Acceptor removal in silicon pad diodes with different resistivities

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Acceptor removal

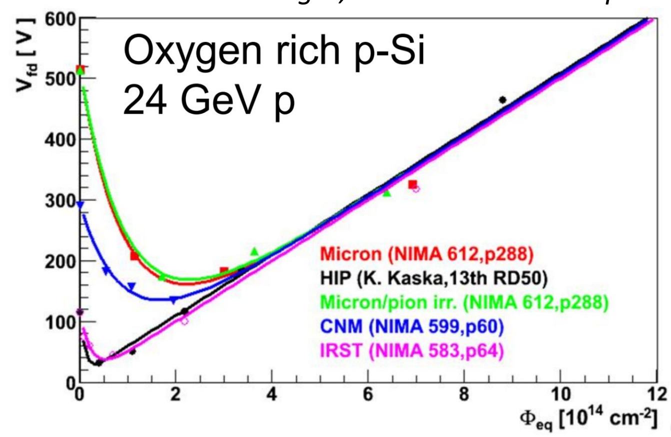
- **Apparent** dopant removal due to the irradiation
- Parameterization as

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

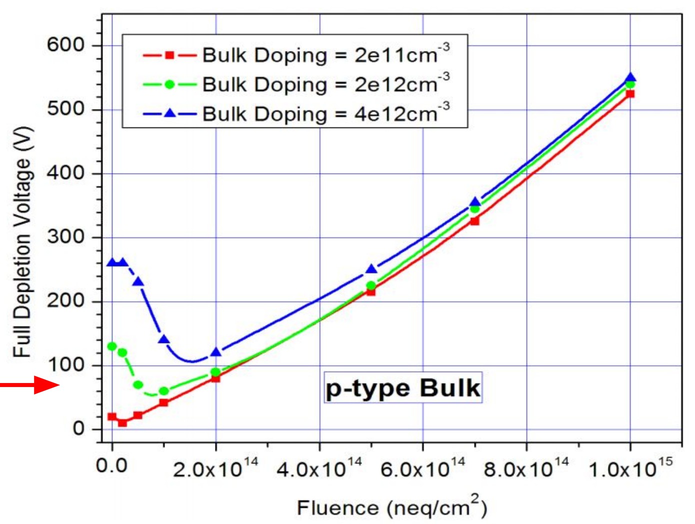
- For neutron irradiation, incomplete acceptor removal is also considered ($N_c < N_{eff0}$)

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

G. Kramberger, 23rd RD50 Workshop



Ranjeet Dalal et al, 25th RD50 Workshop

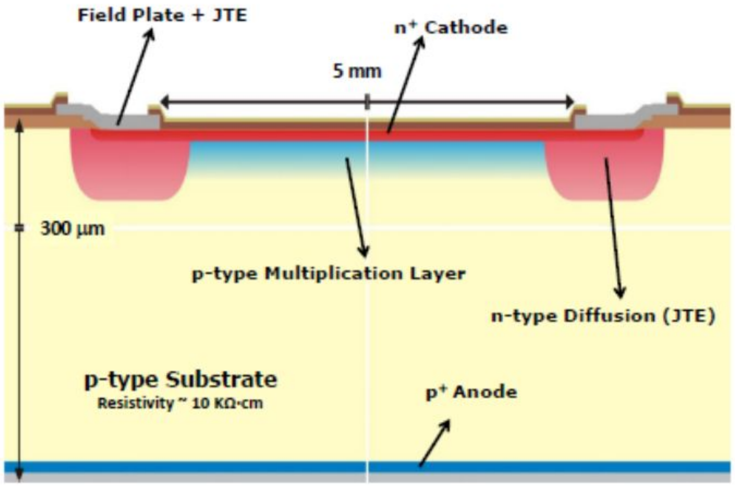


Simulation can qualitatively reproduce this behaviour **without** Boron removal

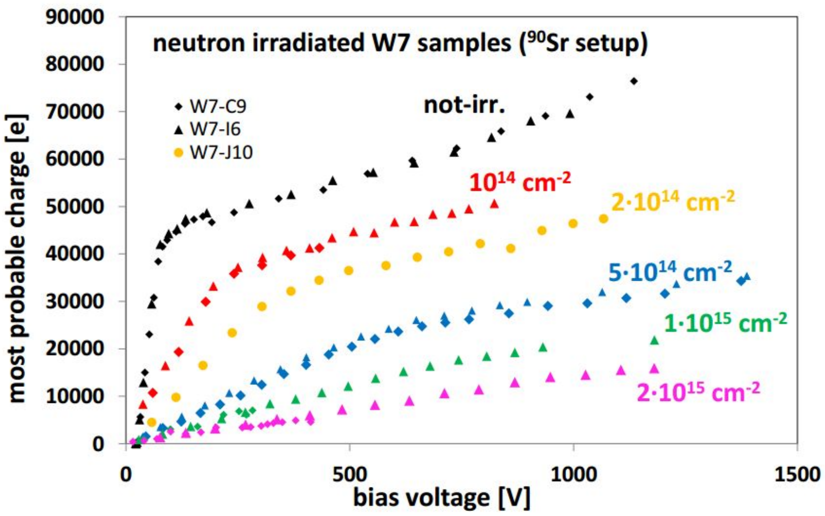
Motivation

Example: Low Gain Avalanche Detectors (LGADs)

- LGADs have a highly doped layer to achieve gain
- Interesting for their timing capabilities
- However, the gain decreases when exposed to radiation due to ‘acceptor removal’



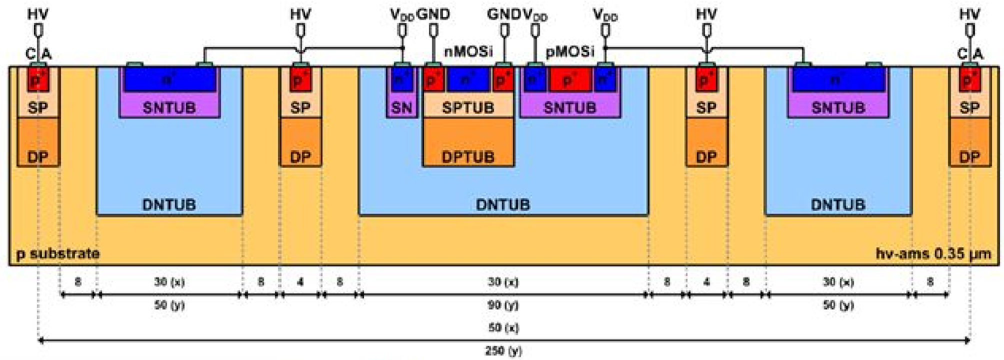
G. Kramberger et al, JINST (2015)

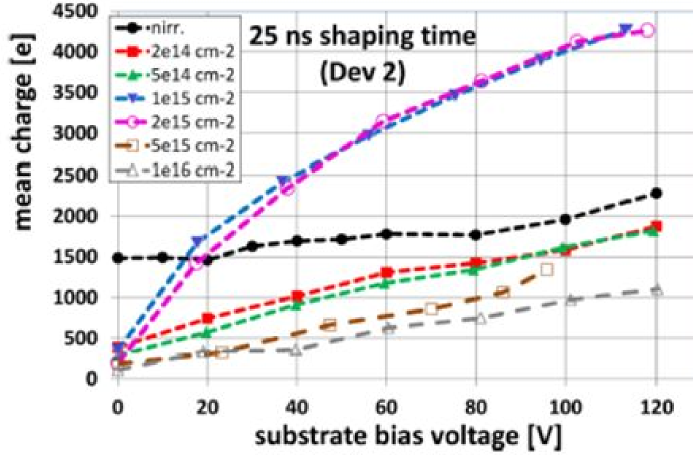


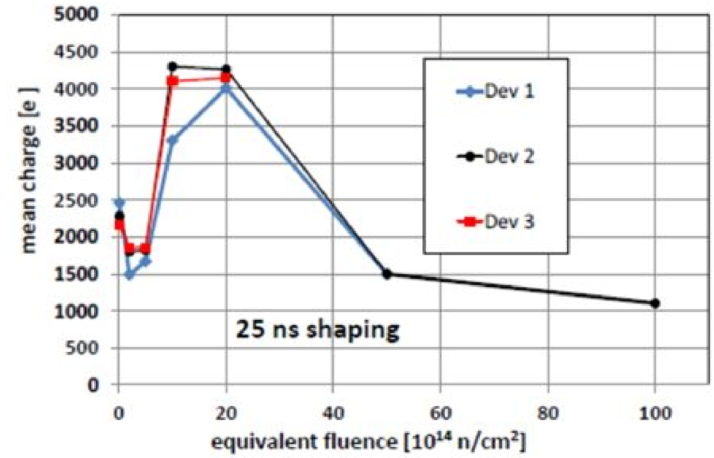
Motivation

Example #2: HVCMOS

- HVCMOS is an interesting technology for monolithic pixel sensors
- However, its charge collection varies with fluence
- Increase of CCE with fluence due to 'acceptor removal' observed



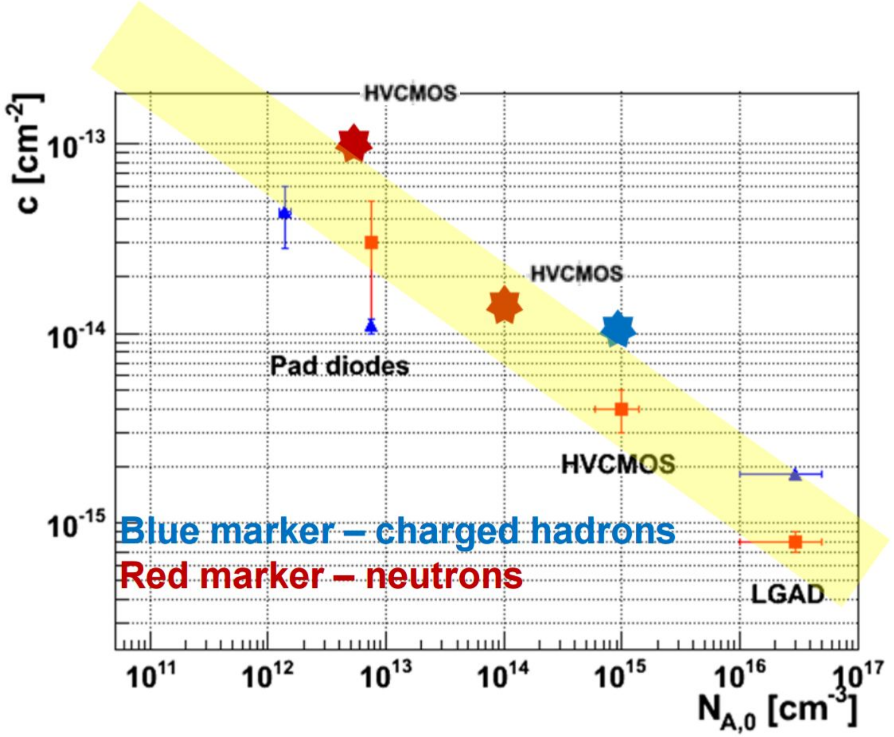




A. Affolder et al, J. Instrumentation (2016)

Motivation

No systematic study, hard to compare results from literature:



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

G. Kramberger, VERTEX (2016)

<u>Solution:</u> <u>dedicated characterization experiment</u>

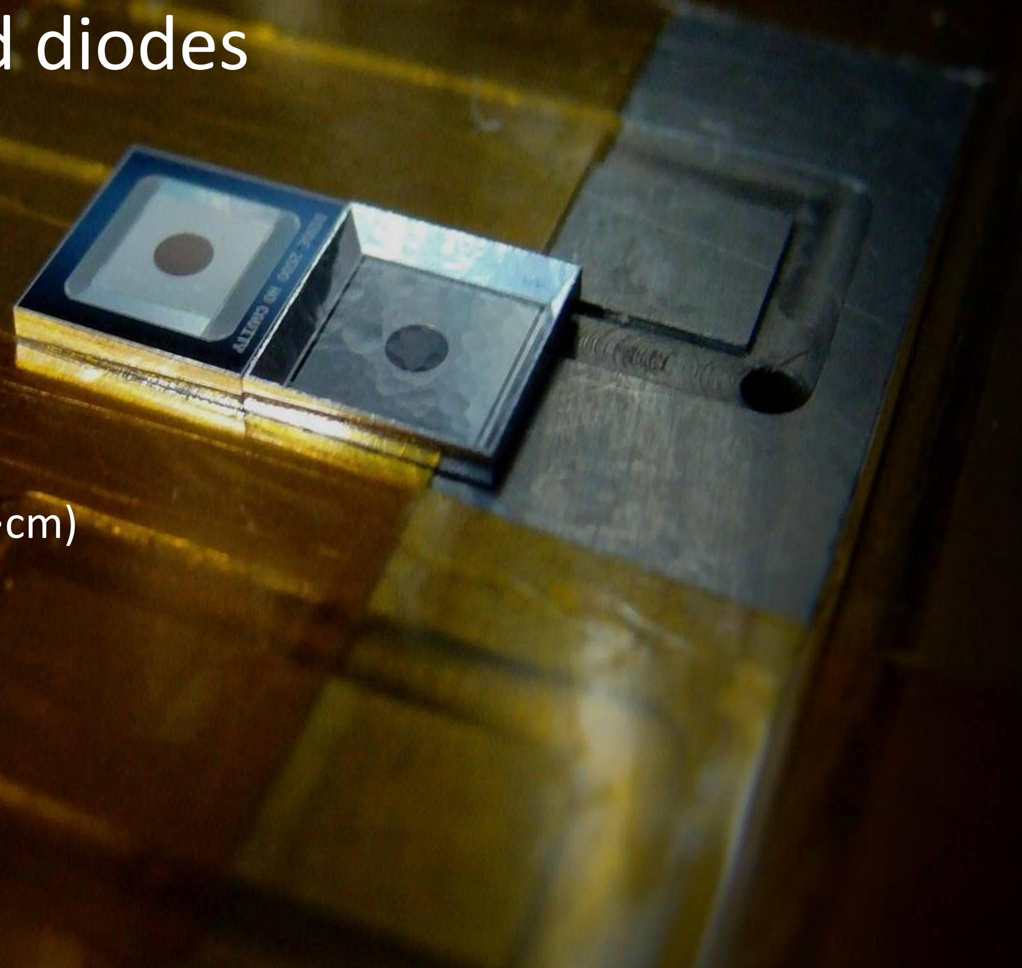
A large number of sensors with the same structure with varying thicknesses, resistivities and material types

Materials and Devices

Simple p-type pad diodes

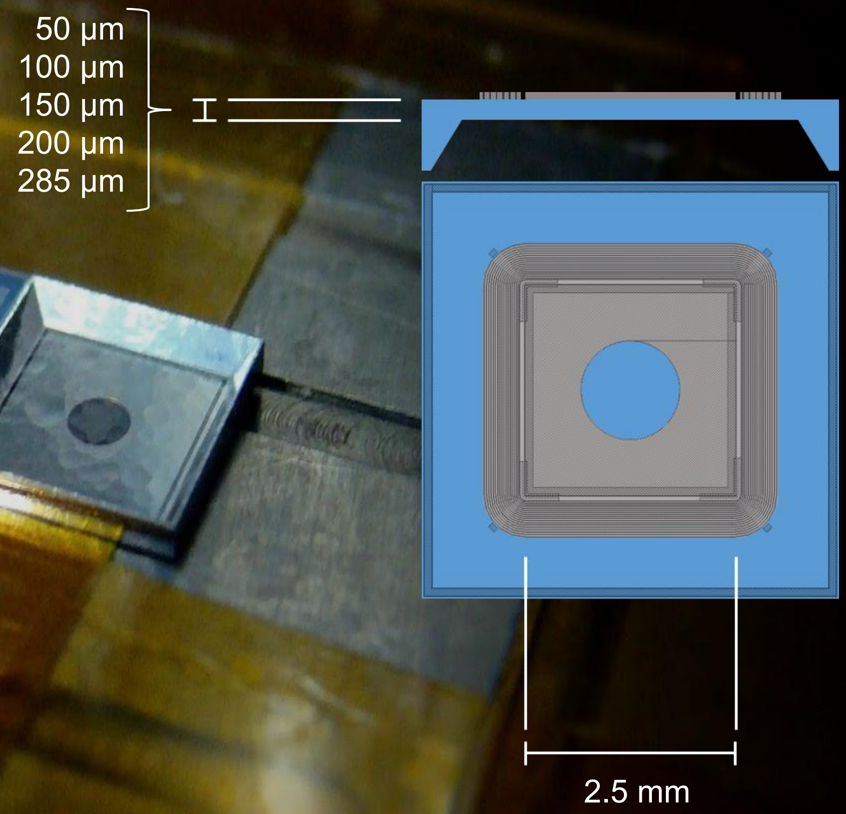
Epitaxial (50 µm)
- 10 Ω·cm
- 50 Ω·cm
- 250 Ω·cm
- 1000 Ω·cm

Float zone (>10 000 Ω·cm)
- 100 µm
- 150 µm
- 200 µm
- 285 µm



Materials and Devices

Simple p-type pad diodes



Epitaxial (50 µm)

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Float zone (>10 000 Ω·cm)

- 100 µm
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- 200 µm
- 285 µm

Irradiation

Forschungsinstitut für Mikrosensorik GmbH

Proton and neutron irradiation

From ~ $7x10^{13}$ to $7x10^{15}$ $n_{eq}cm^{-2}$

CERN IRRAD Proton Facility

Institut "Jožef Stefan" 50 let REAKTORJA TRIGA

Acceptor Removal Used Methods

From CV curves, two methods were used to measure Neff:

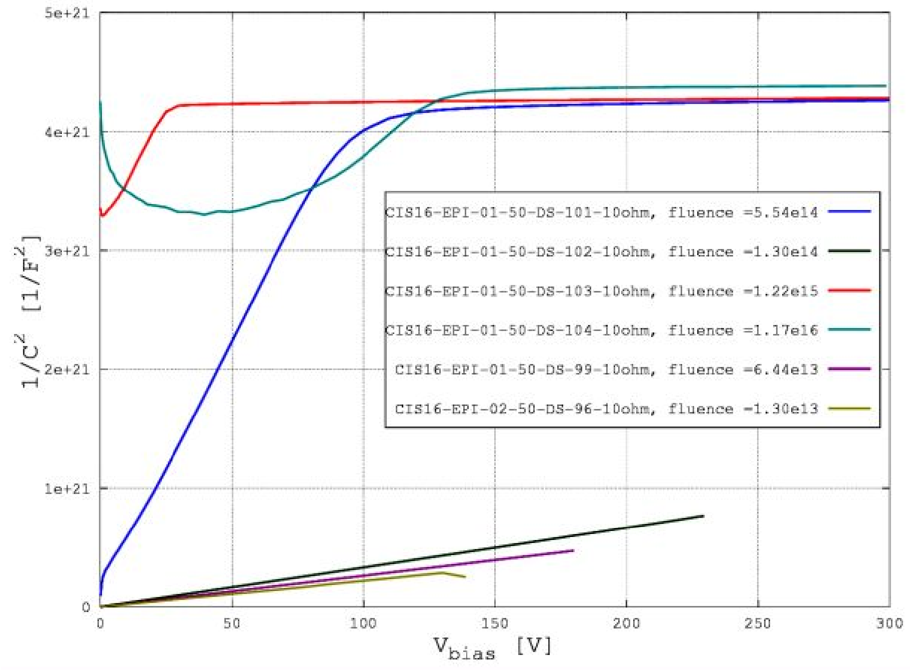
- Depletion Voltage*:

$$N_{eff} = \left(\frac{C}{A}\right)^2 \frac{2V_{dep}}{\varepsilon\varepsilon_0 q_0}$$

- $1/C^2$ Slope:

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

Epitaxial (10 Ωcm; @-20°C; annealing: 10min 60°C)

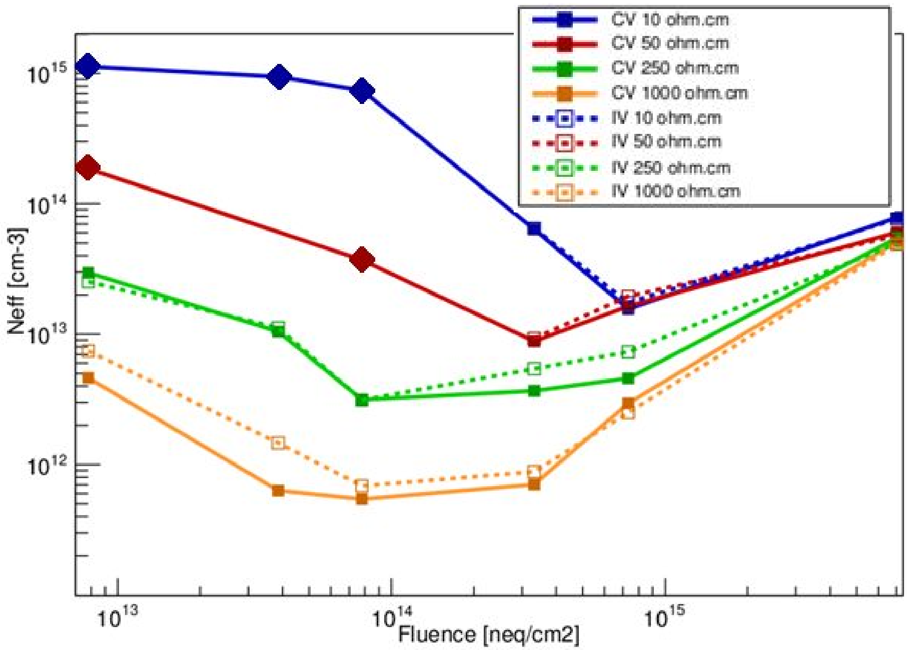


*This method was also applied to IV curves

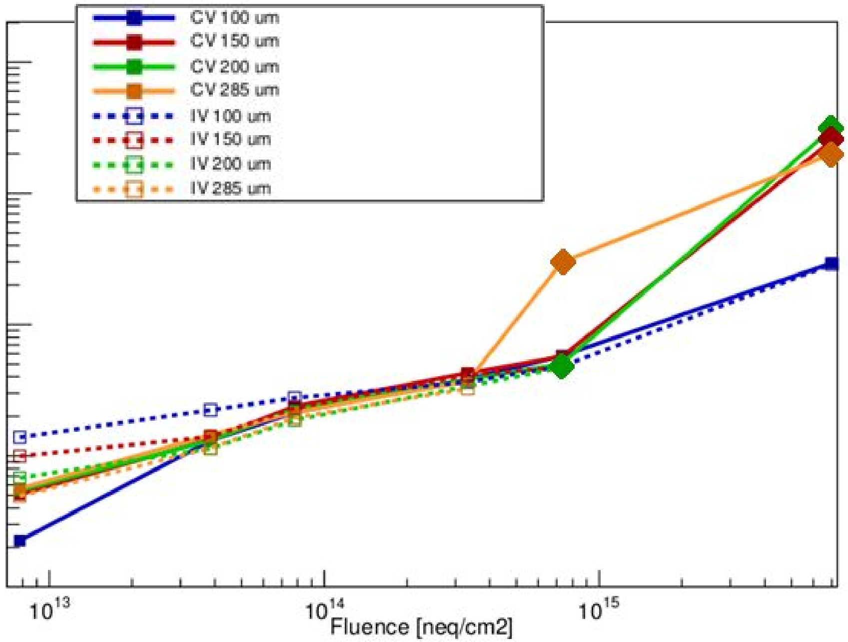
Acceptor Removal Previous Results

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

Epitaxial



Floatzone



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

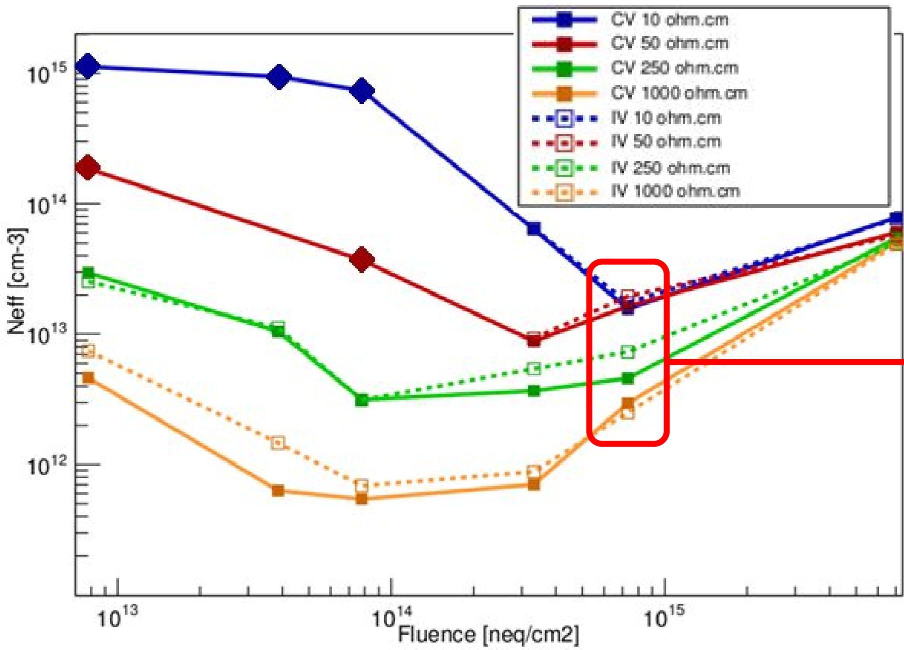
◆ from CV slope: $N_{eff} = \frac{2}{A^2\varepsilon\varepsilon_0 q_0} \frac{1}{d\left(1/C^2\right)/dV}$

Acceptor Removal Annealing Study

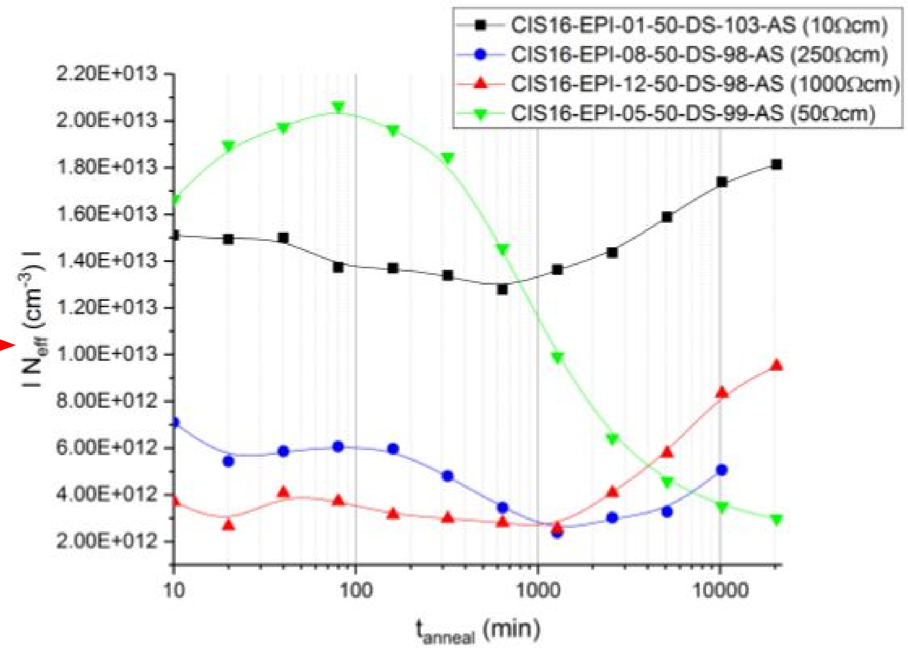
P. Almeida et al, 30th RD50 (2017)

P. Almeida et al, 31st RD50 (2017)

Epitaxial



Annealing Study (@60ºC)

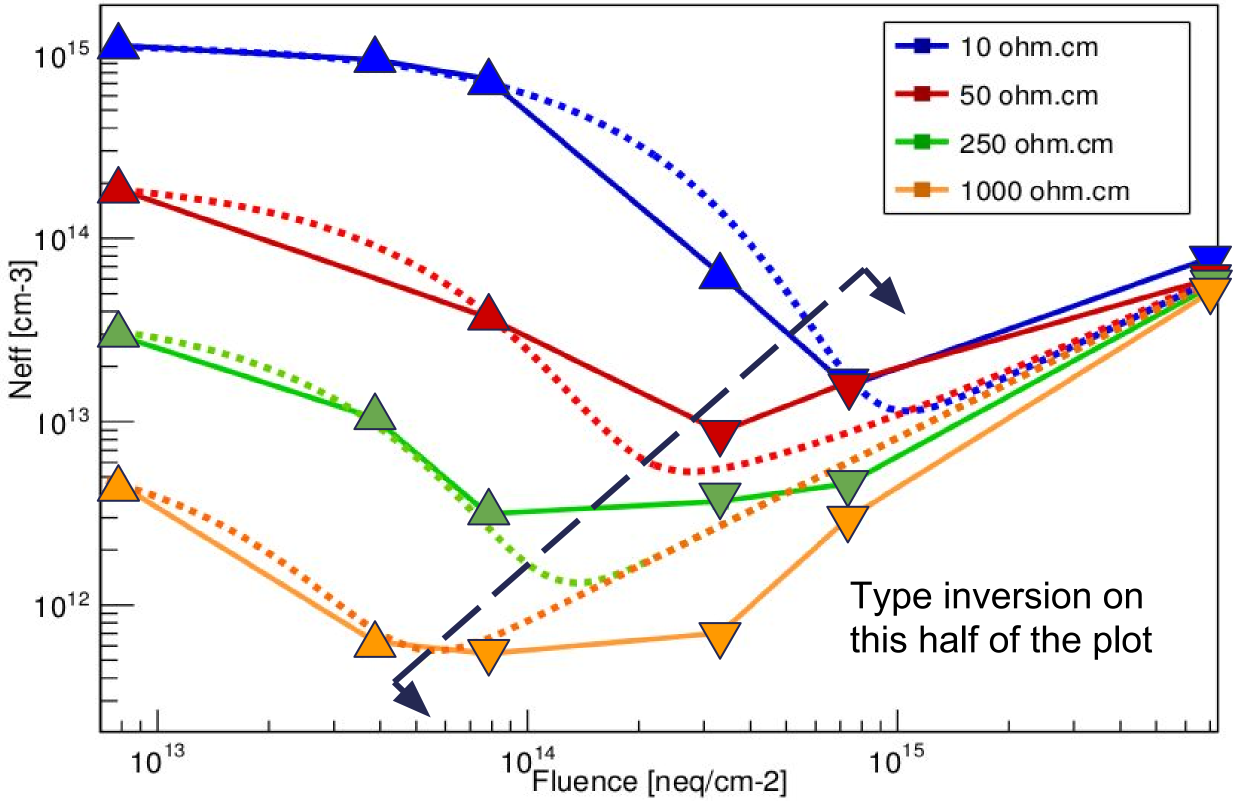


from CV/IV kink: $N_{eff} = \left(\frac{C}{A}\right)^2 \frac{2V_{dep}}{\varepsilon\varepsilon_0 q_0}$

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

Annealing curves show evidence of **type inverted** detectors — later confirmed by TCT. For more details, see dedicated presentation in the 31st RD50 workshop.

Acceptor Removal Type Inversion

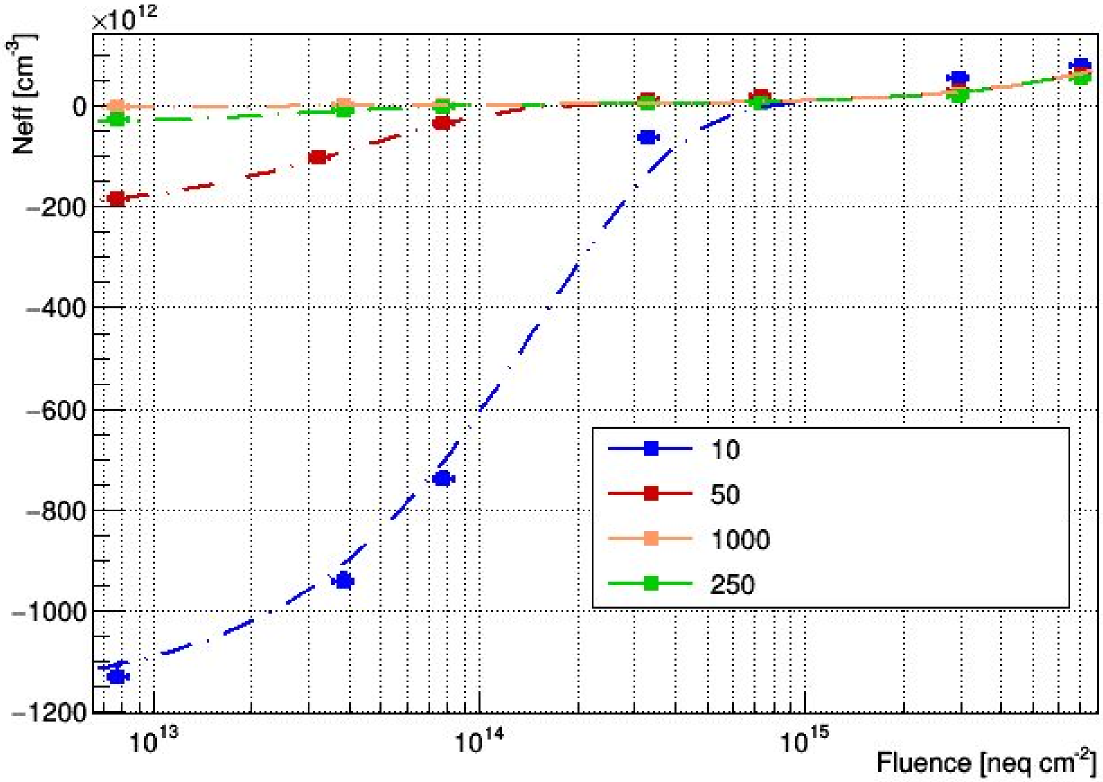


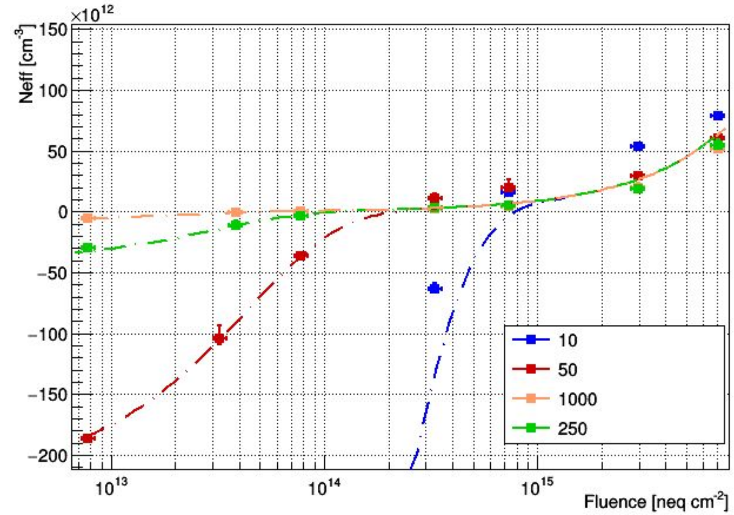
△ Depletes from the top
▽ Depletes from the bottom

Every detector was measured in TCT (top, bottom and infrared) and checked for type inversion — at higher fluences half of the plot was found to be **type inverted**.

Acceptor Removal by Proton Irradiation

Annealing: 10 min @ 60ºC



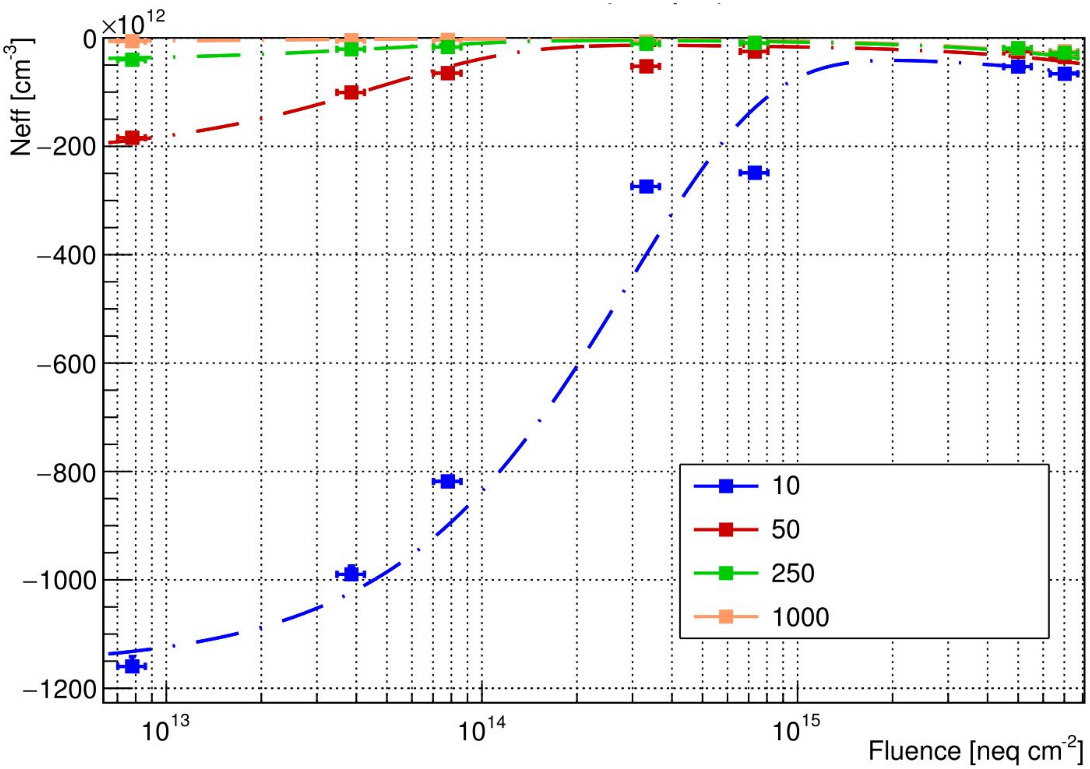


Fitted function:

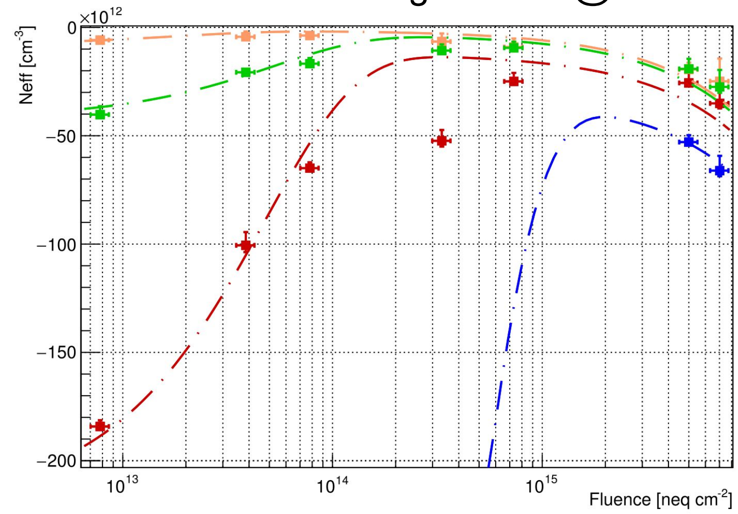
$$N_{eff}(\Phi) = N_{eff0} \cdot e^{-c \cdot \Phi} + g_c \Phi$$

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

Acceptor Removal by Neutron Irradiation



Annealing: 10 min @ 60ºC

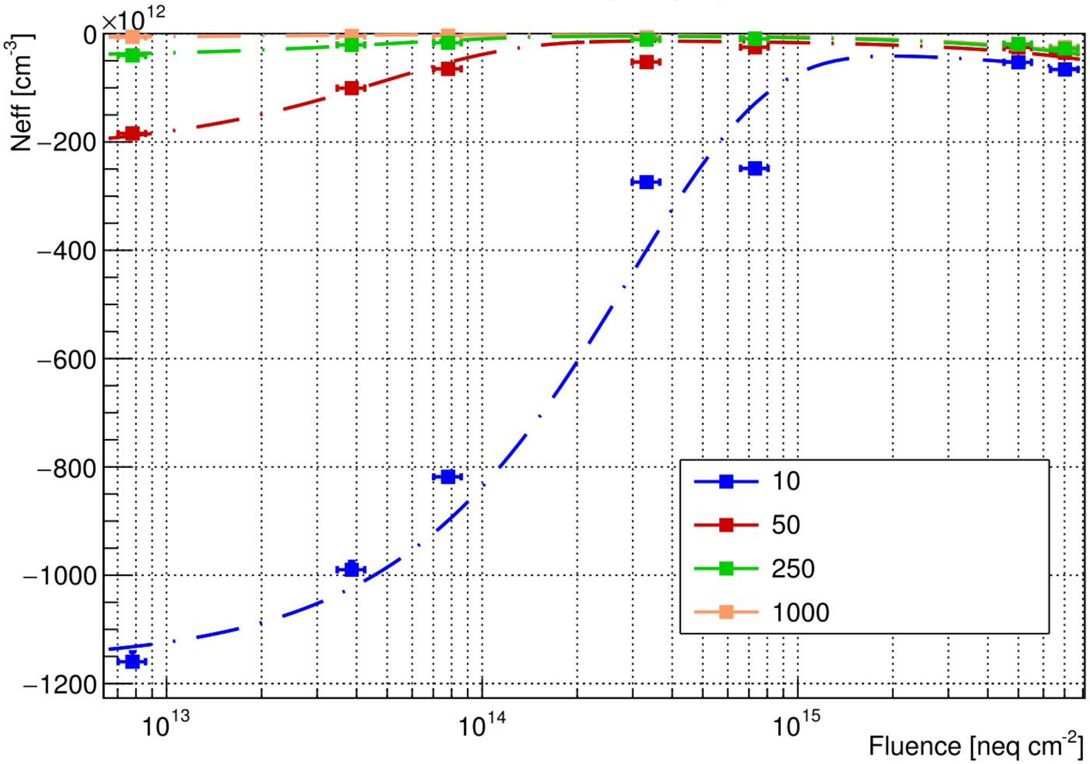


Fitted function:

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

	measured	fitted		
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	

Acceptor Removal by Neutron Irradiation



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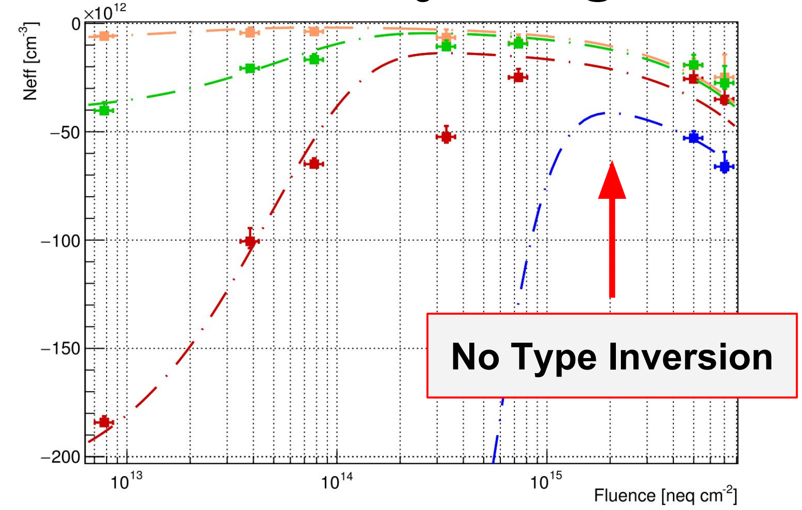

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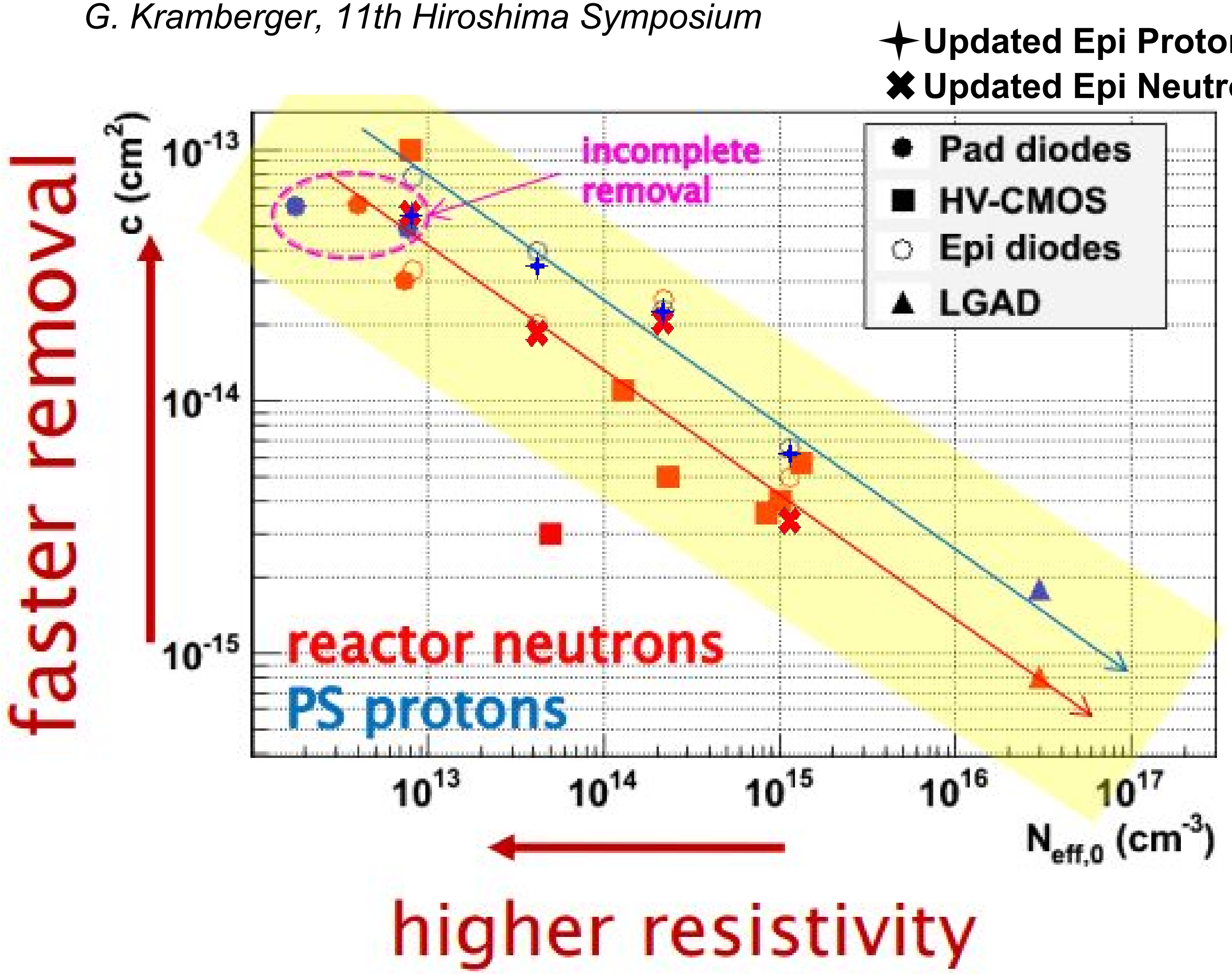
Acceptor Removal

G. Kramberger, 11th Hiroshima Symposium



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

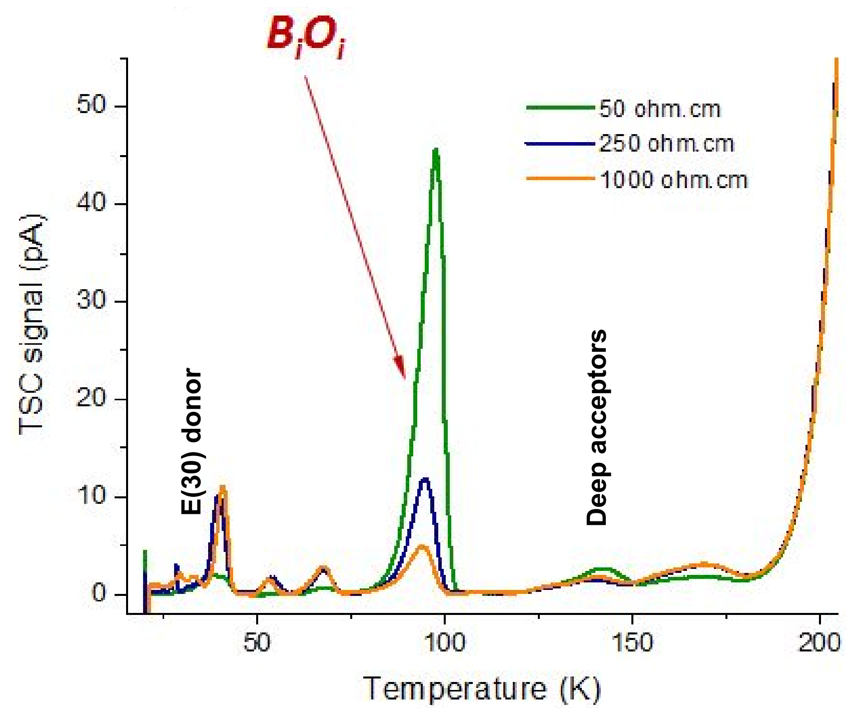
Thermally Stimulated Current (TSC)

- Gives a spectrum of the defects in the detector by measuring the leakage current while ramping up the temperature

- Allows for the estimation of defect concentration by measuring released charge by the defect's peak

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:

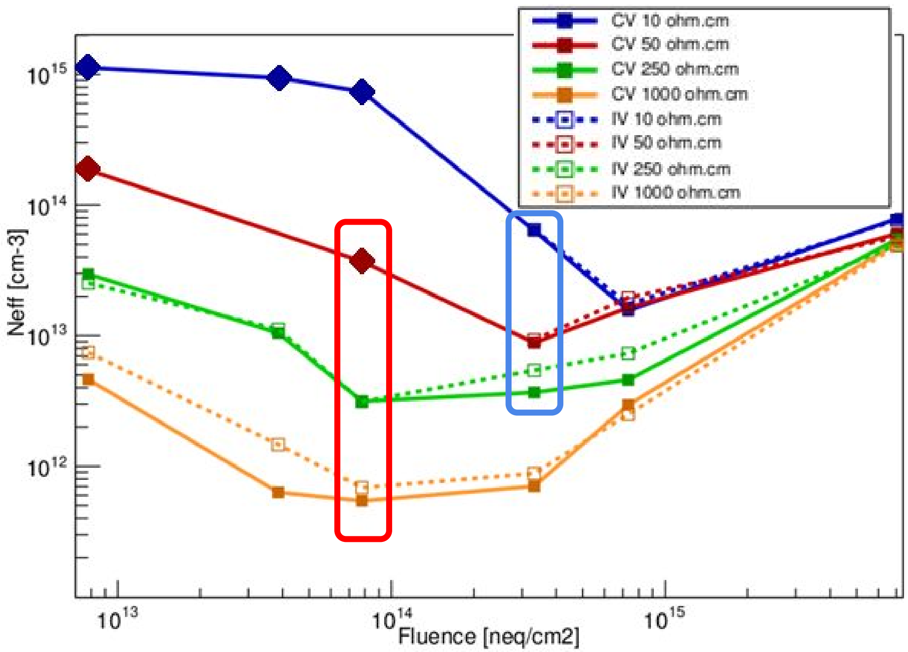
$$\begin{cases} I + B_s \rightarrow B_i \\ B_i + O_i \rightarrow B_iO_i \end{cases}$$

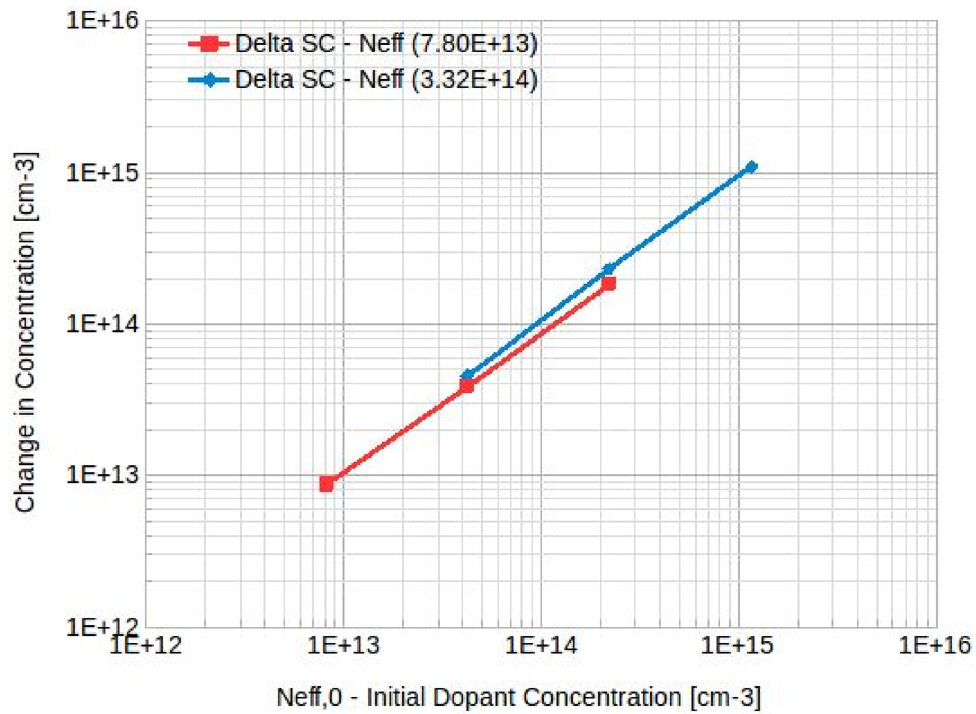


50 µm, $\Phi_{neq} = 7.80 \cdot 10^{13}$ cm^{-2}, 10 min @ 60°C annealing

Macro vs Micro

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





Assumptions:

- E(30) are donor like defects and contribute positive space charge
- H(116)-H(140)-H(152) are acceptor like defects and contribute negative space charge
- B_iO_i contributes twice its concentration

Macro vs Micro

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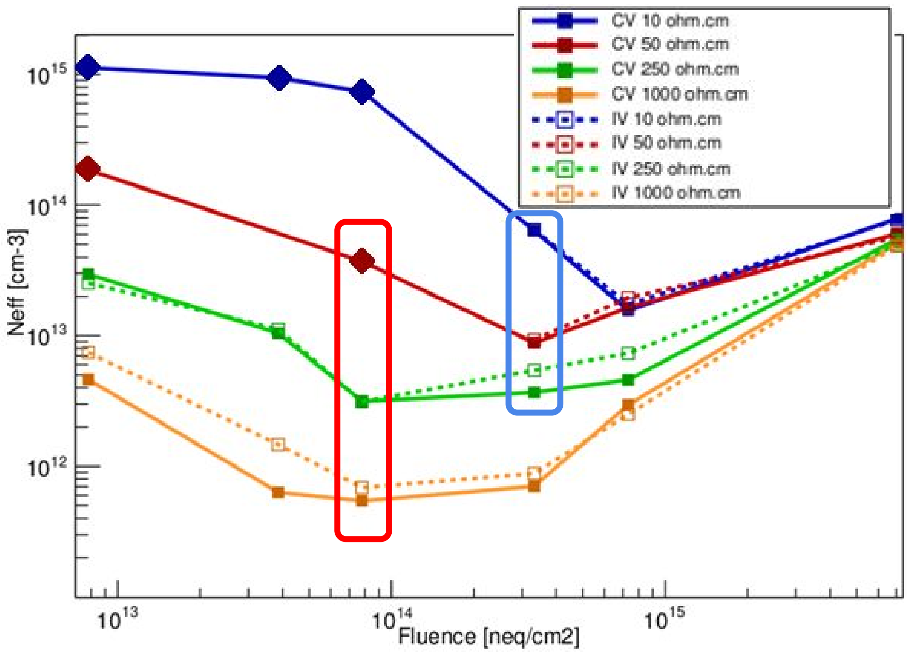

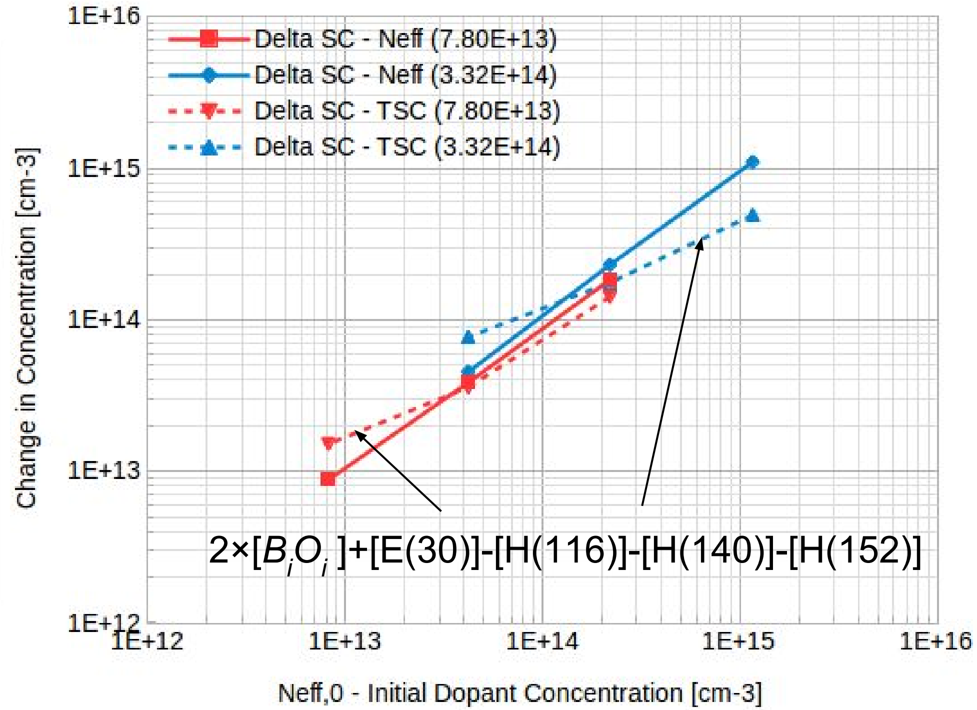

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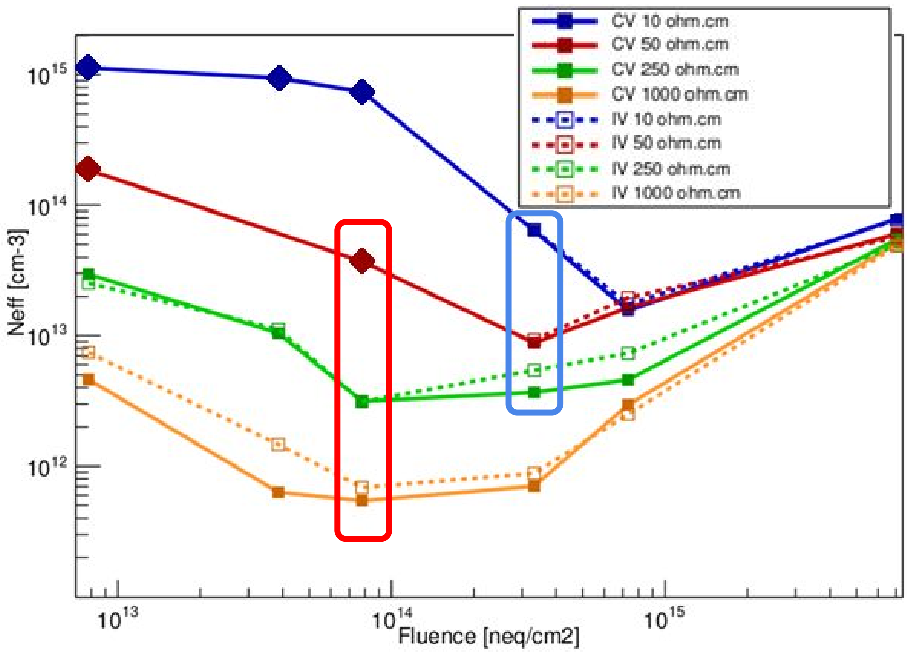
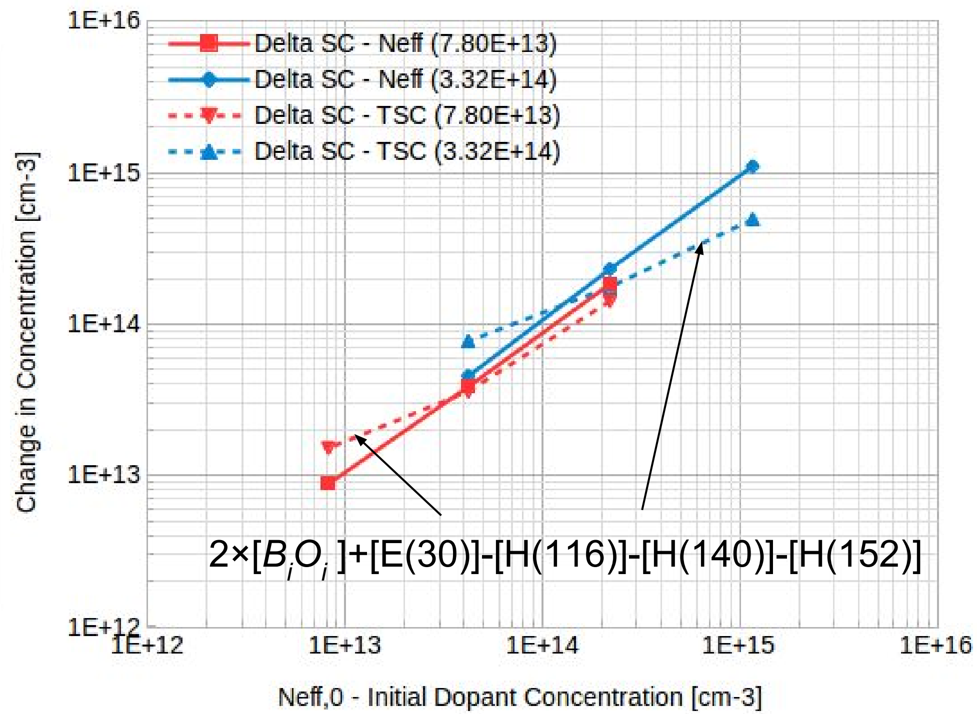




There is a clear correlation between the concentration of the defects observed through TSC, and the Neff change measured by CV

Summary and Outlook

Work in progress to study acceptor removal:

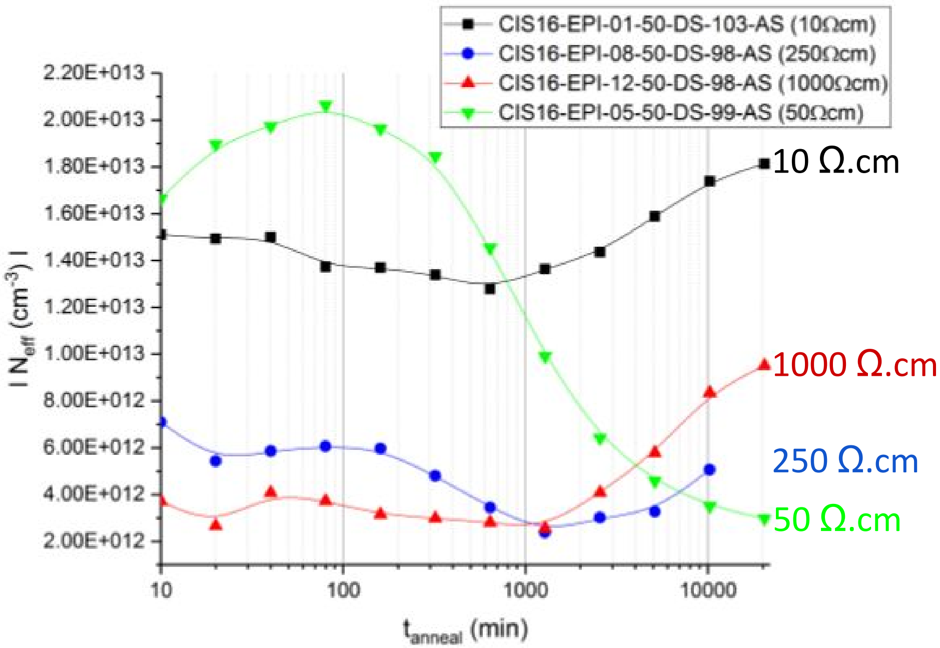
- CV, IV, TCT and TSC was used to investigate the evolution of Neff vs fluence of detectors of different resistivities irradiated by protons and neutrons
- An annealing study and TCT measurements confirmed type inversion in some of the proton irradiated detectors
- After correction for type inversion,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

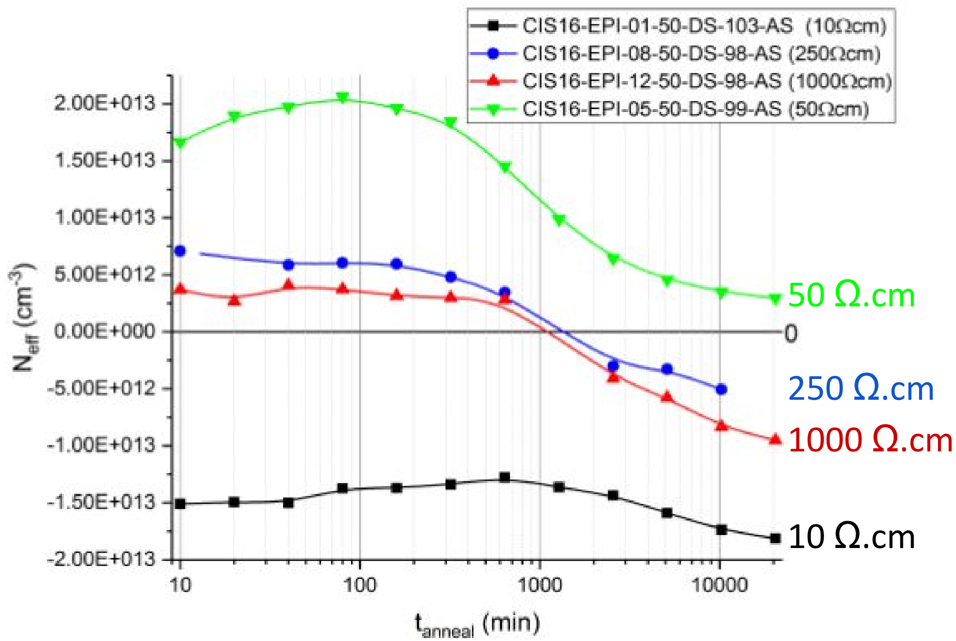
- We want to perform SIMS measurements, as we don't know the Oxygen concentration at the moment
- We're improving our TSC setup to study the B_iO_i defect in more detail

Spare Slides

Annealing Study Interpretation of Neff

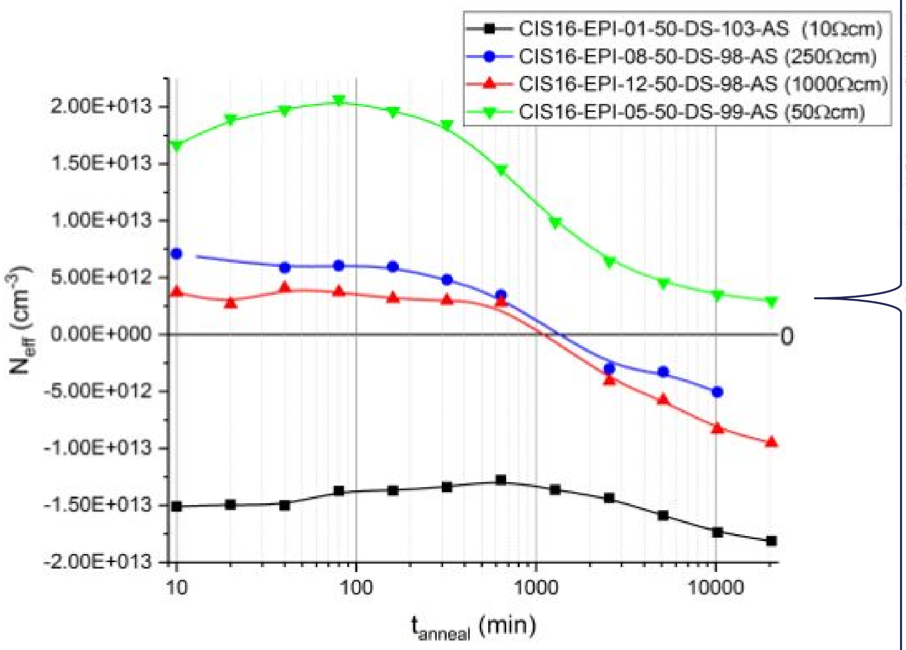
Data → **Interpretation of the data assuming type inversion**

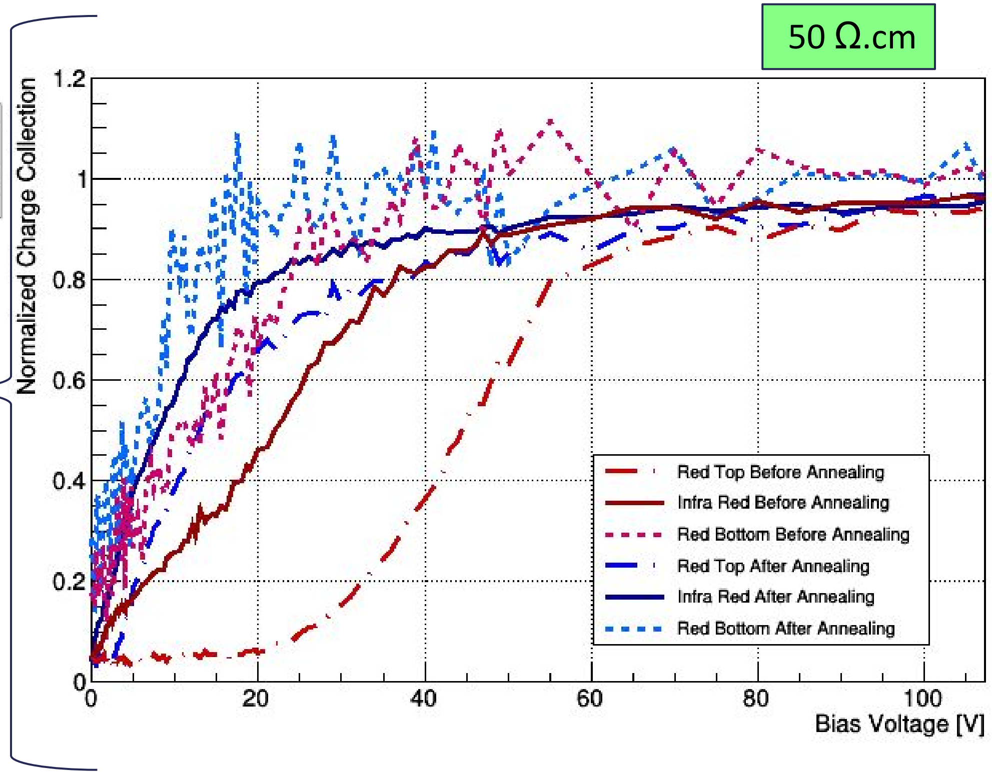




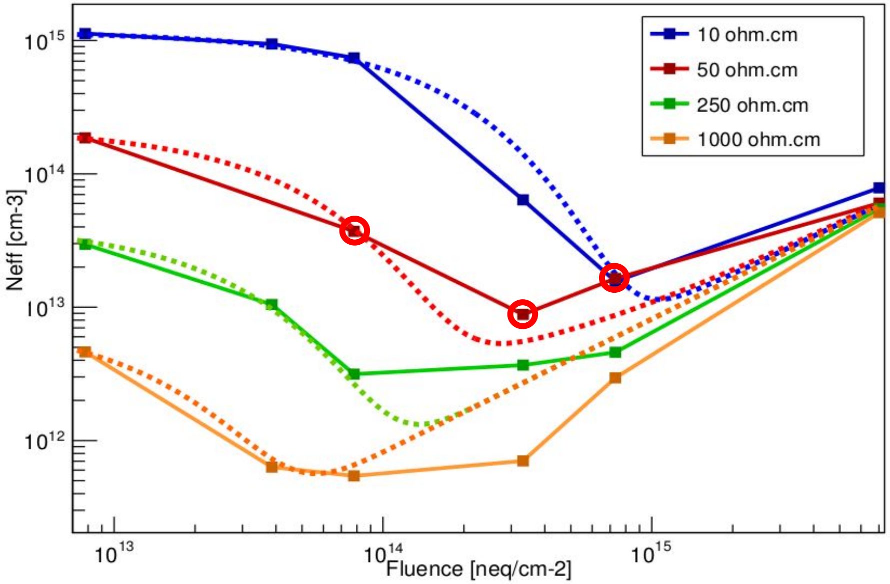
- Annealing at 60ºC
- Up to 20480 min or ~14 days of accumulated annealing
- Neff calculated from CV measurements

Annealing Study TCT confirmation





Acceptor Removal



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50 Ω.cm