Characterization of acceptor removal in silicon pad diodes irradiated by protons and neutrons

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Motivation

- The so-called acceptor removal is an apparent deactivation of the doping in p-type silicon due to irradiation

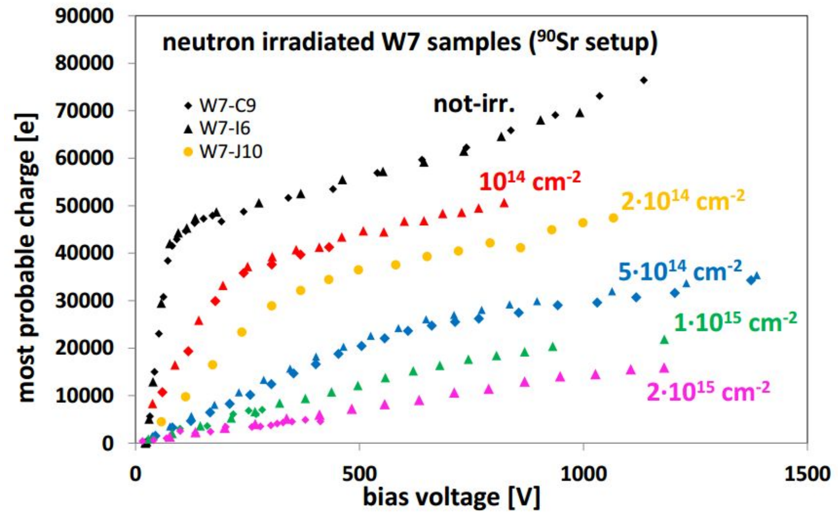
- Usually parameterized as

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

- For neutron irradiation, incomplete acceptor removal is also considered ($N_c < N_{eff0}$)

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

Example:
In LGADs, acceptor removal destroys the highly doped layer reducing the device gain

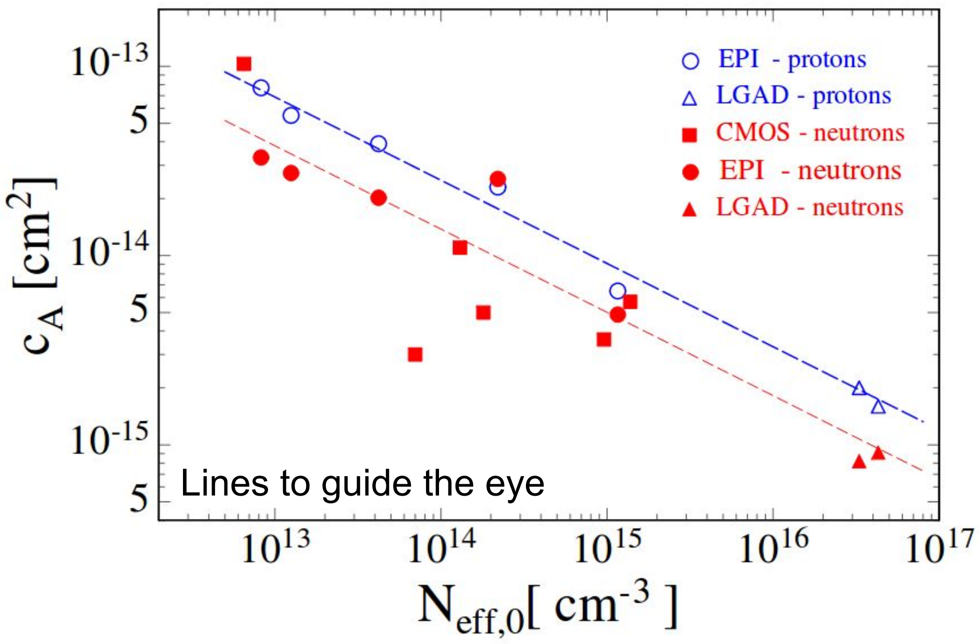


G. Kramberger et al, JINST (2015)

Motivation

M. Moll (2017) https://doi.org/10.1109/TNS.2018.2819506

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



K. Kaska (2014)
http://repositum.tuwien.ac.at/obvutwhs/content/titleinfo/1633435

A. Affolder *et al.* (2016)
https://doi.org/10.1088/1748-0221/11/04/P04007

E. Cavallaro *et al.* (2017)
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B. Hiti *et al.* (2017)
https://doi.org/10.1088/1748-0221/12/10/P10020

I. Mandić *et al.* (2017)
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P. Dias de Almeida (2017)
https://indico.cern.ch/event/637212/

G. Kramberger (2017)
https://indico.cern.ch/event/577879/

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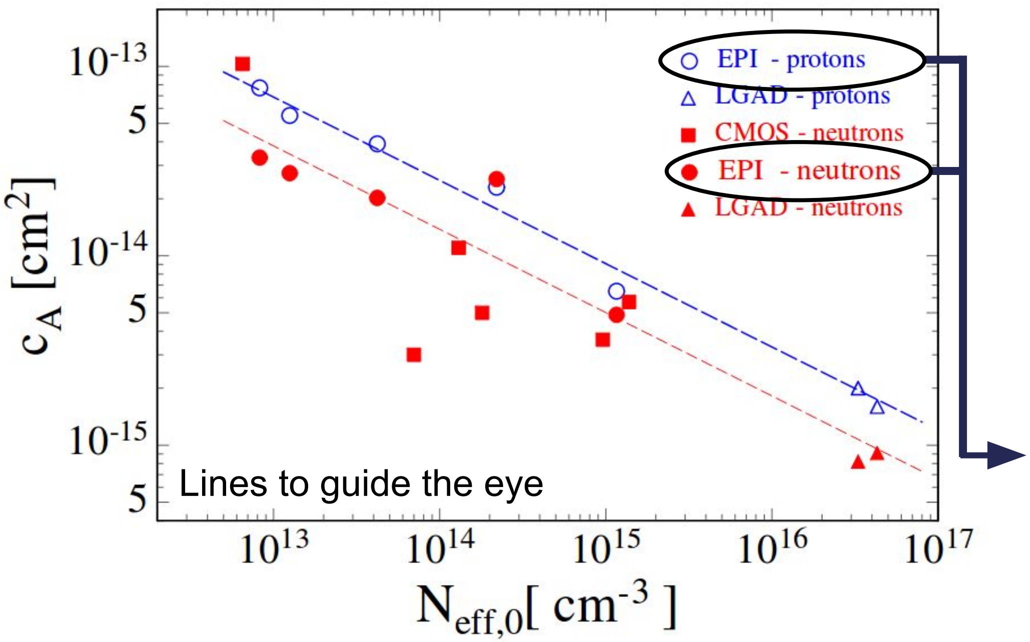

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First results presented in Krakow (30th RD50), however evidence of type inversion motivated the refitting of the data.

Materials

Simple p-type pad diodes

Epitaxial

10, 50, 250, 1000 Ω·cm
50 μm

Float zone

>10 000 Ω·cm
100, 150, 200, 285 μm

Forschungsinstitut für Mikrosensorik GmbH

Proton and Neutron Irradiation

From ~ 7×10^{12} to 7×10^{15} $n_{eq}cm^{-2}$

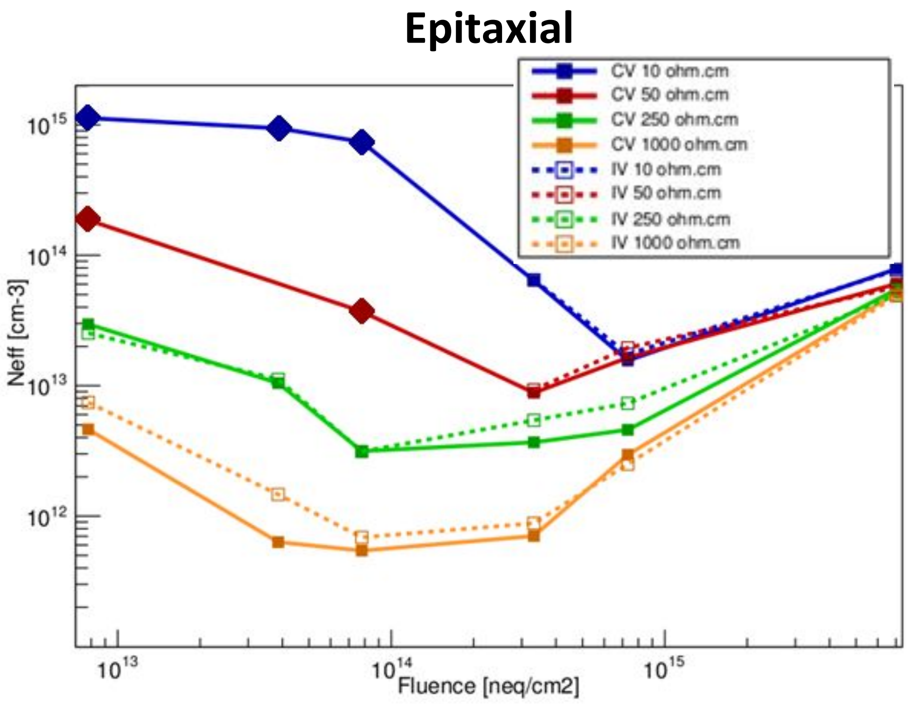
CERN IRRAD Proton Facility

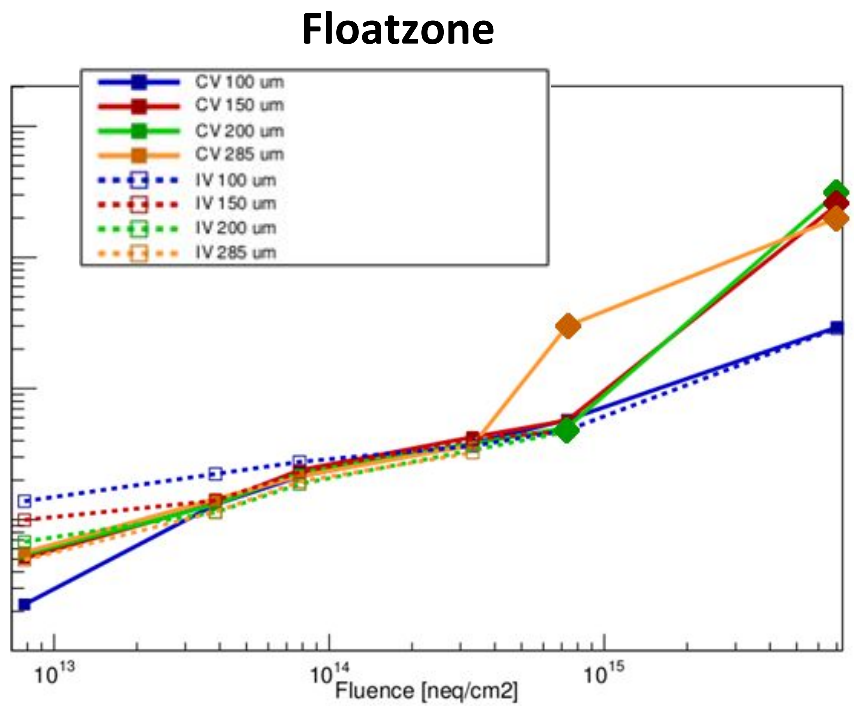
Institut "Jožef Stefan" 50 let REAKTORJA TRIGA

Acceptor Removal Previous Results

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

Proton irradiated

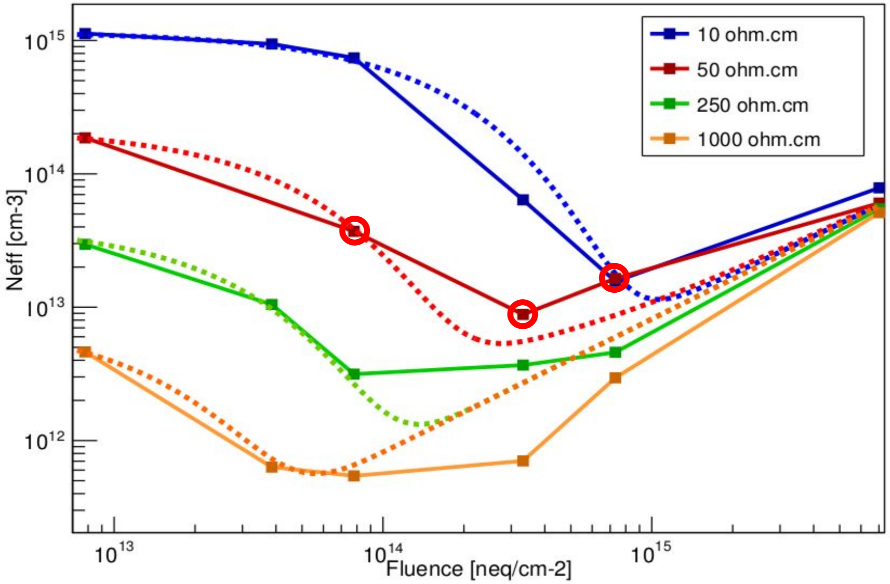




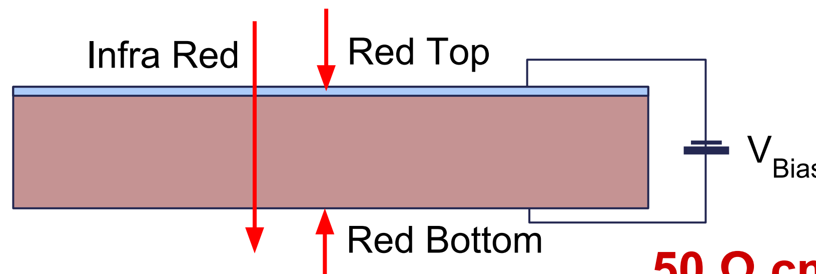
■ from CV/IV kink: $$N_{eff} = \left(\frac{C}{A}\right)^2 \frac{2V_{dep}}{\varepsilon\varepsilon_0 q_0}$$

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

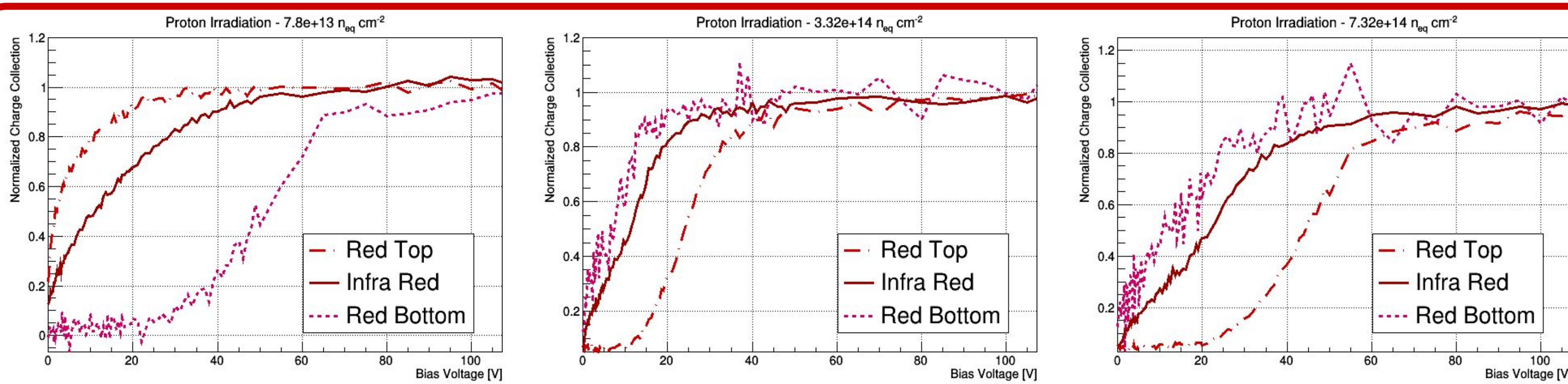
Acceptor Removal Space Charge



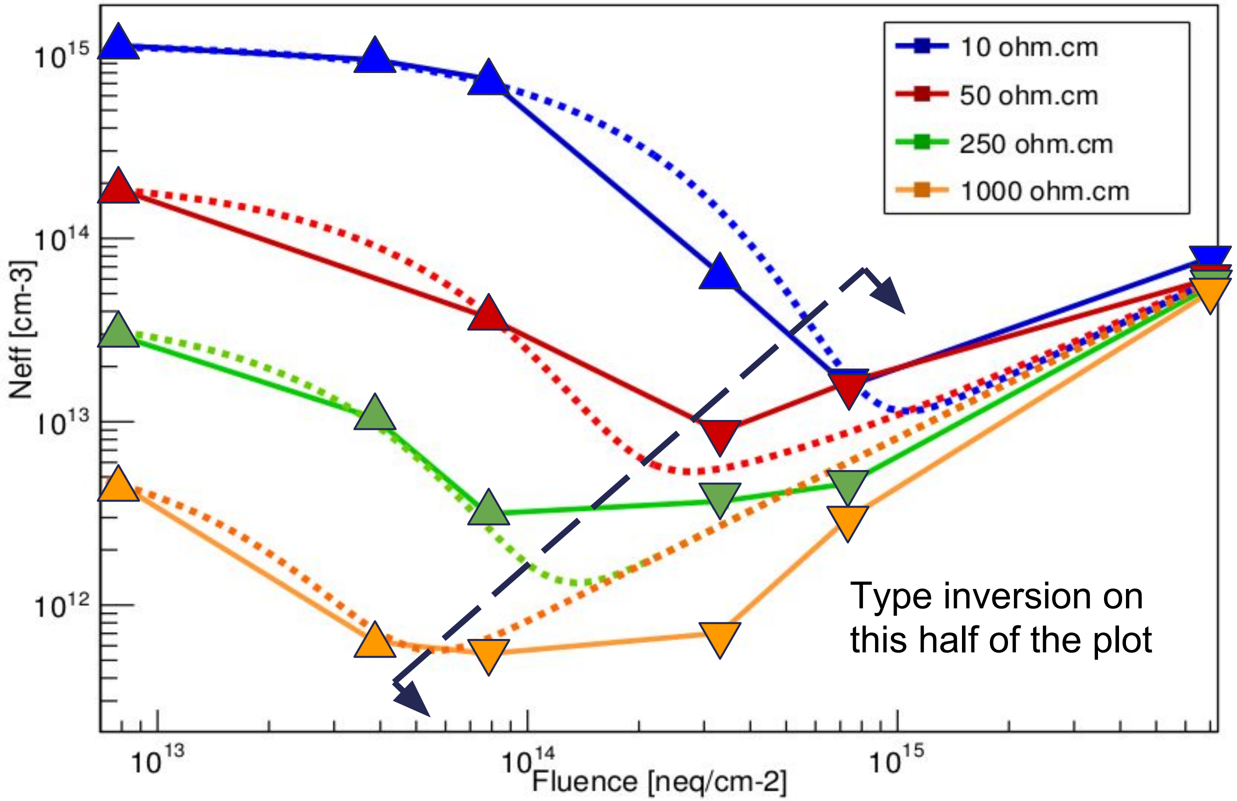
The shape of the TCT waveform could not be used to check sign inversion because the sensors are just 50 µm. But by comparing the charge collected over bias for different light injections, **it was possible to verify type inversion**.



50 Ω.cm



Acceptor Removal Type Inversion

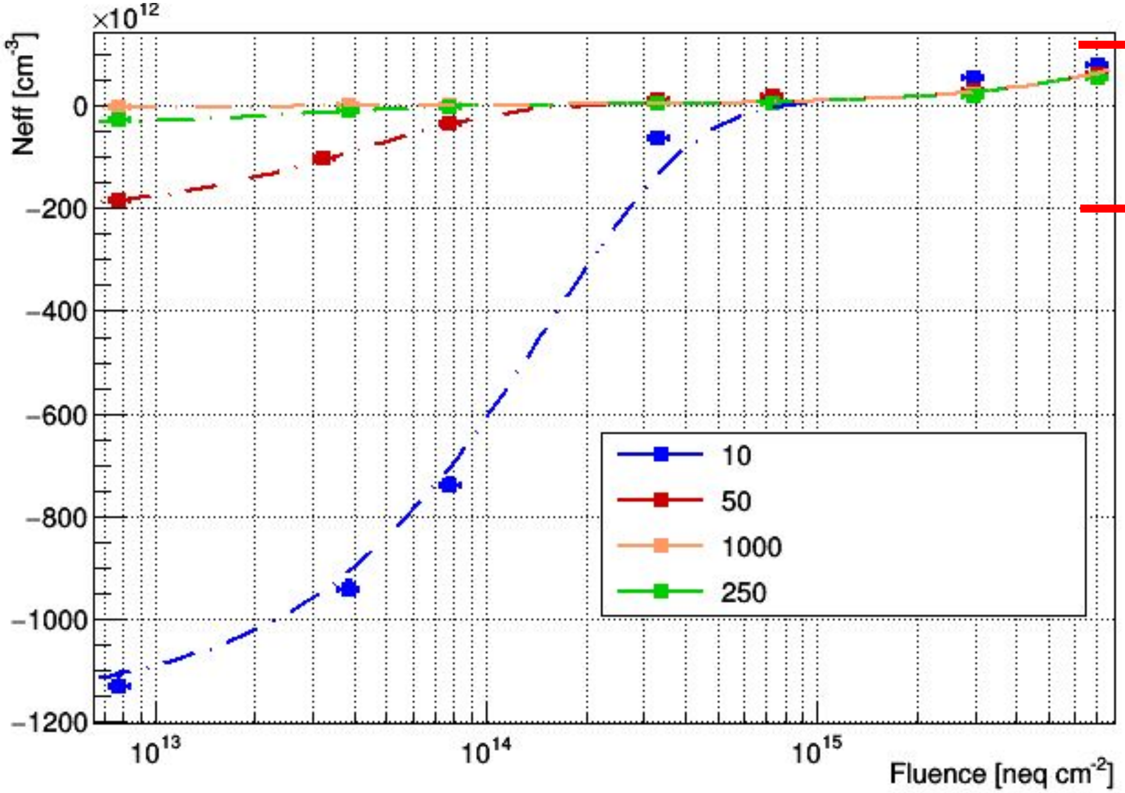


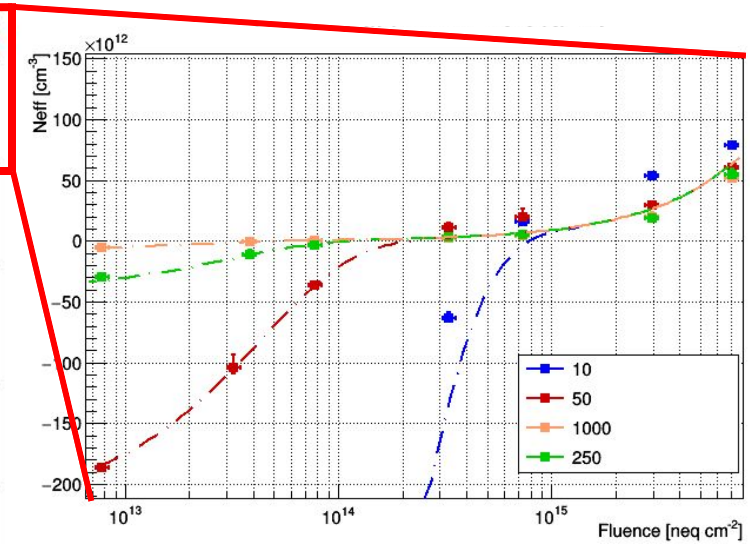
△ Depletes from the top
▽ Depletes from the bottom

NB: Additional evidence of type inversion from an annealing study: P. Dias de Almeida *et al.* 31st RD50

Acceptor Removal by Proton Irradiation

Annealing: 10 min @ 60ºC



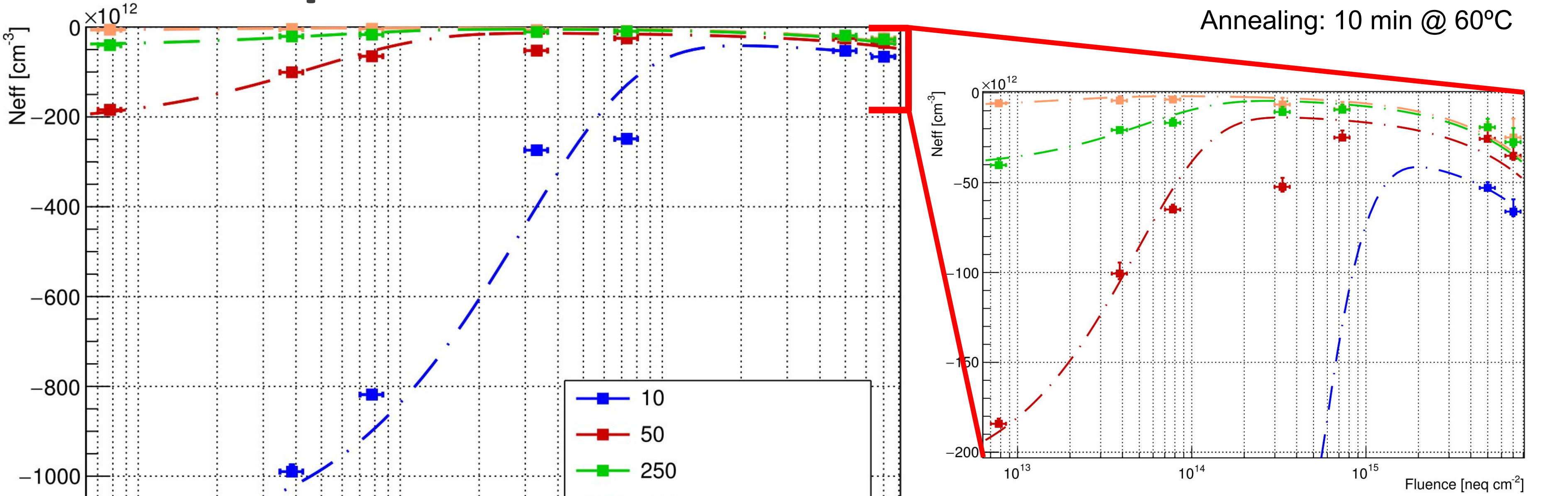


Fitted function:

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

	measured	fitted	
ρ [Ω.cm]	$-N_{eff0}$ [cm^{-3}]	c [cm^2]	g_c [cm^{-1}]
10	1.16e15	6.20e-15	7.63e-3
50	2.20e14	2.28e-14	
250	4.21e13	3.44e-14	
1000	8.25e12	5.47e-14	

Acceptor Removal by Neutron Irradiation



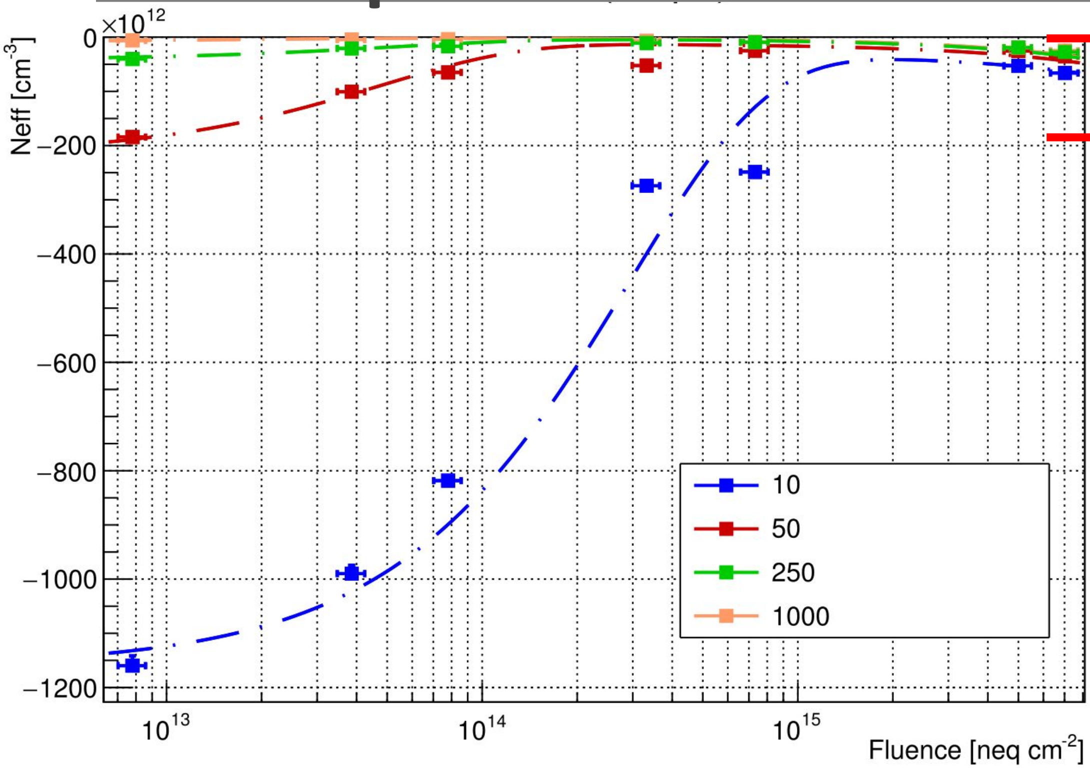
ρ [Ω.cm]	$-N_{eff0}$ [cm^{-3}]	$-N_c$ [cm^{-3}]	c [cm^2]	g_c [cm^{-1}]
10	1.16e15	1.13e15	3.39e-15	
50	2.20e14	2.08e14	2.08e-14	-4.50e-03
250	4.21e13	3.90e13	1.87e-14	
1000	8.25e12	6.81e12	5.43e-14	

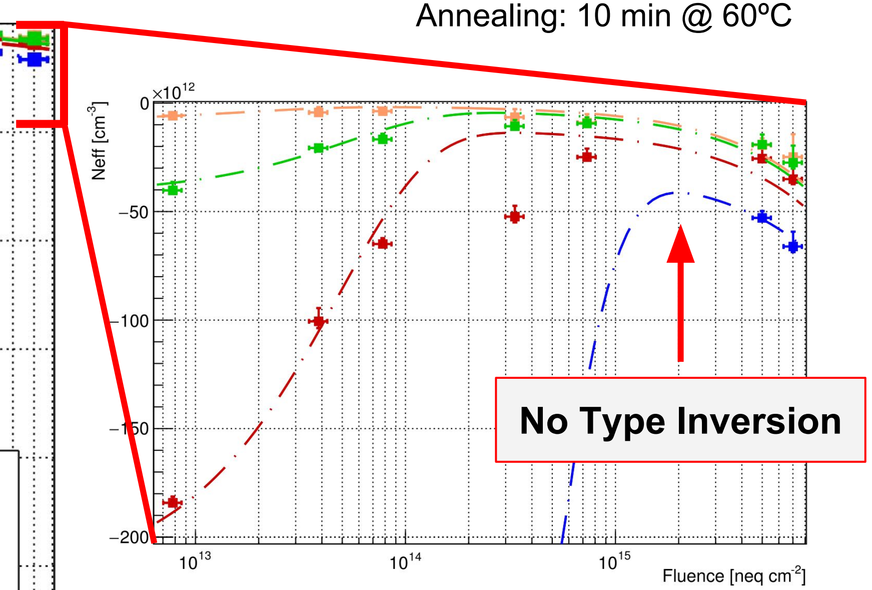
Fitted function:

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

Acceptor Removal by Neutron Irradiation

Annealing: 10 min @ 60ºC





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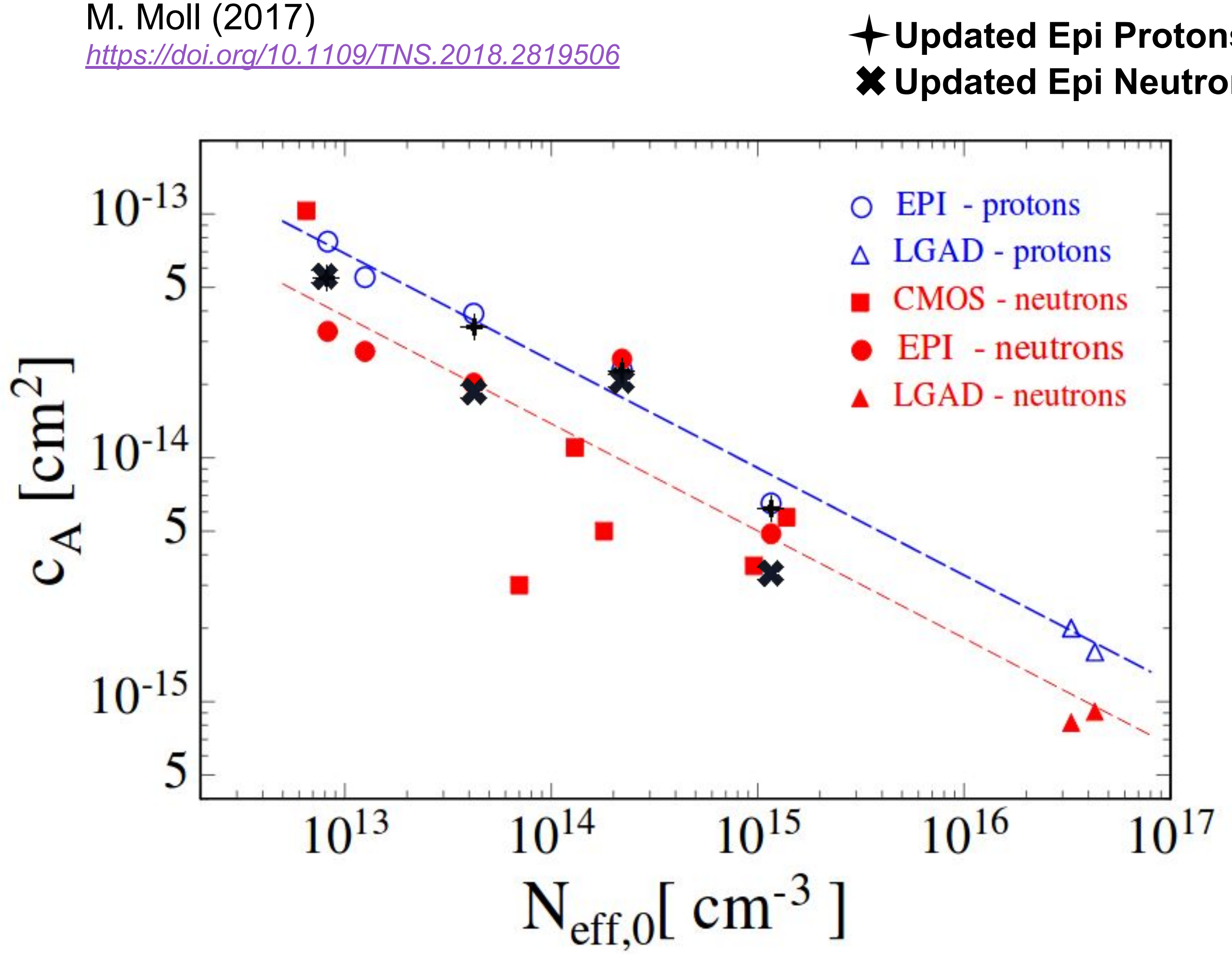
Acceptor Removal

M. Moll (2017)
https://doi.org/10.1109/TNS.2018.2819506



Taking type inversion into account doesn't change the acceptor removal rate **c** in a significant way, keeping the trend previously seen.

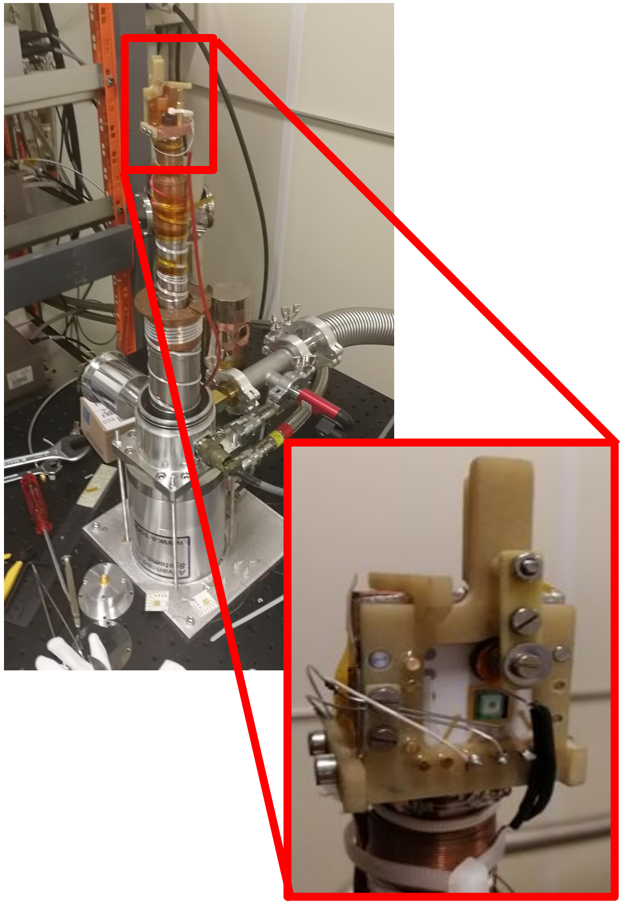
This parametrization is important by itself, but we would like to understand the defect dynamics of acceptor removal

TSC

Thermally stimulated current (TSC) consists in bringing the DUT to low temperatures (e.g. 20K), fill the traps caused by the defects (e.g. by applying forward current) and ramp up the temperature while monitoring the current.

- Gives a spectrum of the defects, since the temperature at which the trapped charges are released is correlated to the energy level of the defect

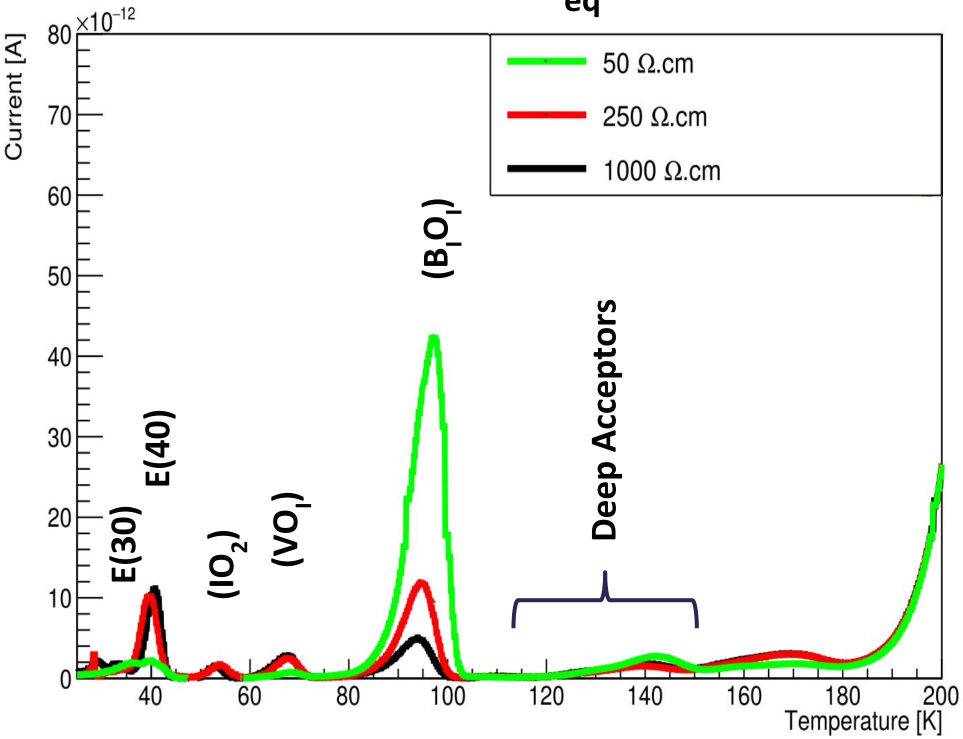
- Allows for the estimation of defect concentration by measuring charge released by the defects’ peaks



TSC Proton Irradiation

Annealing: 10 min @ 60ºC

$7.80 \times 10^{13}\ n_{eq}/cm^2$

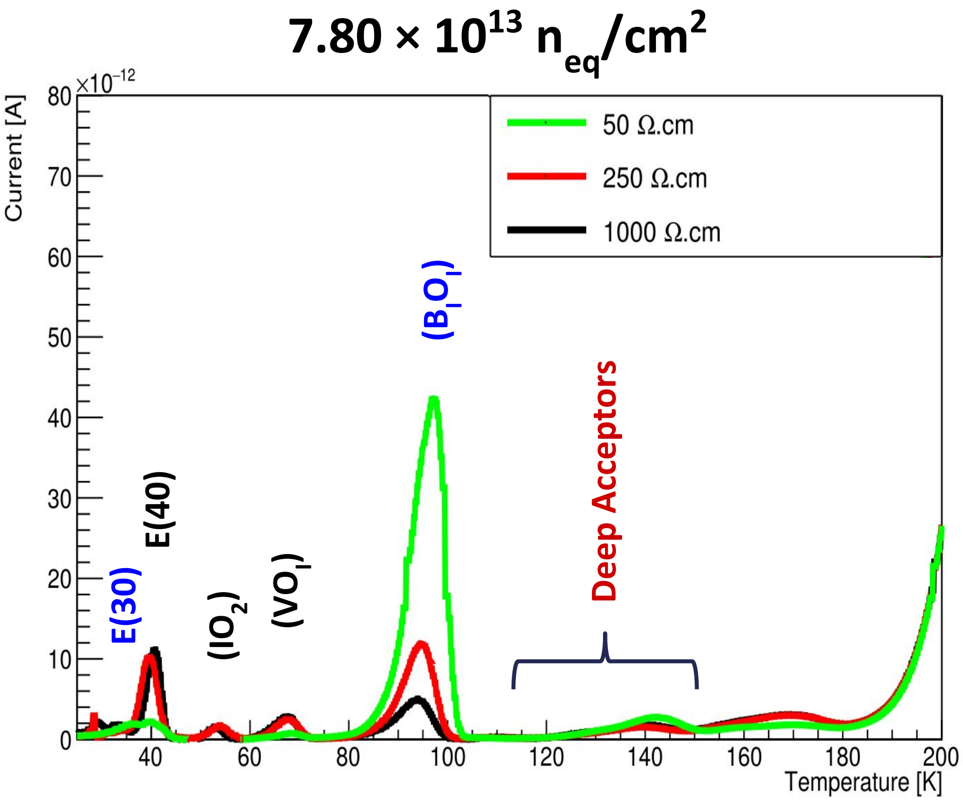


There is a clear dependence of the B_iO_i peak with the initial Boron concentration. Suggesting that the main mechanism for acceptor removal is:

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

TSC Proton Irradiation

Annealing: 10 min @ 60ºC



<u>Assumptions:</u>

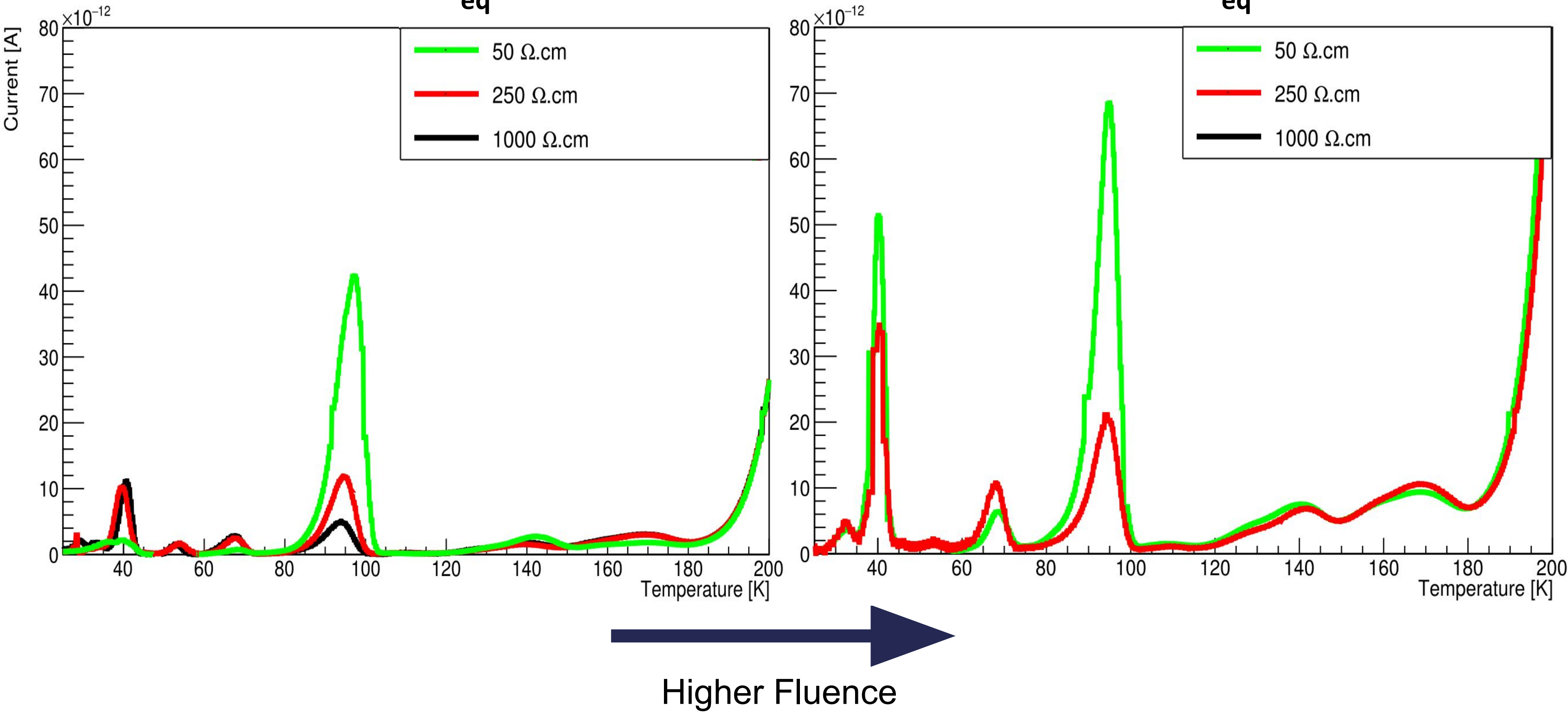
- E(30) behave as a donor, and therefore contributes to positive space charge
- H(116), H(140) and H(152) behave as acceptors, and therefore contributes to negative space charge
- B_IO_I also behaves as a donor, but for each B_iO_I created there is one less B acceptor. For this reason the concentration of B_IO_I is counted twice for space charge considerations in the upcoming analysis

Elena Donegani *et al.* (2015), 27th RD50 Workshop

TSC Proton Irradiation

Annealing: 10 min @ 60ºC

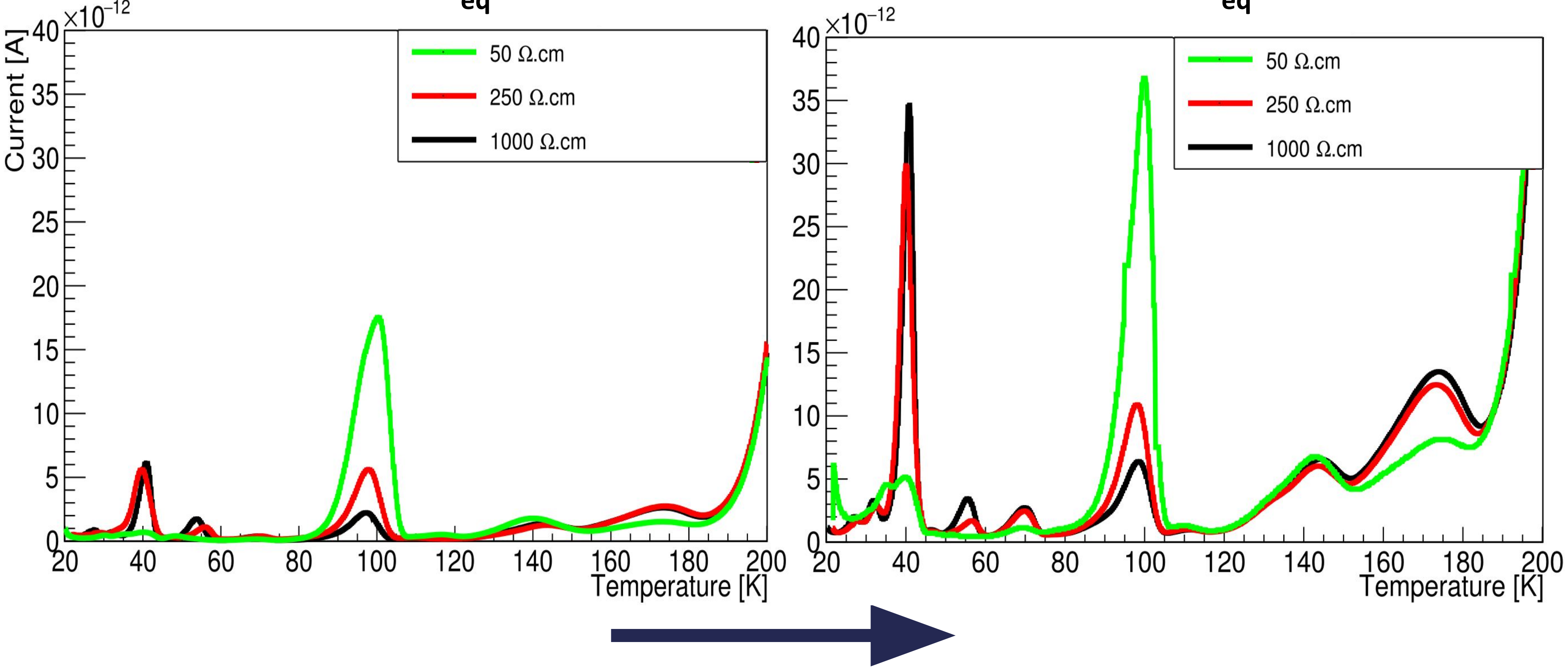
7.80×10^{13} n_{eq}/cm^2 | **3.32×10^{14} n_{eq}/cm^2**



TSC Neutron Irradiation

Annealing: 10 min @ 60ºC

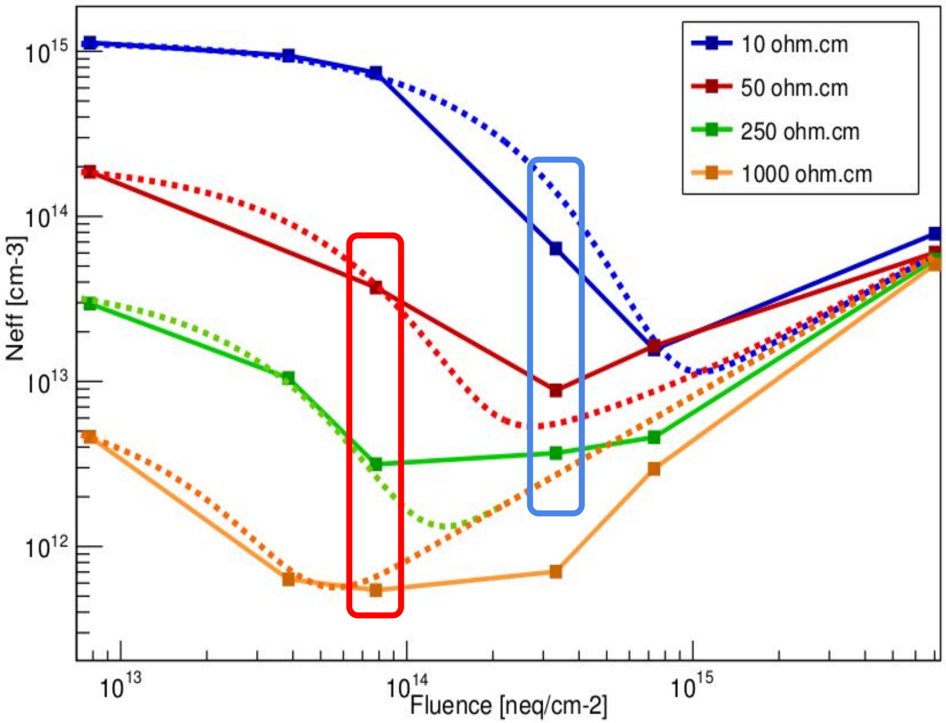
7.80×10^{13} n_{eq}/cm^2 **3.32×10^{14} n_{eq}/cm^2**

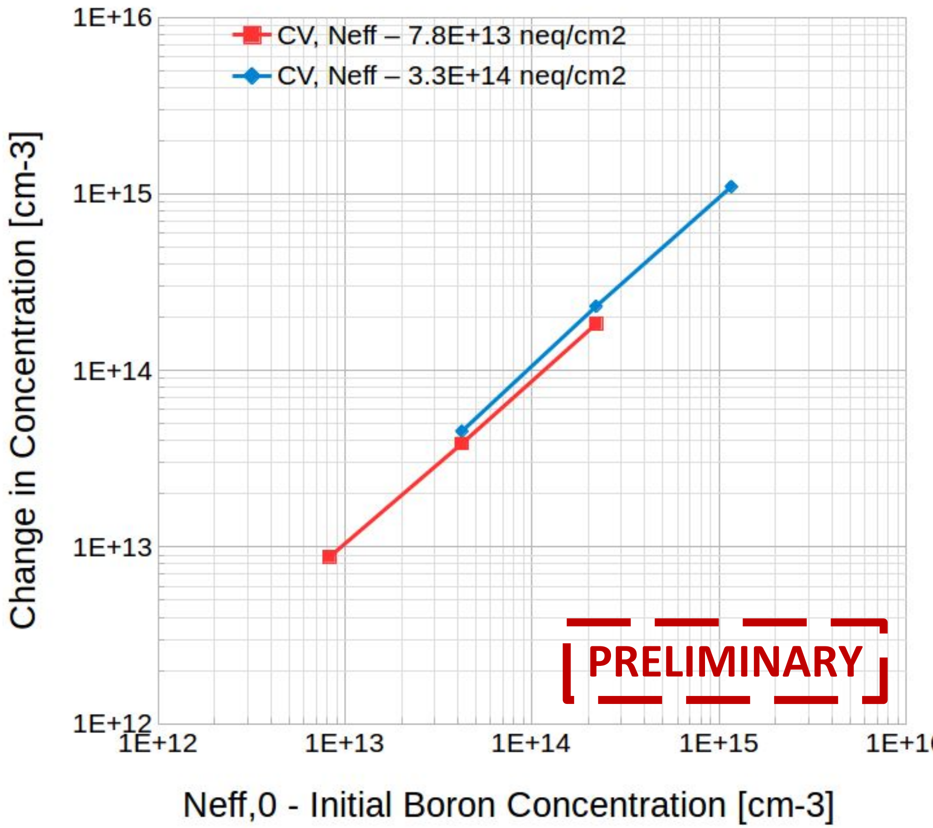


Higher Fluence

Protons Macro vs Micro

Is there a match between defects observed through TSC and the measured N_{eff} from CV?





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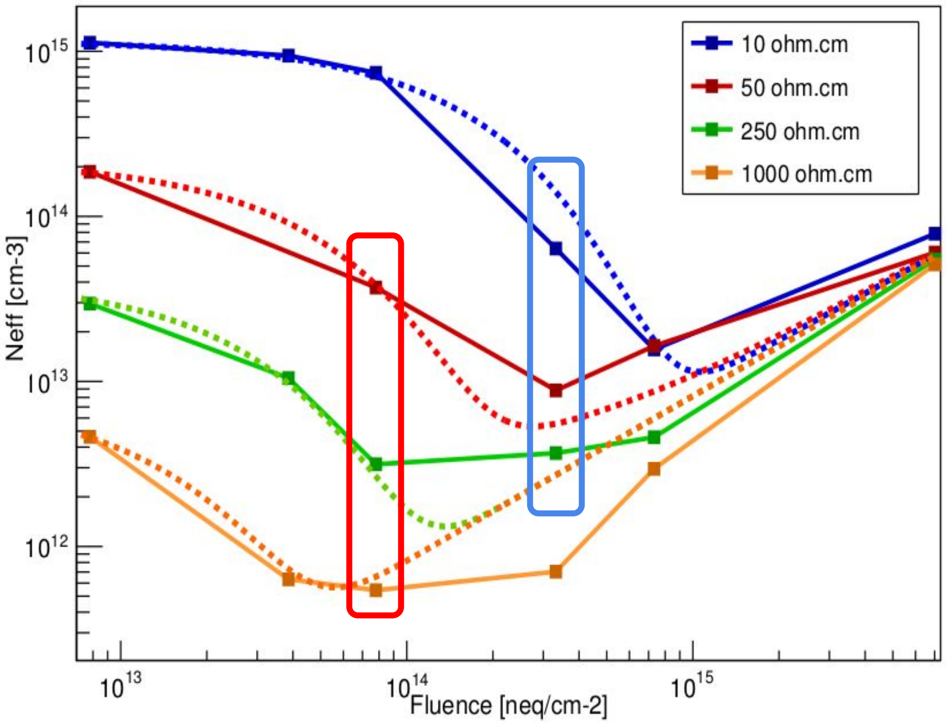
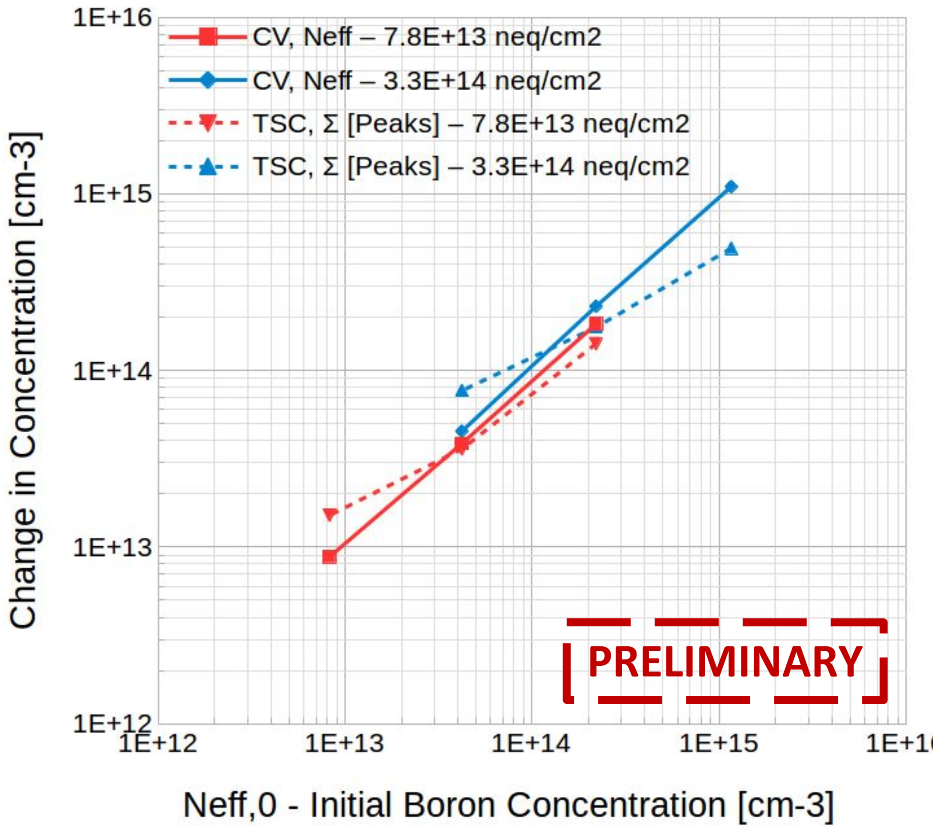
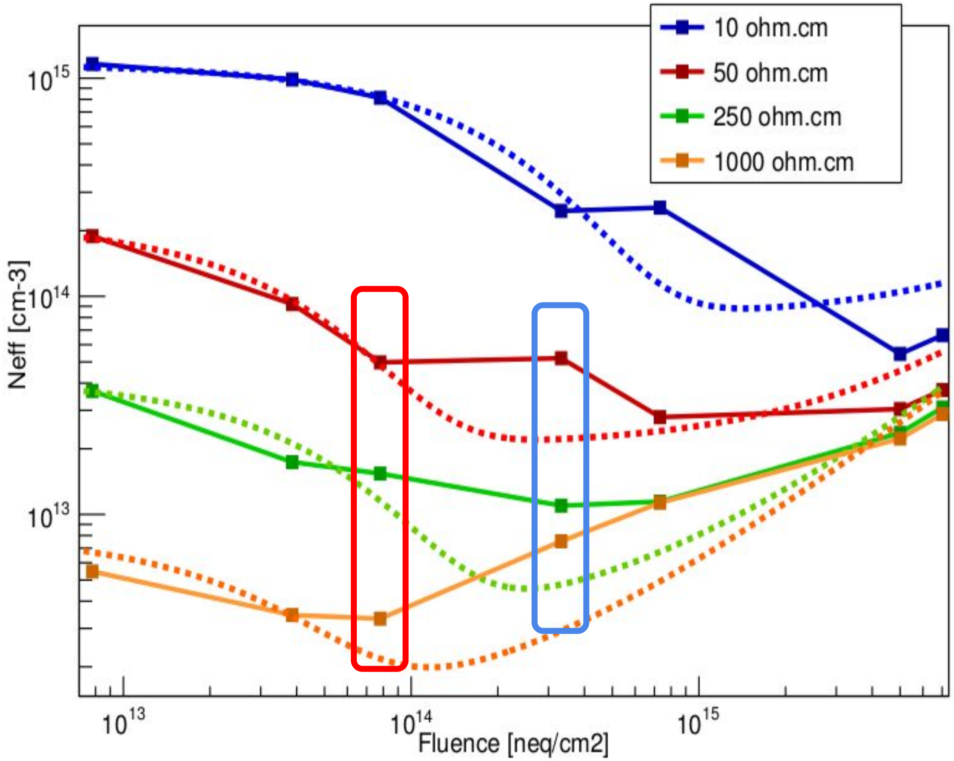
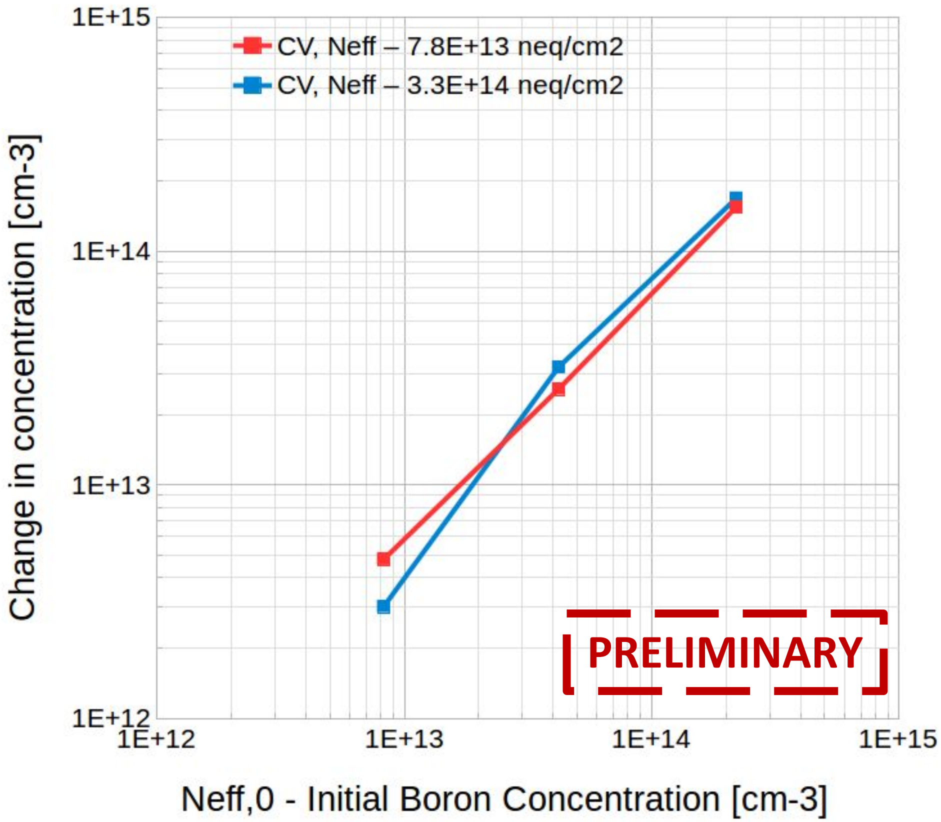




Neutrons Macro vs Micro

Is there a match between defects observed through TSC and the measured N_{eff} from CV?





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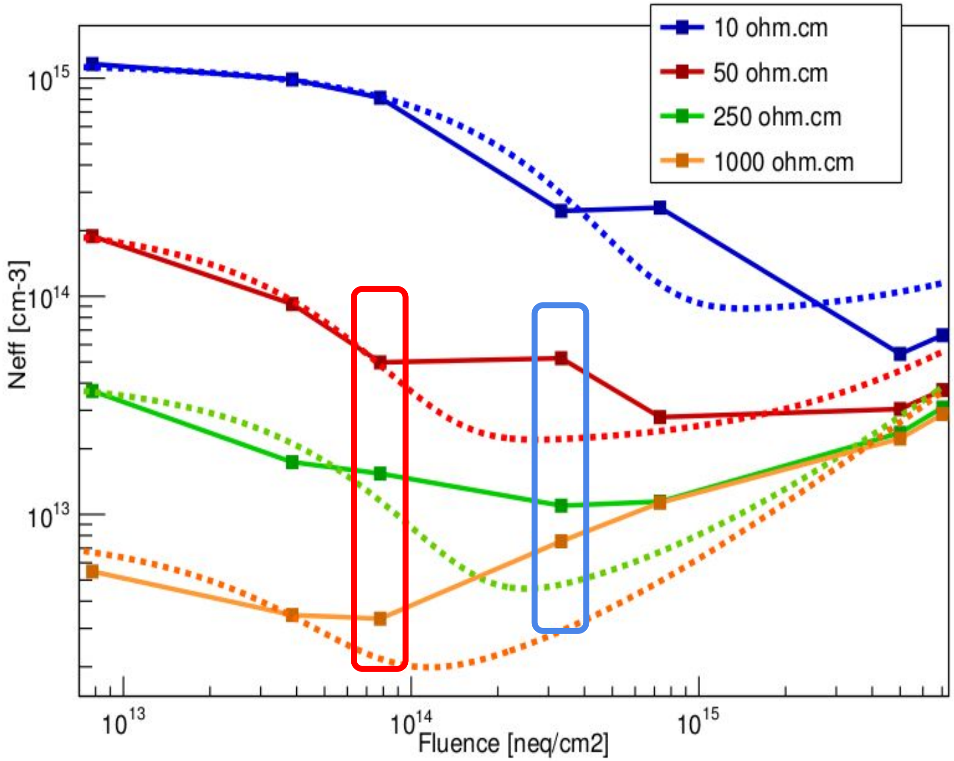
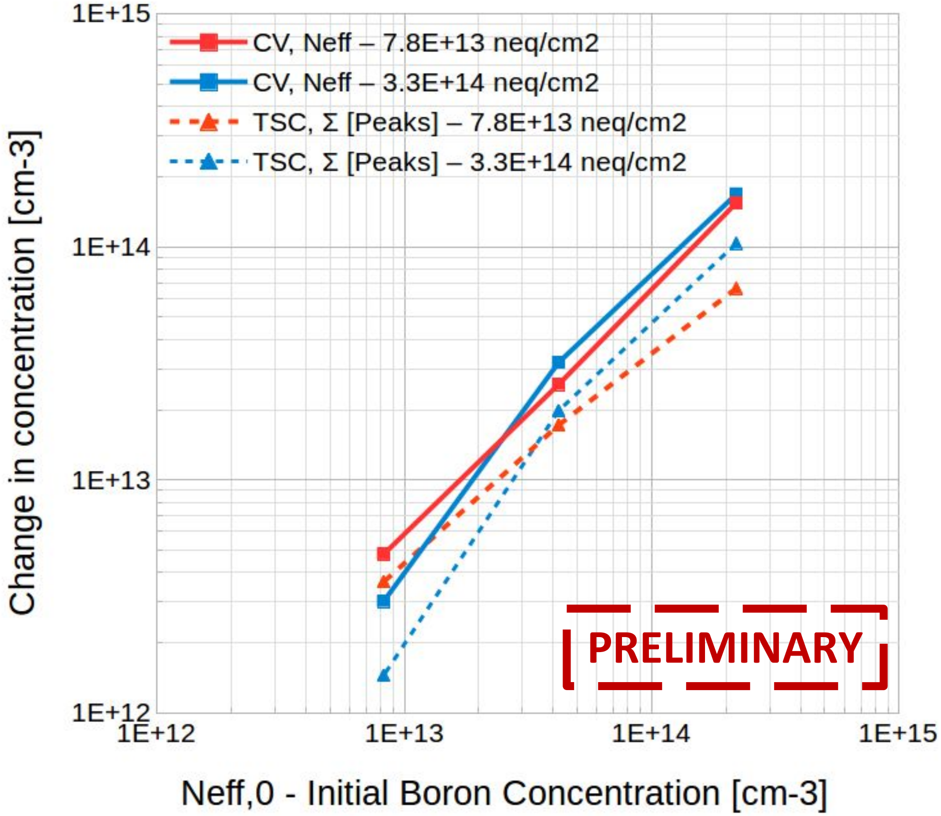




Summary and Outlook

Work in progress to study acceptor removal:

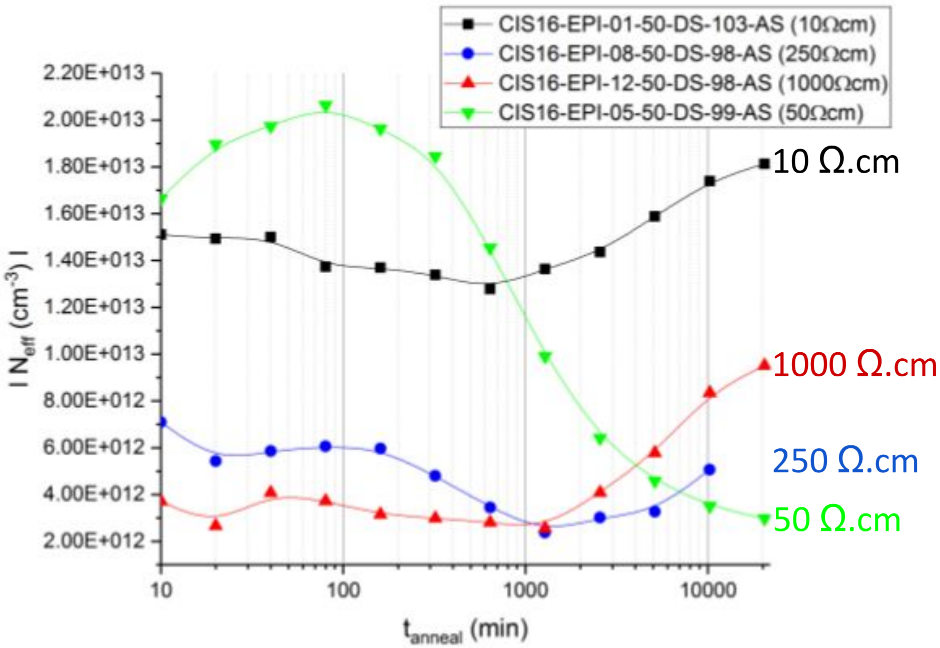
- CV, IV, TCT and TSC were used to investigate the evolution of Neff vs fluence of detectors of different resistivities irradiated by protons and neutrons
- Evidence of type inversion in p-type silicon was observed for some proton irradiated sensors
- After correction for type inversion, Neff vs fluence plots were fitted to extract the acceptor removal parameter **c**
- Strong dependence between BiOi production and resistivity was detected by TSC measurements

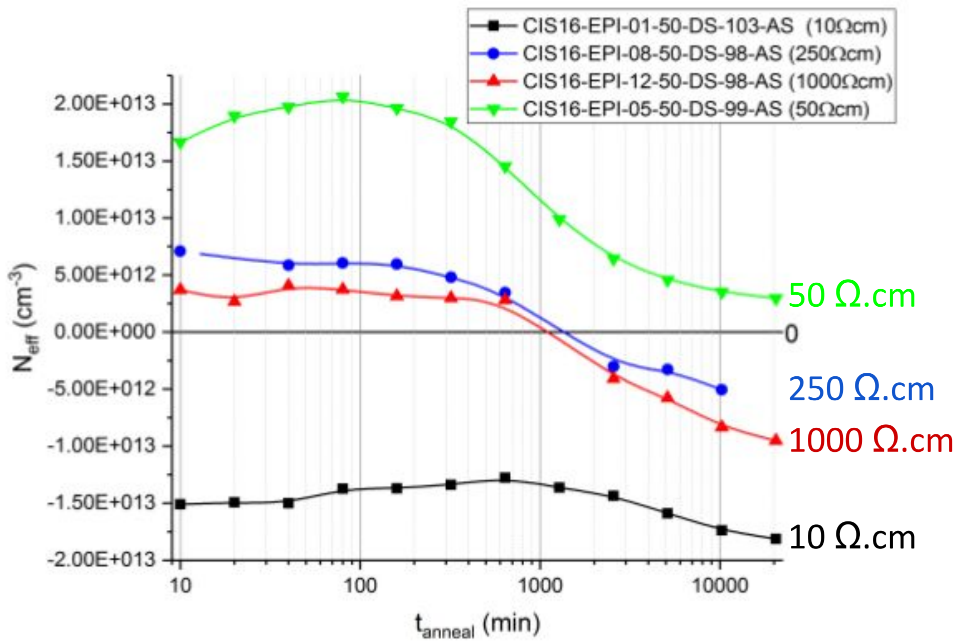
- SIMS needed to measure Oxygen concentration
- Gamma irradiation should provide a cleaner environment to study BiOi properties
- TSC with light injection is in progress (single charge carrier filling)

Spare Slides

Annealing Study Interpretation of Neff

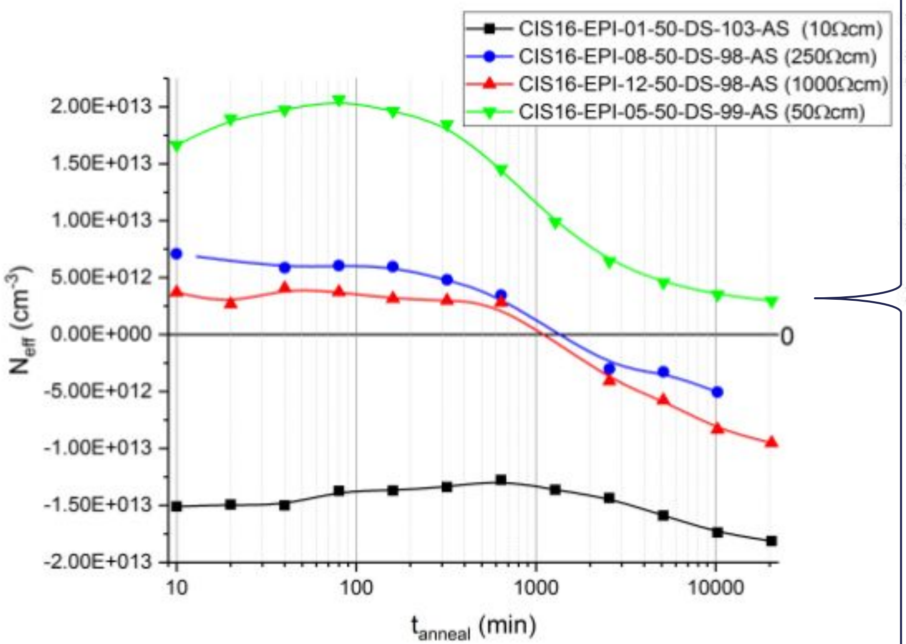
Data → **Interpretation of the data assuming type inversion**

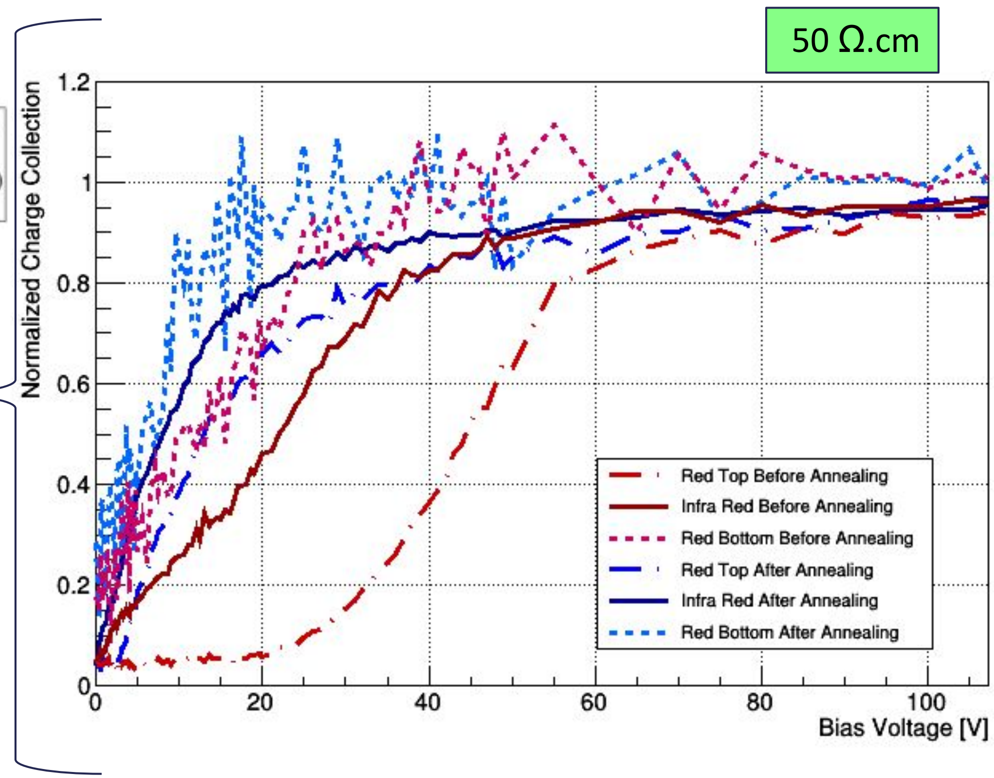




- Annealing at 60ºC
- Up to 20480 min or ~14 days of accumulated annealing
- Neff calculated from CV measurements

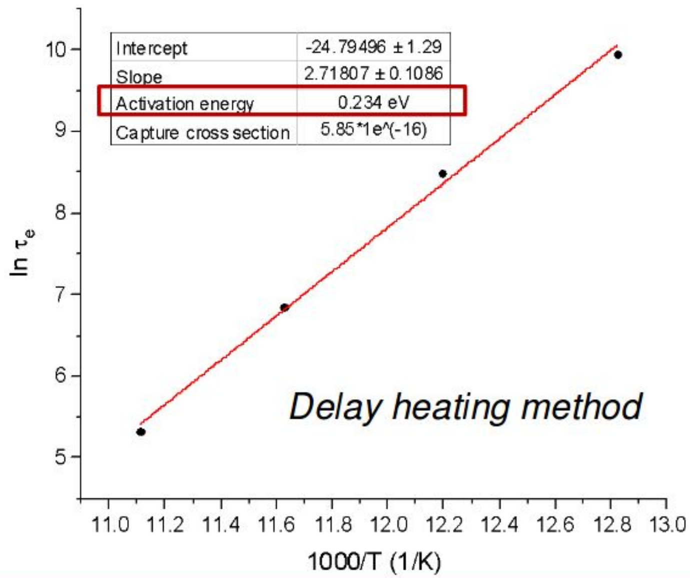
Annealing Study TCT confirmation





BiOi energy level

Defect	Emission parameters: E_a(eV), σ (cm²), 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:

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

BiOi Pool-Frankel