# RD50 Acceptor Removal Project and Defect Characterization at CERN

33rd RD50 Workshop, 26-28 of November, 2018, CERN, Geneva, Switzerland

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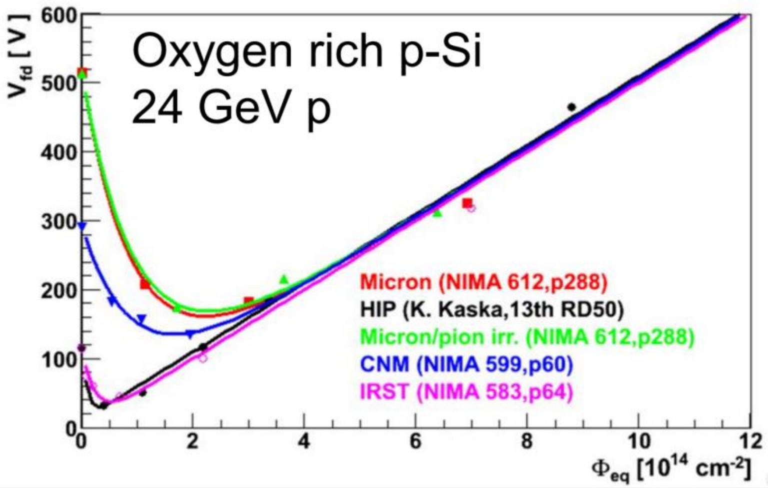
# Motivation

**‘Acceptor removal’:**

- Apparent de-activation of B as a shallow dopant with fluence leading to the change of $V_{dep}$ and $N_{eff}$ on the macroscopic level

## Macroscopic studies:

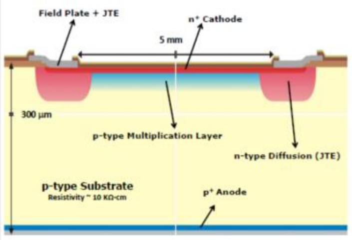
‘Acceptor removal’ is observed in sensors mainly as a shift of $V_{dep}$ obtained from CV measurements

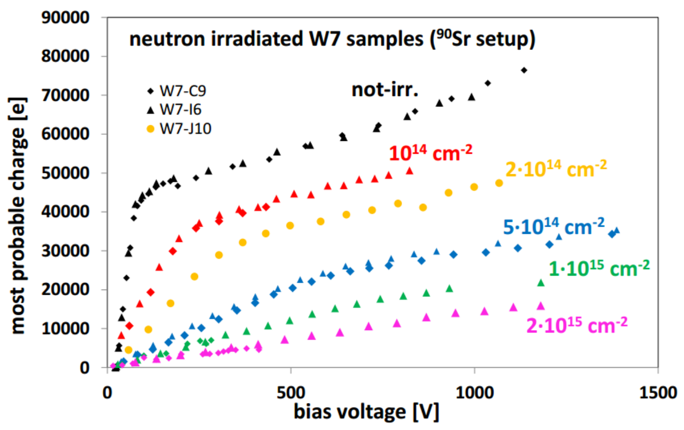


*G. Kramberger et al, VERTEX (2016)*

## Fast timing sensors:

- LGAD (Low Gain Avalanche Detector)





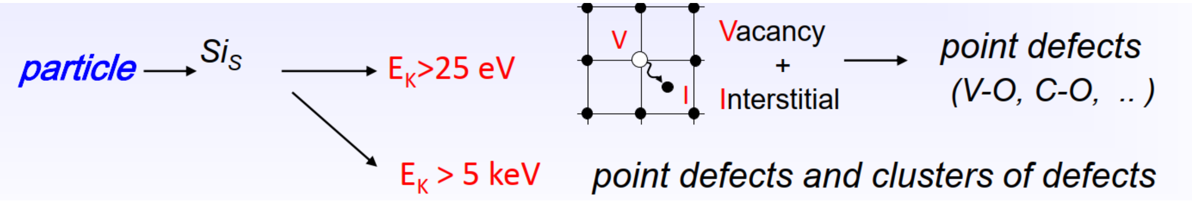
*G. Kramberger et al, JINST (2015)*

Gain of these sensors decreases with exposure to the radiation due to the ‘acceptor removal’

# Motivation

**'Acceptor removal':**

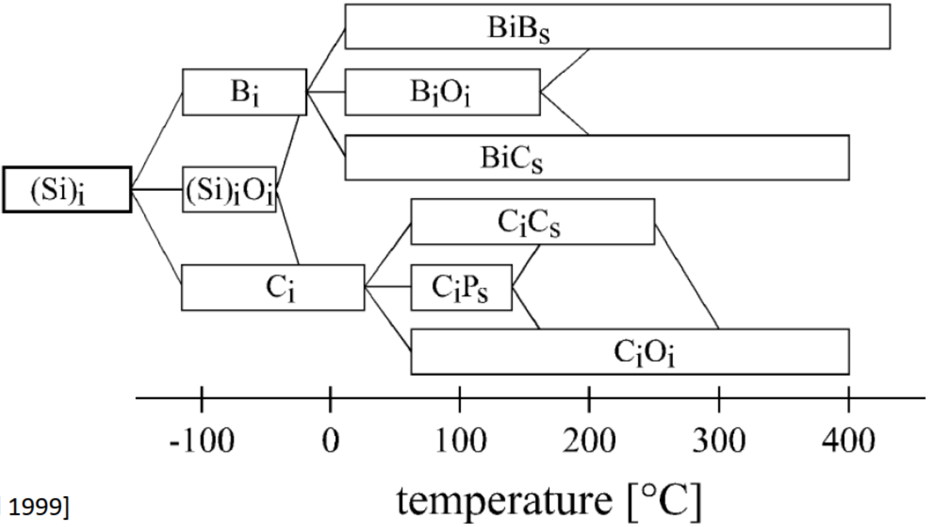
- Originated from $B_iO_i$ complex formation on the microscopic level



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

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

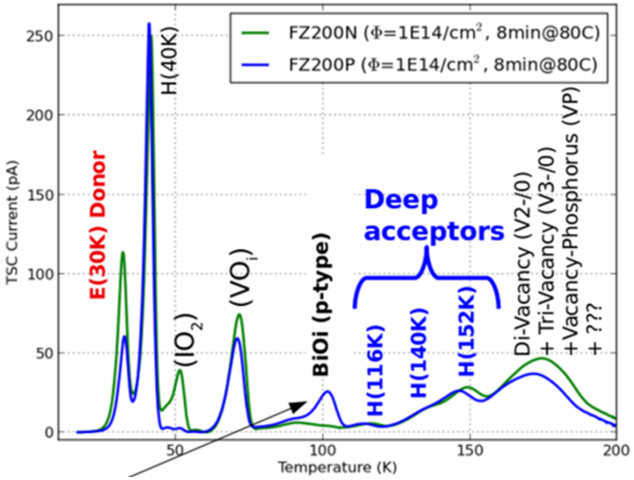
$$\begin{cases} I + B_s \rightarrow B_i \\ B_i + O_i \rightarrow B_iO_i \end{cases}$$



[Moll 1999]

Figure 3.8: Hierarchy and stability of self-interstitial related defects as function of temperature. For annealing parameters and references see Tab. B.1.

- B and C competing for interstitials
- High ***ρ*** Si: O≫C≫B leading to the production of mainly CiOi

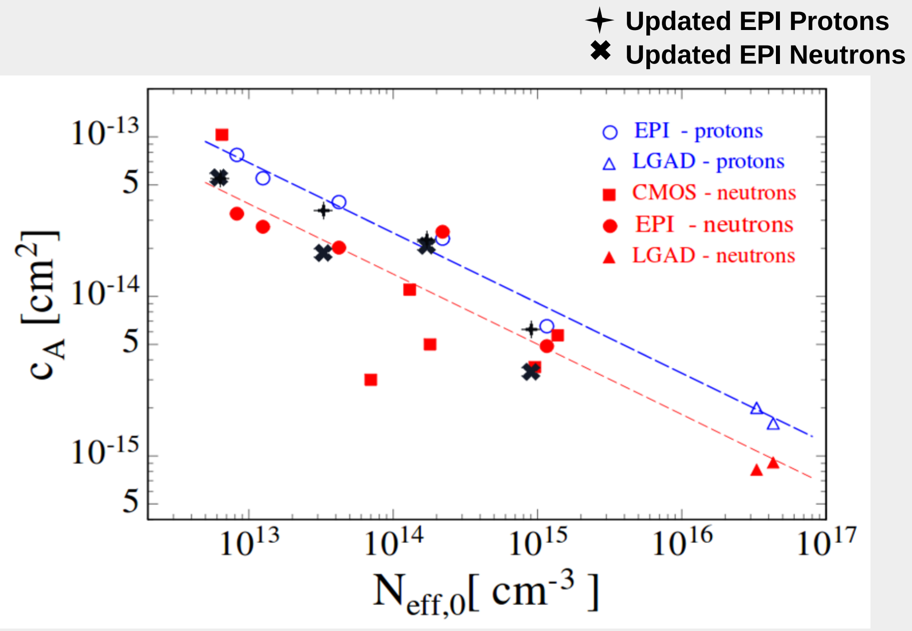


TSC measurement on defects produced by 23 MeV protons

# Motivation

Parameterisation as $N_{eff}(\Phi)=N_{C0}exp(-c\,\Phi)$

with (often) complete acceptor removal ($N_{C0}=N_{eff,0}$) for proton and incomplete - for neutron irradiation



*P. Almeida et al, 32nd RD50 workshop (2018)*

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)
https://doi.org/10.1088/1748-0221/12/01/C01074
B. Hiti *et al.* (2017)
https://doi.org/10.1088/1748-0221/12/10/P10020
I. Mandić *et al.* (2017)
https://doi.org/10.1088/1748-0221/12/02/P02021
P. Dias de Almeida (2017)
https://indico.cern.ch/event/637212/
G. Kramberger (2017)
https://indico.cern.ch/event/577879/
M. Moll (2018)
https://doi.org/10.1109/TNS.2018.2819506

**Solution:** dedicated defect and material characterization experiment

A large number of simple test structures with known B content in order to concentrate on the bulk features: unify list of the defects and their impact on sensor properties including introduction rates and annealing behaviour for different types of irradiations and materials

# Acceptor Removal project

In the framework of RD50 collaboration

## Working group

EP-DT
Detector Technologies

### CERN, Geneva

**TSC** and **DLTS** starting from 2019

Fluence dependence
Isothermal annealing @60°C

Universität Hamburg
DER FORSCHUNG | DER LEHRE | DER BILDUNG

### University of Hamburg, Hamburg

**TSC** and **DLTS**

Isochronal annealing

INFM

### NIMP, Bucharest

**TSC** and **DLTS**

Isothermal annealing @80°C

Belarusian
State University

### BSU, Minsk

**DLTS**

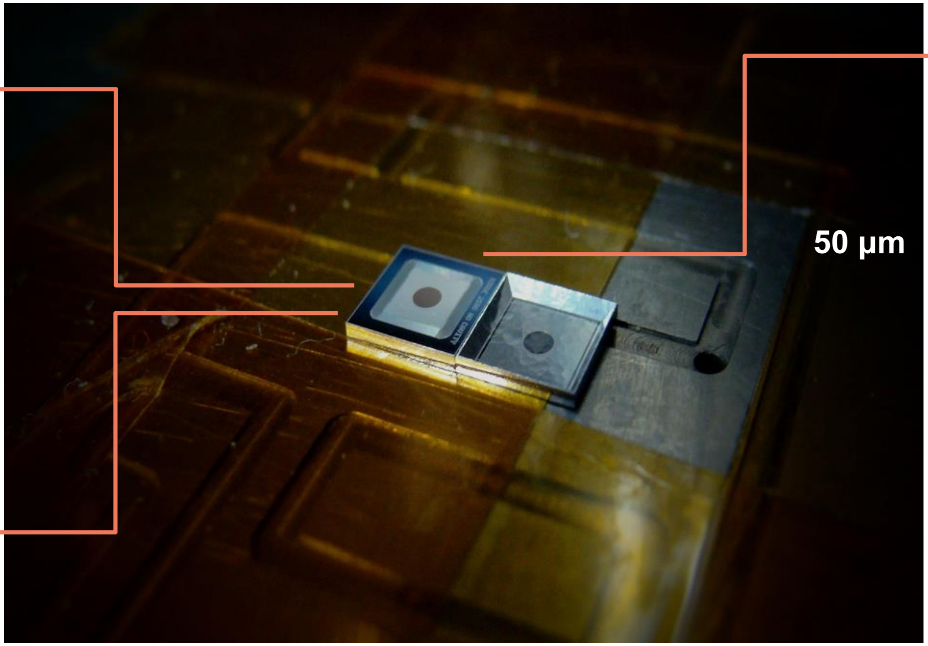
Isochronal annealing
Forward current injection annealing

# Acceptor Removal project: materials and samples

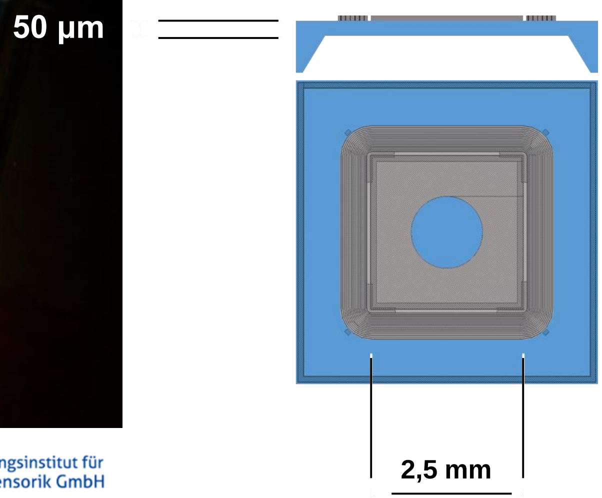
In the framework of RD50 collaboration

**Fz**
Resistivity $\rho$ >10 000 Ω·cm
285 μm

**Cz**
Resistivity $\rho$ ~ 100 Ω·cm
100 or 285 μm



**EPI**
Resistivity $\rho$ ~ 10
(limited amount),
50, 250 or 1000 Ω·cm
50, 100 or 275 μm



Forschungsinstitut für Mikrosensorik GmbH

# Irradiation Campaign and Distribution

In the framework of the Acceptor Removal project

## Proton Irradiation

CERN IRRAD Proton Facility

**24 GeV/c**

46 samples in total irradiated with 10 different fluences (1E10 - 5E14 p/cm$^2$)

## Neutron Irradiation

Institut "Jožef Stefan" 50 let REAKTORJA TRIGA

**reactor**

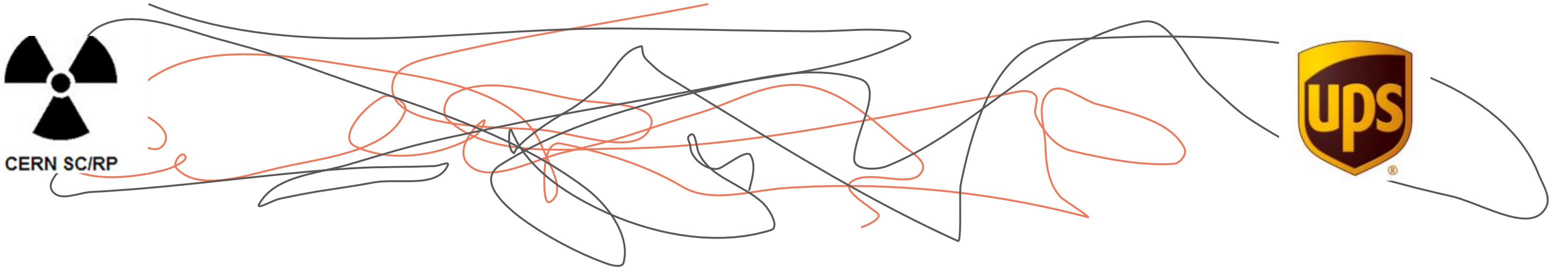
43 samples in total irradiated with 10 different fluences (6E09 - 3E14 $n_{1MeV}$/cm$^2$)

## Electron Irradiation

Belarusian State University

**3.5 MeV**

Discussion in progress



**distribution**

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 654168

# Status of TSC measurements at CERN

## Proton vs Neutron irradiation

Preliminary TSC results, irradiation type and fluence dependence

## Filling conditions variation

Filling temperature dependence and field-enhanced behaviour of TSC spectra

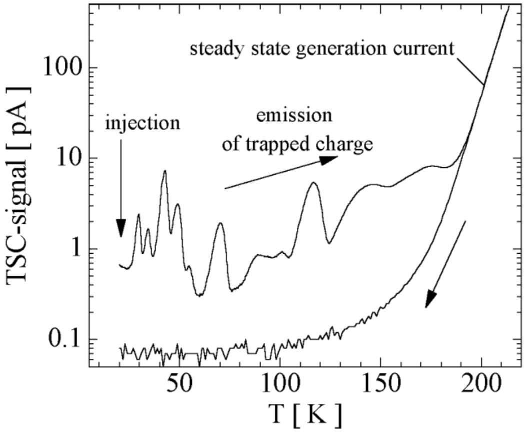
## Annealing study

Isothermal annealing study on p-type EPI proton irradiated small pad diodes, Neff vs fluence by TSC measurements

## Summary and Outlook

Future plans

# Experimental **Details**



## Materials:

Standard EPI
Resistivity $\boldsymbol{\rho}$ ~ 50, 250 or 1000 Ω·cm
EPI layer 50 μm
Substrate under EPI layer 0-255 μm

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

Pad area *A*: 2.5×2.5 $\text{mm}^2$ with guard rings
Passivated with openings for connection, window opening on FS and BS for light injection
Active thickness *d*: 50 μm in this particular case

## Irradiation:

PS protons (CERN): fluences 7.8E13 and 3.32E14 $n_{eq}/cm^2$
Reactor neutrons (Ljubljana): fluences 7.8E13 and 3.32E14 $n_{eq}/cm^2$

## Microscopic measurements:

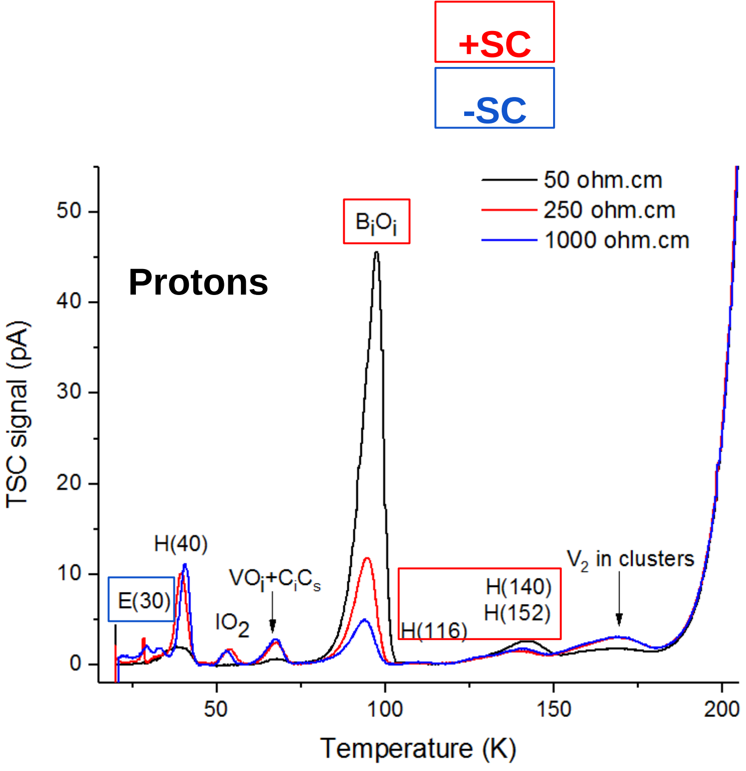
TSC (Thermally Stimulated Current) technique: colling (250K ▶ 20K) under -100V, trap filling with 1 mA forward current during 60 sec, ramping up to 250K under reverse bias (standard -100V but can vary) with constant heating rate $\boldsymbol{\beta}$=11 K/min

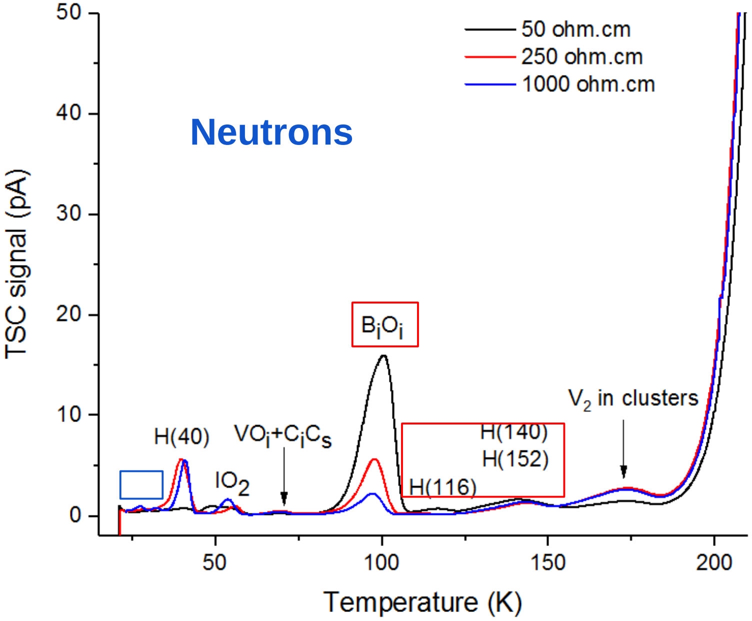
## Macroscopic measurements:

IV and CV measurements @ +20 and -20 °C, guard ring connected to the ground (analysis of data in progress)

# Proton vs **Neutron** irradiation ($\phi$=7.8E18 $n_{eq}/cm^2$). TSC spectra

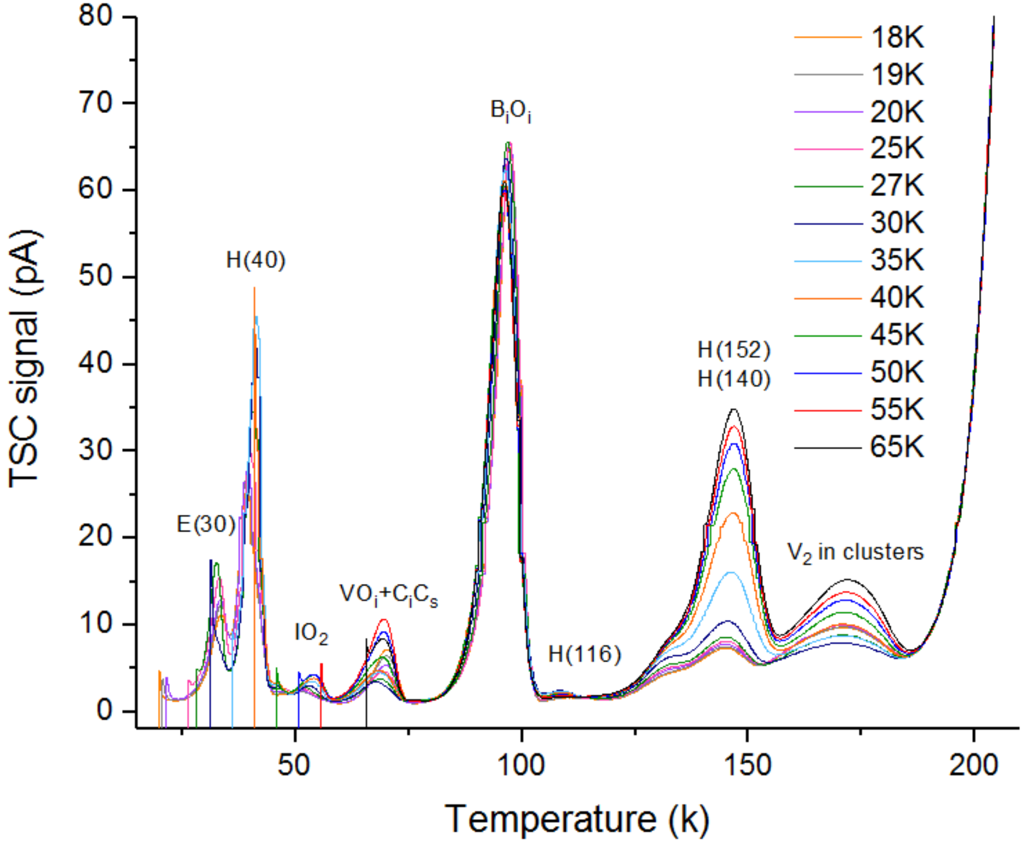
Annealing: 10 min @60ºC





Comparison of TSC spectra measured on **proton** and **neutron** irradiated with fluence 7.8E13 $n_{eq}/cm^2$ thin EPI Si pad diodes with different resistivity.

# Filling **Temperature** variation. Protons ($\phi$=3.32E14 $n_{eq}/cm^2$)

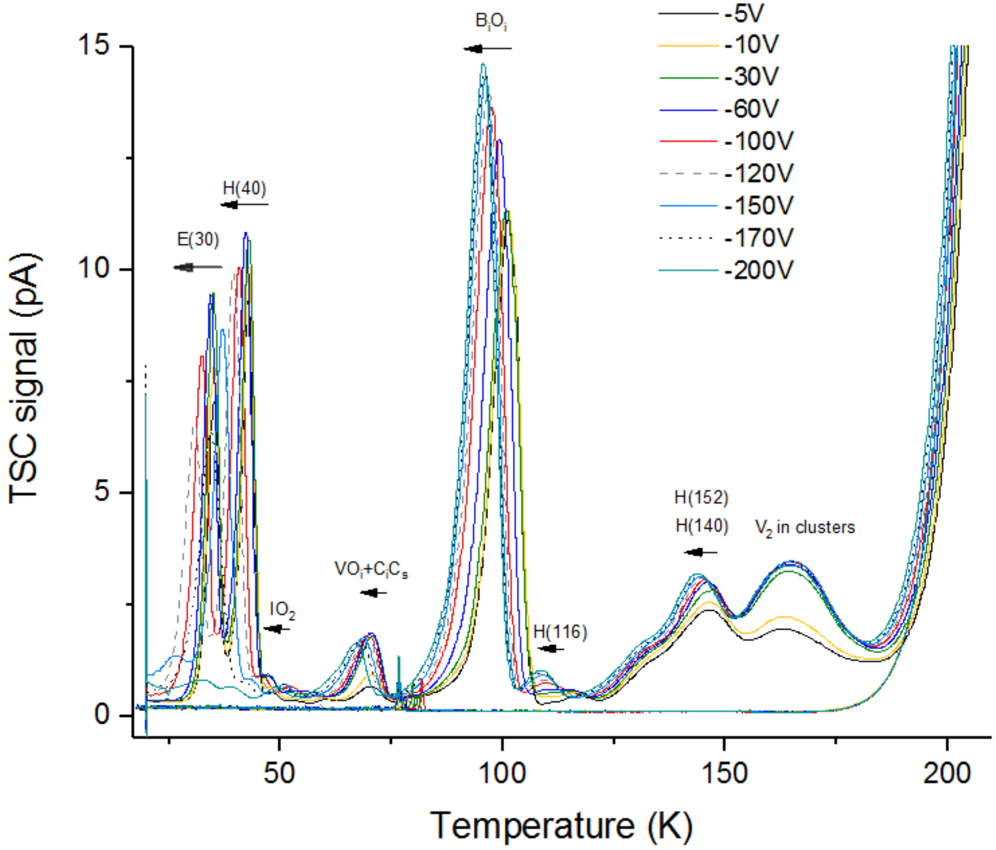


Annealing: 10 min @60ºC

Peak height of the TSC signal in dependence of the filling temperature $T_{fill}$=>strong dependence of the peak height for E(30), H(40), H(140-152), $V_2$ is observed =>can be governed by fractional occupation of the defect or T-dependent capture cross section $\boldsymbol{\sigma}$

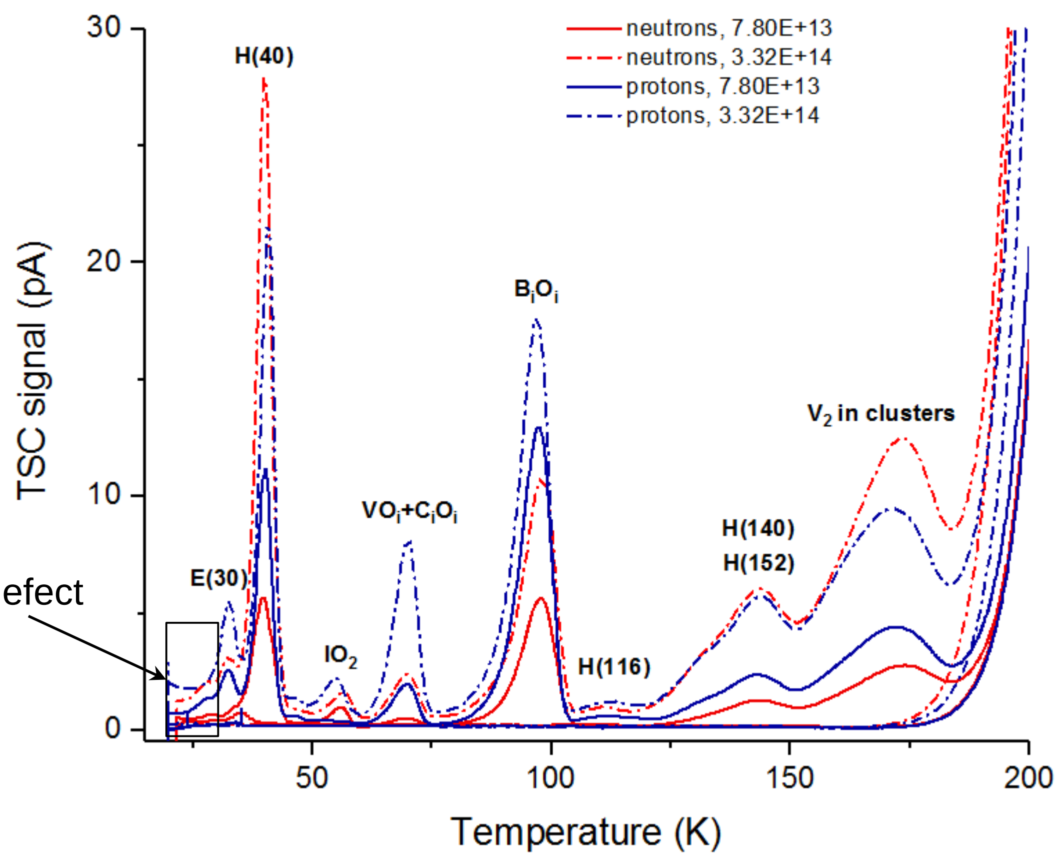
# Bias Voltage variation. Protons ($\phi$=3.32E14 $n_{eq}/cm^2$)

Annealing: 10 min @60ºC



TSC spectra and temperature shift in the peak position due to the variation of the bias voltage => *Poole-Frenkel effect*

# Proton vs Neutron irradiation. TSC comparison

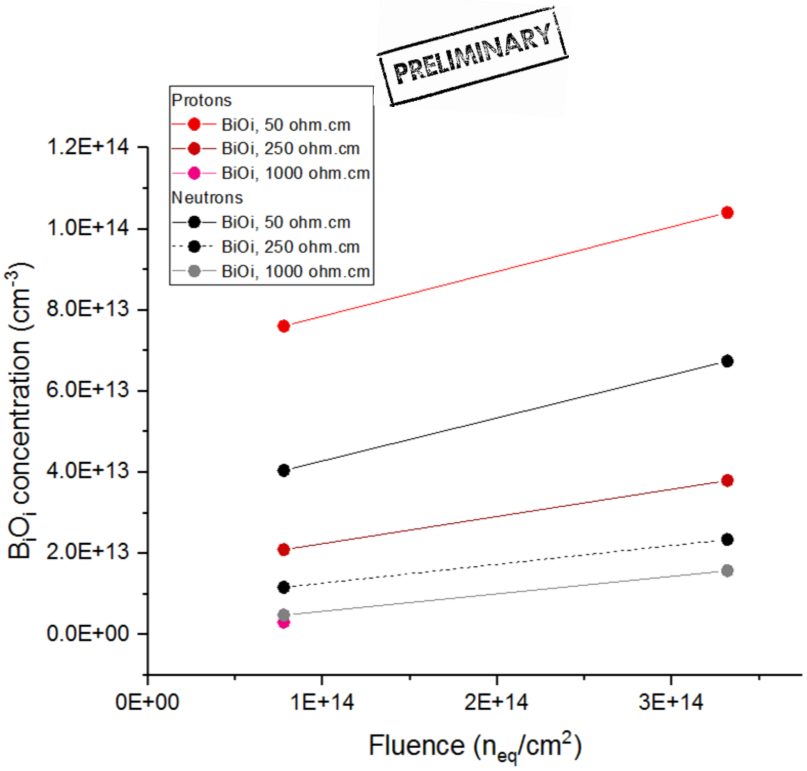


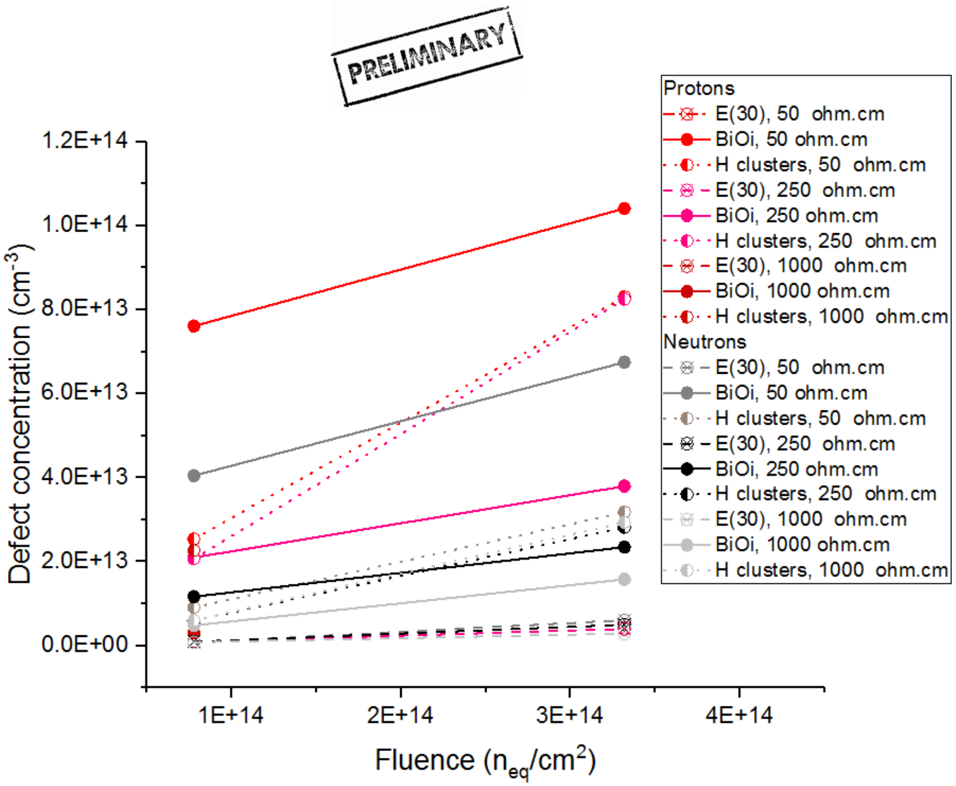
$\rho$ = 250 Ω·cm
Annealing: 10 min @60ºC

High $\rho$ - E(27) defect

Fluence and particle type dependance of TSC spectra measured on thin EPI Si pad diodes with 250 ohm.cm resistivity

# Proton vs Neutron irradiation. Defect concentration



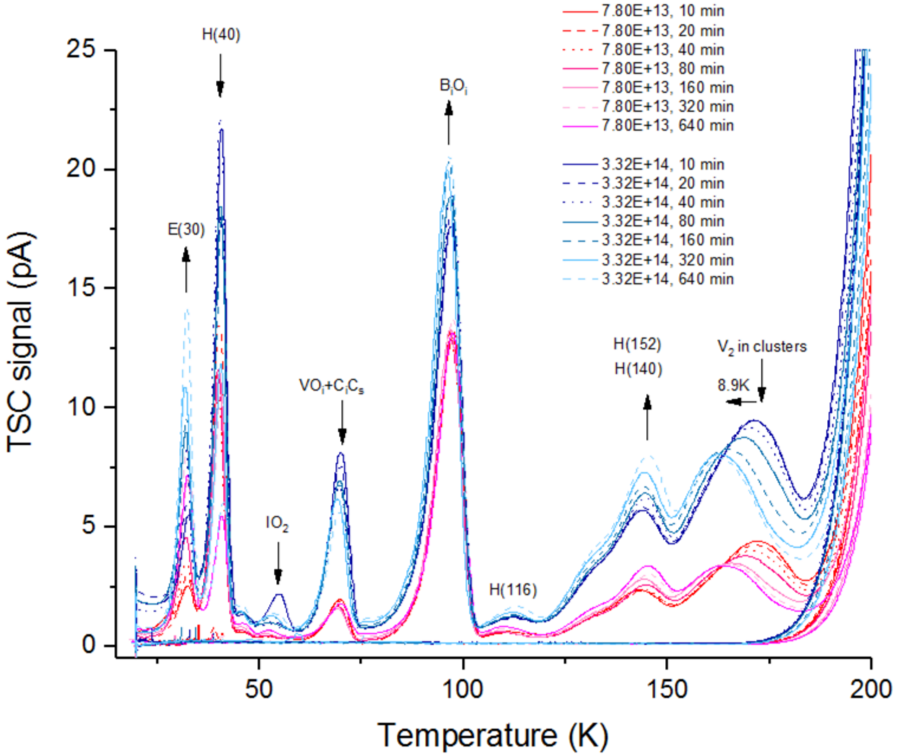


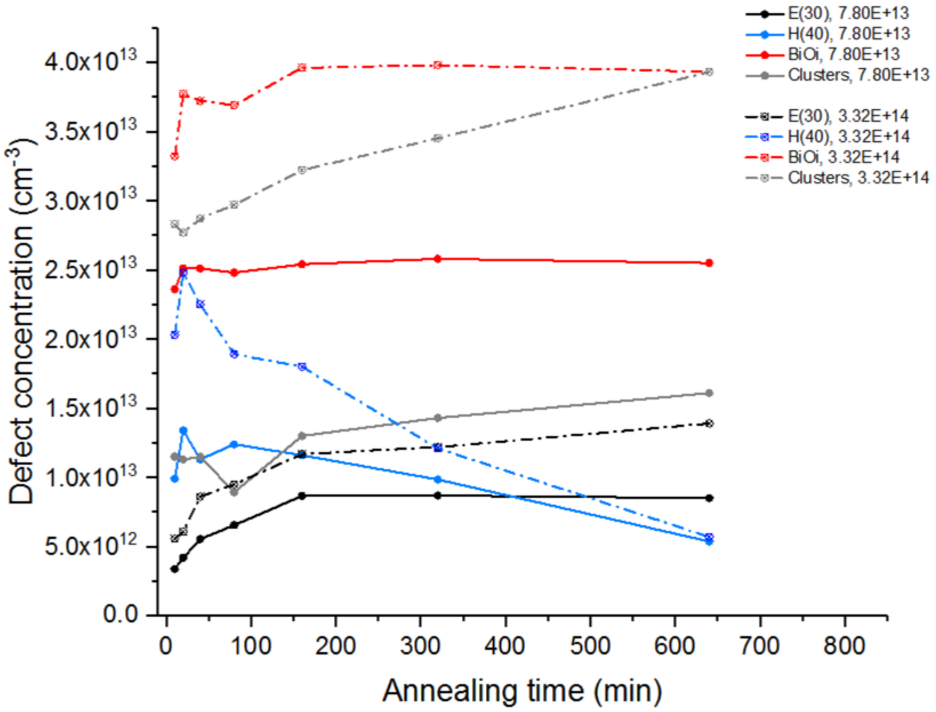
Concentration of the defects $B_iO_i$ and E(30), H(40), $B_iO_i$ and clusters vs resistivity and type of irradiation

# Isothermal **Annealing** @60°C. Protons

Annealing evolution of the TSC spectra and defects concentration in p-type EPI silicon sensors obtained by TSC spectroscopy method due to the proton irradiation with two different fluences: 7.8E13 $n_{eq}/cm^2$ and 3.32E14 $n_{eq}/cm^2$.

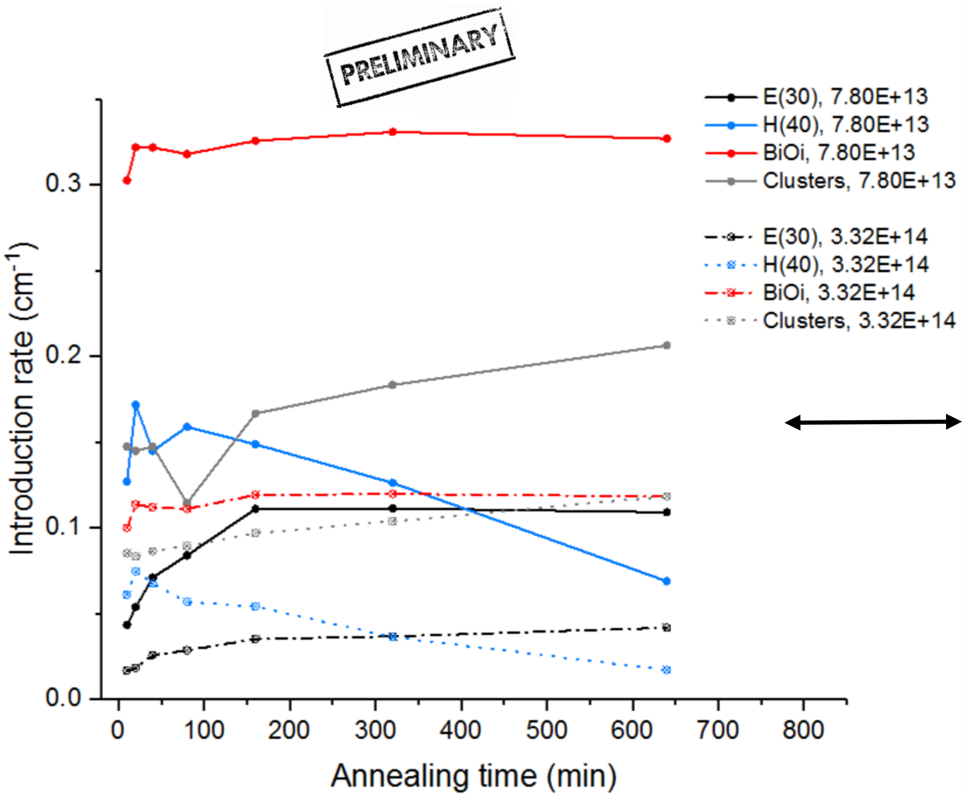
PRELIMINARY

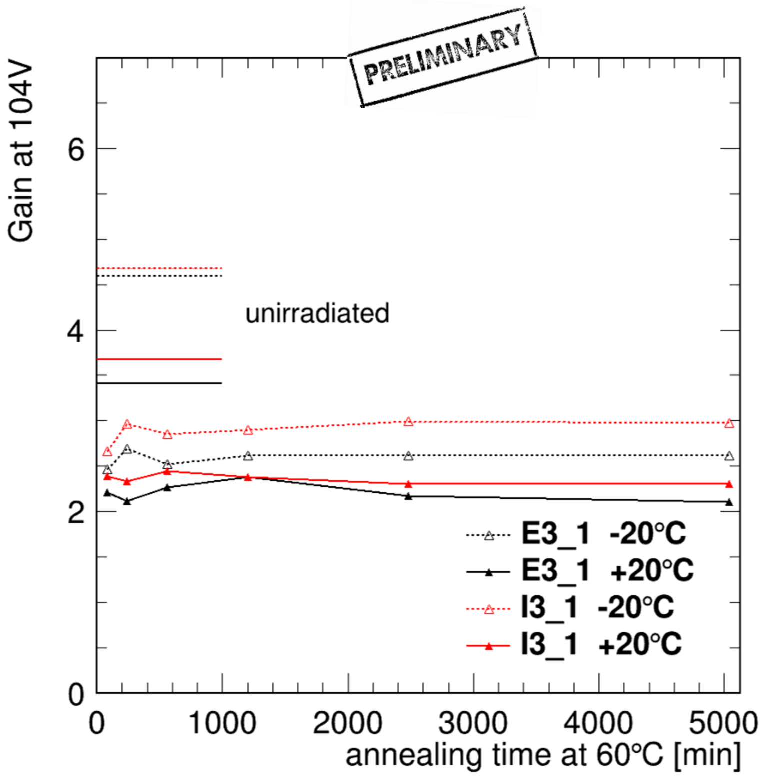




# Isothermal Annealing @60°C. Protons

Evolution of the defects concentrations normalized by fluence in p-type EPI silicon sensors obtained by TSC spectroscopy method due to the proton irradiation with two different fluences of 7.8E13 $n_{eq}/cm^2$ and 3.32E14 $n_{eq}/cm^2$ with isothermal annealing. Comparison with the results on annealing study of LGADs.





$B_iO_i$ concentration is flat → doesn't change much with annealing

Stable gain after irradiation
→ Annealing does not affect the gain layer

See presentation of *Moritz O. Wiehe "Annealing and Characterization of LGADs"*

# TSC workstation

>10 000 hours of working time

☎ sudden loss of cooling power

to *Advanced Research Systems*

# Summary and Outlook

- A new acceptor removal measurement campaign was started within four RD50 research centers - CERN, Hamburg University, NIMP Magurele/Bucharest and University of Minsk: irradiations and distribution of the samples are on the way, first data are presented or will be presented in the workshop

- Strong dependence between $B_iO_i$ production and the resistivity was detected for both proton and neutron irradiation

- First thermal annealing studies show that $B_iO_i$ does not anneal @60ºC (max 640 min), which is coherent with the annealing study results on LGADs: the gain is not affected by the annealing

- Further measurements should be performed for additional fluences and other materials - Cz and Fz. Additional TSC with red light illumination, determination of the signatures for other observed defects should be obtained to complete existing result. Comparison with macroscopic measurements is on its way


Thank You!

# Spare slides

# Acceptor removal

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

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

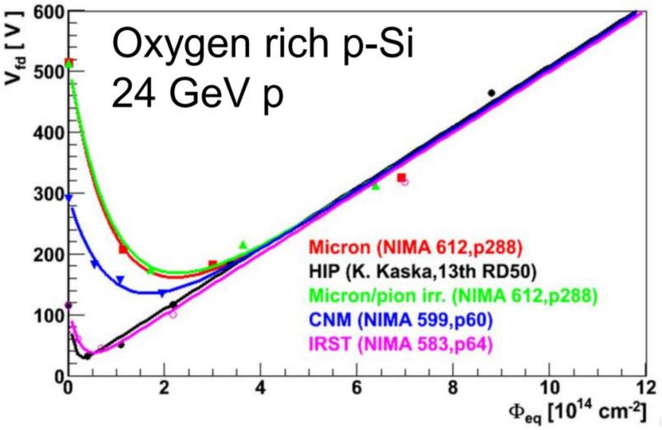
- For neutron irradiation, incomplete acceptor removal is also considered ($N_c < N_{eff0}$)

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

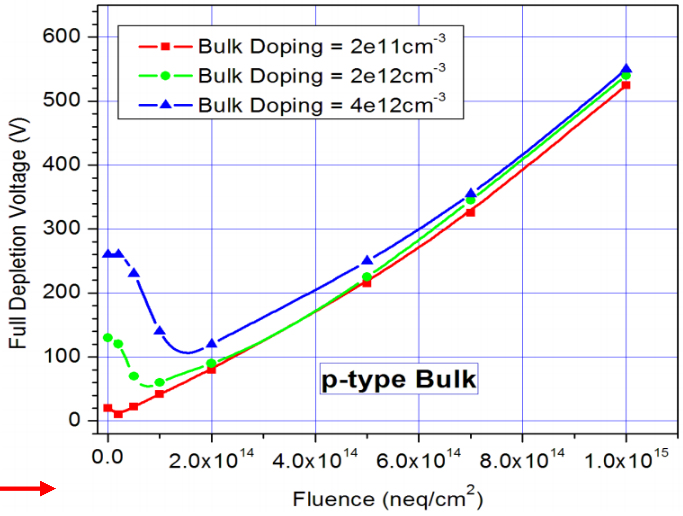
- However, simulations can produce similar Vdep data without changing the background doping concentration (Double junction effect).

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

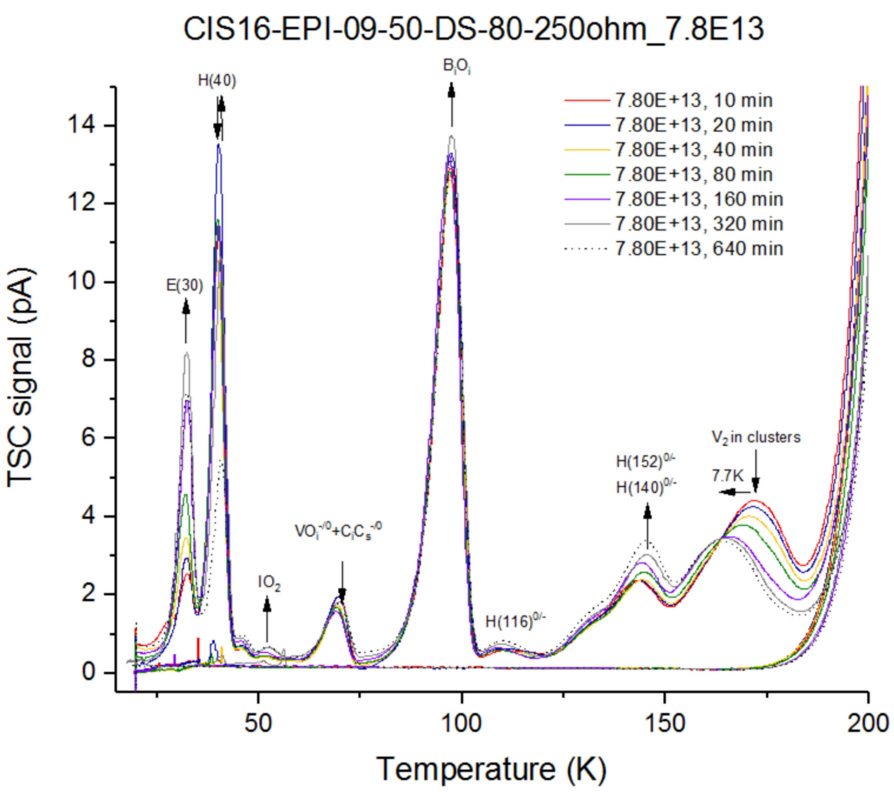
*G. Kramberger, 23rd RD50 Workshop*

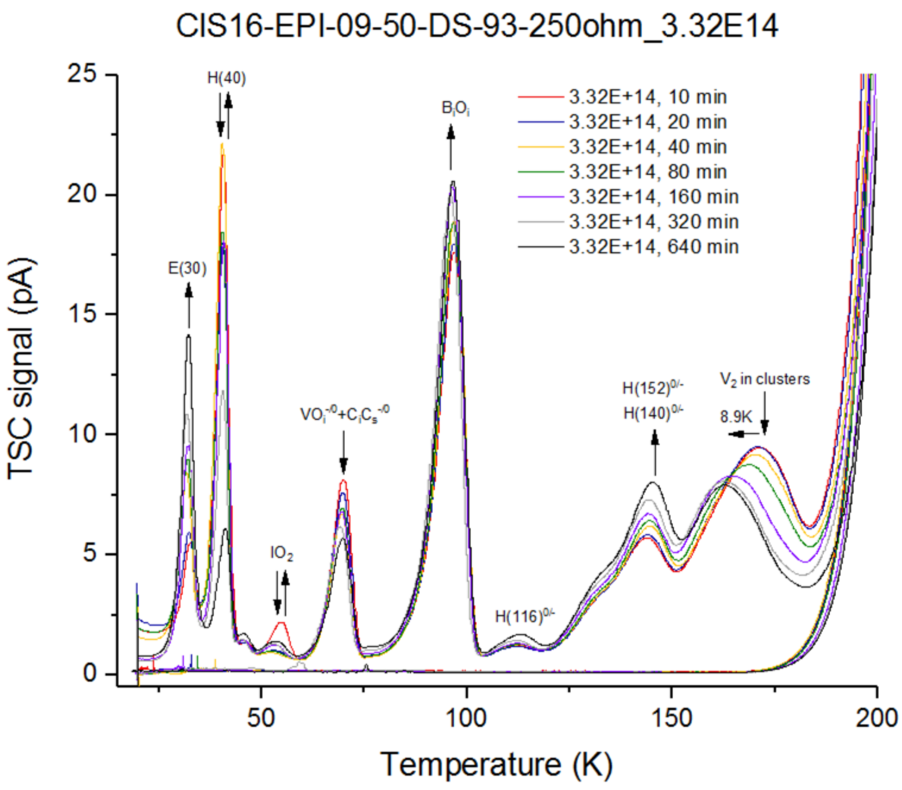


*Ranjeet Dalal et al, 25th RD50 Workshop*



# Isothermal Annealing @60°C. Protons





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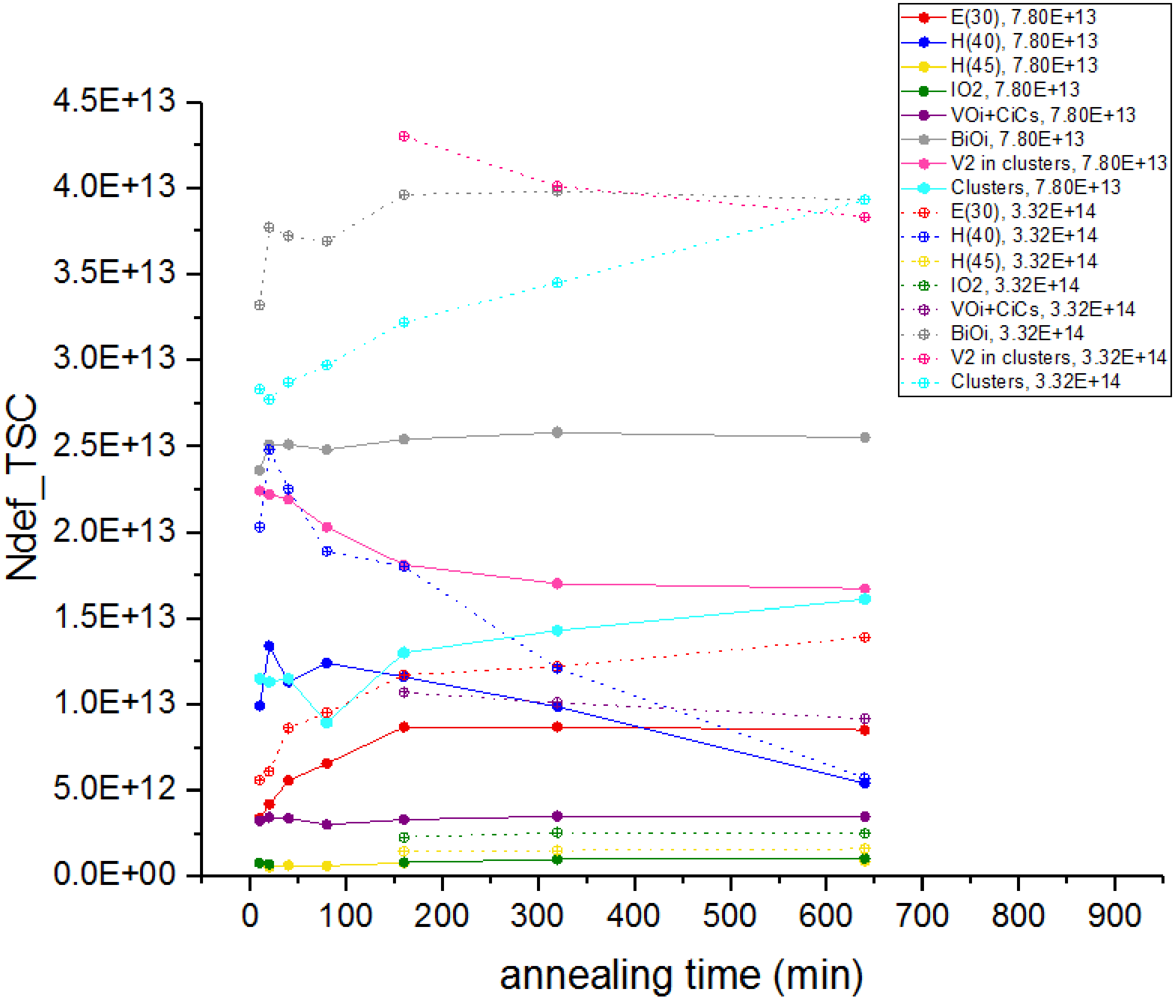
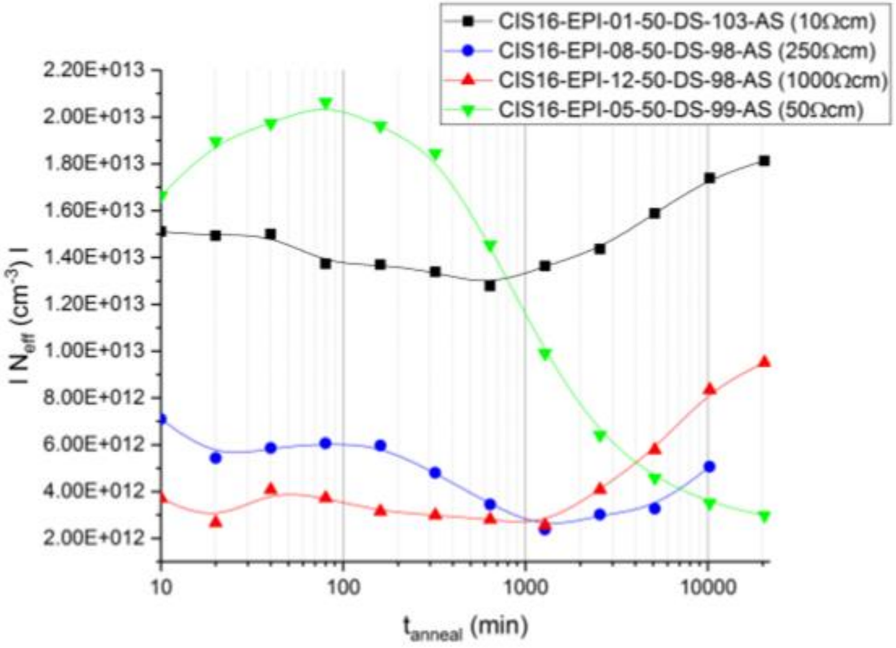


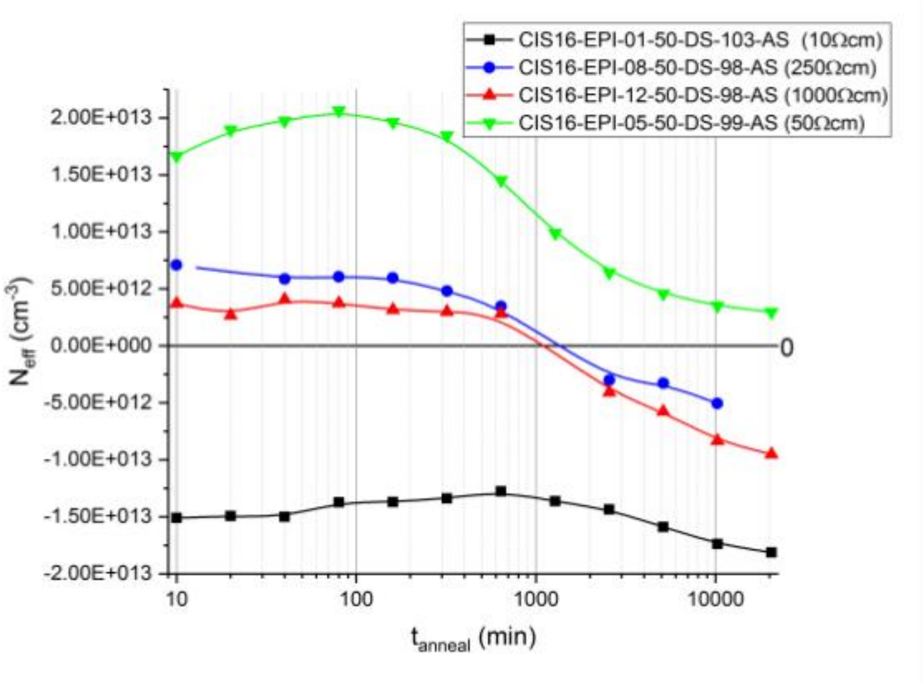
Yana Gurimskaya, 33rd RD50 Workshop, 26-28 of November, 2018, CERN, Geneva, Switzerland

# 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