Acceptor removal in irradiated silicon devices

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Radiation damage effects in Si detectors

REMINDER

→ **Surface** — **accumulation of positive charge in SiO_2 and the Si/SiO_2 interface**

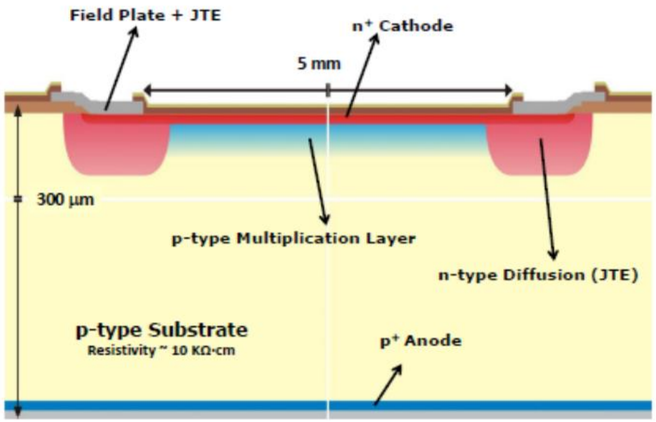
→ **Bulk** — **displacement damage, built up of crystal defects**

- Change of effective doping concentration & acceptor/donor removal
 (higher depletion voltage, under-depletion)
- Increase of leakage current (increase of shot noise, thermal runaway)
- Increase of charge carrier trapping (loss of charge)

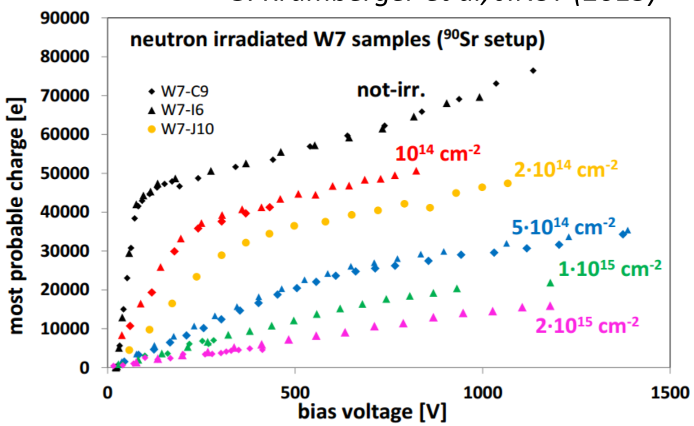
Impact on detector performance and Charge Collection Efficiency (CCE)

Example: Low Gain Avalanche Detector (LGAD)

- LGADs have a highly doped layer to achieve gain
- Interesting for their timing capabilities
- Gain decreases when exposed to radiation due to 'acceptor removal'



G. Kramberger et al, JINST (2015)



Degradation of gain with fluence

…Further devices suffering from 'acceptor removal' such as HV-CMOS, p-type strip detectors in ATLAS and CMS

Acceptor removal

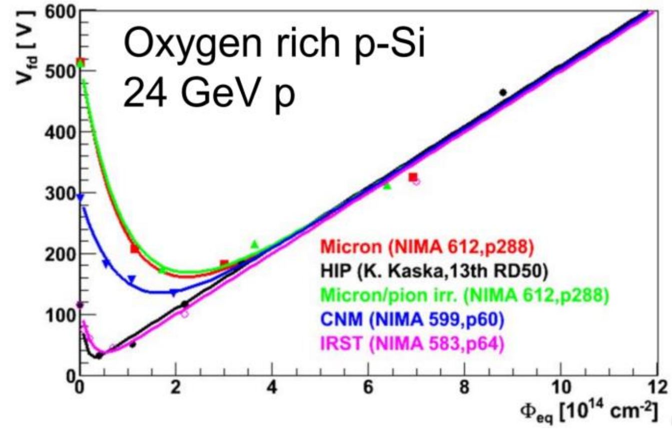
- Apparent (initial) dopant removal due to the irradiation
- 'Acceptor removal' observed in diodes mainly as a shift of full depletion voltage obtained from CV measurements
- Parameterization as

$$N_{eff}(\Phi) = N_{eff0}.e^{-c\cdot\Phi} + g_c\Phi$$

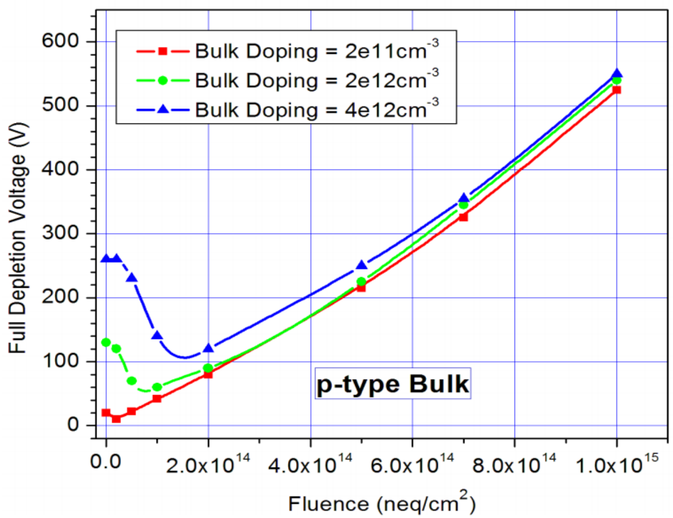
with complete acceptor removal ($N_{A,0}$ = $N_{eff,0}$) after proton irradiation and incomplete acceptor removal after neutron irradiation

- Simulations can reproduce similar V_{dep} behaviour <u>*without*</u> B removal

G. Kramberger, 23rd RD50 Workshop



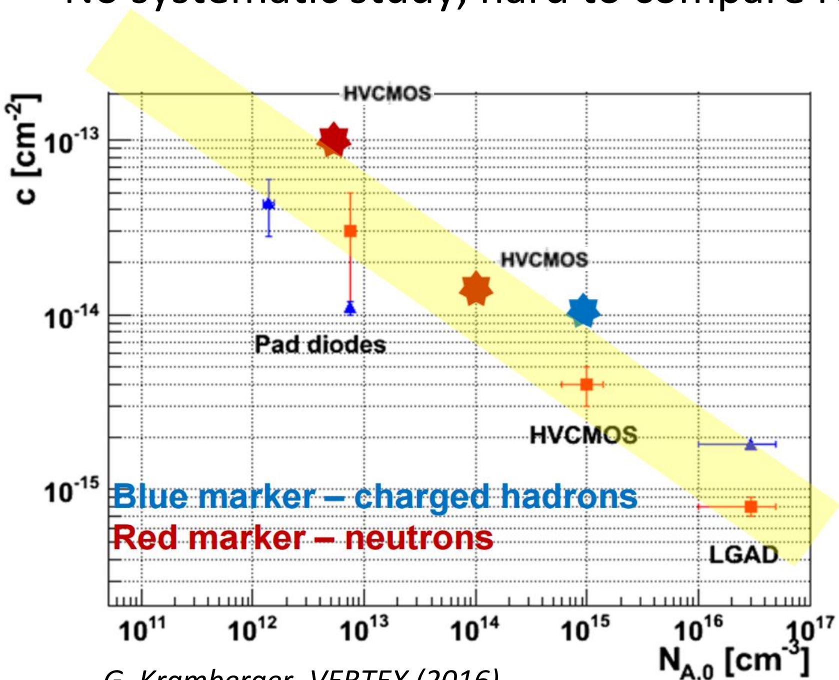
Ranjeet Dalal et al, 25th RD50 Workshop



Motivation

$$N_{eff}(\Phi) = N_{eff0} \cdot e^{-c \cdot \Phi} + g_c \Phi$$

No systematic study, hard to compare results from literature:



G. Kramberger, VERTEX (2016)

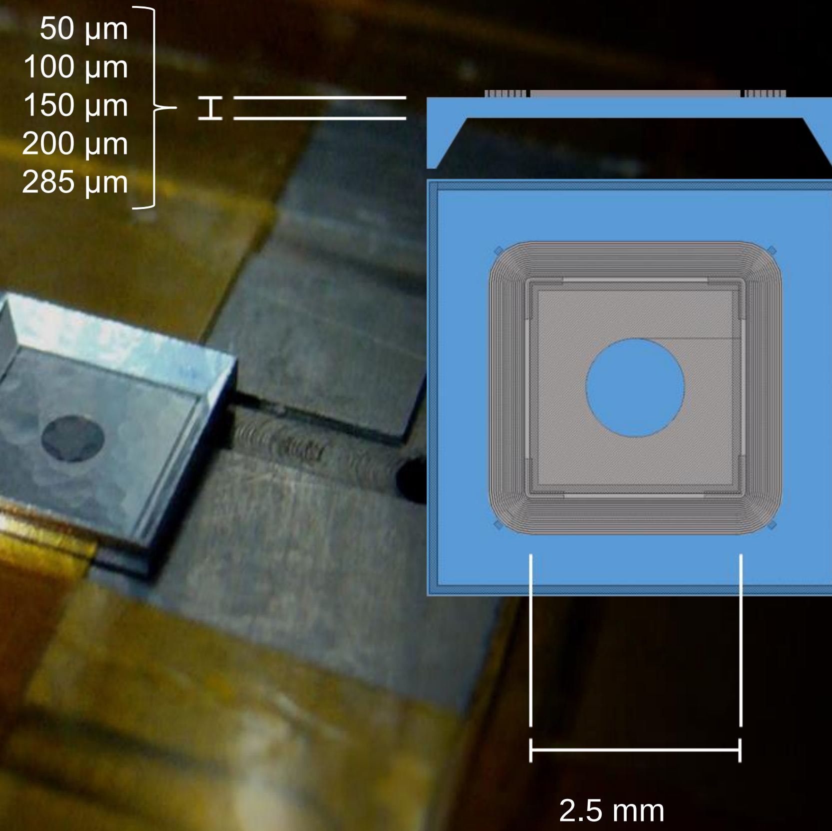
- Different devices
- Different oxygen content
- Different material types
- Different measurement techniques

Solution: dedicated characterization experiment

A large number of simple test structures with the same (or known) B content in order to concentrate on the bulk features

Materials and Devices

Simple p-type pad diodes



EPI (50 µm)

10 Ω·cm
50 Ω·cm
250 Ω·cm
1000 Ω·cm

FZ (>10 000 Ω·cm)

100 µm
150 µm
200 µm
285 µm

Irradiation

Proton and neutron irradiation

From ~ 7×10^{13} to 7×10^{15} $n_{eq}cm^{-2}$

Experimental procedure

CV/IV/TCT

macroscopic

- before and after irradiation
- during **isothermal annealing**
- **IV/CV :** T= -20°C
- **TCT :** three temperatures:
  T= -20°C, T= -10°C, T= 0°C

TSC

microscopic

1. **cooling**: reverse bias condition
2. **injection**: T=20K, forward bias
3. **recording** of TSC signal,
   reverse bias, T↑, β = 11 K/min

Diode properties

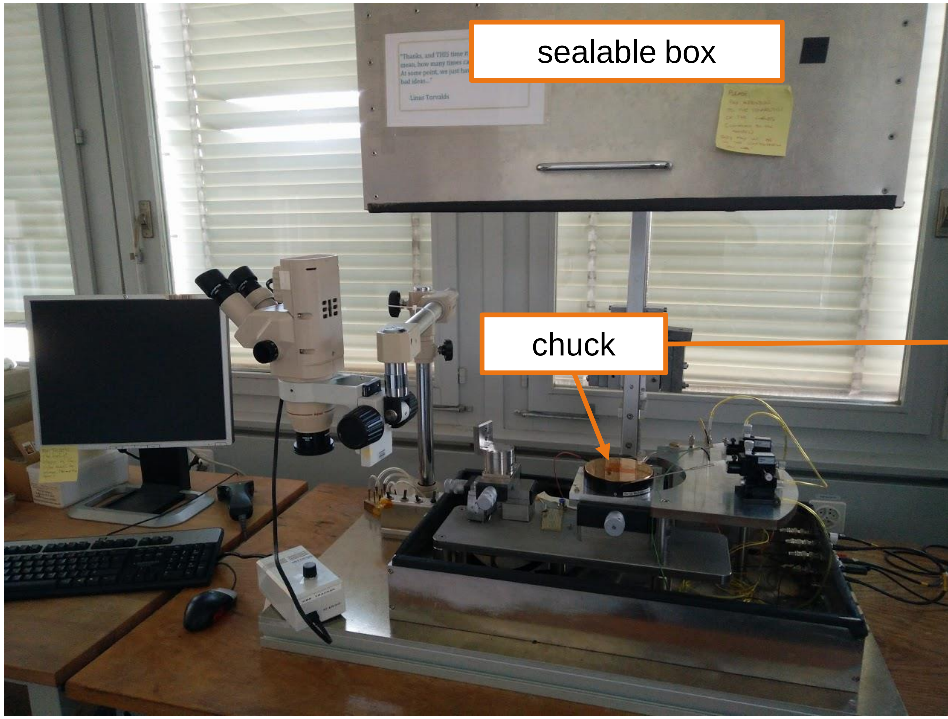
- V_{dep}, leakage current, N_{eff}

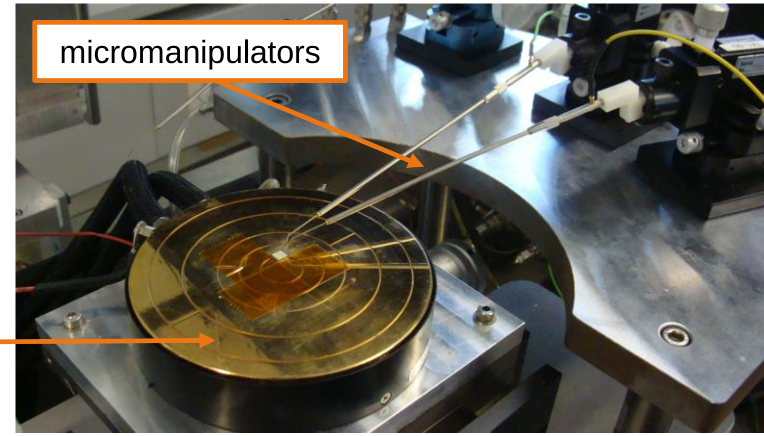
Defect properties (and impact)

- E_a, $\sigma_{n,p}$, N_c

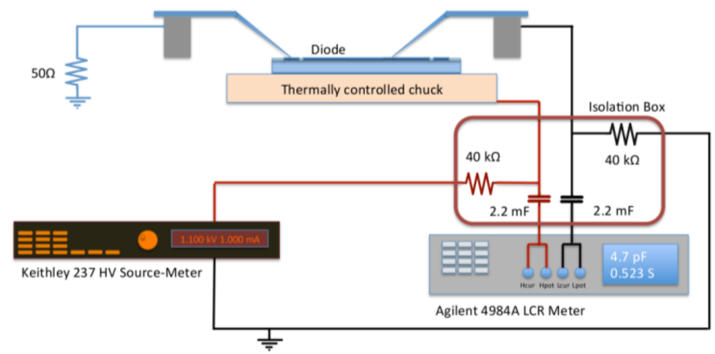
defects with an impact on the macroscopic diode parameters ⟶ TCAD simulations

CV(capacitance-voltage)/IV(current-voltage) workstation





Depletion voltage V_{dep} and effective doping concentration N_{eff}

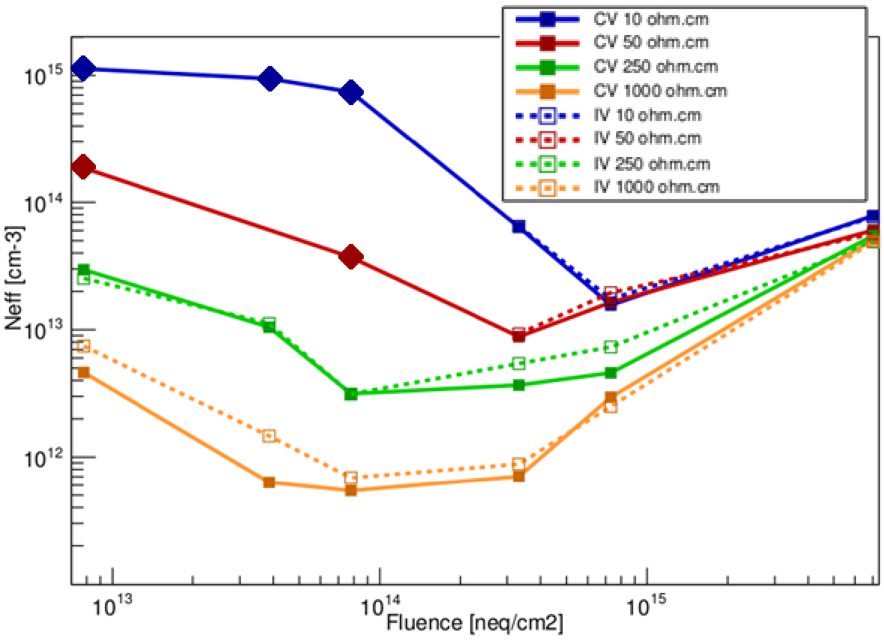


Nicola Pacifico, PhD thesis, Bari University (2012)

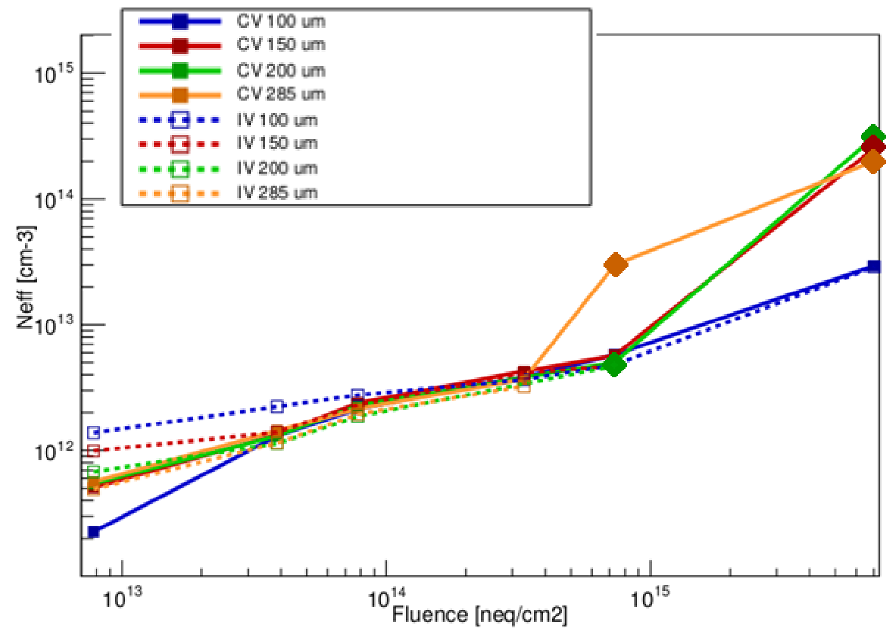
Proton Irradiation Campaign

CV/IV measurements

EPI



FZ



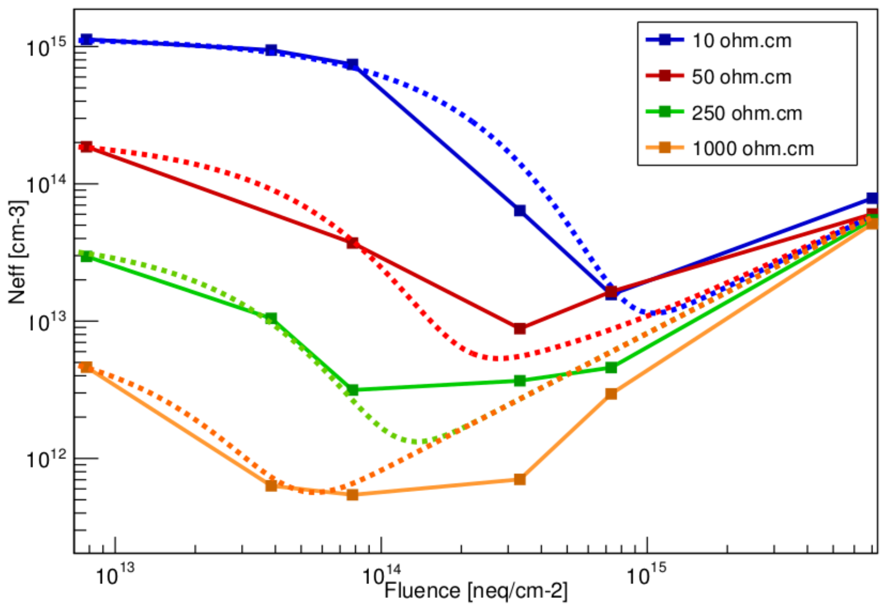
P. Almeida et al, 30th RD50 (2017)

■ from CV/IV kink: $N_{eff} = \left(\frac{C}{A}\right)^2 \frac{2V_{dep}}{\varepsilon\varepsilon_0 q_0}$

◆ from CV slope: $N_{eff} = \frac{2}{A^2\varepsilon\varepsilon_0 q_0}\frac{1}{d\left(1/C^2\right)/dV}$

Proton Irradiation Campaign

EPI



P. Almeida et al, 30th RD50 (2017)

- Fitting function:

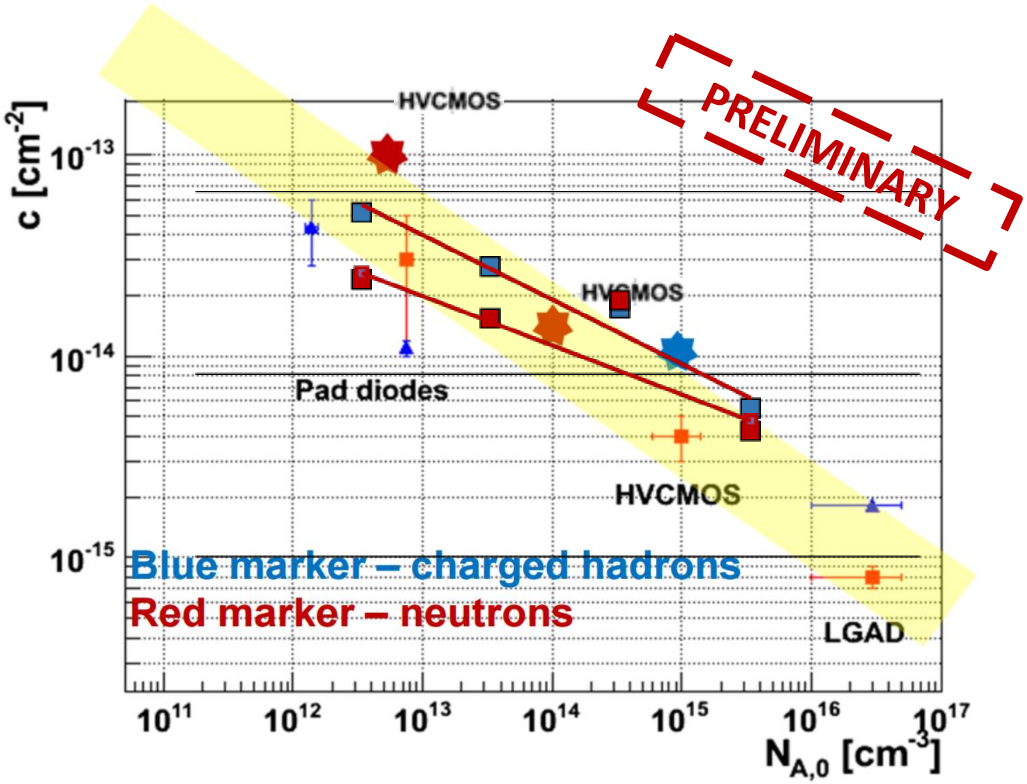
$$N_{eff}(\Phi) = N_{A,0} \cdot e^{-c\cdot\Phi} + g_c \cdot \Phi$$

- The linear slope g_c was constrained to be the same across the different resistivities

	measured	fitted	
ρ [Ω cm]	$N_A(0)$	C [cm²]	g_c [cm⁻¹]
10	1.16e15	6.5e-15	8.2e-3
50	2.20e14	2.3e-14	
250	4.21e13	3.9e-14	
1000	8.25e12	7.7e-14	

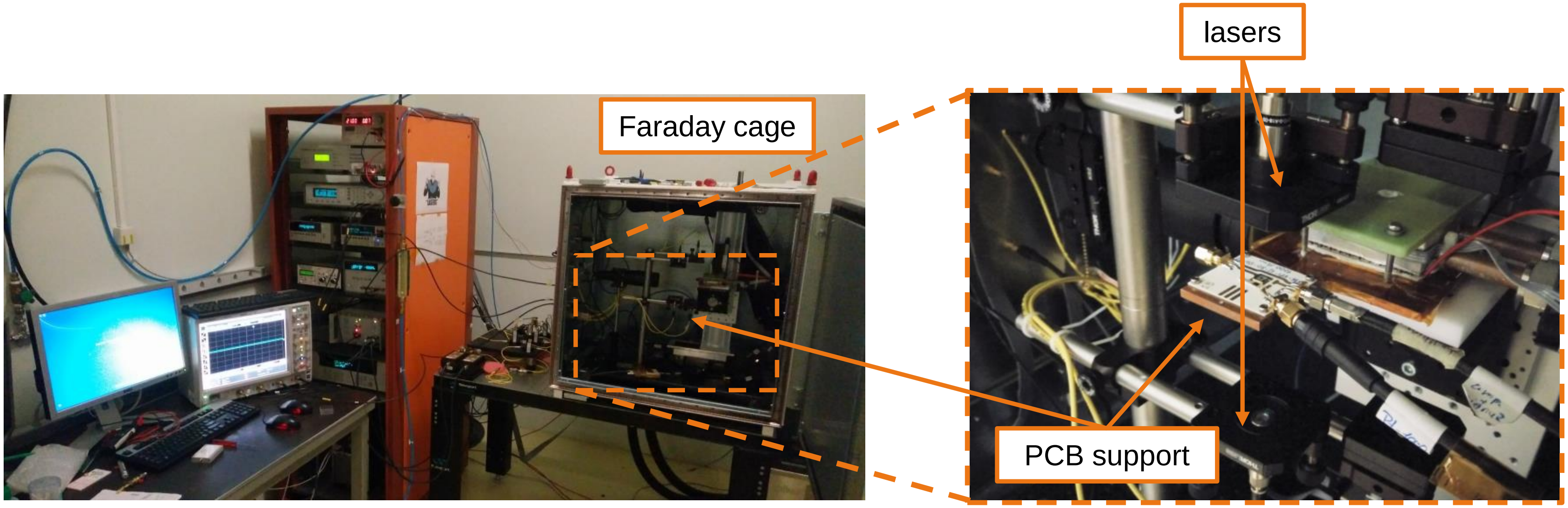
…Same fitting procedure was applied for neutron irradiated sensors, incomplete acceptor removal was taken into account

Our impact to systematic study

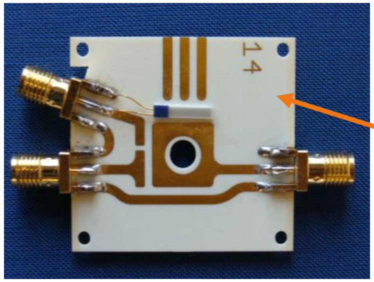


Significant results as they are obtained on materials differing only in B content!

TCT (Transient Current Technique) workstation



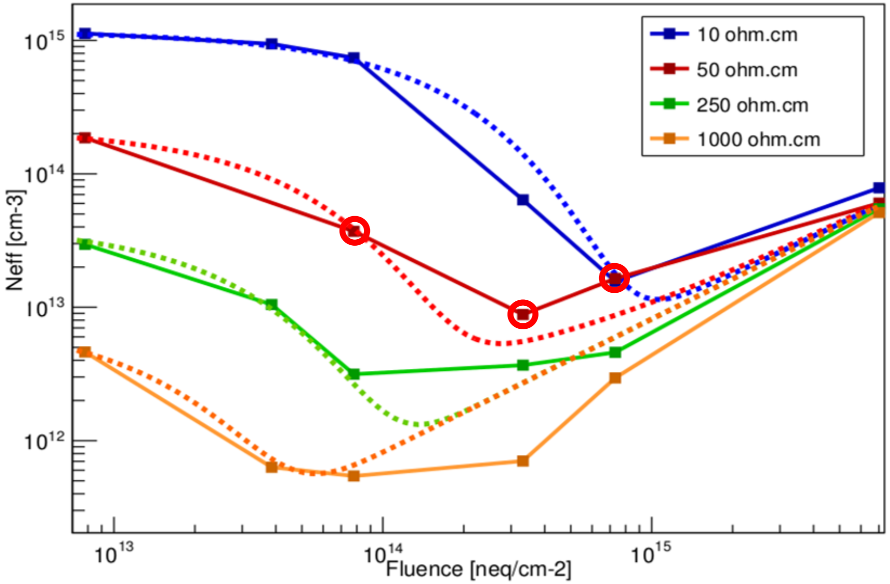
Electric field and Charge Collection Efficiency



For more details see presentation of Marcos Fernandez and Sofia Otero Ugobono

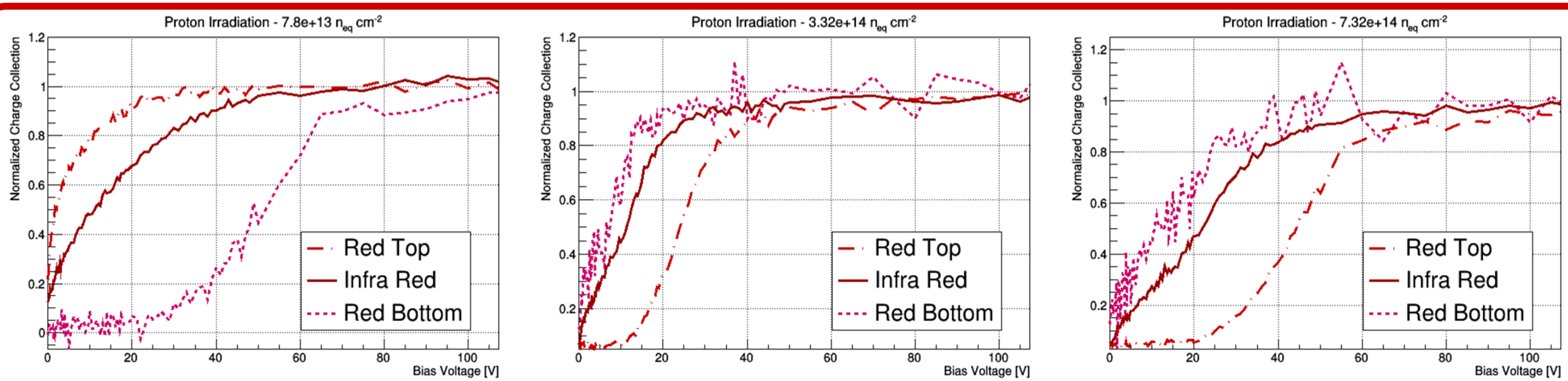
https://indico.cern.ch//TCT_DT_training_seminar.pdf

TCT results

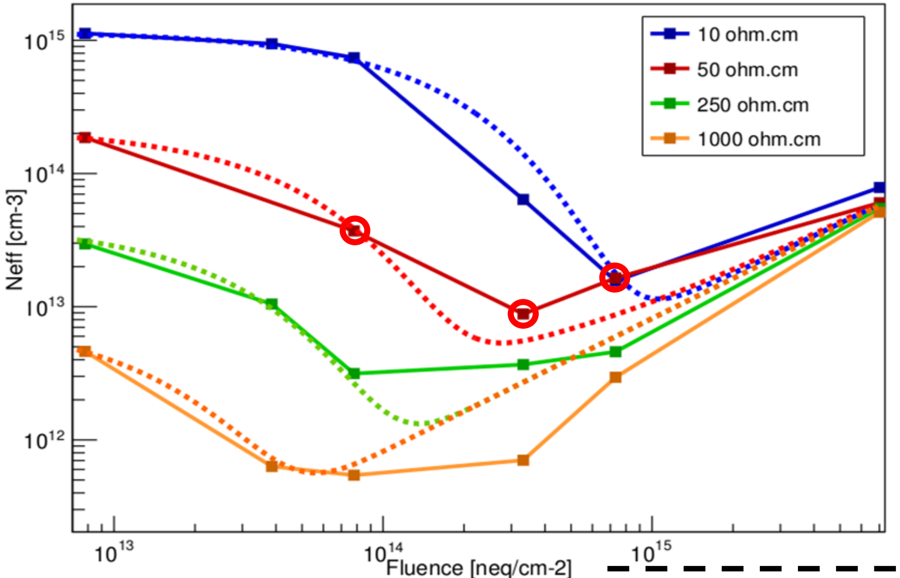


Fluence dependence of Charge Collection Efficiency

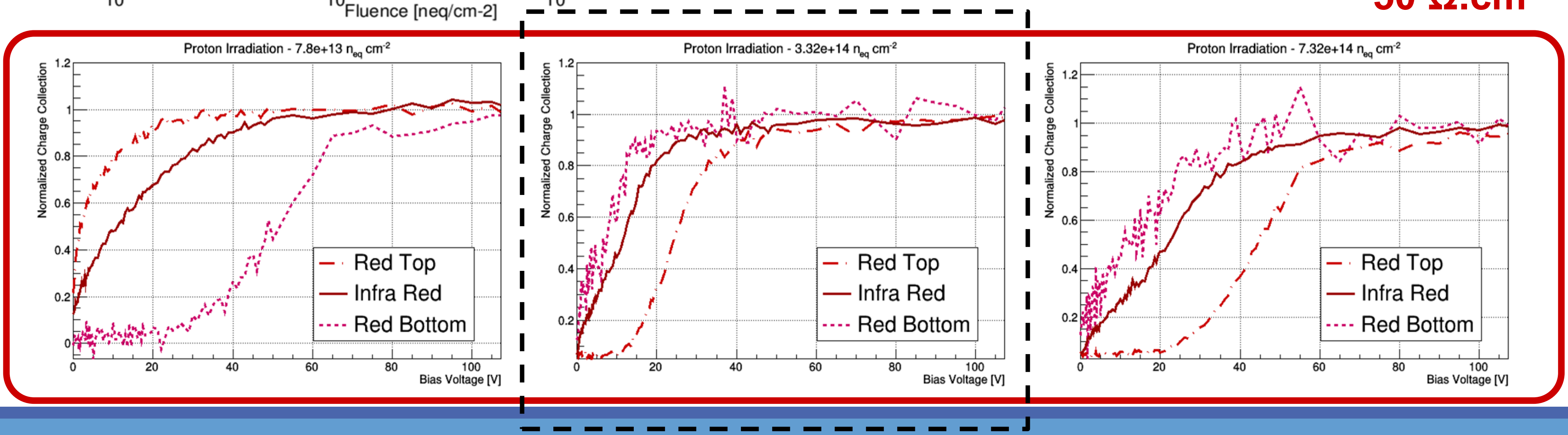
50 Ω.cm



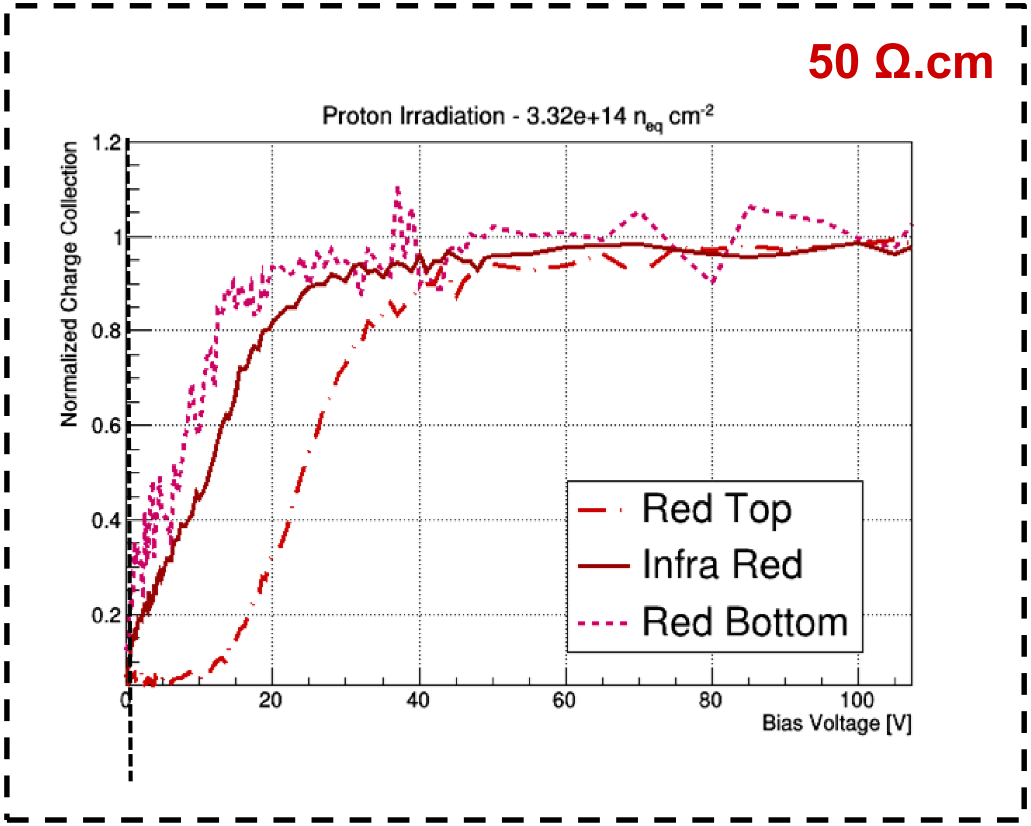
TCT results

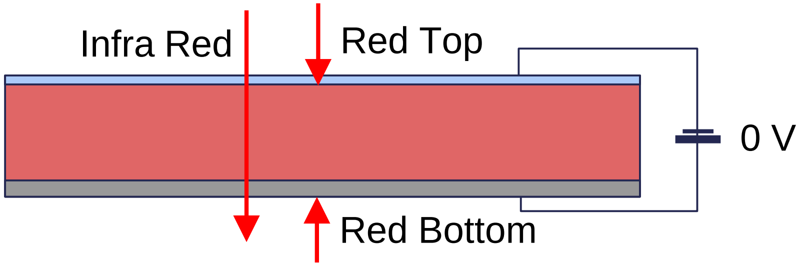


50 Ω.cm

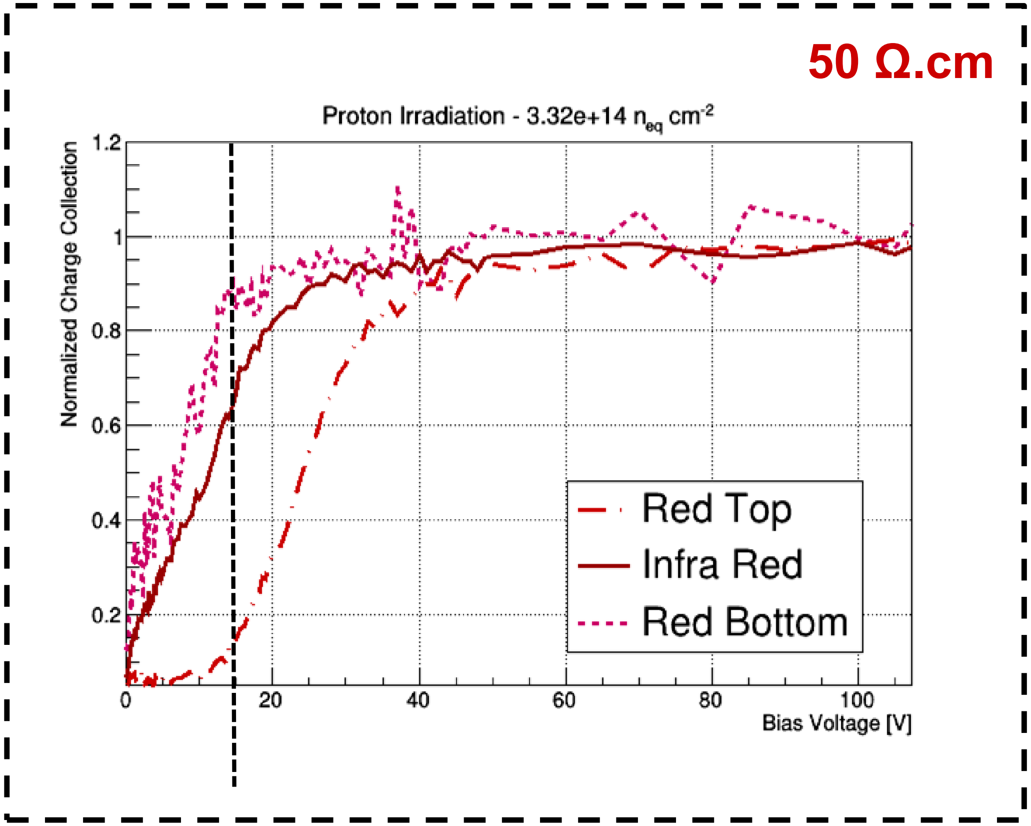


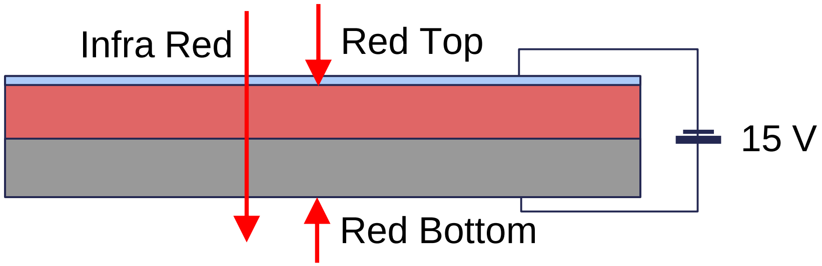
TCT results


50 Ω.cm
Proton Irradiation - 3.32e+14 n_{eq} cm^{-2}
Normalized Charge Collection
Bias Voltage [V]
Red Top
Infra Red
Red Bottom


Infra Red
Red Top
0 V
Red Bottom

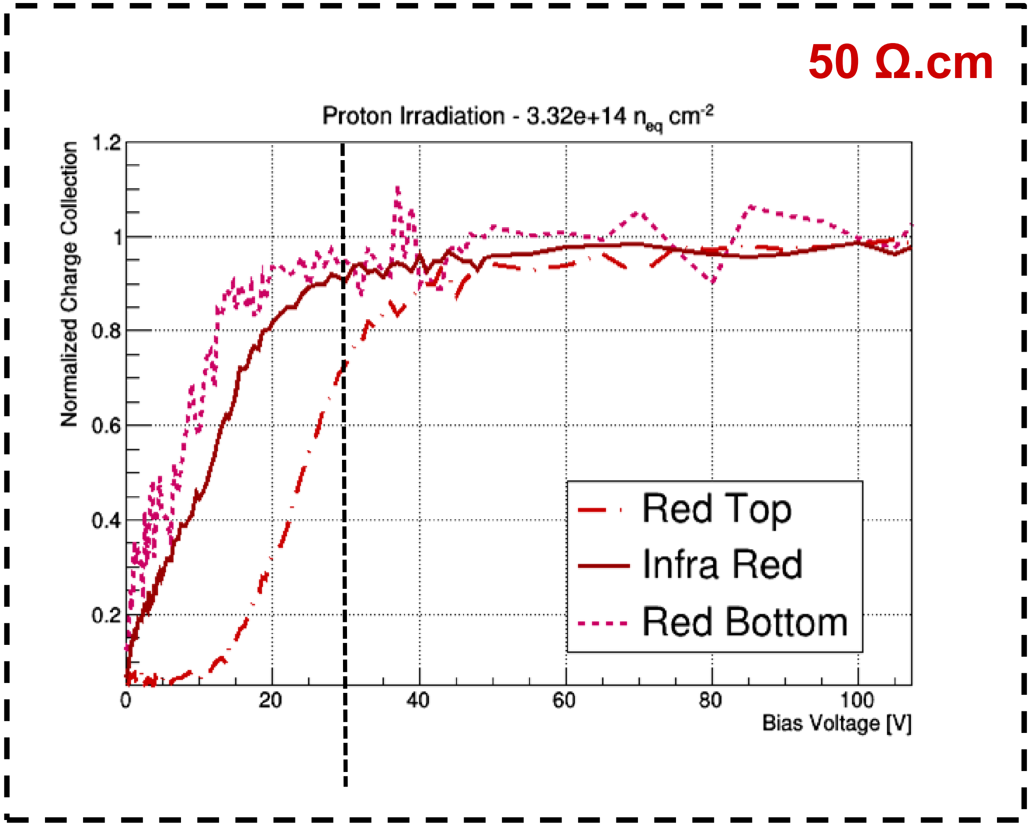
TCT results

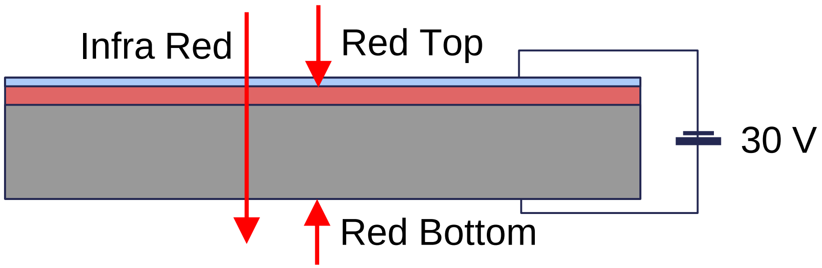




Sensor is depleting from the back first

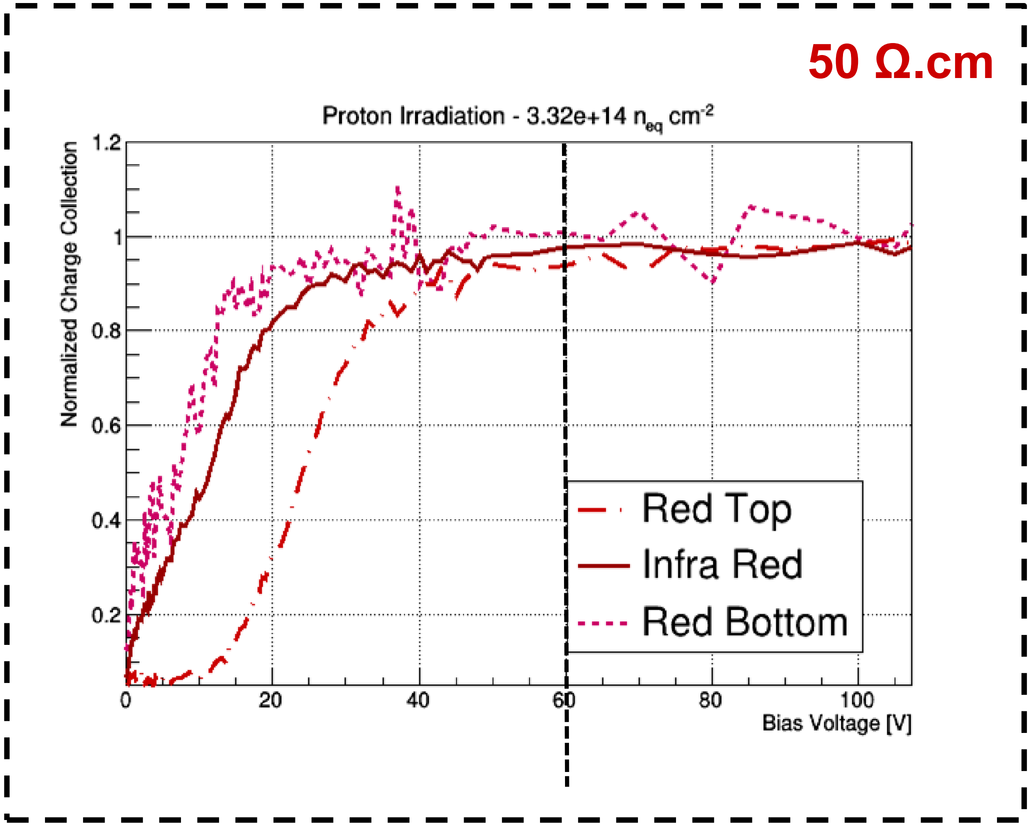
TCT results





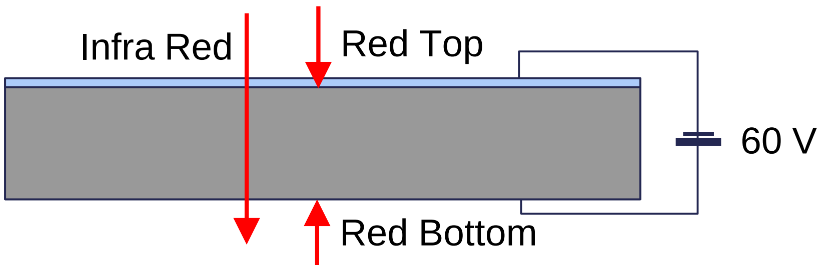
Sensor is depleting from the back first

TCT results

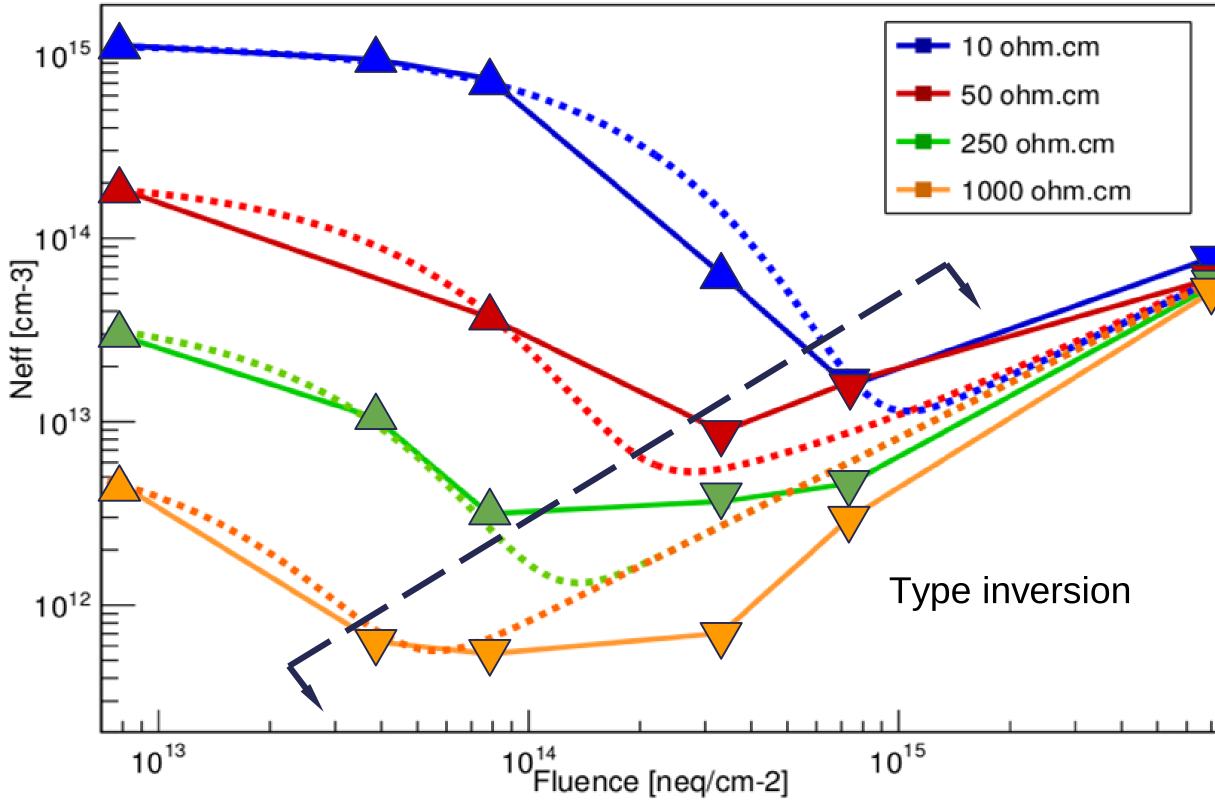


Sensor is depleting from the back first

Type Inversion!



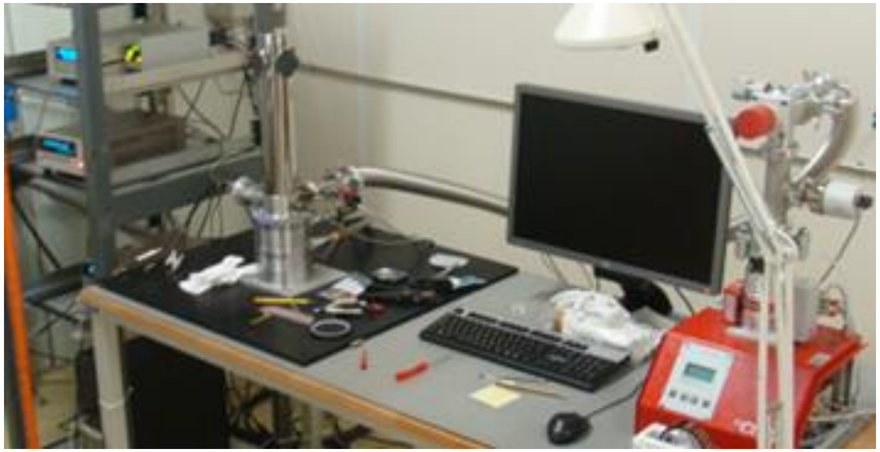
TCT results. Type inversion



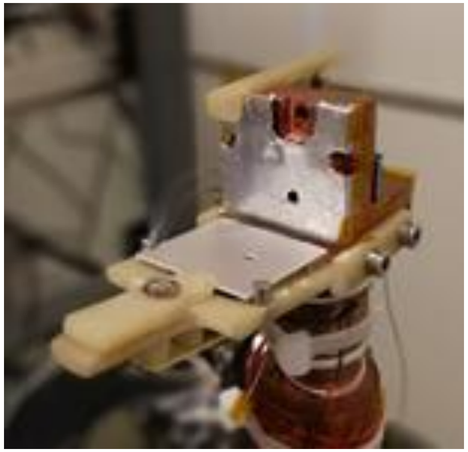
△ Depletes from the top

▽ Depletes from the bottom

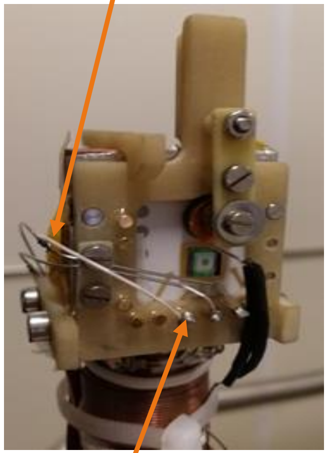
TSC (Thermally Stimulated Current) workstation



New sample holder

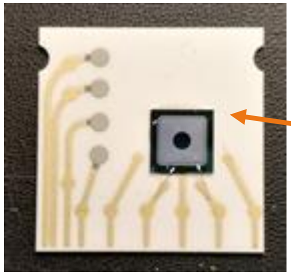


Lightweight coaxial cables



Spring loaded contacts to PCB

Design by Robert Loos (CERN)

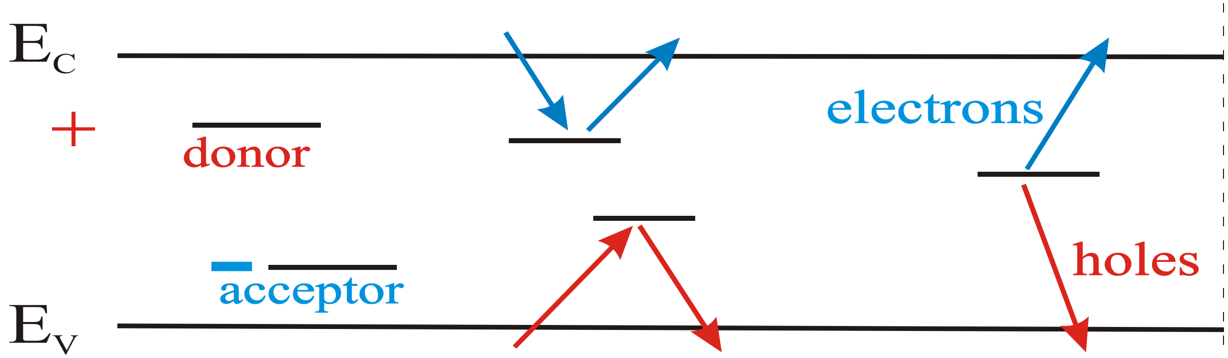


New ceramic PCB for better thermal conductivity
(No connectors to reduce thermal mass)

Impact of defects on detector properties

Shockley-Read-Hall statistics

REMINDER



charged defects
⇒ N_{eff} , V_{dep}

e.g. donors in upper half, acceptors in lower half of band gap

trapping (e and h)
⇒ **CCE**

shallow defects do not contribute at RT due to fast de-trapping

generation
⇒ **leakage current**

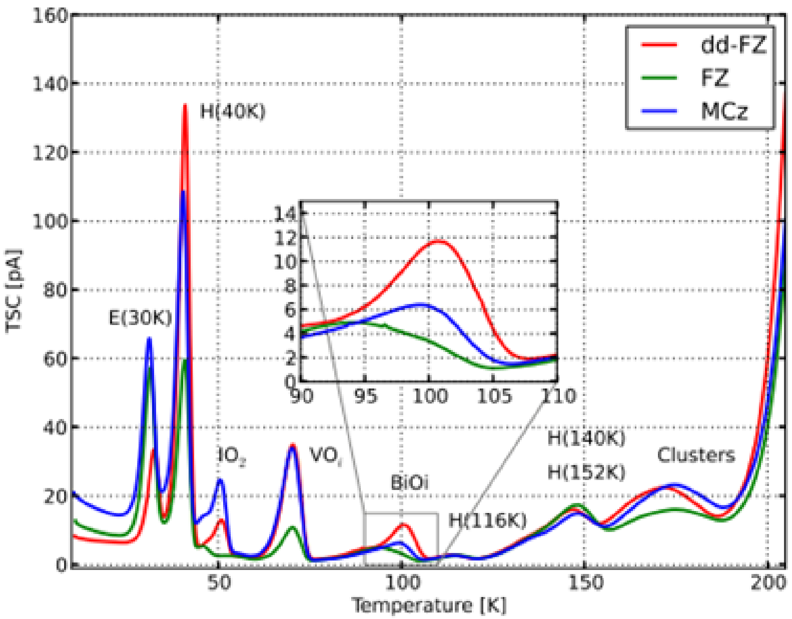
levels close to midgap most effective

- Impact on detector properties can be calculated if defect parameters are known:

$\sigma_{n,p}$: cross sections ΔE : ionization energy N_t : concentration

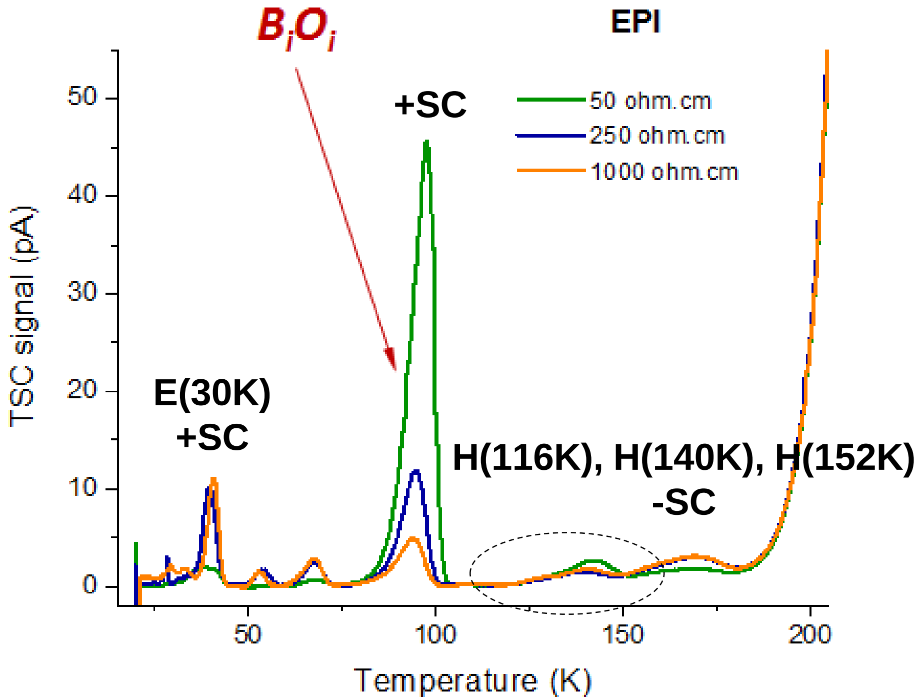
Standard TSC scans

- E. M. Donegani, E. Fretwurst, E. Garutti, University of Hamburg, Germany, *RADECS 2016*



200 µm, Φ_{neq}=0.5·10^{14} cm^{-2}, 8 minutes @ 80°C annealing

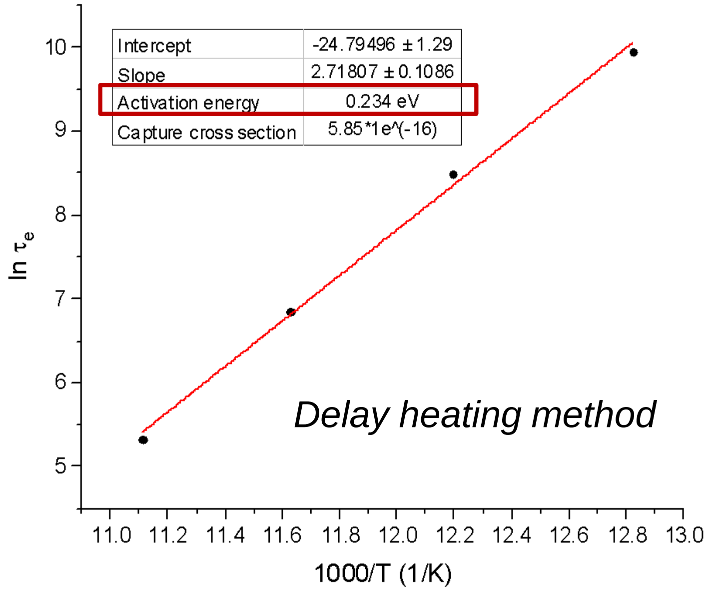
- <u>our preliminary results for fully-depleted diodes</u>



50 µm, Φ_{neq} = 7.80 · 10^{13} cm^{-2}, 10 min @ 60°C annealing

TSC results vs Literature

Defect	Emission parameters: E_a(eV), σ (cm^2), T_{TSC} (K),T_{DLTS} (K)	Reference
B_iO_i	-0.23	L. C. Kimerling et al., "Interstitial Defect Reactions in Silicon", Materials Science Forum, Vols. 38-41, pp. 141-150, 1989
B_iO_i	-0.25	P. M. Mooney, L. J. Cheng, M. Süli, J. D. Gerson, and J. W. Corbett Phys. Rev. B 15, 3836, 1977
B_iO_i	-0.24,4E-15, 98, 118	Trauwaert, Radiation and Impurity Related Deep Levels in Si, PhD thesis, IMEC-KUL, Leuven, 1995
B_iO_i	-0.27, 3E-13, 96, 113	Schmidt, J., Berge, C., Aberle, G., Appl. Phys. Lett. 73, 2167, 1998



B_iO_i – donor level at E_c-0.23 eV

Boron removal:

$$\begin{cases} I + B_s \longrightarrow B_i \\ B_i + O_i \longrightarrow B_i\,O_i \end{cases}$$

TSC. Defect Concentration

Sensor: CIS16-EPI-08-50-DS-93

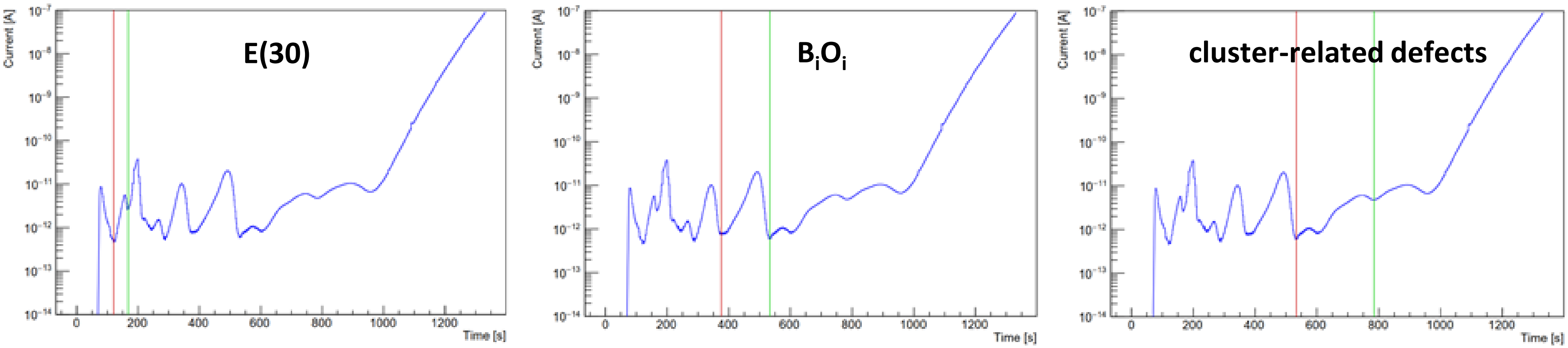
$\Phi = 7.80 \cdot 10^{13}\ n_{eq}/cm^2$

$\rho = 250\ \Omega$ cm

annealing = 10 min @ 60°C

PRELIMINARY

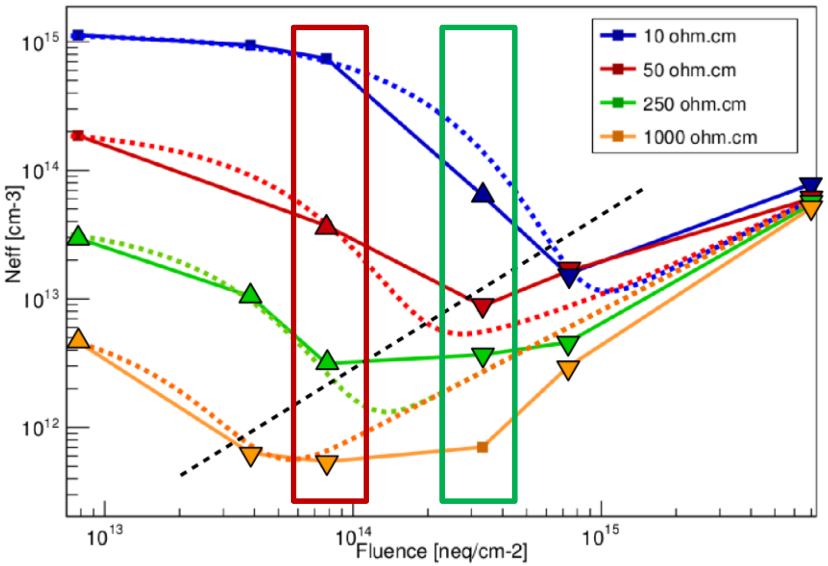
Integration over the observed TSC peak in time allows us to calculate the defect concentration:



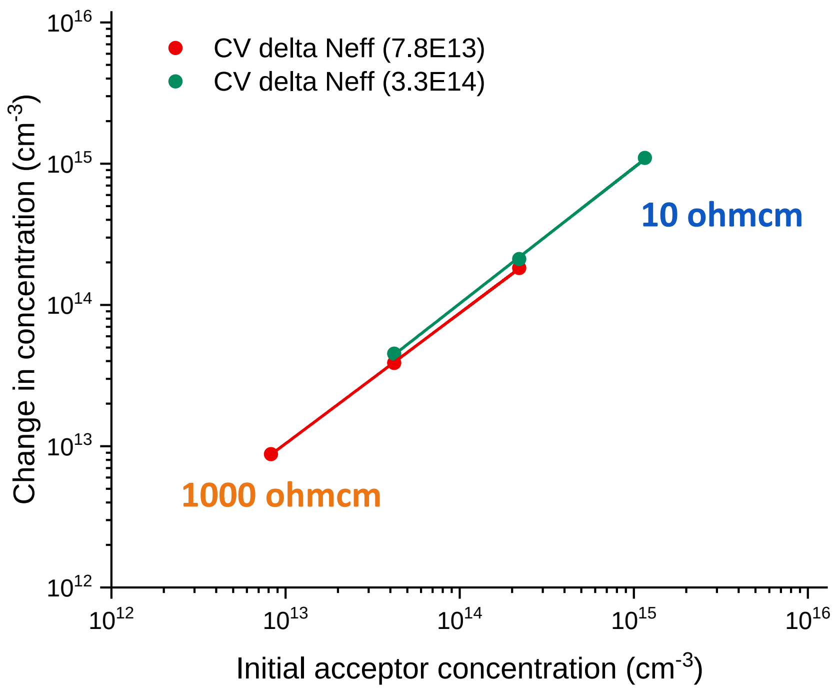
Sensor			TSC		
Name	Fluence	Resistivity	E[30]	[BiOi]	[H116+H140+H152]
EPI-05-94	7.80E+13	50		3.80E+13	1.01E+13
EPI-08-93	7.80E+13	250	9.30E+11	4.65E+11	7.09E+12
EPI-12-93	7.80E+13	1000	3.22E+12	1.61E+12	7.25E+12
EPI-01-101	3.32E+14	10	1.22E+13	6.10E+12	5.28E+13
EPI-05-98	3.32E+14	50	4.80E+12	2.40E+12	3.74E+13
EPI-08-97	3.32E+14	250	3.12E+13	1.56E+13	3.06E+13

Assuming B_iO_i is double-charged

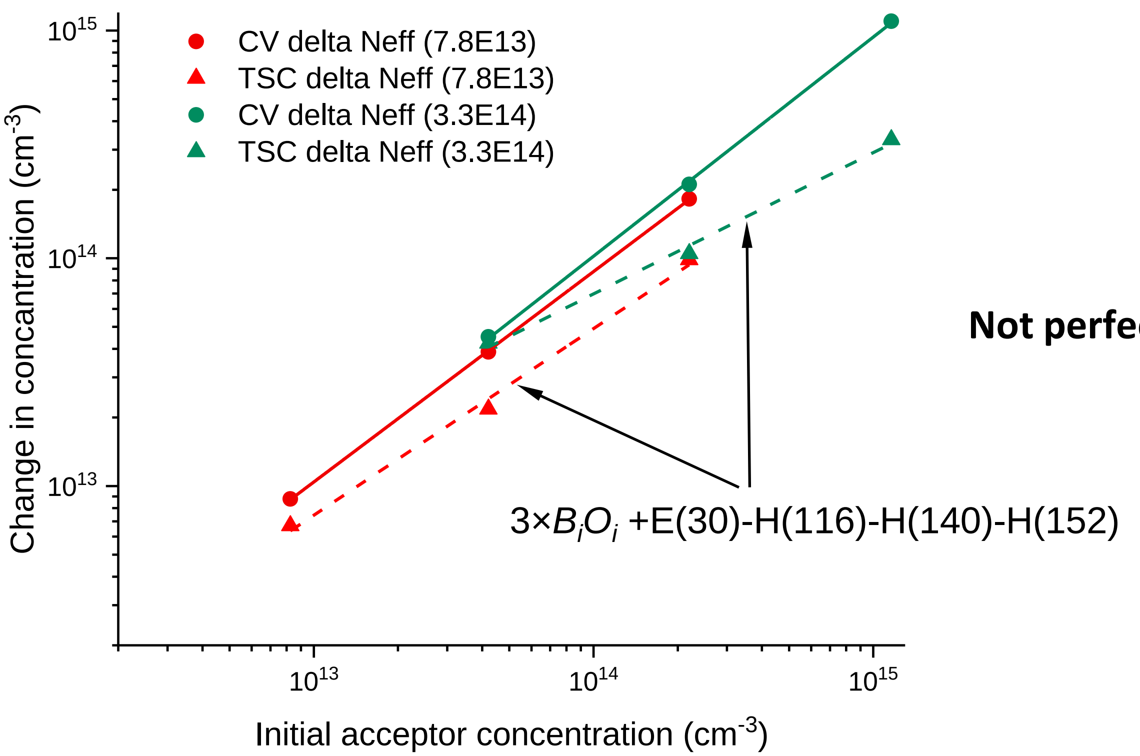
ΔN_{eff} vs $N_{eff,0}$



<u>Type inversion</u>



Concentration of defects with impact on N_{eff} (space charge)



Not perfect agreement, but same tendency!

Summary and Outlook

Work to study acceptor removal in progress :

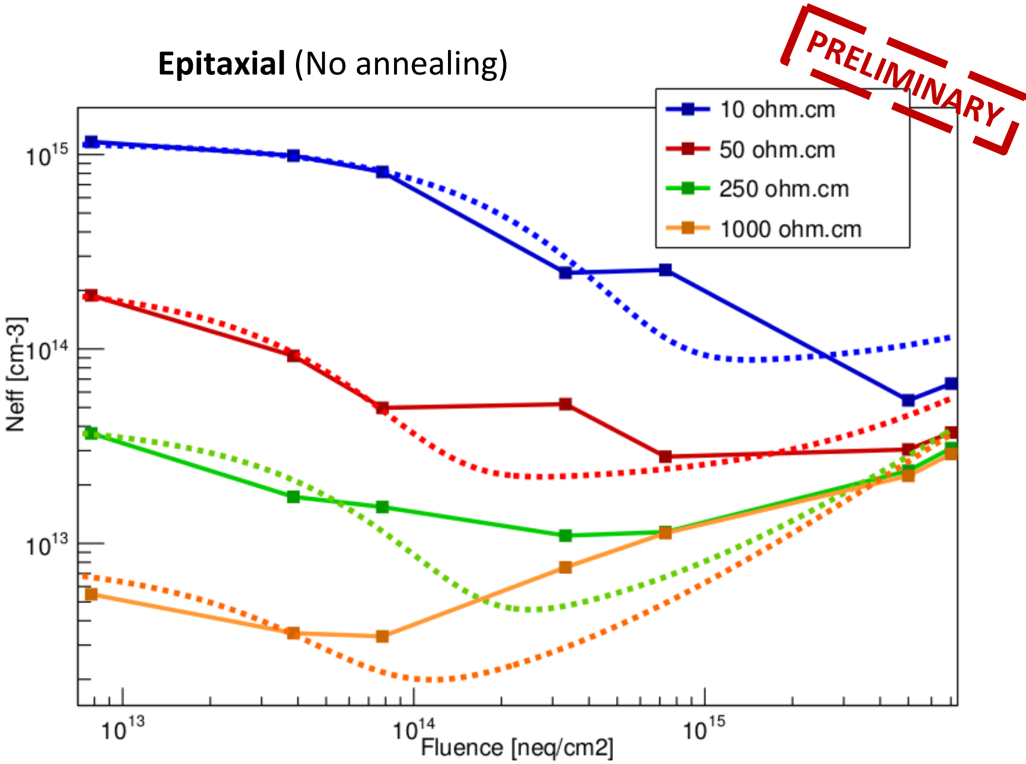
- Defects contributing to the space charge (V_{dep}, N_{eff}) were investigated with CV/IV and TSC measurements, charge collection vs bias (type inversion) – with TCT measurements
- B_iO_i is identified to have a potentially big impact on radiation damaged p-type highly doped Si
- Strong dependence between B_iO_i production and resistivity was detected by TSC measurement
- B_iO_i is detrimental for the detectors performance (could be protected by introducing more Carbon and less Oxygen or using Gallium instead of Boron to impact on defect kinetics)

- Results should be checked for other materials, higher fluences and different types of irradiation. Additional annealing study, TSC with red light illumination, determination of parameters for other observed defects should be presented to complete existing result

Backup slides

Neutron Irradiation Campaign

Epitaxial (No annealing)



- Fitted function:

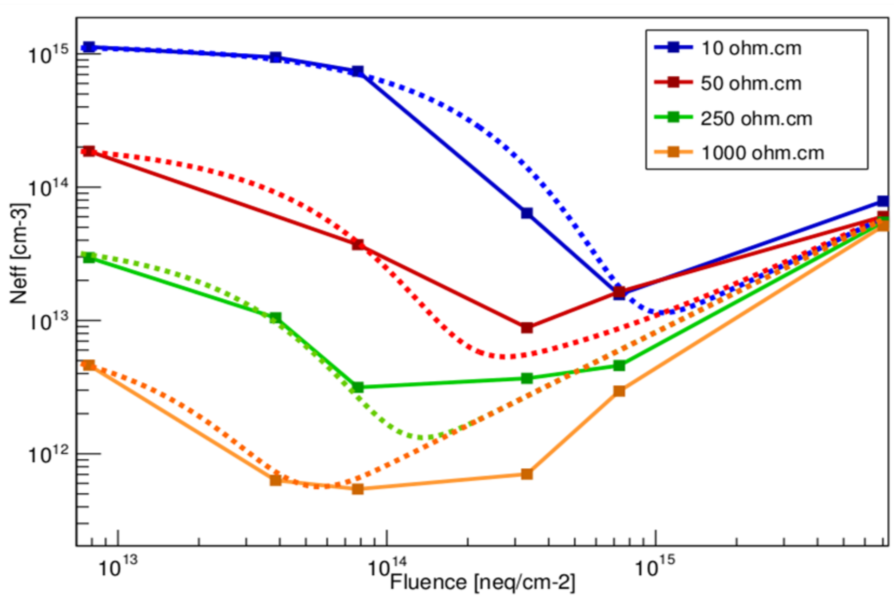
$$N_{eff}(\Phi) = N_{eff0} - N_c\left(1 - e^{-c\Phi}\right) + g_c\Phi$$

- The linear slope g_c was constrained to be the same across the different resistivities

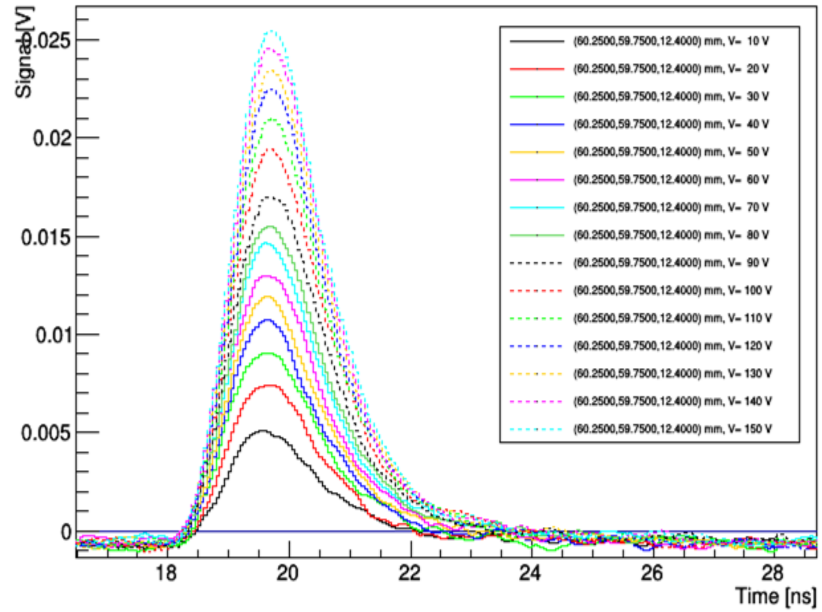
	measured	fitted		
ρ [Ω cm]	**$N_A(0)$ [cm^{-3}]**	**N_c [cm^{-3}]**	**C [cm^2]**	**g_c [cm^{-1}]**
10	1.16e15	1.08e15	4.88e-15	5.02e-3
50	2.20e14	1.99e14	2.54e-14	
250	4.21e13	3.90e13	2.02e-14	
1000	8.25e12	6.99e12	3.30e-14	

Incomplete acceptor removal

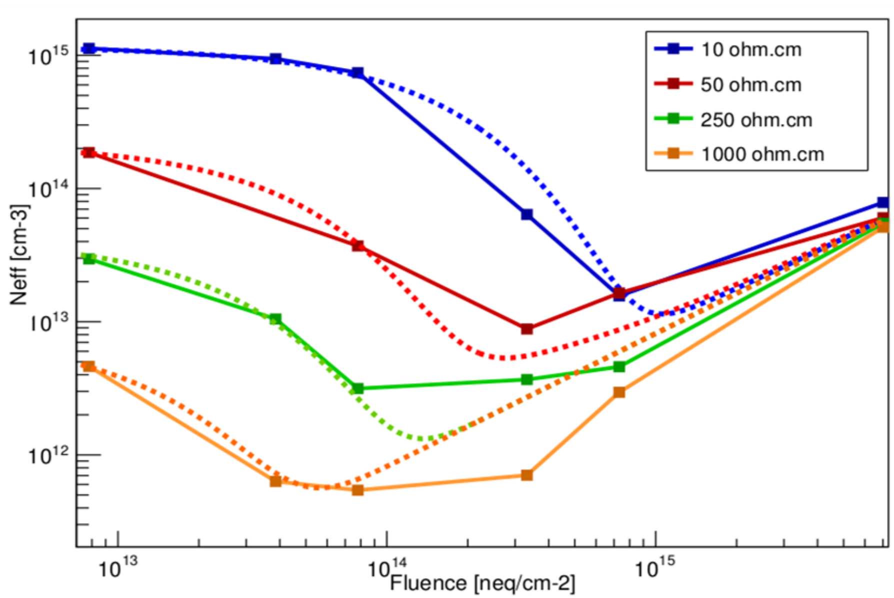
TCT results



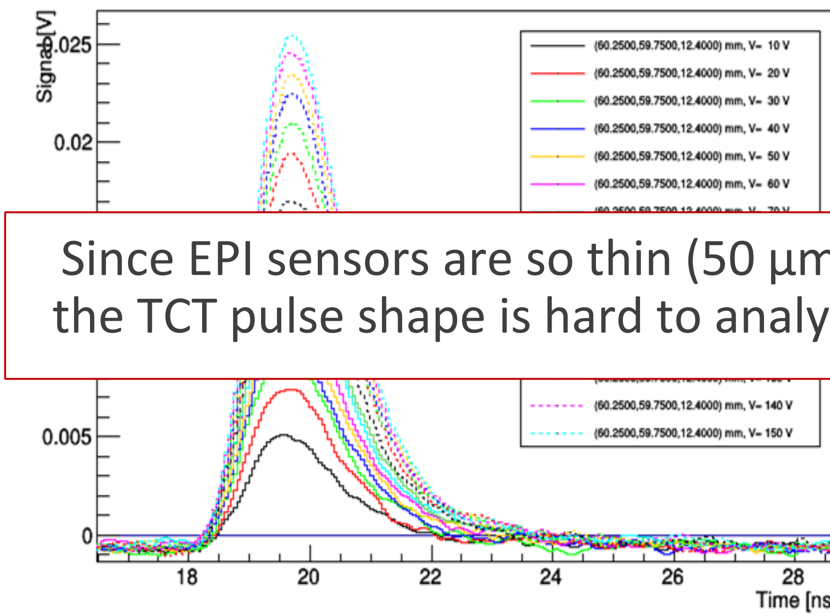
Example of a TCT voltage scan



TCT results



Example of a TCT voltage scan



Since EPI sensors are so thin (50 µm), the TCT pulse shape is hard to analyse

However, a comparison between the charge collection of red top, red bottom and infra-red TCT can be used to confirm the type inversion

New fitting (to be done)