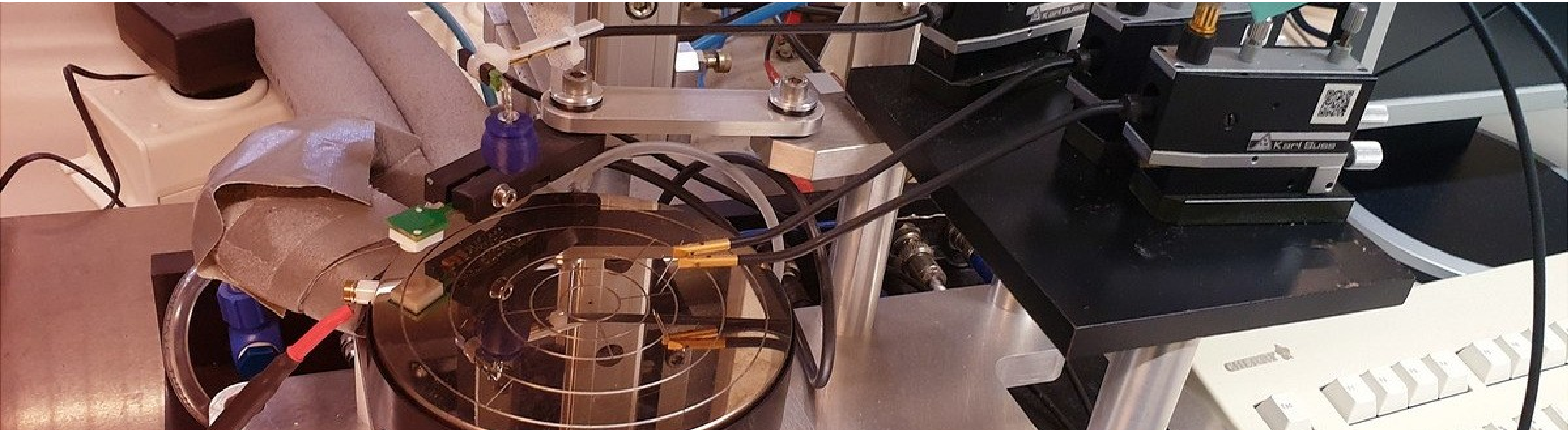
Boron removal effect in silicon sensors



Chuan Liao[a], E. Fretwurst[a], E. Garutti[a], J.Schwandt[a], A. Himmerlich[b], M. Moll[b], Y. Gurimskaya[b], I. Pintilie[c], L. Makarenko[d]

[a]Institut für Experimentalphysik, Universität Hamburg

[b]European Organization for Nuclear Research (CERN), Geneva, Switzerland

[c]National Institute of Materials Physics, Bucharest, Romania

[d]Belorussian State University, Minks, Belarus

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High-D

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HIGH-D

Outline

I. Motivation

II. Background

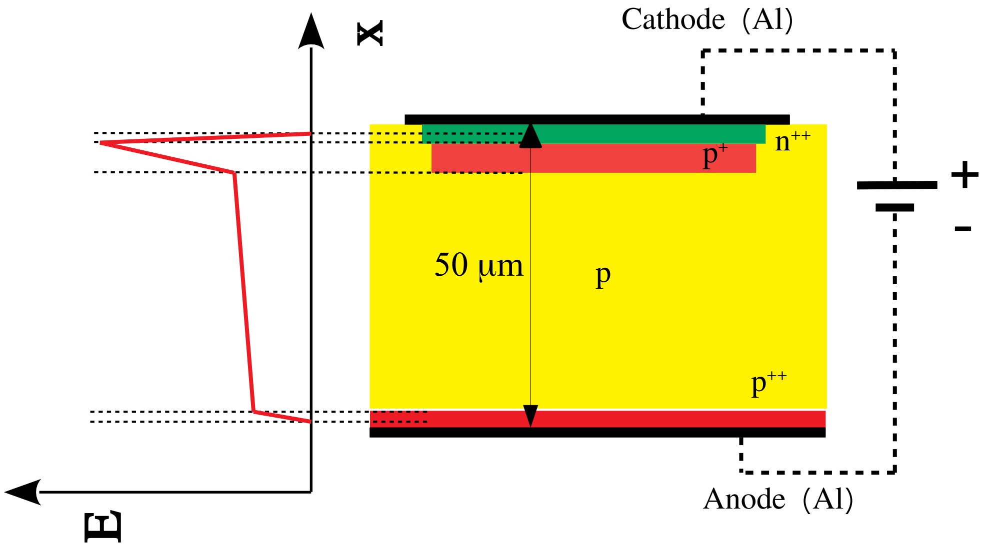
III. Experimental details

IV. Results

V. Summary

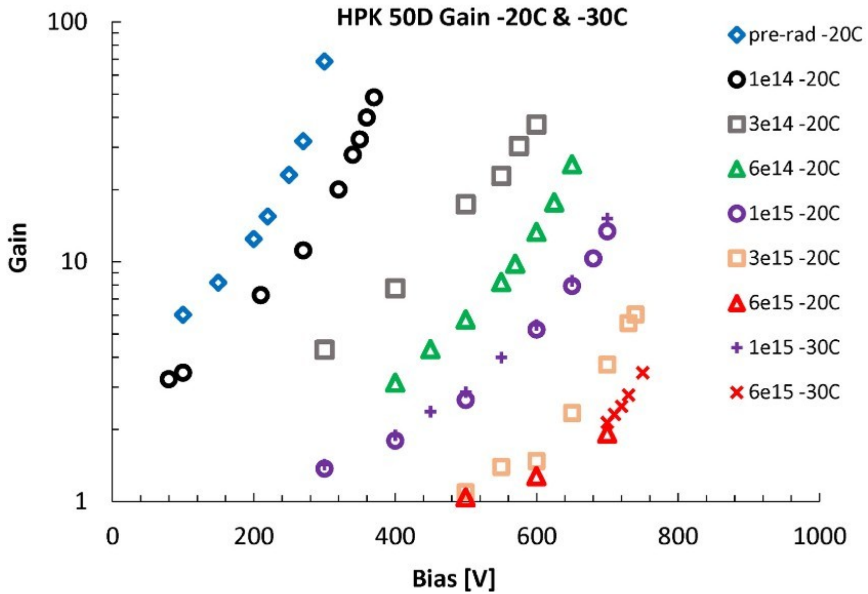
Motivation

Radiation damage of LGADs (Low Gain Avalanche Diodes)



Schematic of LGAD

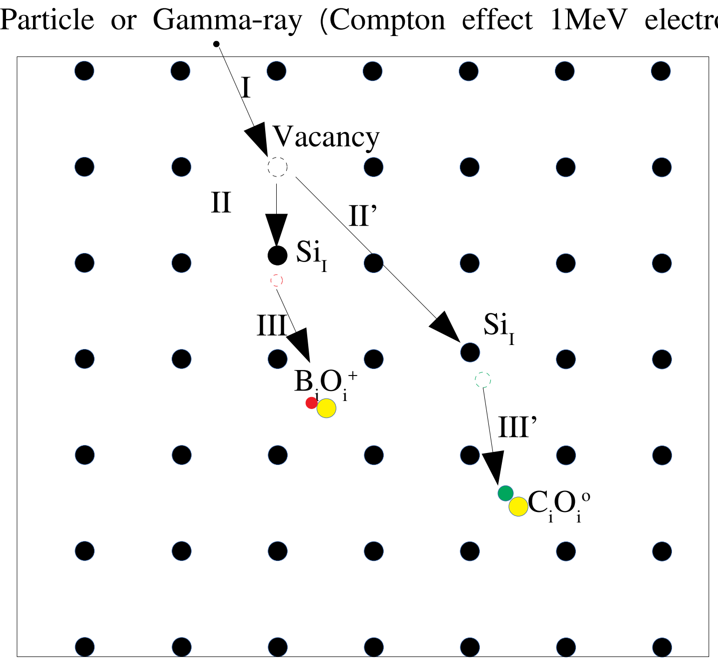
- Aluminum
- p type bulk (Boron doping, ~10^{13} cm^{-3})
- p^{+} (Boron doping B_s^-, ~ 10^{16} cm^{-3})
- p^{++} (Boron doping B_s^-, ~ 10^{19} cm^{-3})
- n^{++} (phosphorus doping P_s^+, ~ 10^{21} cm^{-3})



Gain value vs. bias for different fluences

Significant decrease of Gain value after irradiation

Bulk damage in p-type silicon sensor



Schematic of radiation damage in p-type silicon sensor

I: Lattice Silicon atom (Si_s) was knocked out by incident particle and Si_s got recoil energy and turns to interstitial silicon (Si_i)

II: Si_i diffusion in the bulk and impact on Lattice Boron atom (B_s)

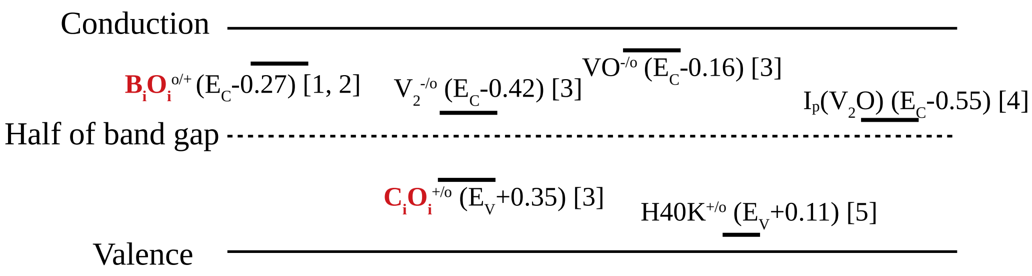
III: B_s was knocked out Si_i and turns to interstitial Boron (B_i) and finally captured by interstitial Oxygen (O_i)

Ph.D works:

Type of Radiation

- 23 GeV Protons (4.3×10^{13} n_{eq}/cm^2, $N_{eff} = 10^{12}$~10^{15} cm^{-3} – **Doping dependent**):
  Comparing the decreases of N_{eff} with defect formation;
  Current related damage parameter α (Hamburg model, cluster related defect);
  Annealing behavior
- 5.5 MeV electrons (10^{13}~10^{14} n_{eq}/cm^2 – **Fluence dependent**, $N_{eff} = 10^{15}$ cm^{-3}):
  N_{eff}, α and annealing behavior comparing with proton irradiation;
  Comparing the Cz (**[C]** $\approx 2 \times 10^{15}$ cm^{-3}) and EPI (**[C]** $\approx 3 \times 10^{16}$ cm^{-3}) diodes
- $^{60}Co - \gamma$, 1.3 MeV Photon (FZ silicon, point defects)

The observed results from both literature and our works(depend on initial doping, type of radiation and fluence):



Diodes Information (23 GeV Protons)

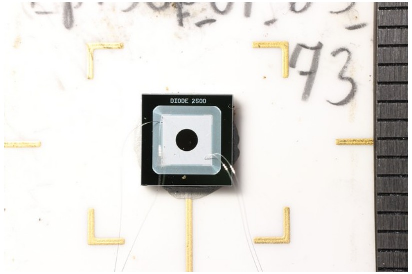
Expitaxial silicon (CIS and CERN)

Diodes with different initial doping concentration

label	EPI50P_01_DS_73	EPI50P_06_DS_71	EPI50P_09_DS_73	EPI50P_12_DS_74
Initial doping (cm^{-3})/Resistivity (Ωcm)	1.4e15/10	2.0e14/50	4.5e13/250	6.2e12/2000
irradiated (23GeV Proton)	Φ_{eq}=4.28e13 cm^{-2}			
Area	0.06927 cm^2			
Thickness	50 µm			
Carbon concentration	~ 2e15 cm^{-3}			

Diodes irradiated with different fluence

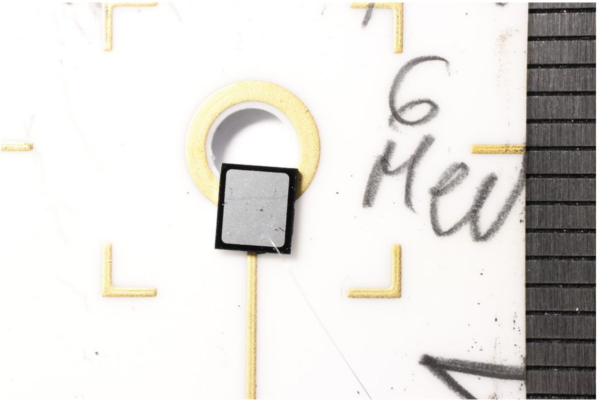
label	EPI50P_06_DS_71	EPI50P_06_DS_73	EPI50P_06_DS_74
Resistivity	50 Ωcm		
irradiated	Φ_{eq}=4.28E13 cm^{-2}	Φ_{eq}=2.5E13 cm^{-2}	Φ_{eq}= 2.49E13 cm^{-2}
Area	0.06927 cm^2		
Thickness	50 µm		
Carbon concentration	~ 2e15 cm^{-3}		

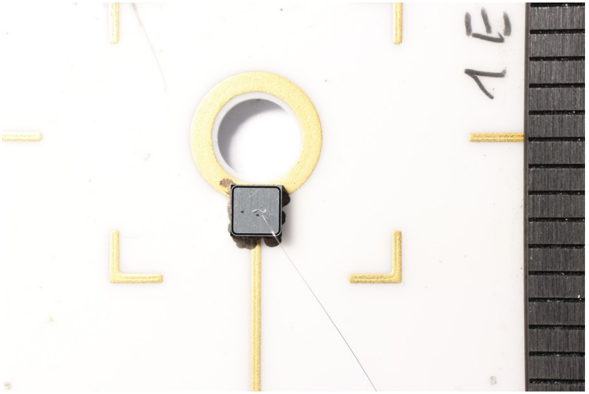


Diodes Information (5.5 MeV electrons)

Minsk

Label	EPI50P_06_DS_3	EPI50P_06_DS_7	EPI50P_06_DS_9	CZ300P_06_DS_3	CZ300P_06_DS_7()
Initial doping/resistivity	Expitaxial silicon, P-type 1.15e15 cm^{-3} / ~ 10 Ωcm			Cz silicon, P-type 1.05e15 cm^{-3} / ~ 10 Ωcm	
Irradiation (6 MeV electrons)	1e15 e/cm^2 (3.98e13 n_{eq}/cm^2)	4e15 e/cm^2 (1.59e14 n_{eq}/cm^2)	6e15 e/cm^2 (2.39e14 n_{eq}/cm^2)	1e15 e/cm^2 (3.98e13 n_{eq}/cm^2)	4e15 e/cm^2 (1.59e14 n_{eq}/cm^2)
Area	0.0621 cm^2			0.029 cm^2	
Thickness	50 μm			400 μm	
Carbon concentration	~ 2e15 cm^{-3}			~ 3e15 cm^{-3}	

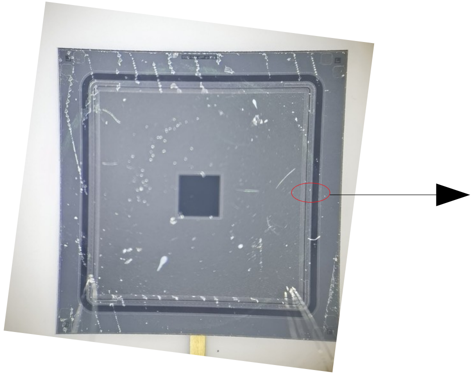


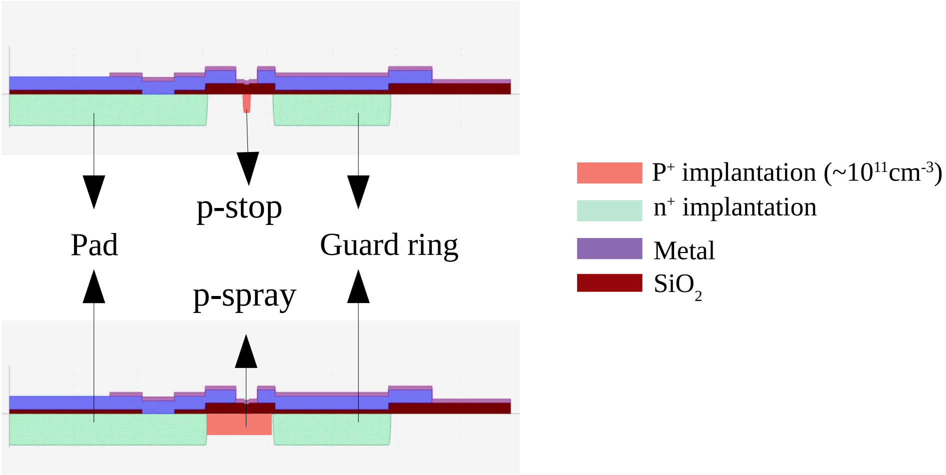


Diodes Information (^{60}Co γ-ray)

Details of samples investigated (high resistivity ~3 kΩcm p-type FZ material from Hamamatsu)

Initial doping, bulk	~3.5 × 10^{12} cm^{-3}			
^{60}Co-γ irradiation	94±0.96 kGy	189±3.9 kGy	924±27 kGy	1860±56 kGy
Area	0.25 cm^2			
Thickness	150 μm			
Carbon concentration	~1e15 cm^{-3}			





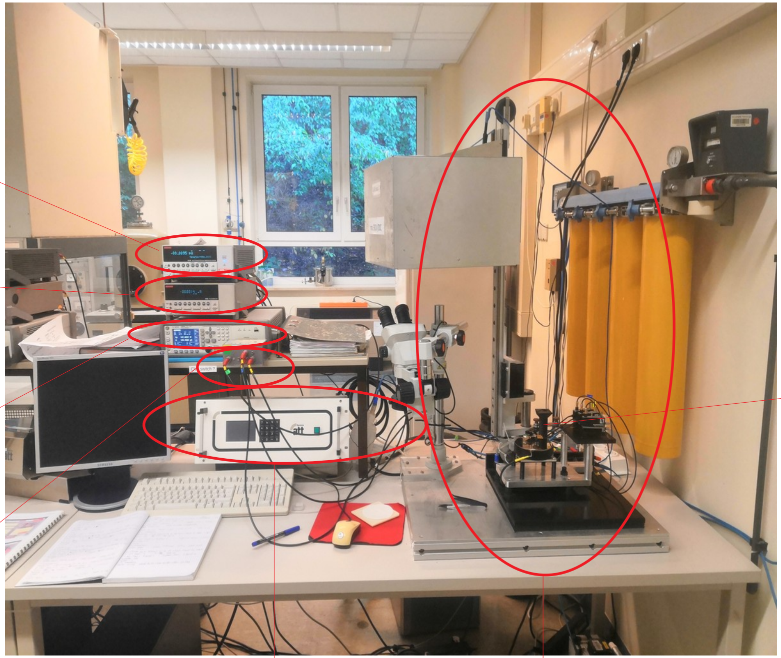
Experimental detail (I-V/C-V)

Instrument 1: Current meter for pad and voltage source

Instrument 2: Current meter for guard ring

Instrument 3: LCR meter for C-V measurements

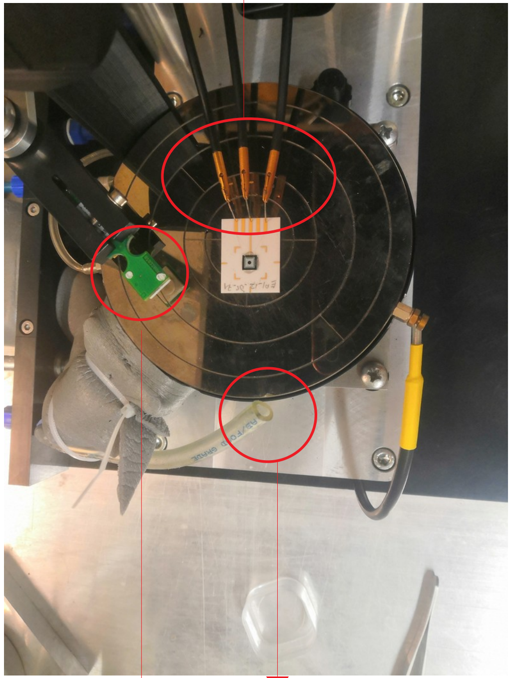
Switch box, for selection of C-V or I-V measurement



Temperature controller

Probe Station for diode characterization

Probes needles connected to Pad, back side, guard ring of diode (from left to right)



Humidity sensor

Dry air for control humidity

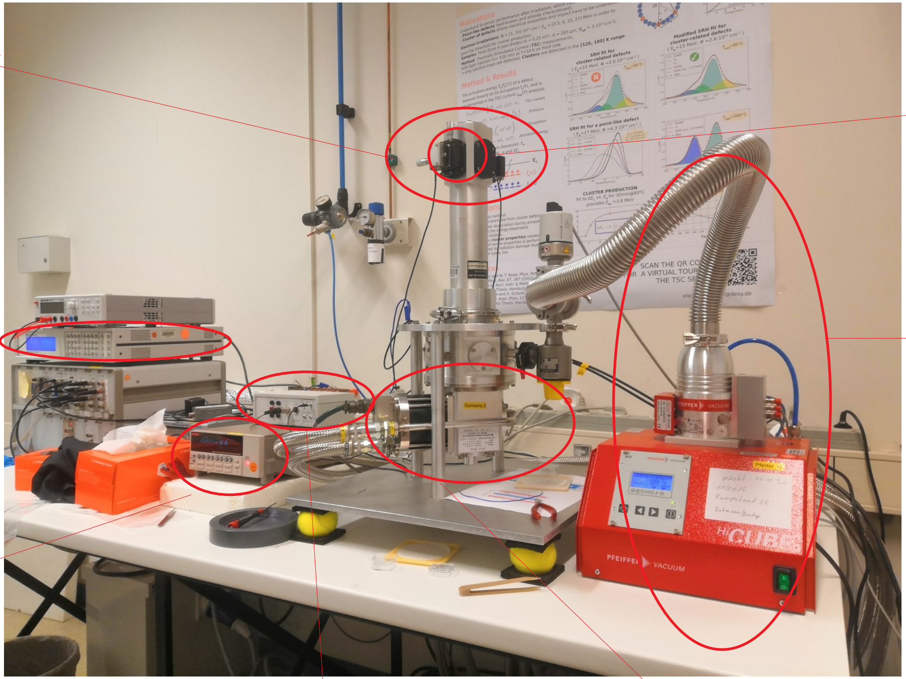
Thermally Stimulated techniques

Thermally Stimulated Current or capacitance – TSC or TS-Cap:

LED support for light injection

Temperature controller

Keithly 6517A Electrometer or LCR meter (TSC or TS-Cap)

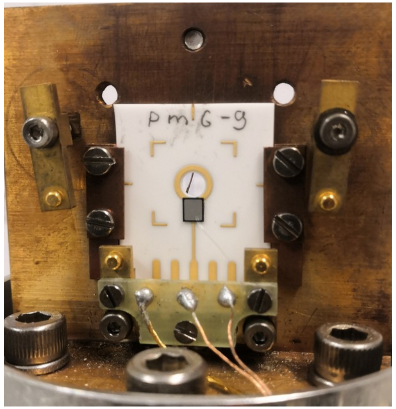


Switch box for PC control of He compressor and power supply for light injection

Cooling system

High vacuum pump system

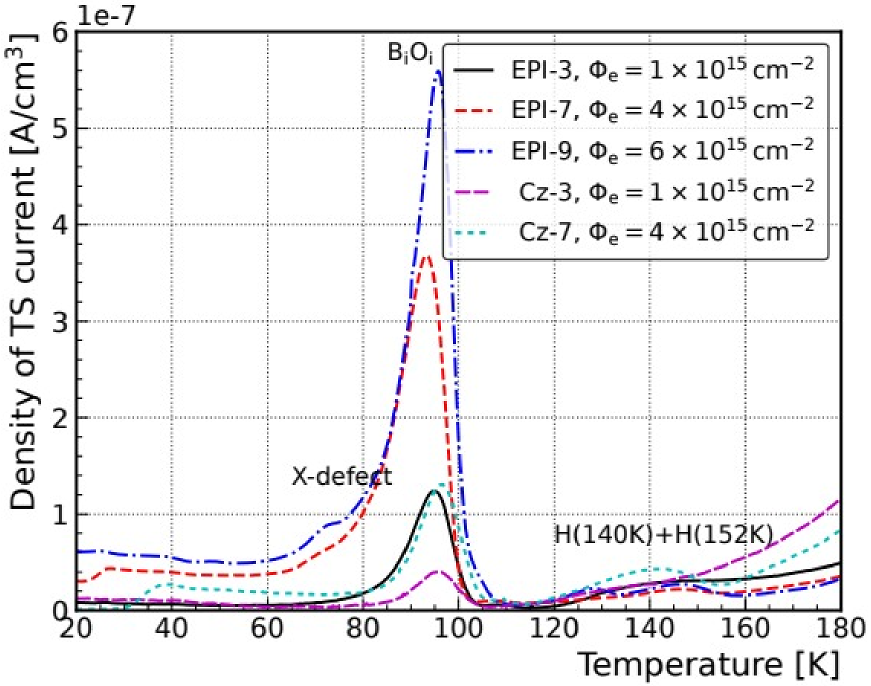
Hot stage with sample holder, temperature sensor and heater

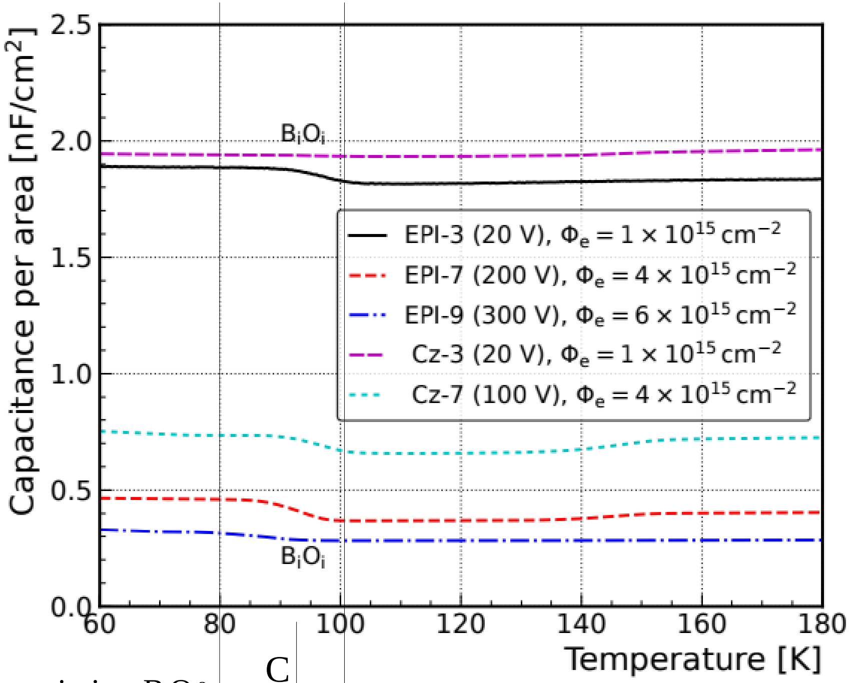


Experimental parameter (TSC):

Cooling down bias: 0 V
Filling temperature: typical 10 K
Filling: Forward bias filling, 0 V filling or light injection
Filling time: 30 s
Delay time: 30 s
Heating rate: 0.183 K/s
Heating up bias: depends on effective space charge concentration after irradiation

Example of microscopic measurements





C

Before emission-$B_iO_i^o$
$|N_{eff}| = |N_0|$

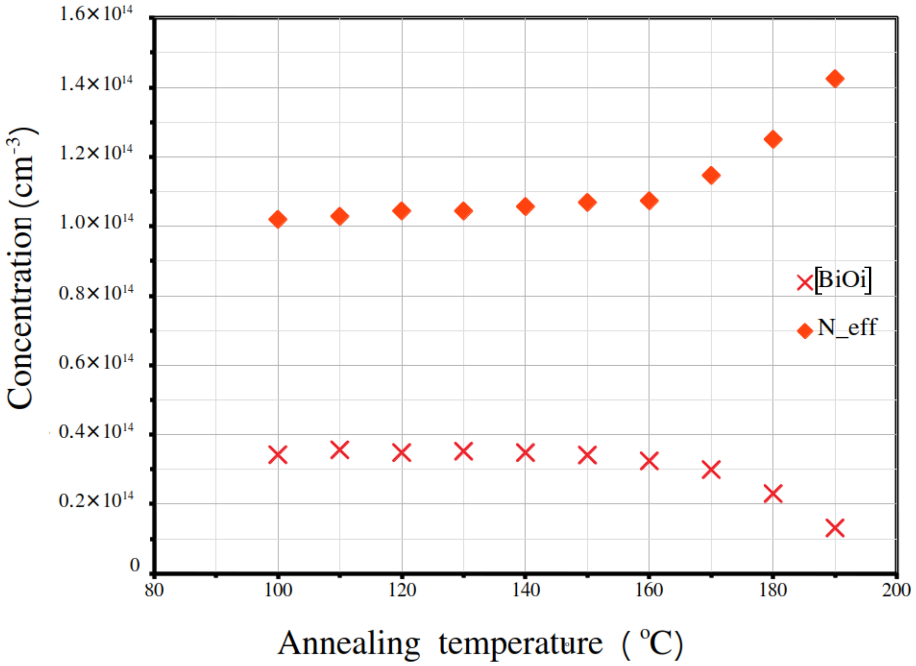
After emission-$B_iO_i^+$
$|N_{eff}| = |N_0| - [B_iO_i]$

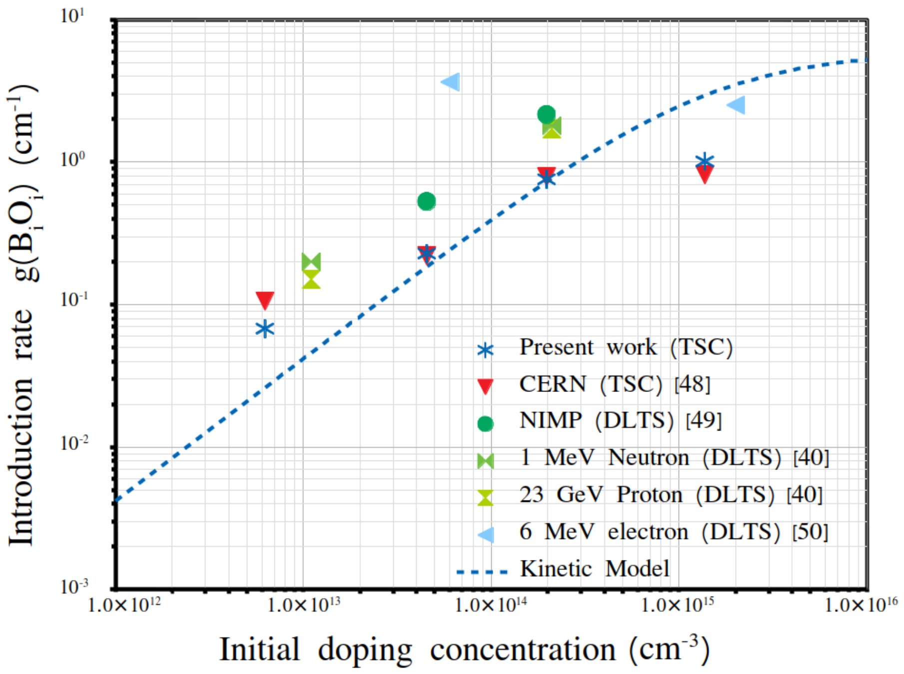
For the uniform N_{eff} and V, $N_{eff} \neq 0$:

$$C = A\sqrt{\frac{\varepsilon\varepsilon_0 q_0 N_{eff}}{2V}}$$

- Diodes irradiated by 5.5 MeV electrons
- TSC spectra after modified by the TS-Cap (depleted volume), forward bias filling (left)
- TS-Cap, forward bias filling (right)

Results of protons irradiation (**Main**)



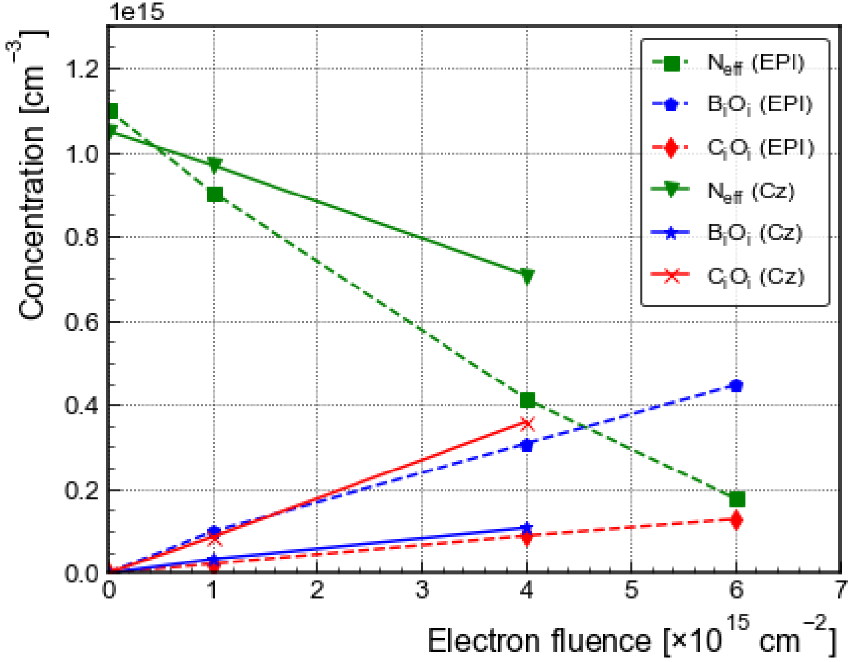


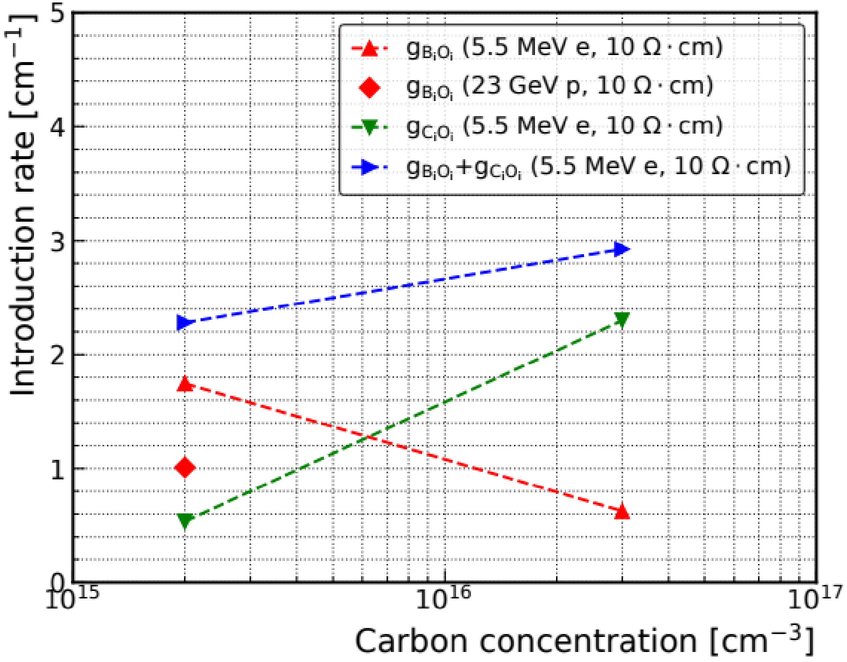
- $[B_iO_i]$ and N_{eff} extracted from TSC and C-V measurement
- If $T_{ann} > 150\ ^oC$, $[B_iO_i]$ decrease
- Higher initial doping concentration leads to higher B_iO_i introduction rate after the same fluence value. But the increase is not linear
- $\Delta N_{eff} \approx 2 \times \Delta N_t\,(B_iO_i)$ as expected from $B_s(-) \rightarrow B_iO_i\,(+)$

Introduction rate:

$$g(B_iO_i) = \frac{\Delta[B_iO_i]}{\Delta\,\phi_{eq}}$$

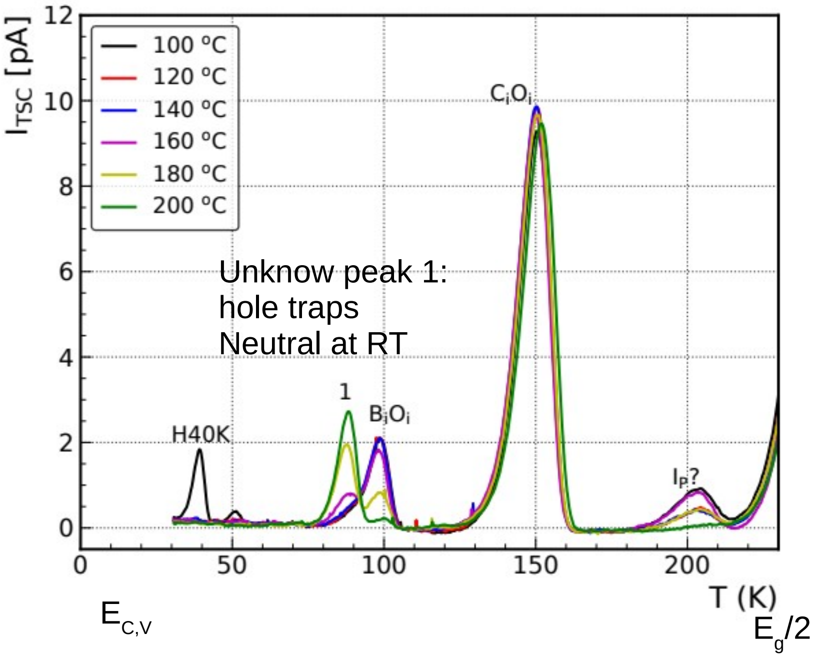
Results of electron irradiation (Main)

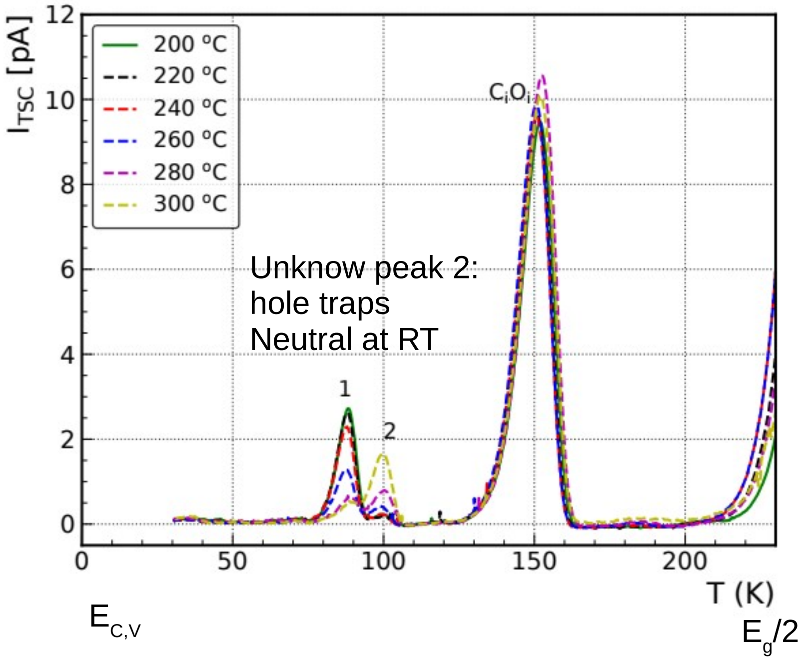




- $\Delta N_{eff} \approx 2 \times \Delta N_t\,(B_iO_i)$ as expected from $B_s(-) \rightarrow B_iO_i\,(+)$
- A higher peak of B_iO_i appeared on EPI-diodes compared to Cz-diodes at the same fluence value, and the reverse for C_iO_i

Results of γ-ray irradiation (**Main**)





- TSC spectra ($T_{fill} \approx 30$ K, $V_{bias} = 300$ V, $I_{fill} \approx 1$ mA) for p-stop diode irradiation by ^{60}Co-γ with 1864 kGy. $T_{ann} = 100 \rightarrow 200$ °C (left) and $T_{ann} = 200 \rightarrow 300$ °C (right)
- H40K is eliminated by annealing when **T_{ann} > 100°C**
- B_iO_i is stable with T_{ann} **until 150°C**, then decreases with T_{ann} disappears at **T_{ann} = 200°C** meanwhile peak 1 increases in this range. When **T_{ann} > 200°C**, peak 1 decreases and peak 2 increases.

Summary

I. Results for diodes irradiated by 23 GeV protons:

- The X-defect was discovered
- Development of gB_iO_i with $[B_s]$ increasing
- $[B_iO_i]$ decreasing, when T_{ann} > 150 ^oC

II. Results for diodes irradiated by 5.5 MeV electrons:

- Less cluster defect induced by 5.5 MeV electrons compared to 23 GeV protons for the same n_{eq} fluence
- Higher g(BiOi) for 5.5 MeV electrons compared to 23 GeV protons for the same n_{eq} fluence
- Less g(BiOi) on Cz silicon after 5.5 MeV electrons irradiation compare to EPI silicon
- Developed the TSC methods for Highly doping silicon diodes

III. Results for diodes irradiated by ^{60}Co γ-ray:

- Annealing behaviors of B_iO_i

Back up

literature

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[2] Liao, C., et al. "The Boron–Oxygen (B_iO_i) Defect Complex Induced by Irradiation With 23 GeV Protons in p-Type Epitaxial Silicon Diodes." IEEE Transactions on Nuclear Science 69.3 (2022): 576-586.
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[7] H. Feick “Radiation tolerance of silicon particle detectors for high-energy physics experiments,” Ph.D. dissertation, Dept. Phys., Univ. Hamburg, Hamburg, Germany, 1997
[9] Wodean project. Summary Report, 2010