Defect & Material Characterization

5 Years Work Plan

Work Plan: Material & Defect Characterization

- **Activities: Material and Defect Characterization**
  - Detection and microscopic characterization of standard and material engineered silicon via dedicated techniques (DLTS, TSC, TDRC, SIMS, ICP-MS, PITS, FTIR, TCT, EPR, HRTEM)
  - Identification of electrically active defects induced by irradiation responsible for trapping, leakage current, change of Neff , change of E-Field
  - Studying possible application for radiation hardening
  - Deliver input for device simulations (e.g. TCAD) to predict detector performance under various conditions

Work Plan: Material & Defect Characterization

Identified milestones for next 5 years organized in 3 Work Packages:

Upcoming milestone

- **WP 5.1.1. Electrically active defects in p-type silicon**

  This work will focus on the analysis of electrically active defects and of the radiation induced changes in the electrical characteristics of devices built on p-type silicon.

  - **M1: Detection/characterization of all radiation induced defects in STFZ and engineered silicon (Q3/2019)**
  - **M2: Determine defect annealing behaviour in STFZ and engineered silicon. Correlation with device performances (Q4/2019)**
  - **M3: Determine defect transformations and kinetics in STFZ and engineered silicon after treatments at high temperatures (between 150 °C and 350 °C). Correlation with the device performance (Q3/2020)**
  - **M4: Identify the role of impurities in defect formation (Q1/2021)**
  - **M5: Detection/characterization of radiation induced defects in LGAD and HV-CMOS sensors made with STFZ and engineered p-type silicon, establishing annealing behaviour and correlation with electrical performance (Q3/2021)**
  - **M6: Validity tests on optimized material engineered sensors (pads, LGADs and HV-CMOSs). Comparison between prediction and experiments (Q1/2022)**
  - **M7: Validity tests on finally optimized material engineered sensors (pads, LGADs and HV-CMOSs) (Q3/2023)**

Work Plan: Material & Defect Characterization

- **WP 5.1.2. Microstructural Investigations on extended and clustered defects**

This work targets microstructural investigations of extended and clustered defects by electron microscopy:

- **M1: Microstructural characterization of the radiation induced clustered defects (fluences between 10^{15} and 10^{17} n_{eq} cm^{-2}) and monitoring of the evolution of clusters at 80 °C (Q3/2019)**

Upcoming milestone

- **M2: In situ- annealing studies at 5 temperatures (between 150 °C and 350 °C) in order to determine the structural transformations of the extended and clustered defects (Q3/2020)**
- **M3: Microstructural characterization of the oxide-semiconductor interface in irradiated LGADs and HV-CMOS devices, time evolution at 80 °C (Q3/2021)**
- **M4: Microstructural characterization of the oxide-semiconductor interface in irradiated optimized LGADs and HV-CMOS devices (Q3/2022)**

Work Plan: Material & Defect Characterization

- **WP 5.1.3 Theory of defects and defect kinetics modelling**
  - M1: Modelling of the detected defect generation/kinetics and of the impact on the device performance corresponding to annealing treatments at 80 °C (Q3/2020)
  - M2: Modelling of the detected defect generation/kinetics and of the impact on the device performance corresponding to annealing at temperatures between 150 °C and 350 °C and final assessment of the role of the intentional added impurities (Q1/2021)
  - M3: Identification of the optimal impurity concentrations for pads, LGADs and HV-CMOSs as input for production. (Q3/2021)
  - M4: Improvements of the developed models according to validity test foreseen as 5.1.1-M6 and provide new optimization solutions for 5.1.1-M7. (Q3/2022)
  - M5: Validity test for the developed theoretical models based on the results obtained on 5.1.1-M7 optimized sensors (Q3/2023)

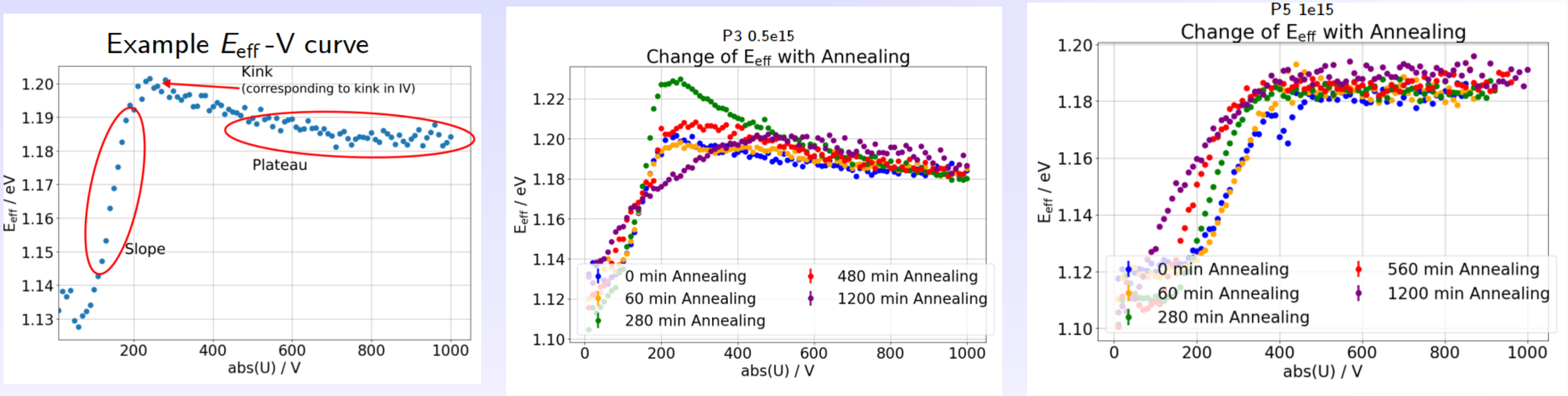
Defect & Material Characterization

This Workshop

Bonn Facility & E_{eff} of I_{Leak}

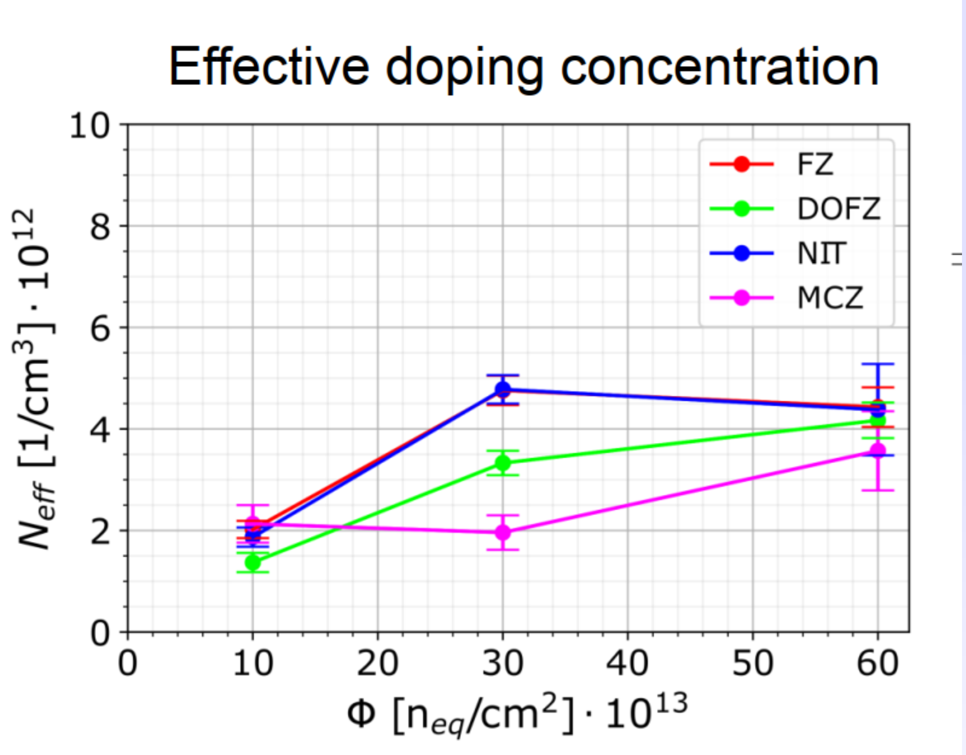
- **Pascal Wolf: New Irradiation Facility at Bonn (up to 14 MeV protons)**
  - **14 MeV protons** with a hardness factor of **κ≈ 3** can be generated with beam currents of **up to ≈ 1 µA** at the HISKP cyclotron

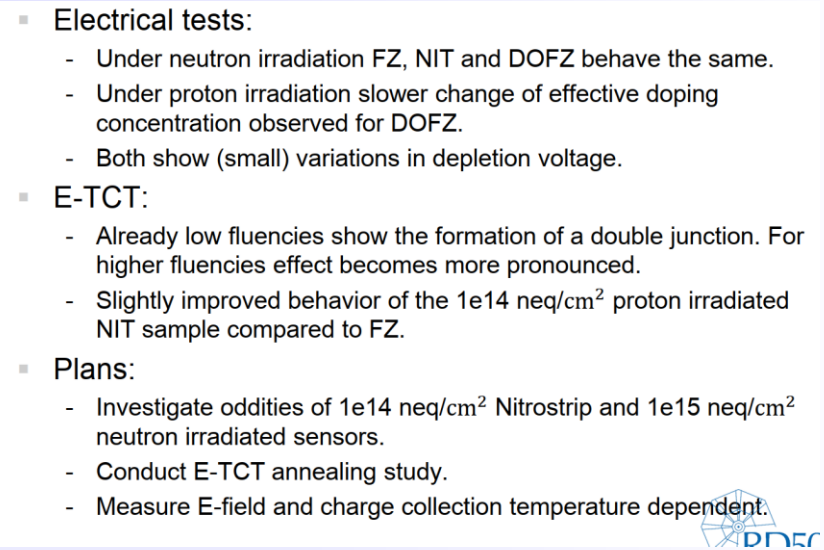
- **Felix Wizemann: Determination of Eeff for Leakage Current scaling**



Nitrogen enriched Silicon

- **Jan Cedric Hoenig – Nitrostrip project**

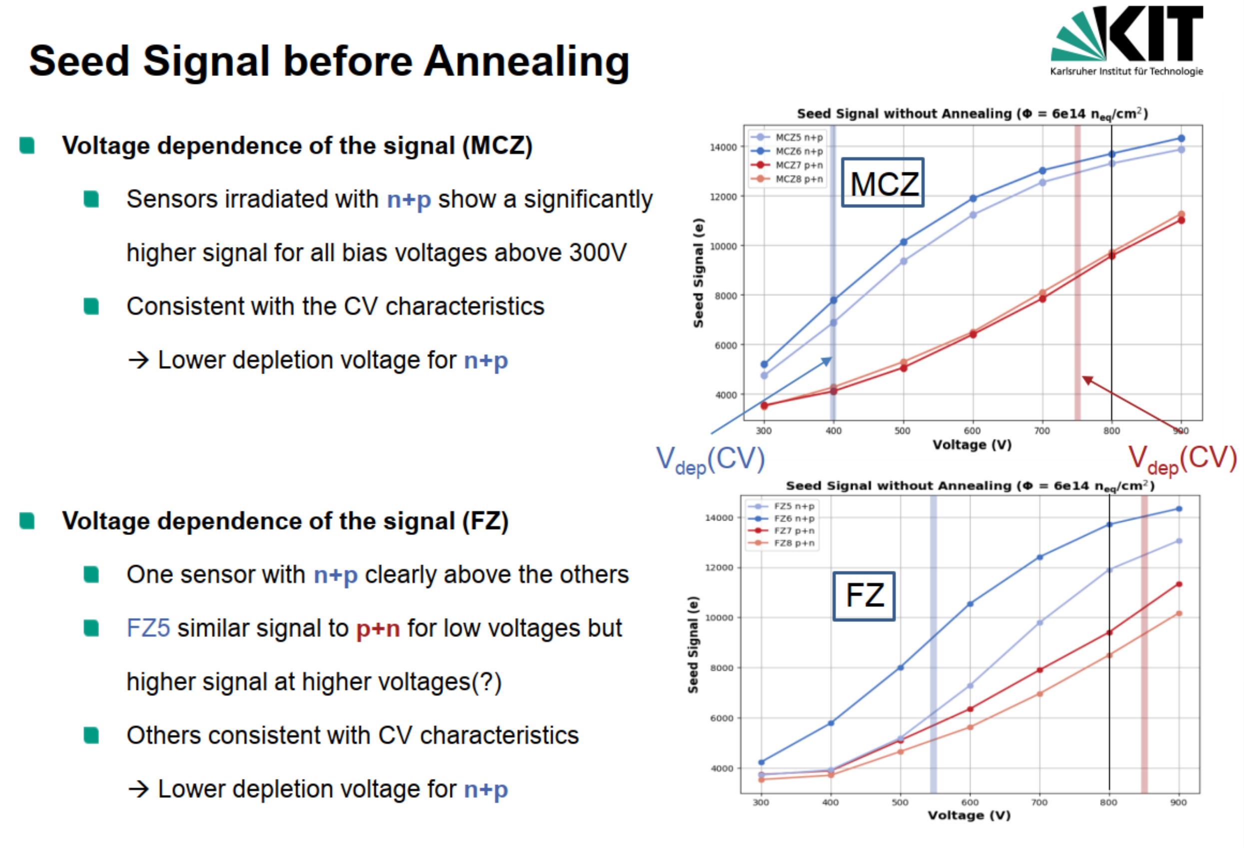




- Electrical tests:
  - Under neutron irradiation FZ, NIT and DOFZ behave the same.
  - Under proton irradiation slower change of effective doping concentration observed for DOFZ.
  - Both show (small) variations in depletion voltage.
- E-TCT:
  - Already low fluencies show the formation of a double junction. For higher fluencies effect becomes more pronounced.
  - Slightly improved behavior of the 1e14 neq/cm^2 proton irradiated NIT sample compared to FZ.
- Plans:
  - Investigate oddities of 1e14 neq/cm^2 Nitrostrip and 1e15 neq/cm^2 neutron irradiated sensors.
  - Conduct E-TCT annealing study.
  - Measure E-field and charge collection temperature dependent.

Mixed irradiations

- **Jan Ole Gosewich -- Proton/Neutron vs. Neutron/Proton**
  - **Order of irradiation matters!**



Seed Signal before Annealing

- **Voltage dependence of the signal (MCZ)**
  - Sensors irradiated with **n+p** show a significantly higher signal for all bias voltages above 300V
  - Consistent with the CV characteristics

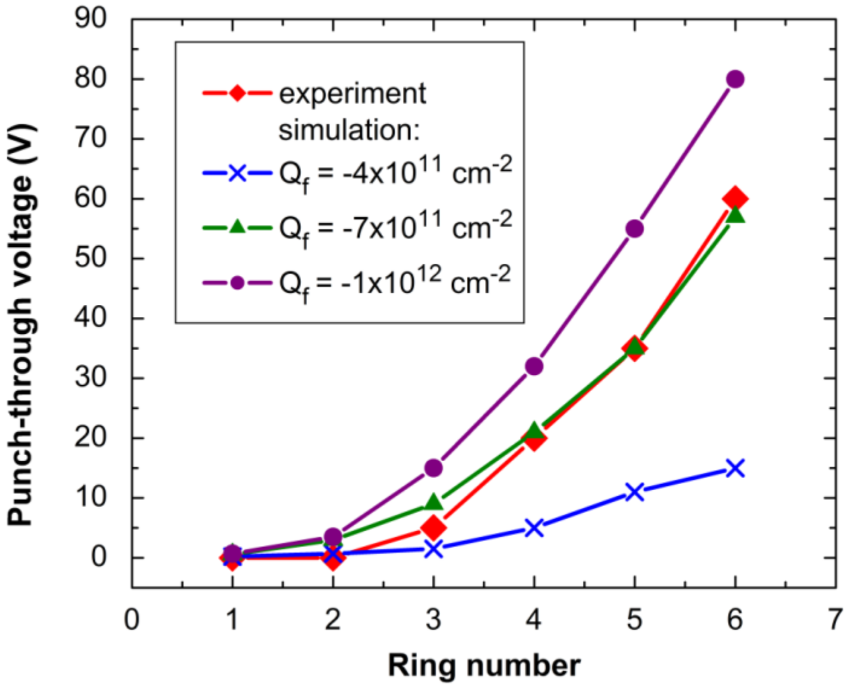
    → Lower depletion voltage for **n+p**
- **Voltage dependence of the signal (FZ)**
  - One sensor with **n+p** clearly above the others
  - FZ5 similar signal to **p+n** for low voltages but higher signal at higher voltages(?)
  - Others consistent with CV characteristics

    → Lower depletion voltage for **n+p**

Surface passivation

- **Elena Verbitskaya – Al_2O_3 passivation**

Extraction of Q_f from comparison of experimental and simulated data on V_{th}

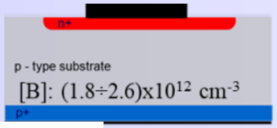


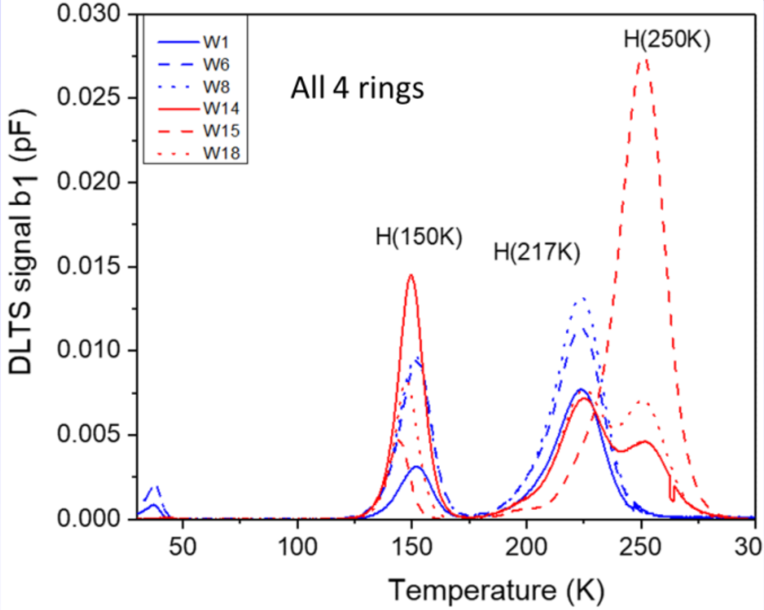
- $Q_f = -1\times10^{11}$ cm^{-2} - no agreement
- $Q_f = -4\times10^{11}$ cm^{-2} - V_{th} agree for the 1st and 2nd rings
- $Q_f = -7\times10^{11}$ cm^{-2} - agreement for rings 4-6 better than 10%
- $Q_f = -1\times10^{12}$ cm^{-2} - all simulated V_{th} values exceed the experimental data

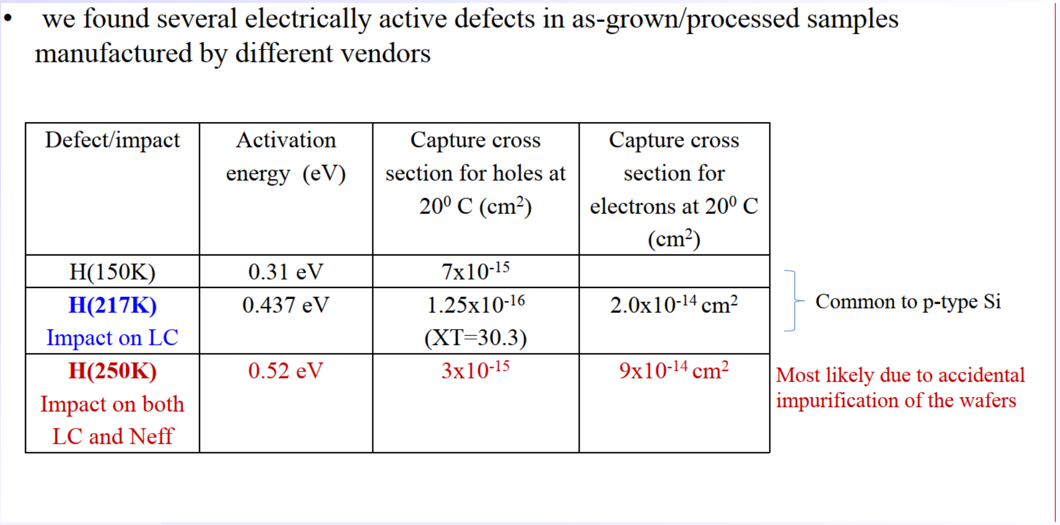
p-type silicon - defects

- **Cristina Besleaga Stan – non irradiated p-type**

DLTS investigations







- we found several electrically active defects in as-grown/processed samples manufactured by different vendors

Defect/impact	Activation energy (eV)	Capture cross section for holes at 20^0 C (cm^2)	Capture cross section for electrons at 20^0 C (cm^2)
H(150K)	0.31 eV	7x10^{-15}	
H(217K) Impact on LC	0.437 eV	1.25x10^{-16} (XT=30.3)	2.0x10^{-14} cm^2
H(250K) Impact on both LC and Neff	0.52 eV	3x10^{-15}	9x10^{-14} cm^2

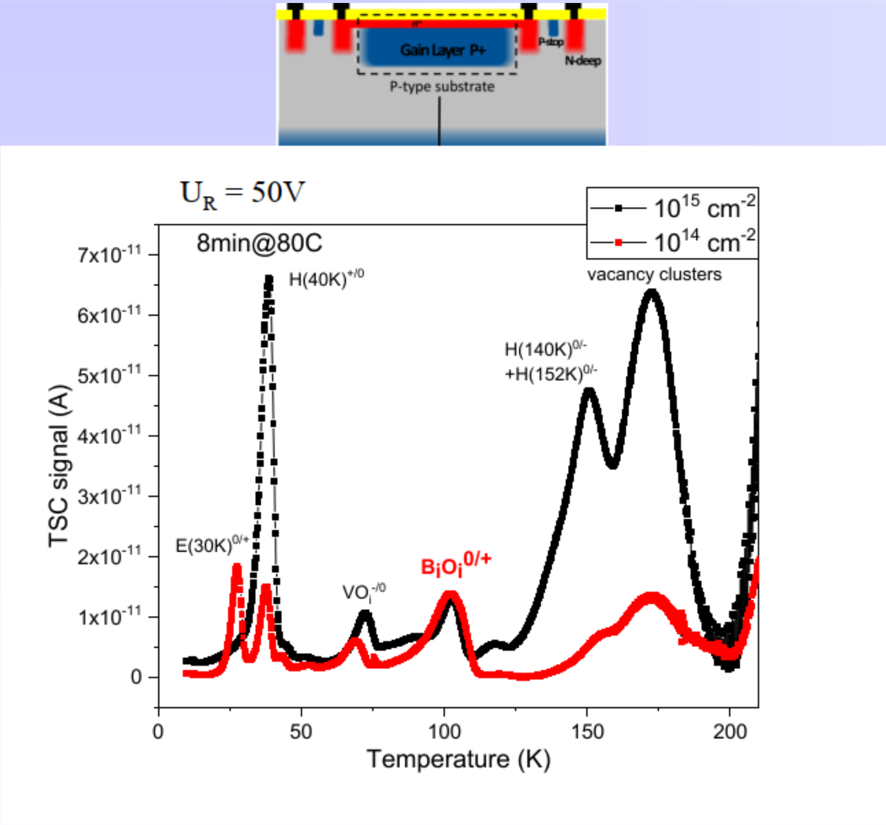
Common to p-type Si

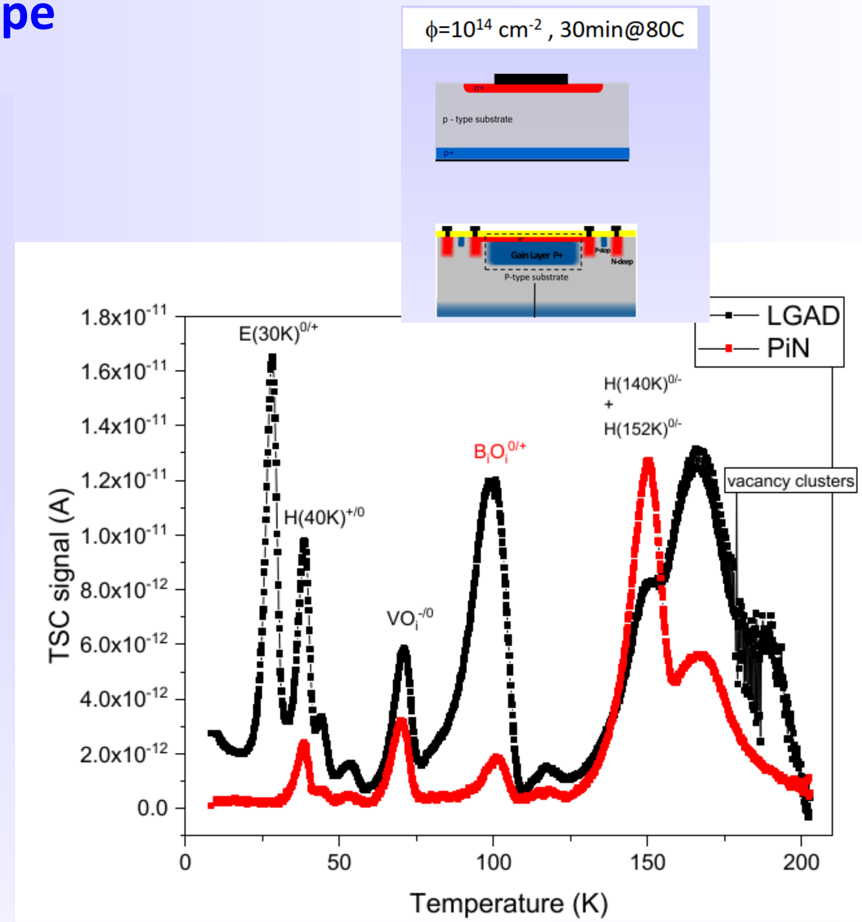
Most likely due to accidental impurification of the wafers

H(250K) trapping parameters: E_a*=0.52 eV,* σ_p*= 3x10*$^{-15}$ *cm*^{2} (di

p-type silicon - defects

- **Cristina Besleaga Stan – irradiated p-type**



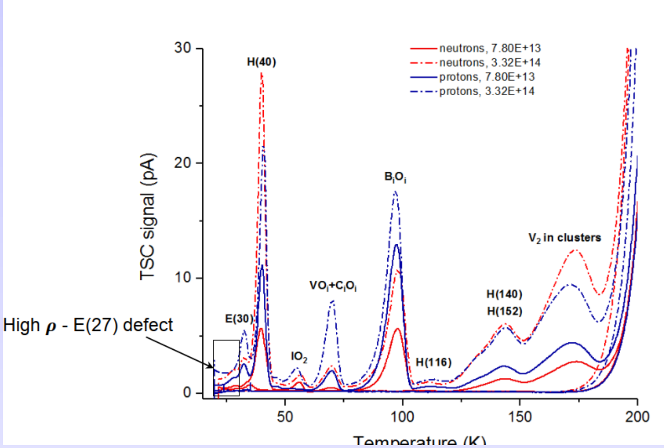


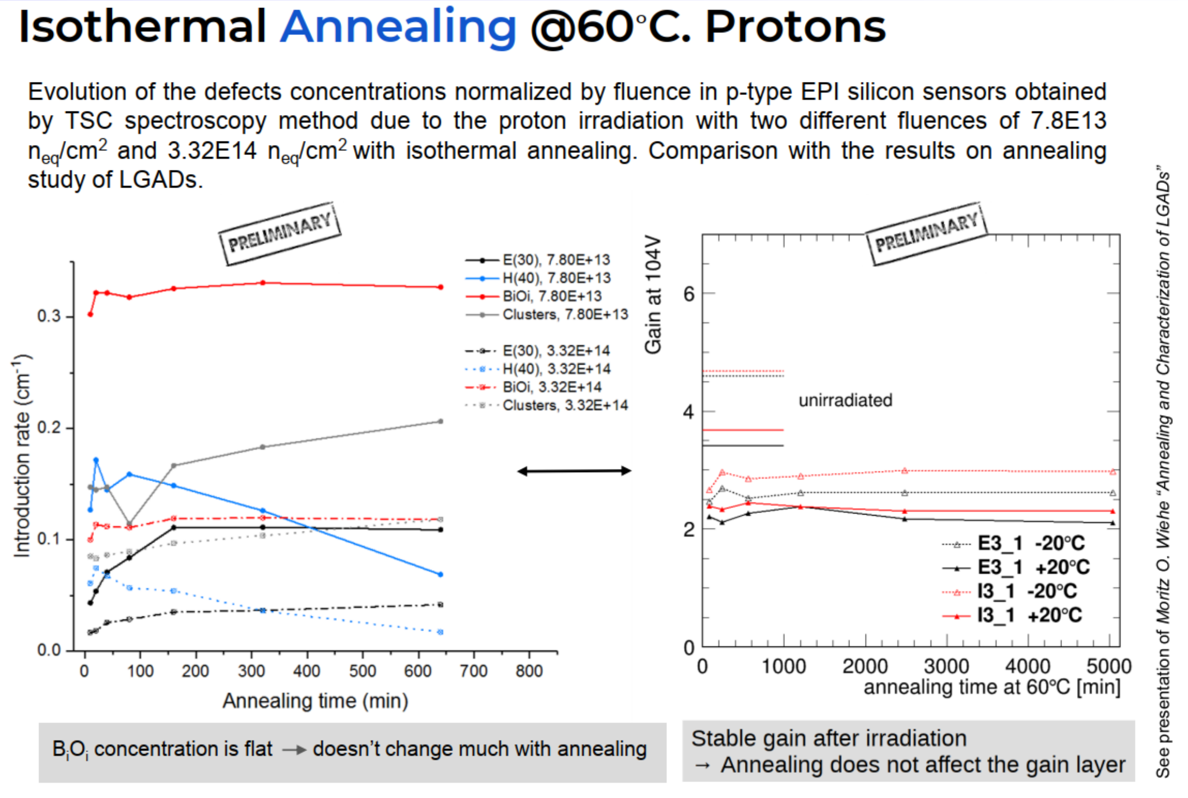
- In LGAD diodes most of the defects increase in concentration with fluence but the BiOi

⇒ A saturation of BiOi possible caused by the limited amount of Oi

Epi p-type : defect formation

- **Yana Gurimskaya : TSC on proton and neutron irradiated Epi p-type**





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.

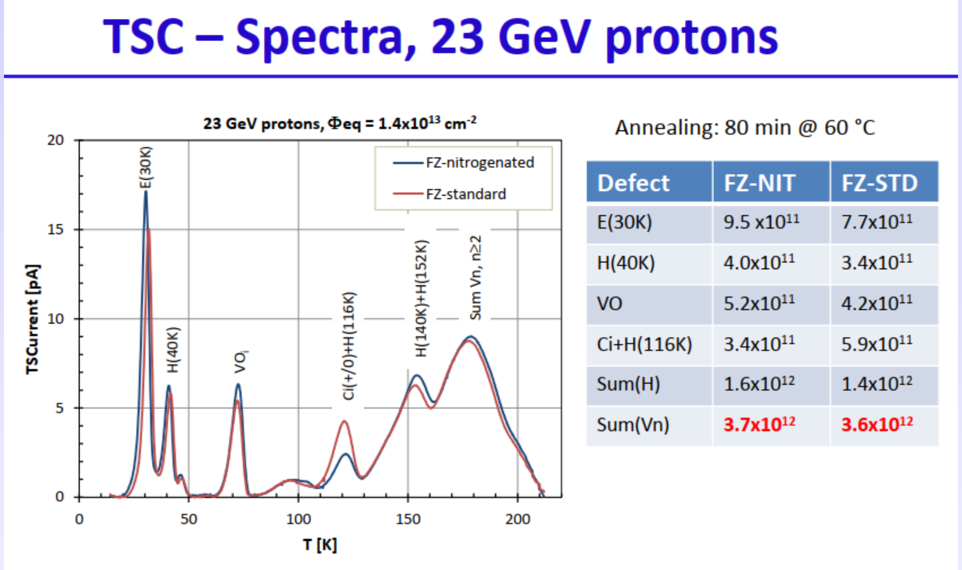
B_iO_i concentration is flat → doesn't change much with annealing

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

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

TSC on N- and B- doped Silicon

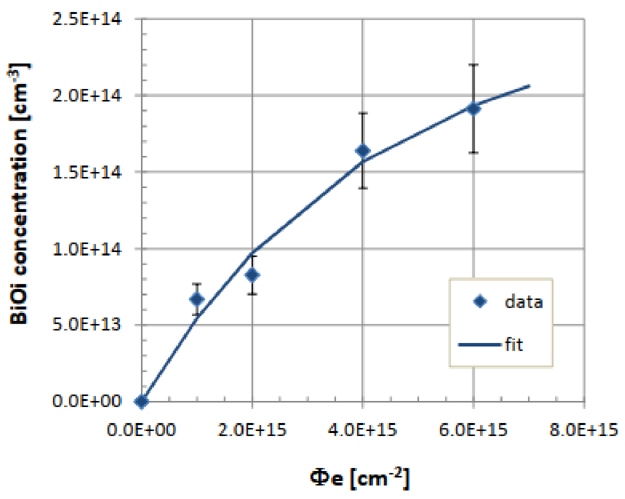
- **Eckhart Fretwurst – Nitrogenated vs. Standard silicon**
  - No clear difference between standard and N doped silicon



TSC – Spectra, 23 GeV protons

Annealing: 80 min @ 60 °C

Defect	FZ-NIT	FZ-STD
E(30K)	9.5 x10^{11}	7.7x10^{11}
H(40K)	4.0x10^{11}	3.4x10^{11}
VO	5.2x10^{11}	4.2x10^{11}
Ci+H(116K)	3.4x10^{11}	5.9x10^{11}
Sum(H)	1.6x10^{12}	1.4x10^{12}
Sum(Vn)	3.7x10^{12}	3.6x10^{12}



B_iO_i concentration versus Φ_e

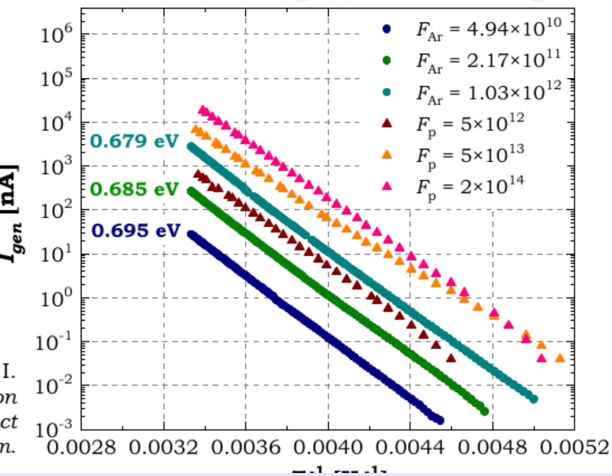
- Boron removal parameter
  $c_e \approx 2.4x10^{-16}$ cm^2 ,
- For a hardness factor of
  κ_{neq}(5.5 MeV, e)=$3.98x10^{-2}$ *
  $c_{neq} \approx 6.1x10^{-15}$ cm^2

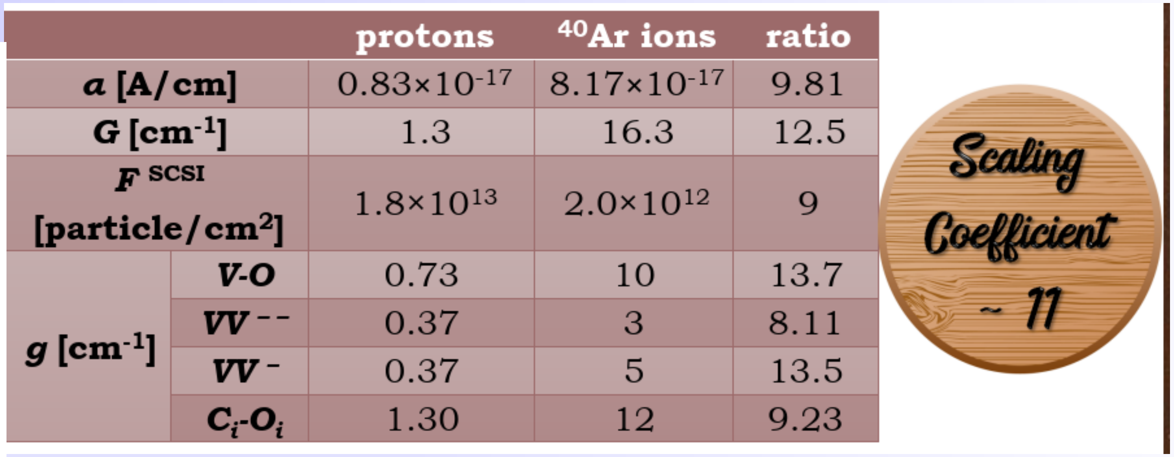
* (*I. Jun et al., IEEE TS Nucl. Sci. Vol.56, No.6, 2009*)

- **Electron irradiation**
  - BiOi generation with e-irradiation measured

Proton, Ion Damage and SRIM

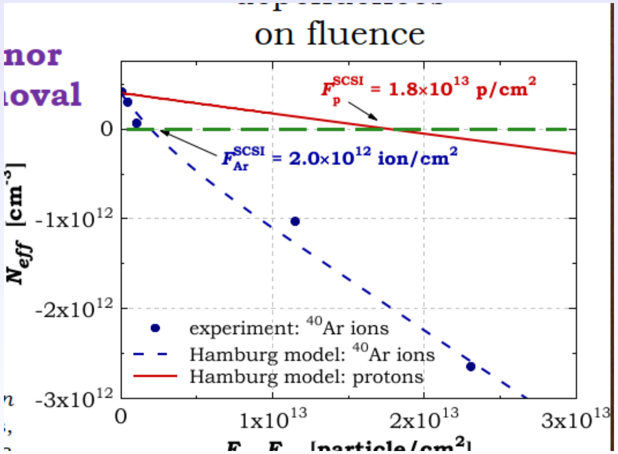
- **Daria Mitina 40 Ar Ions // 50 MeV protons**

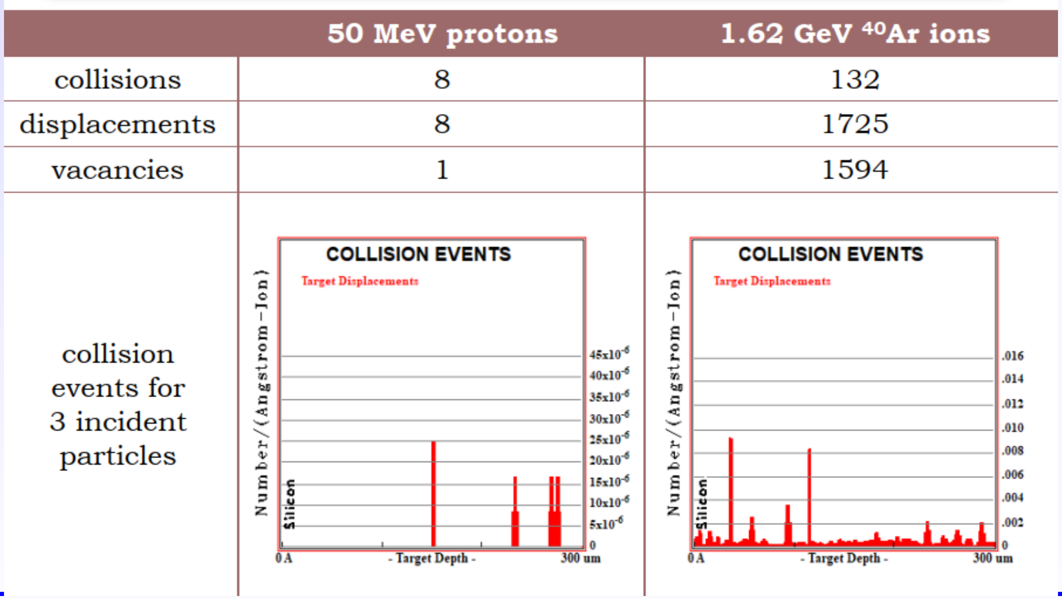




		protons	^{40}Ar ions	ratio
***a* [A/cm]**		0.83×10^{-17}	8.17×10^{-17}	9.81
G [cm^{-1}]		1.3	16.3	12.5
***F* SCSI [particle/cm^2]**		1.8×10^{13}	2.0×10^{12}	9
***g* [cm^{-1}]**	***V-O***	0.73	10	13.7
	VV^{--}	0.37	3	8.11
	VV^{-}	0.37	5	13.5
	C_i-O_i	1.30	12	9.23

Scaling Coefficient ~ 11

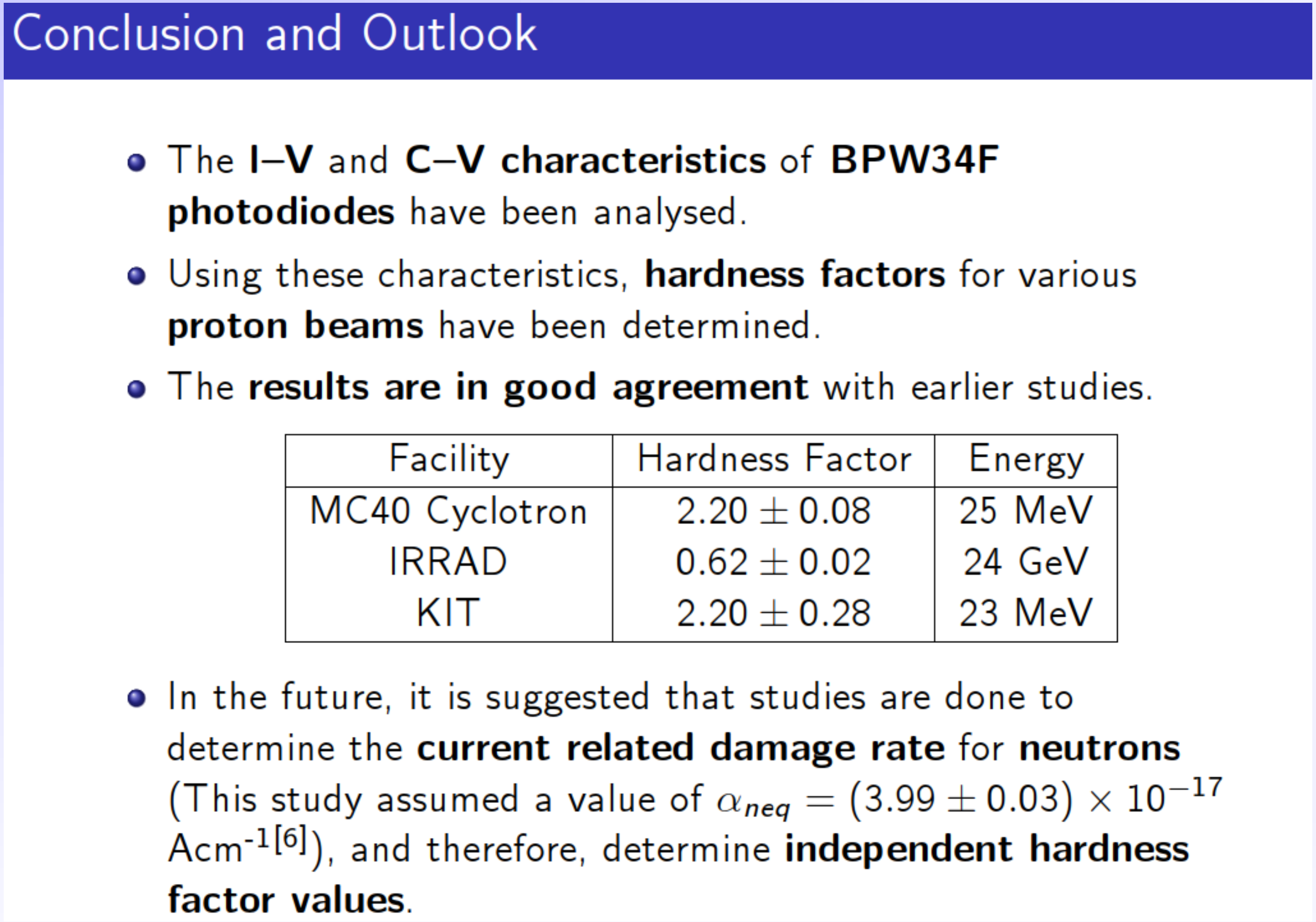




	50 MeV protons	1.62 GeV ^{40}Ar ions
collisions	8	132
displacements	8	1725
vacancies	1	1594
collision events for 3 incident particles		

Hardness Factors

- **Cameron Simpson-Allsop**



Conclusion and Outlook

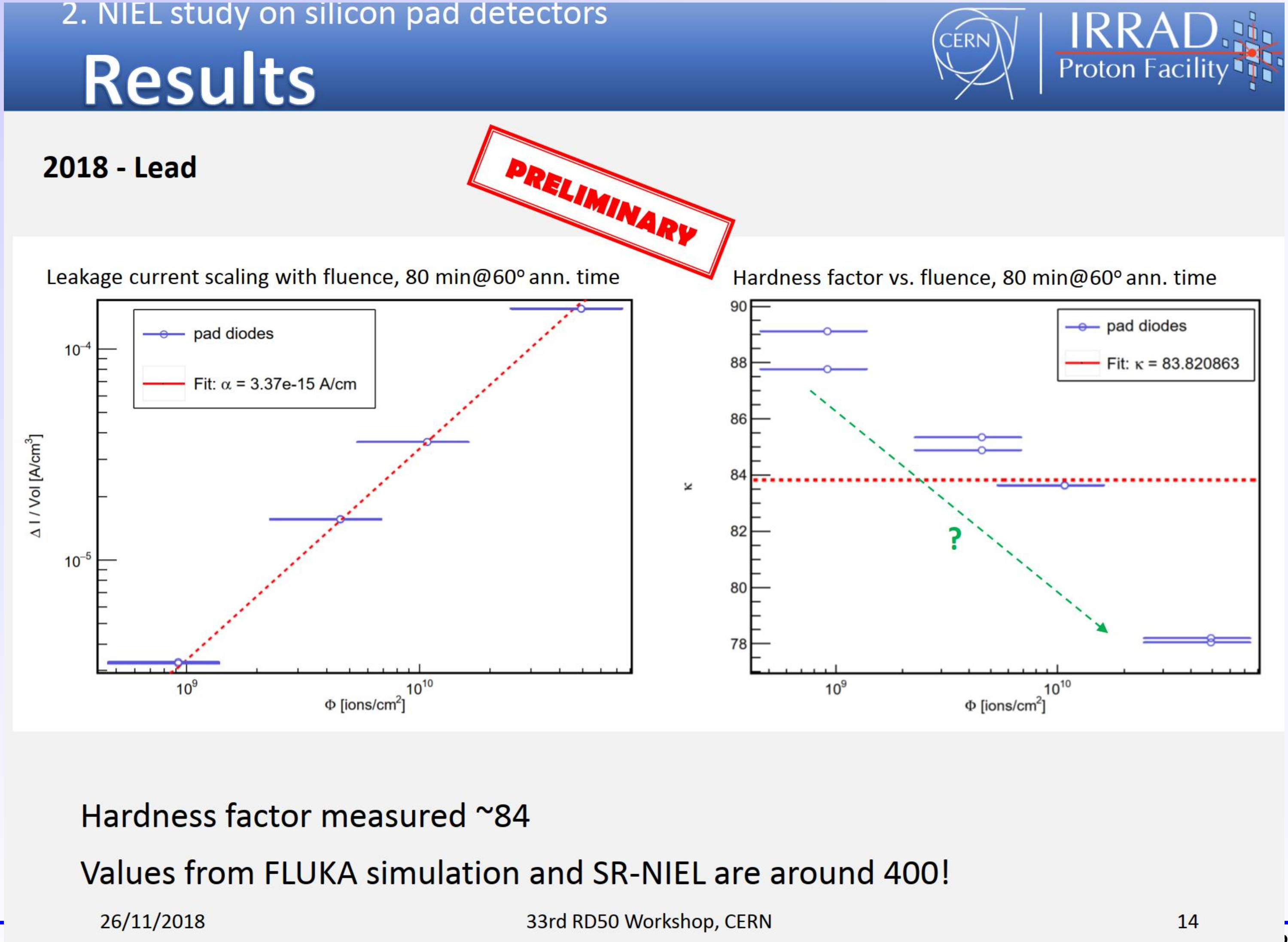
- The **I–V** and **C–V characteristics** of **BPW34F photodiodes** have been analysed.
- Using these characteristics, **hardness factors** for various **proton beams** have been determined.
- The **results are in good agreement** with earlier studies.

Facility	Hardness Factor	Energy
MC40 Cyclotron	2.20 ± 0.08	25 MeV
IRRAD	0.62 ± 0.02	24 GeV
KIT	2.20 ± 0.28	23 MeV

- In the future, it is suggested that studies are done to determine the **current related damage rate** for **neutrons** (This study assumed a value of $\alpha_{neq} = (3.99 \pm 0.03) \times 10^{-17}$ Acm^{-1}[6]), and therefore, determine **independent hardness factor values**.

Ions at CERN

- **Isidre Mateu**



2. NIEL study on silicon pad detectors

Results

IRRAD Proton Facility

2018 - Lead

PRELIMINARY

Leakage current scaling with fluence, 80 min@60° ann. time

Hardness factor vs. fluence, 80 min@60° ann. time

Hardness factor measured ~84

Values from FLUKA simulation and SR-NIEL are around 400!

Defect & Material Characterization

Discussion

A common project ?

- Repeat proton/neutron and neutron/proton project
- Lots of discussions on Hardness factors.
  - We should "standardize" the procedure to measure this!
- Should we initiate a common project on the production of simple diodes aiming for Hardnessfactor (NIEL) and "basic properties" (e.g. Eeff for leakage current) determination.
- I imagine a 6 inch wafer with mainly diodes (n- or p-type?); Thickness of 300 microns

- **Compare Al2O2 charge in strip sensor vs. MOS capacitor.**
- **Investigate impact of thermal neutrons on Boron removal (B-10 capture)**
- **P-EPI : Look for potential depth dependence of defect production from variation of [O] profile**
- **P-type evaluation: On good way, …. continue the program**