 1	Energy (eV)		0.098	/			0.092	/				
	sigma		2.12E-14	/			8.17376E-15	/				
	NT'		2.89E+12	/			2.74E+12	/				
Level 2	Energy (eV)		0.113	/			/	/				
	sigma		1.70E-14	/			/	/				
	NT'		6.33E+11	/			/	/				
Level 3	Energy (eV)		0.138	/			0.101	/				
	sigma		9.17E-16	/			2.8023E-17	/				
	NT'		3.54E+11	/			6.63E+11	/				
Level 4	Energy (eV)		0.194	/			0.183	/				
	sigma		4.45E-16	/			1.93424E-16	/				
	NT'		5.24E+12	/			3.69E+12	/				
Level 5: Ci	Energy (eV)		/	/			0.286	0.291				
	sigma		/	/			5.11E-15	7.616E-15				
	NT'		/	/			2.89E+12	2.99E+12				
Level 6: CiOi	Energy (eV)		0.361	0.358			0.363	0.360				
	sigma		2.33E-15	1.86E-15			7.81271E-15	2.857E-15				
	NT'		9.76E+12	1.05E+13	1.26E+13		2.74E+12	1.94E+12				
Level 7	Energy (eV)		/	/			0.558	/				
	sigma		/	/			9.05185E-13	/				
	NT'		/	/			4.83E+11	/				
Level 8	Energy (eV)		/	0.103			/	0.099				
	sigma		/	5.89E-14			/	5.2345E-14				
	NT'		/	9.66E+11			/	1.18E+12				

[B_iO_i] increased after higher fluence

TSC – Results:

EPI-06-105 (50 Ωcm, 200 MeV electrons, 8.2e+12 n_{eq}/cm²):

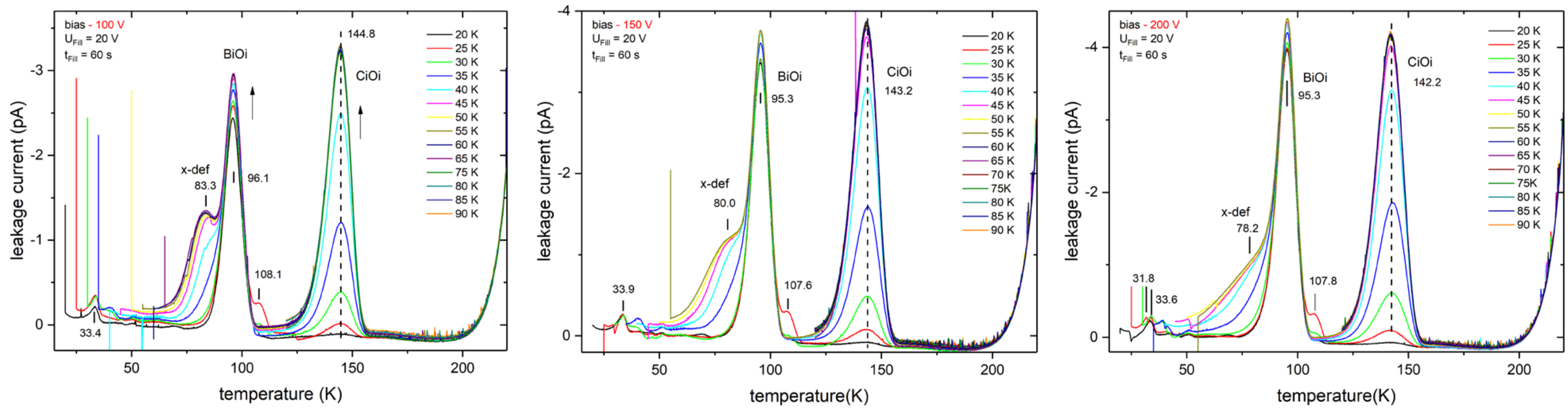


200 MeV
(not annealed)

👉 *plan: annealing studies*

TSC – Results: filling temperature dependence (reverse bias -100 V, -150 V & -200V)

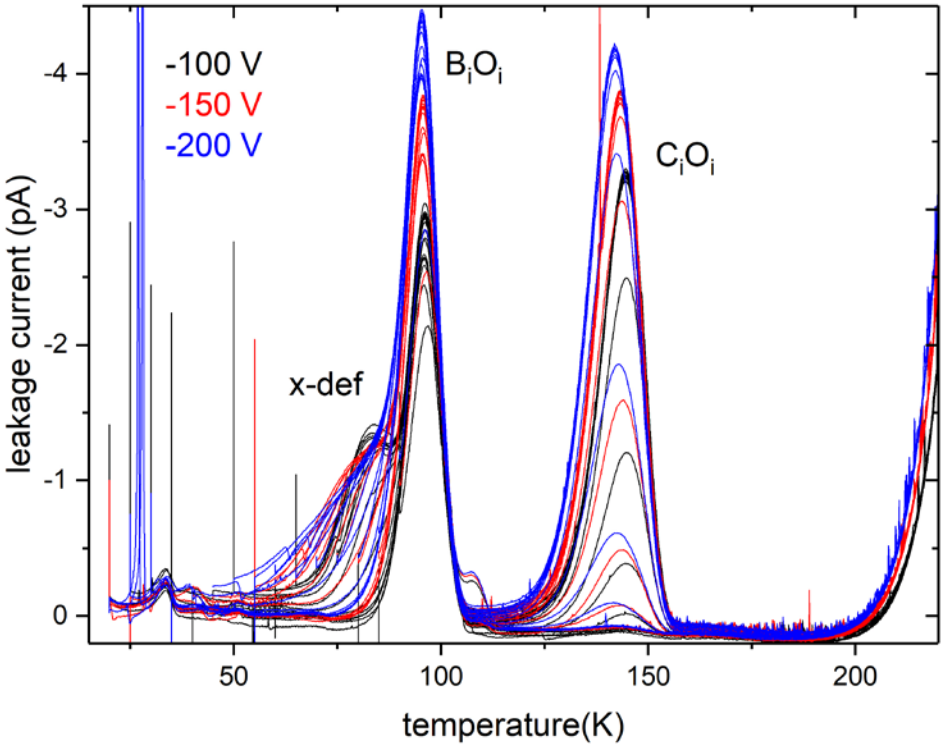
5.5 MeV

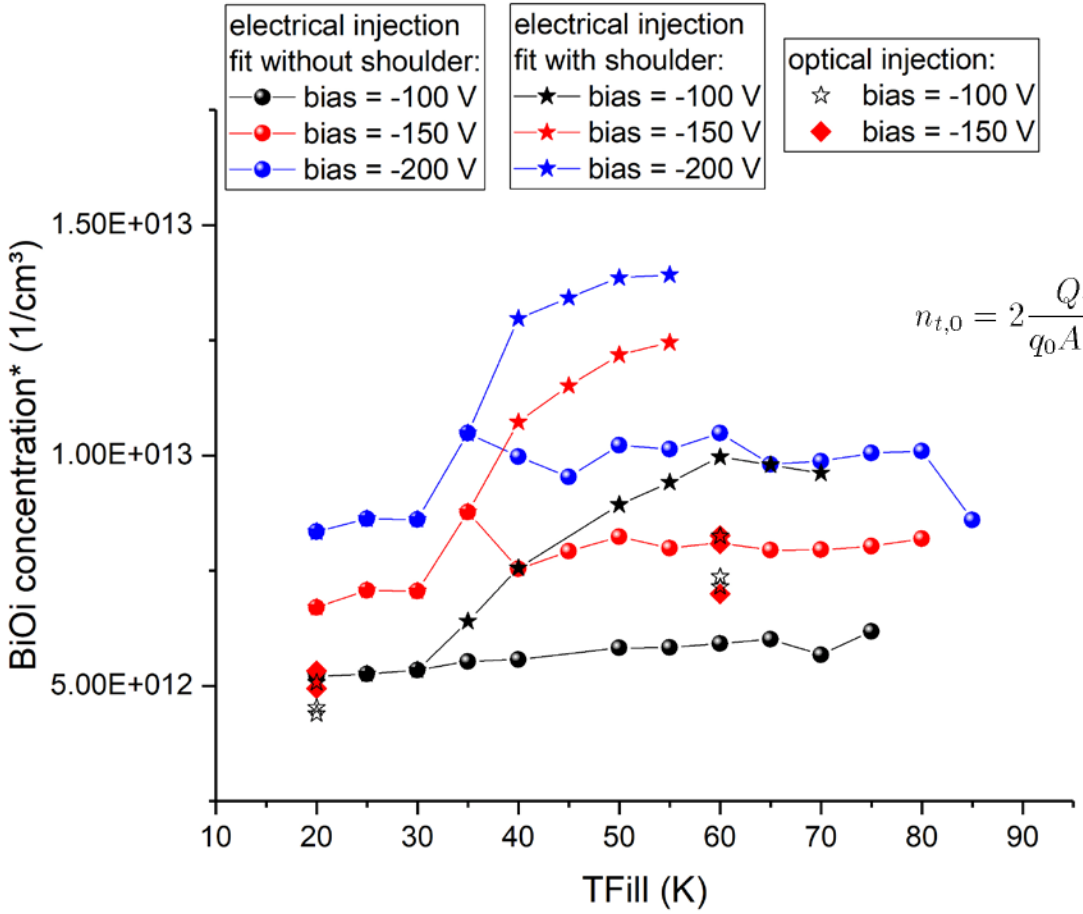


- CiOi: strong filling temperature dependence & Poole-Frenkel Effect
- BiOi: intensity increases with increasing filling temperature
- *x-defect:* field dependent shape -> Poole-Frenkel Effect ⇒ *See also the next talk from Chuan Liao et al.*
- no filling time dependence (60 – 240s) of the main defects *(not shown on the slide)*

EPI-06-88 (50 Ωcm, 5.5 MeV electrons, 7.6e+12 n_{eq}/cm²)

TSC – Results: filling temperature dependence (reverse bias -100 V, -150 V & -200V)





$$n_{t,0} = 2\frac{Q_t}{q_0 A W}$$

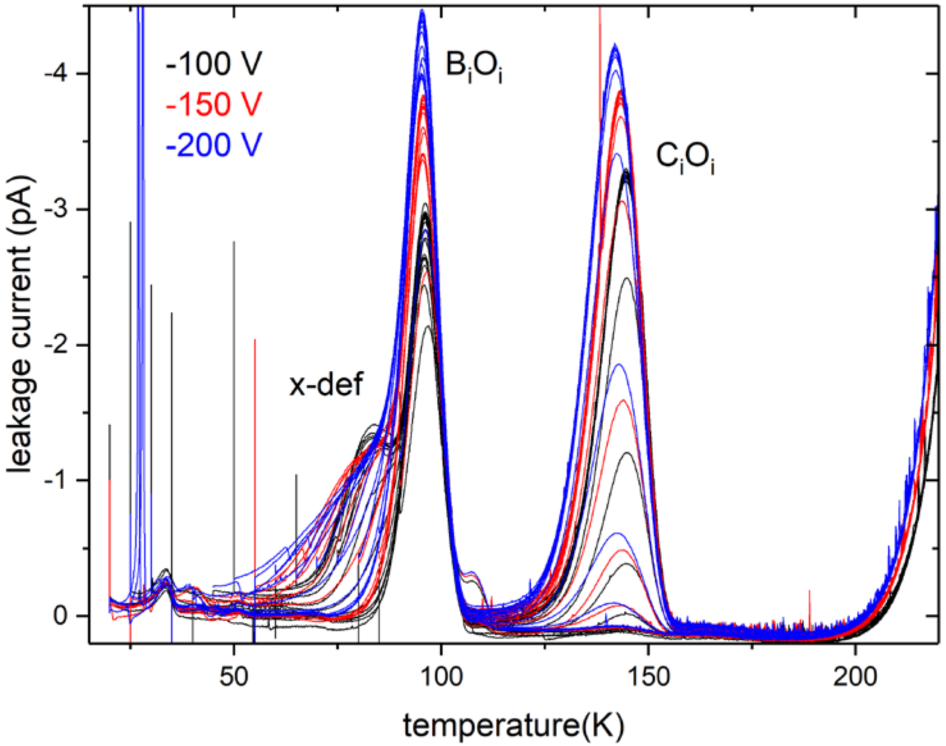
$[B_iO_i]$ (-100 V) = (5.2e+12 – 6e+12)/cm³

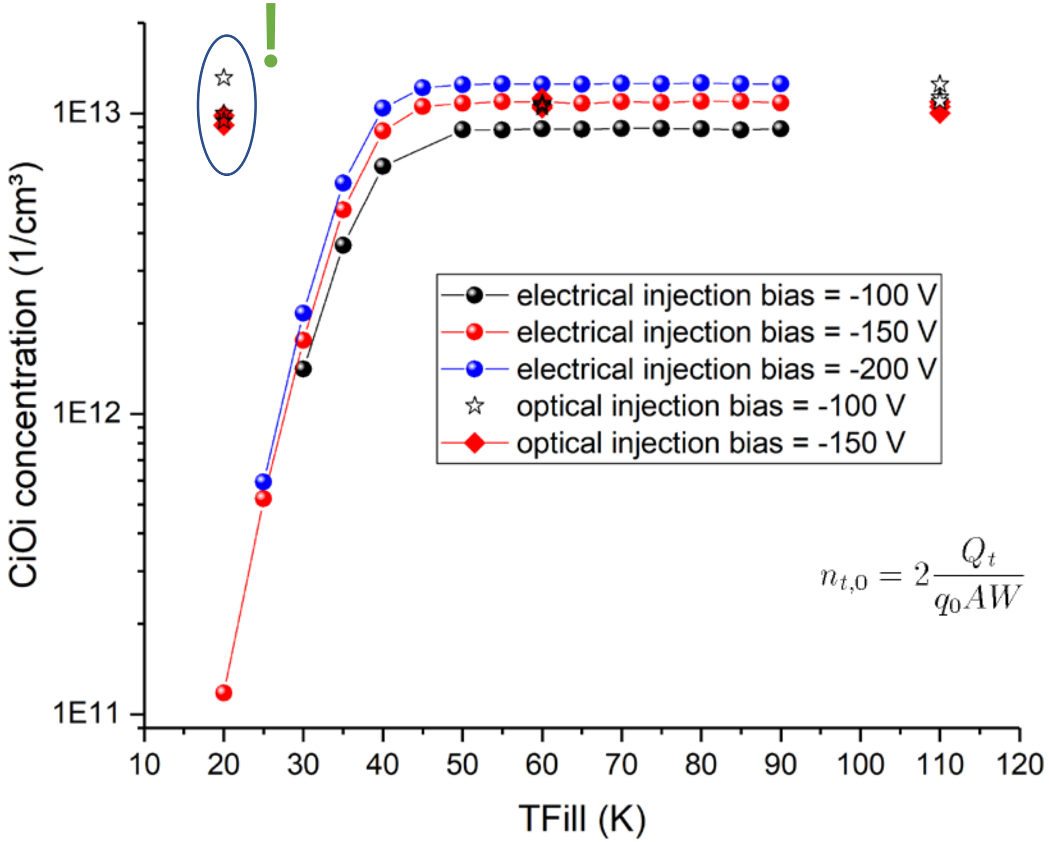
$[B_iO_i]$ (-150 V) = (6.8e+12 – 8.2e+12)/cm³

$[B_iO_i]$ (-200 V) = (8.3e+12 – 1.1e+13)/cm³

EPI-06-88 (50 Ωcm, 5.5 MeV electrons, 7.6e+12 n_{eq}/cm²)

TSC – Results: filling temperature dependence (reverse bias -100 V, -150 V & -200V)





$$n_{t,0} = 2\frac{Q_t}{q_0 A W}$$

$[C_iO_i]$ (-100 V) = (8.9e+12)/cm³

$[C_iO_i]$ (-150 V) = (1.09e+13)/cm³

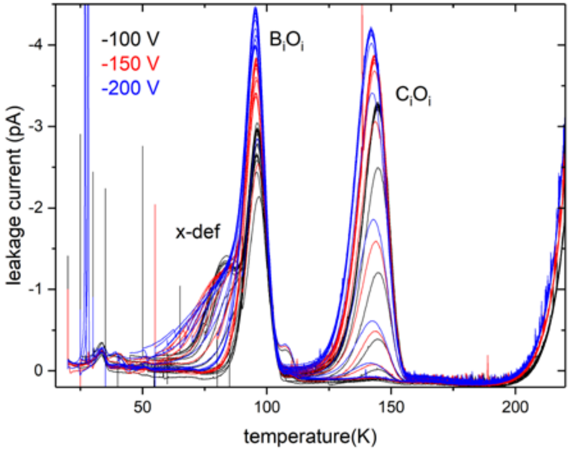
$[C_iO_i]$ (-200 V) = (1.26e-13)/cm³

EPI-06-88 (50 Ωcm, 5.5 MeV electrons, 7.6e+12 n_{eq}/cm²)

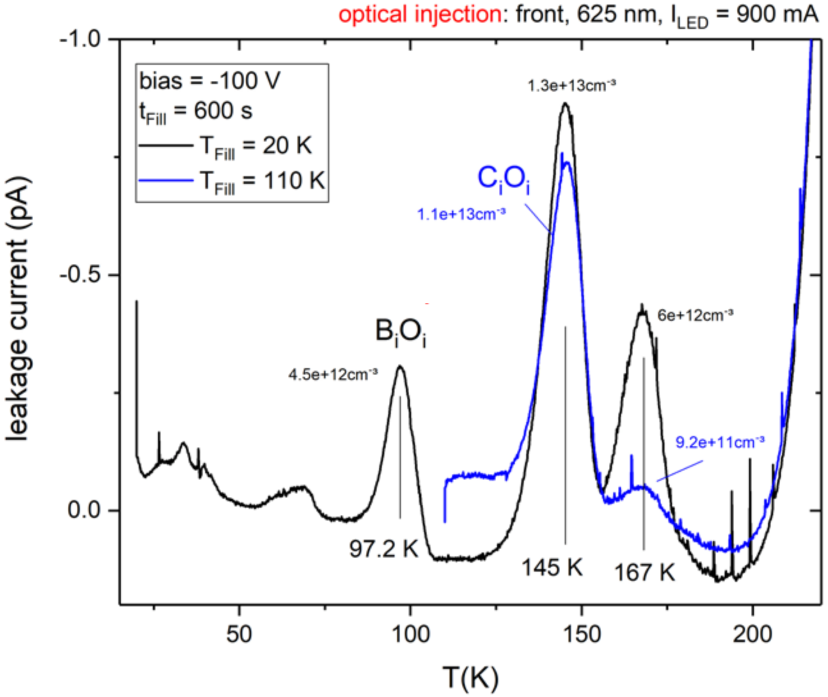
TSC – Results

EPI-06-88 (50 Ωcm, 5.5 MeV electrons, 7.6e+12 n_{eq}/cm²):

Electrical filling (+20V):



Optical filling:



@20K filling
under reverse bias :
→ peaks at 97.2 K, 145K & 167 K

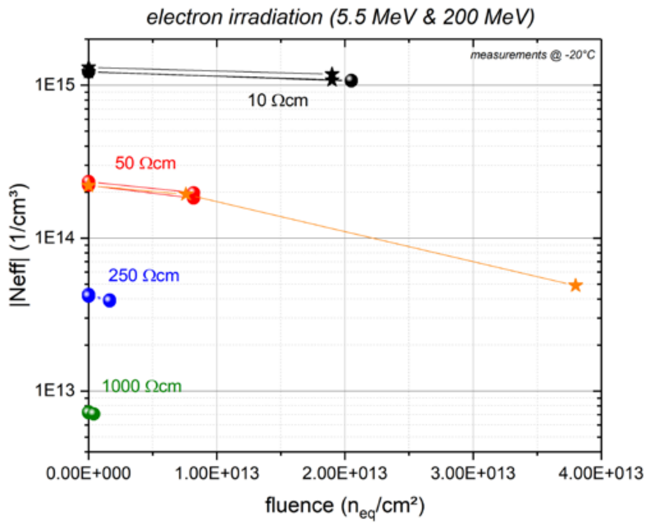
BiOi @ 97.2K (!):
no filling time dependence (60 to 600 s)
& no Poole-Frenkel-Effect
(measurements @ -100 V & -150 V)

C_iO_i observed also at T_{Fill} = 20K

plan: further studies with
optical injection
(front & back illumination)

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}/cm²)

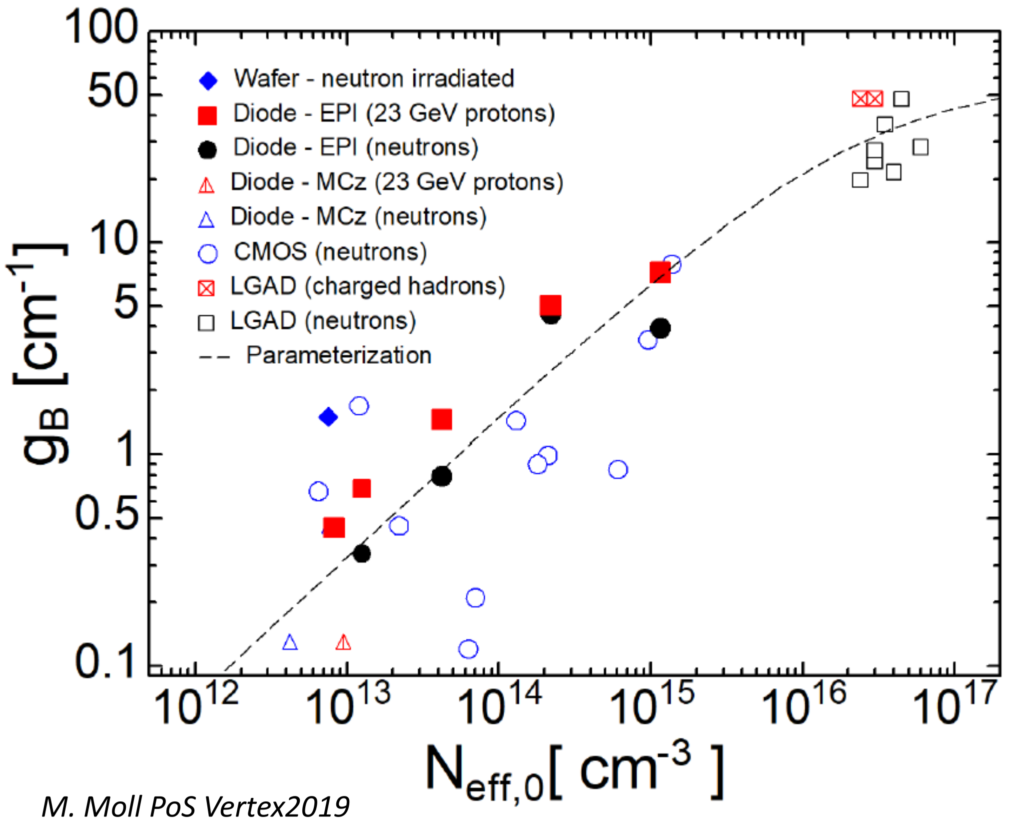


- Irradiation induced decrease of N_{eff}
- Characterisation of the defect levels using DLTS & TSC:
  - B_iO_i concentration higher for higher fluence & filling temperature dependence
  - x-defect: E-field dependence
  - C_i –defect: observed in non-annealed samples
  - C_iO_i –defect: reduced concentration in non-annealed samples filling temperature dependence & Poole-Frenkel effect
  - first measurements with optical filling

*Next step: **annealing studies** to probe the origin of the defects & the defect kinetics*

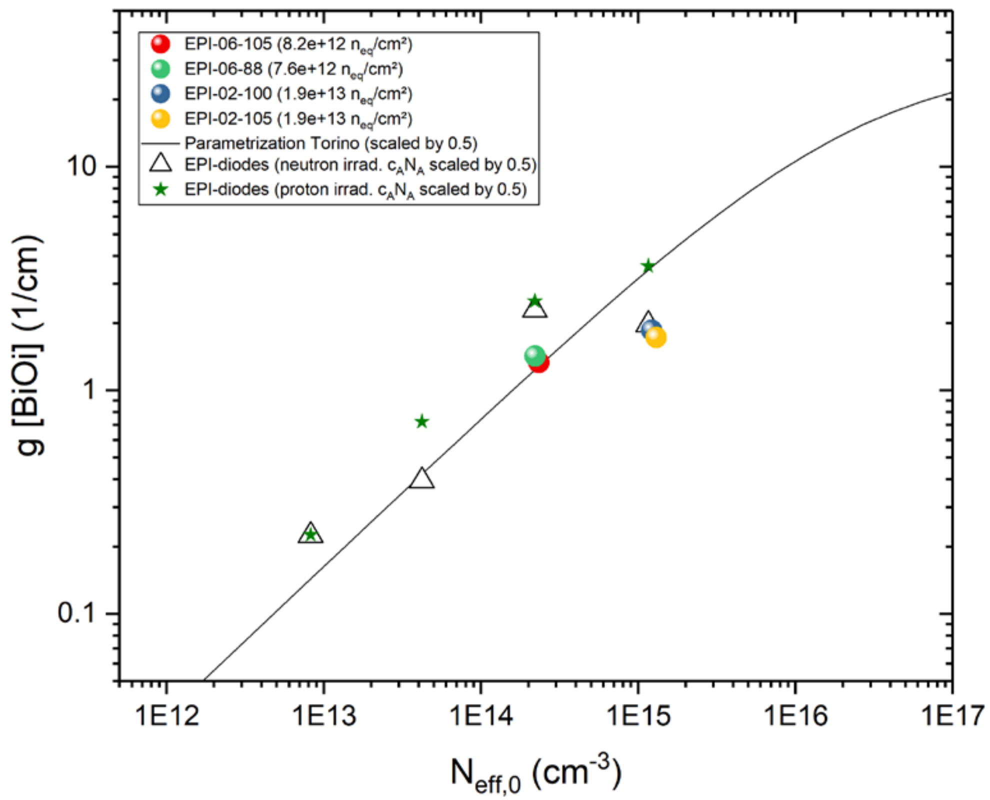
*Next step: further implementation of **optical injection** in TSC & DLTS*

? ***NIEL scaling*** *for electrons compatible with the NIEL scaling for neutrons & protons?*



M. Moll PoS Vertex2019

electron irradiation: BiOi introduction rate



☛ *Next step:* ***further analysis*** *of electron irradiated samples +* ***additional radiation*** *of samples @ CERN*

Thank you for your attention!