Defect characterization studies on ^{60}Co gamma-irradiated p-type Si diodes

EP-DT-DD
Detector Technologies
Detector Development

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DER FORSCHUNG | DER LEHRE | DER BILDUNG

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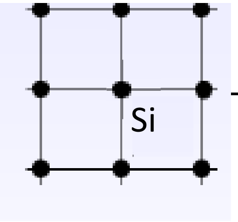
21.06.2022 *anja.himmerlich@cern.ch*

Motivation

Defects:

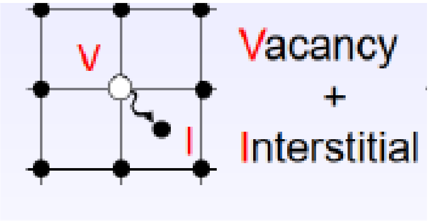
High energy particles →

Si lattice



— ***E > 25 eV*** →

Frenkel-pair



Recombination

Migration & formation of (stable) point & cluster defects

displacement damage defects
dependent on:
particle type
particle energy
particle fluence

Vacancies:

⟹ normally low mobility at low temperatures

⟹ $V + O_i \rightarrow VO_i$ or formation of multi-vacancy-defects (V_2, V_3 …)

Si-interstitials:

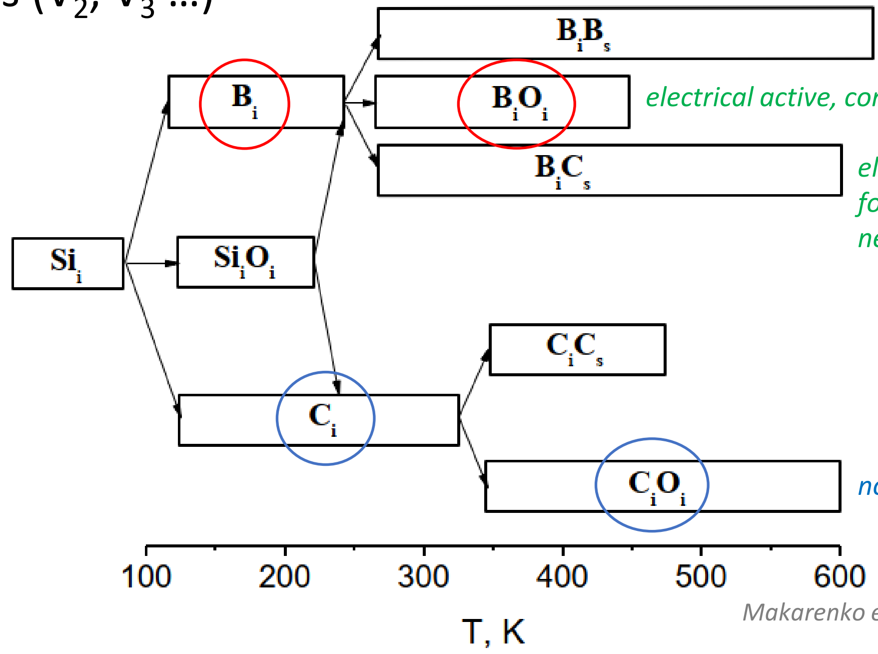
⟹ very mobile even at low temperatures

⟹ interaction e.g. with impurity atoms (e.g. C, B …):

Watkins replacement mechanism

$$I + B_s \rightarrow Si_s + B_i$$
$$I + C_s \rightarrow Si_s + C_i$$

„competition“ for interstitals between C and B
→ increasing C content „protect“ B from removal
→ carbon enrichment mitigates radiation damage in LGADs



not electrical active, high B content needed

electrical active, contributes to Neff

electrical active, lower formation probability due to the neutral Cs

no contribution to Neff

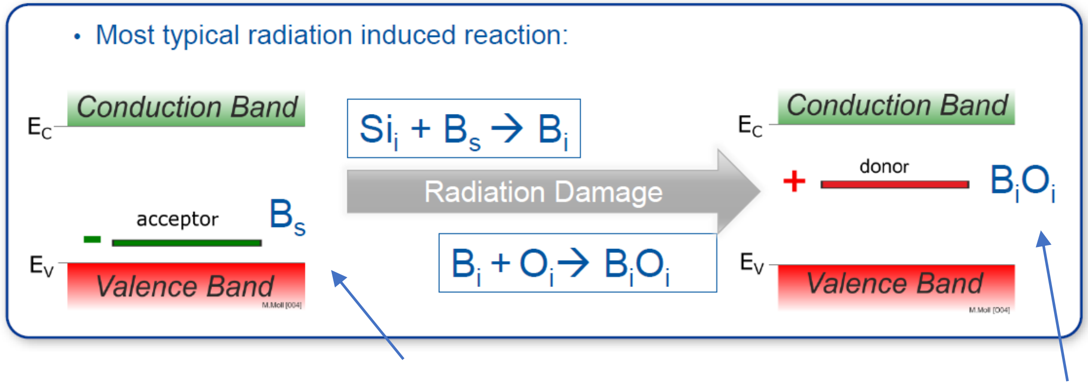
Makarenko et al. ICDS-31, 2021

Motivation

Acceptor Removal Effect in B-doped silicon:

BiOi– defect:

Moll, PoS 2019 VERTEX



*induce **negative** space charge*

*induce **positive** space charge*

$B_{Si}Si_i$ – defect:

- *B stays at its lattice place and captures a positively charged Si-interstitial that was released during irradiation*
- *in the ground state: positively charged donor*

see: 40th RD50 Workshop talk of K. Lauer: "The A_{Si}-Si_i-defect - a possible candidate to explain acceptor removal in LGADs" 21.06.2022

BiOi formation deactivated 2 active boron atoms
and should correlate with a change in Neff by a factor of 2

see also : 40th RD50 Workshop talk from C. Liao
„Investigation of high resistivity p-type FZ silicon diodes after 60Co-γ irradiation" 21.06.2022

Experimental Details

Samples (p-type EPI diodes):

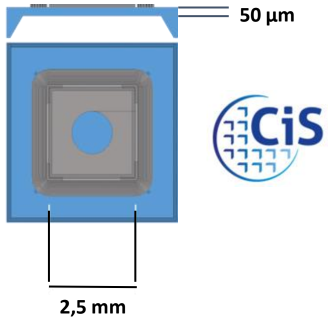
sample	resistivity (Ωcm)	dose (Mrad)	dose (MGy)	annealing status
EPI-06-DS-69 1)	50	20	0.2	not annealed
EPI-06-DS-82 1)	50	100	1	not annealed
EPI-05-DS-73 2)	50	100	1	several month @ RT
EPI-10-DS-80 1)	250	20	0.2	not annealed
EPI-08-DS-80 2)	250	20	0.2	unknown
EPI-10-DS-82 1)	250	100	1	not annealed
EPI-08-DS-79 2)	250	100	1	several month @ RT

1) ^{60}Co gamma irradiation @ IRB, Zagreb ***(100 kGy – 2 MGy)***

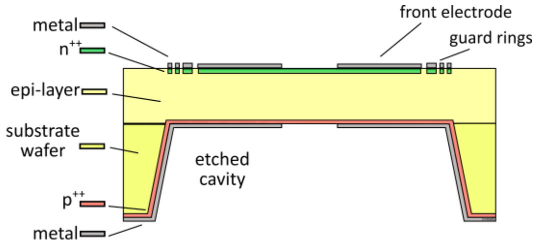
Institut Ruđer Bošković

2) ^{60}Co gamma irradiation @ BGS
Beta-Gamma-Service GmbH & Co., Wiehl, Germany
(200 kGy – 1 MGy)

BGS IDEEN PLUS ENERGIE



CiS Forschungsinstitut für Mikrosensorik GmbH



Characterization methodes:

Electrical Characterization: C(V) & I(V) measurements

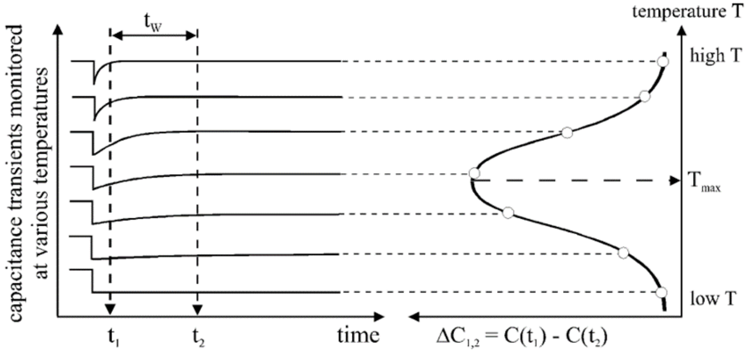
DLTS: Deep Level Transient Spectroscopy

(1) Junction under reverse bias (U < 0) @ different temperatures (20 K – 280 K)→ defect states unoccupied

(2) Electrical injection pulse (UP ≤ 0: majority carrier injection (holes); UP ≥ 0 (forward bias): majority & minority carrier injection (electrons & holes) → occupation of defect levels

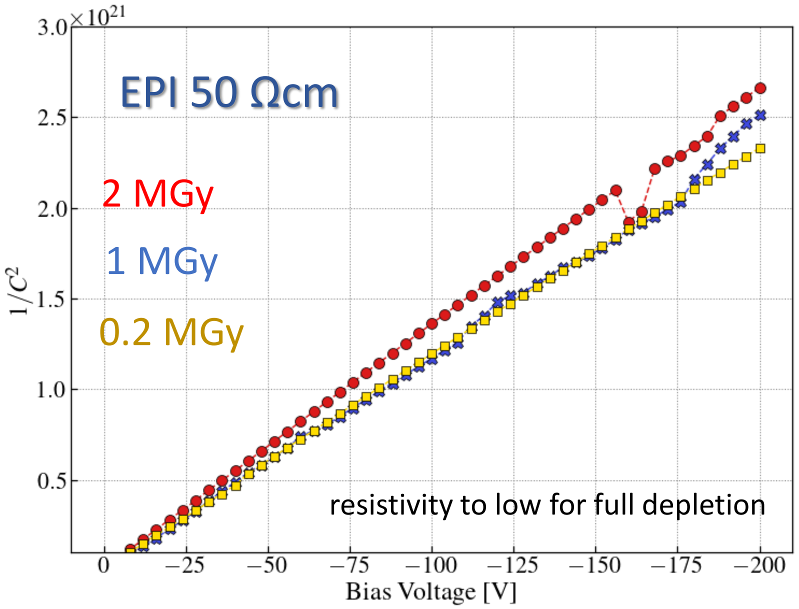
(3) Junction under reverse bias (U < 0) → charge carriers thermally emitted from the defect states
→ Change in capacitance (measure: capacitance transients)

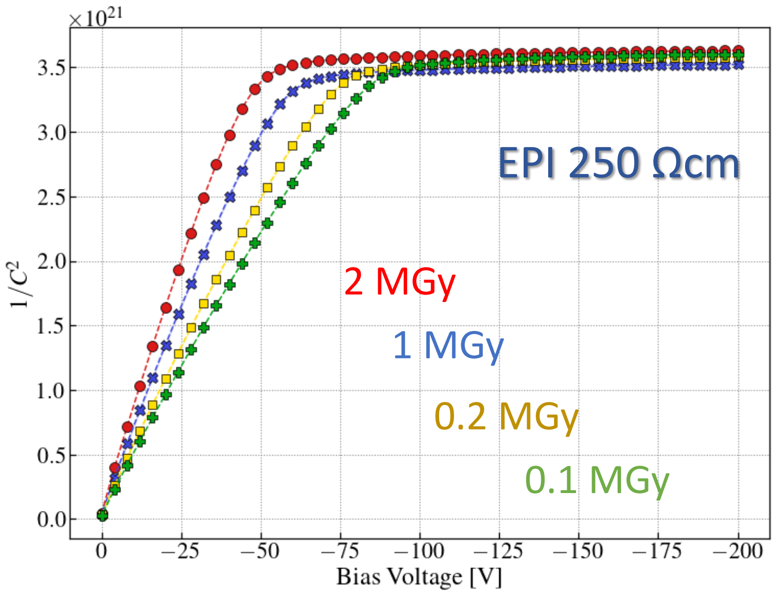
- *Thermal activation energy of defect levels*
- *Capacitance cross section for electrons or holes*
- *Defect concentration*

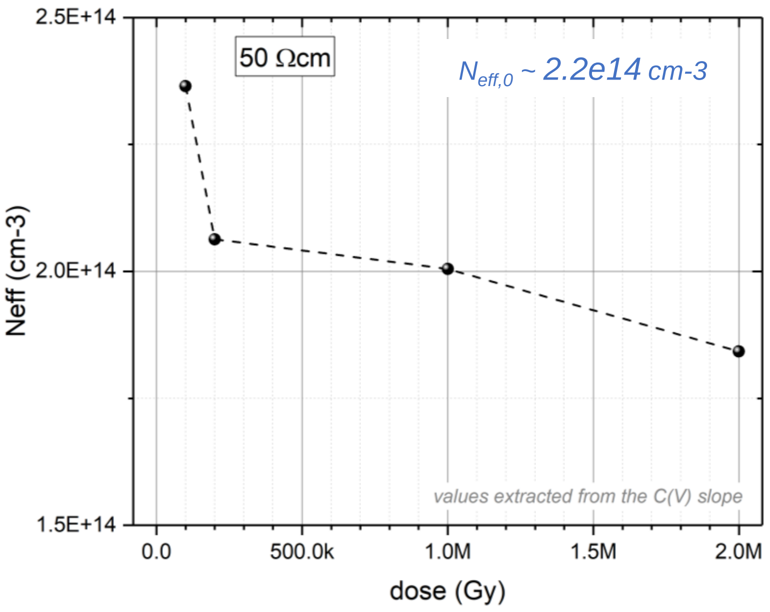


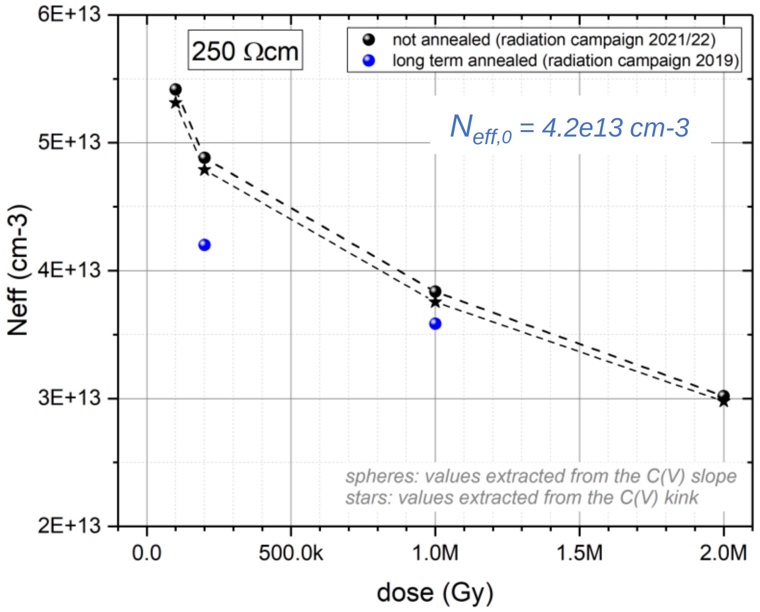
Moll thesis 1999

Electrical characterization : CV after irradiation







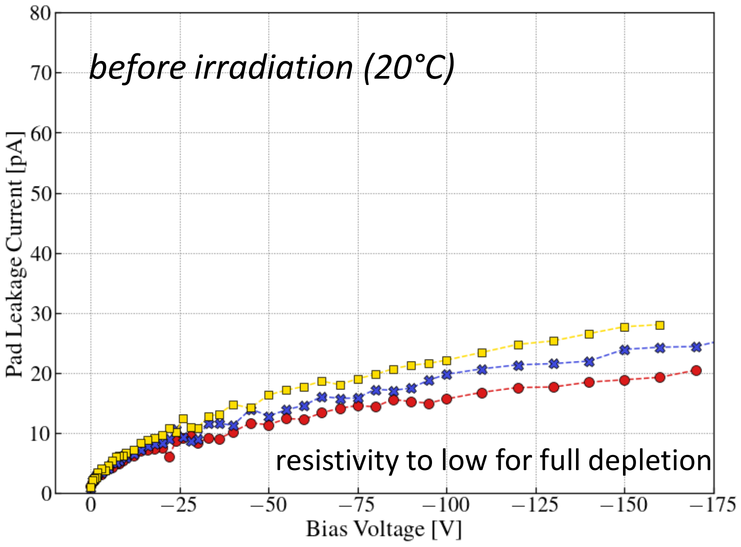


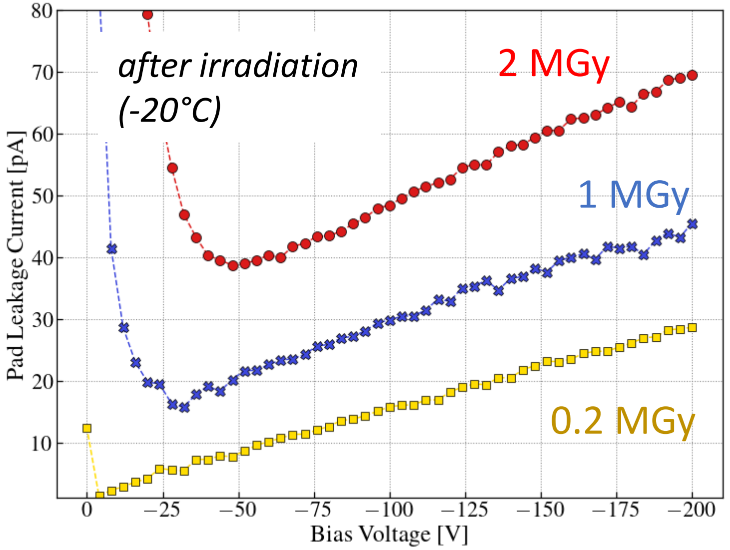
With increasing radiation dose:

- Depletion voltage decreases
- Effective doping concentration decreases
  → Deactivation of active boron

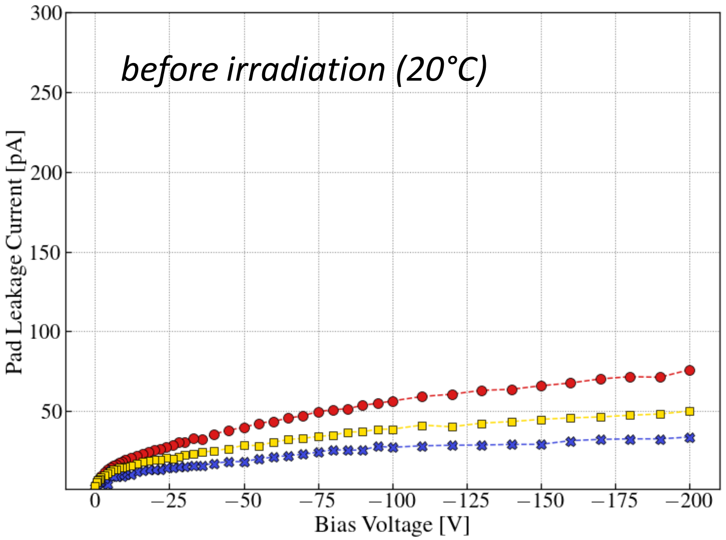
Electrical characterization : IV

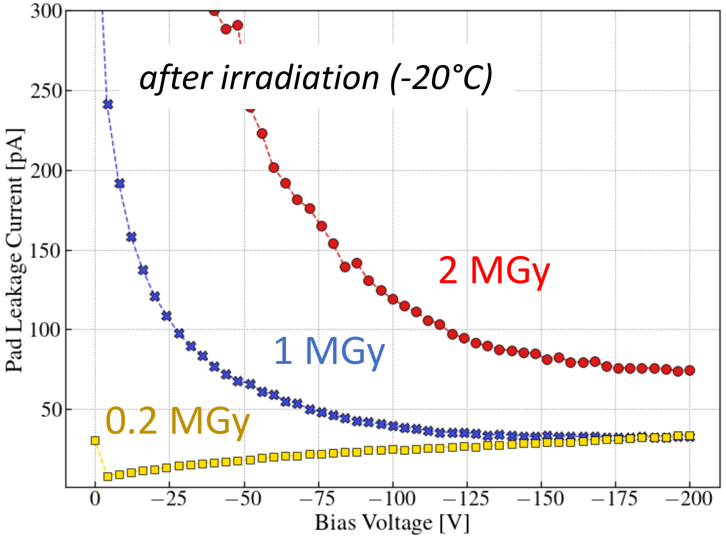
EPI 50 Ωcm





EPI 250 Ωcm



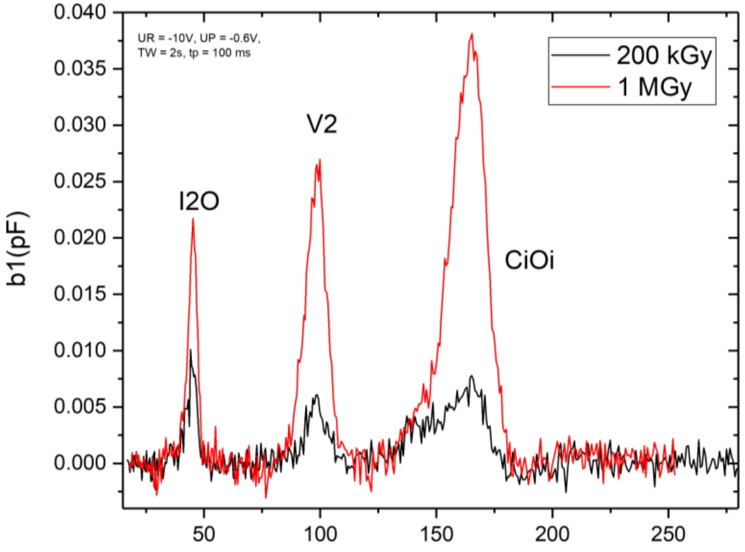


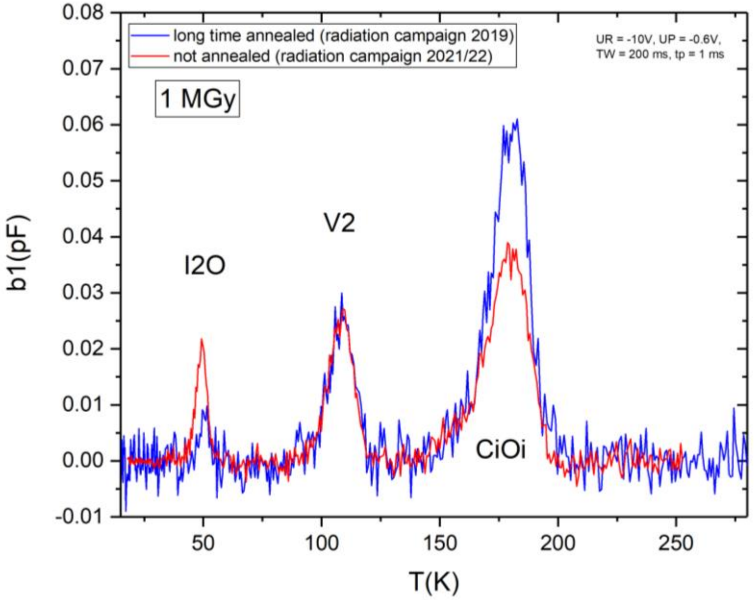
With increasing radiation dose:

- Leakage current increases
- Surface damage makes the analysis of IV difficult

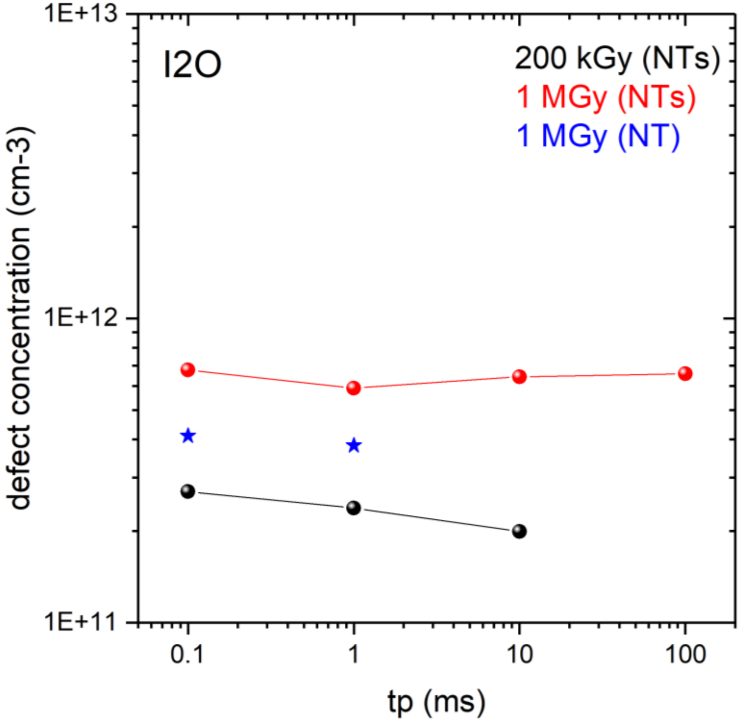
Defect characterization (DLTS) – 50 Ωcm EPI diode

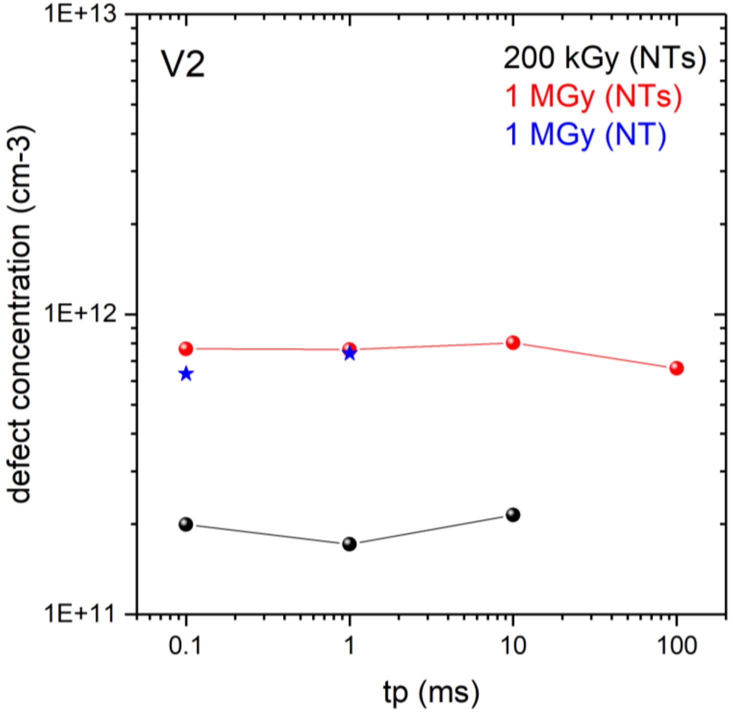
Majority carrier injection:





Defect concentration in dependency of the pulse time:





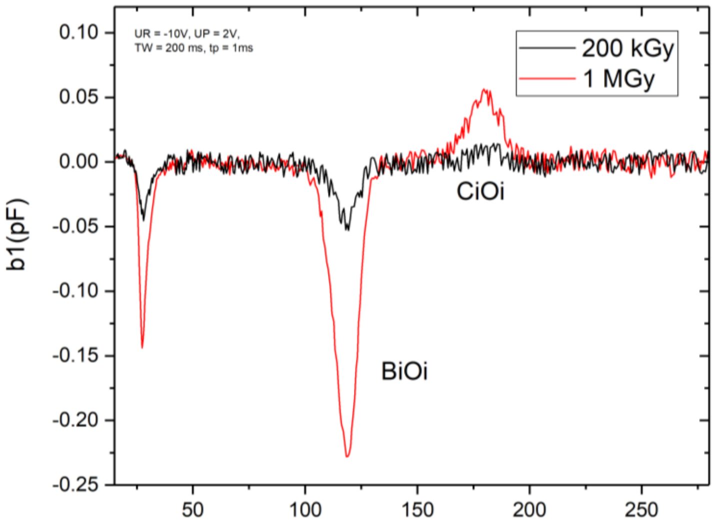
- No dependence on the filling time
- Ratio of the averaged concentration values: I2O = 2.7 and V2 = 3.9

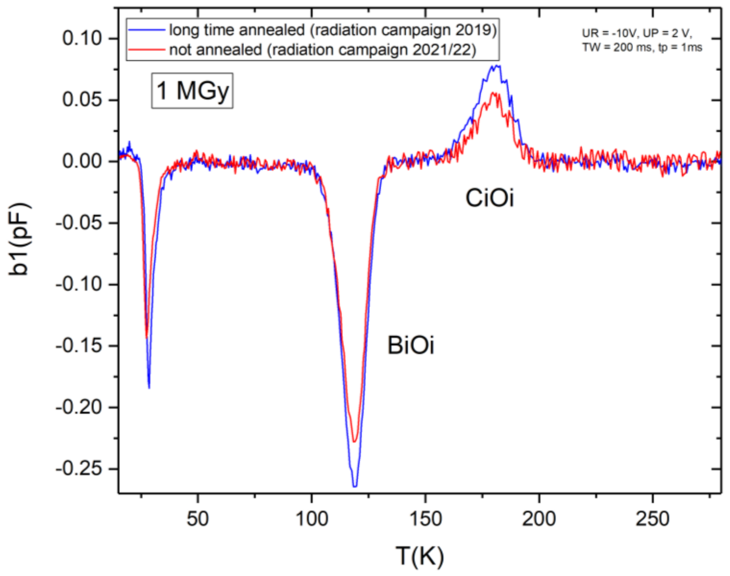
NT: approximated trap concentration

NTs: trap concentration calculated by taking the scr into consideration

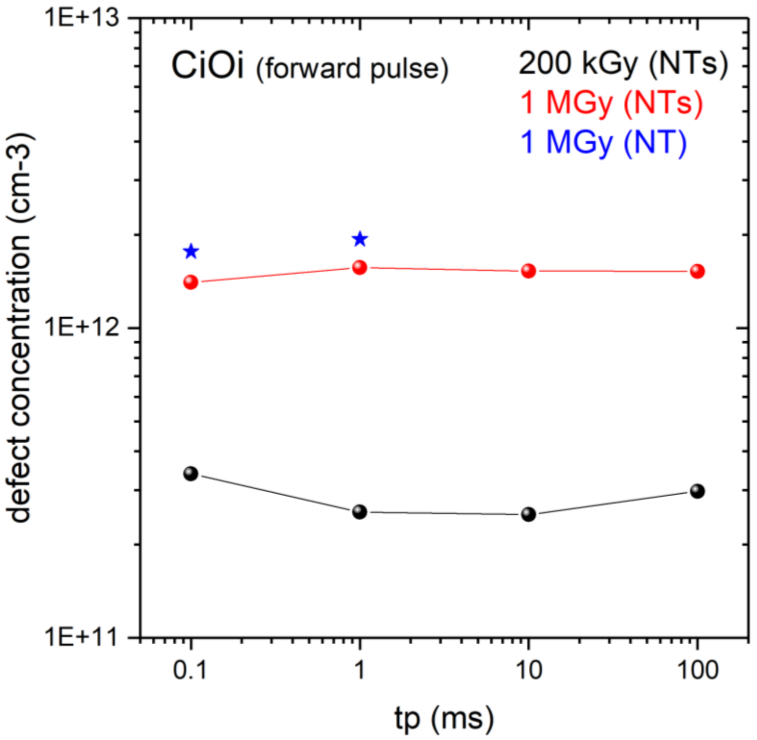
Defect characterization (DLTS) – 50 Ωcm EPI diode

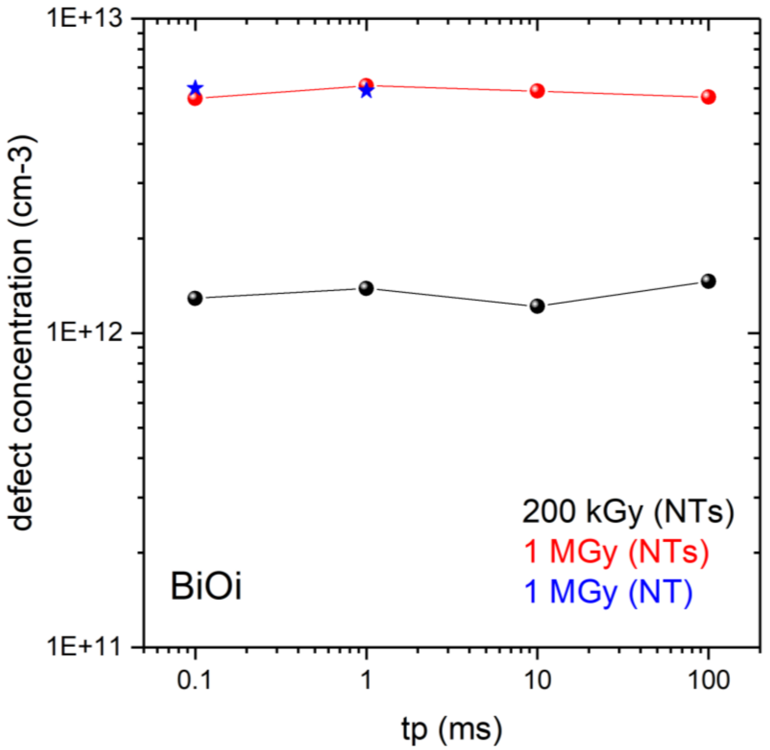
Majority & minority carrier injection:





Defect concentration in dependency of the pulse time:



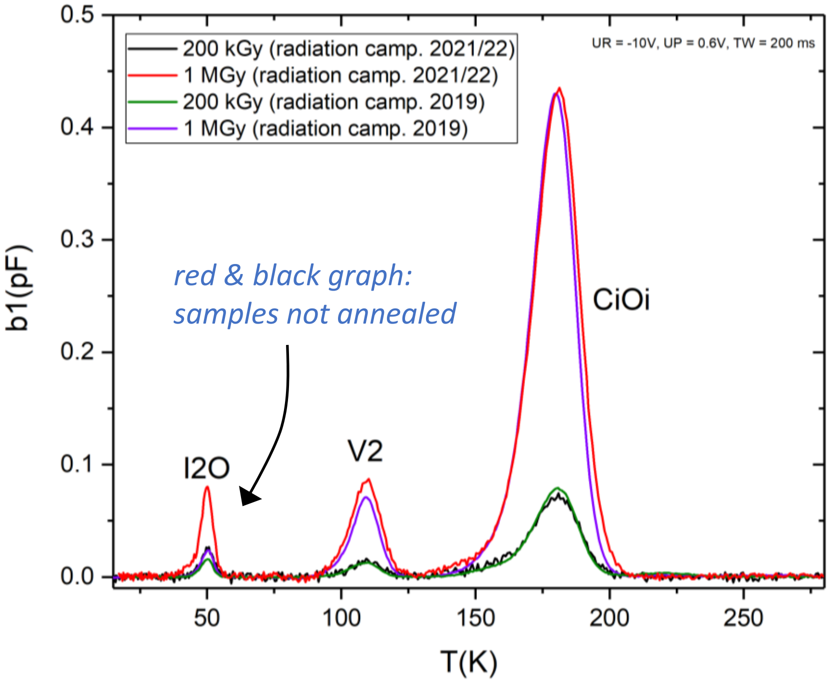


- No dependence on the filling time
- Ratio of the averaged concentration values: CiOi = 5.3 and BiOi = 4.3
- BiOi concentration > CiOi concentration

NT: approximated trap concentration
NTs: trap concentration calculated by taking the scr into consideration

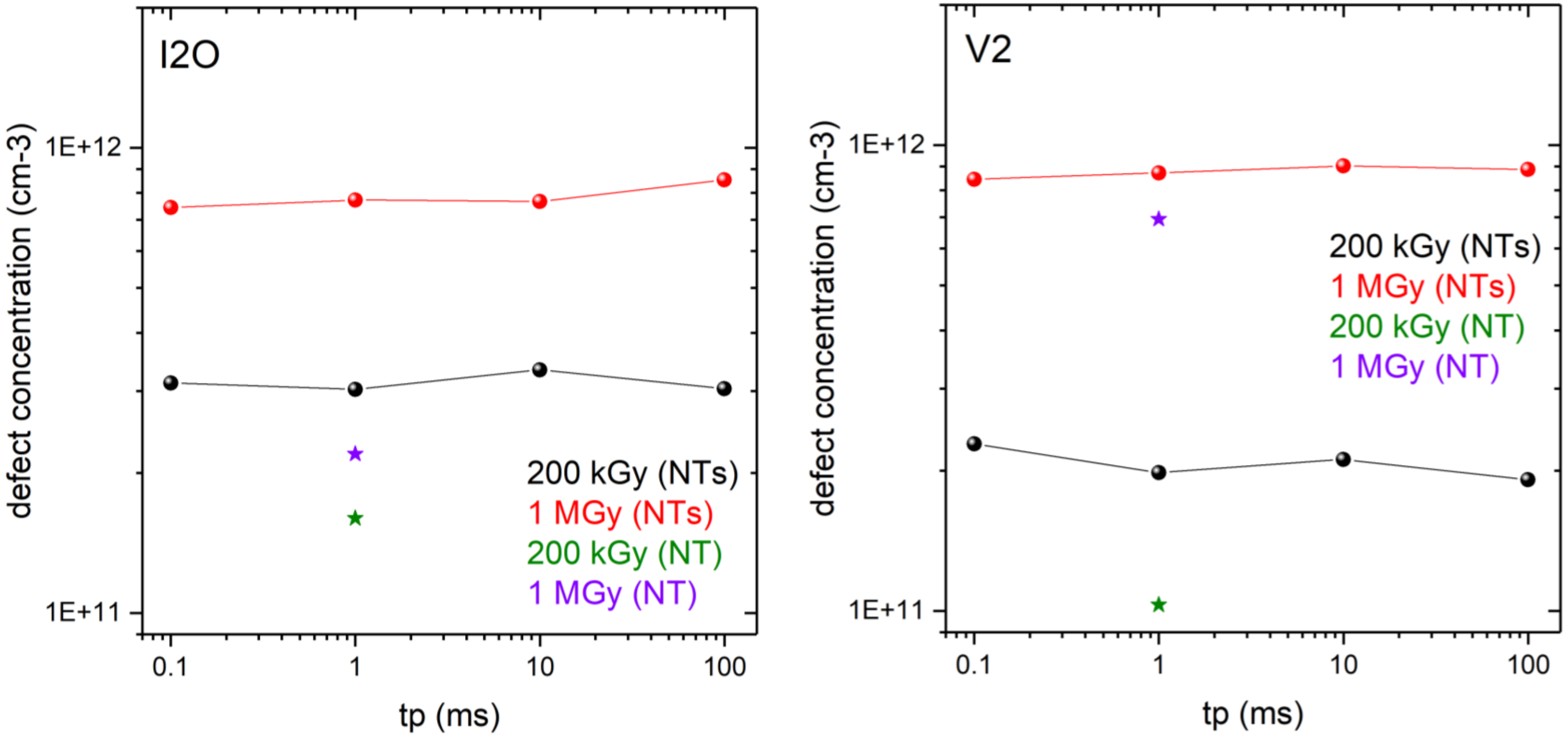
Defect characterization (DLTS) – 250 Ωcm EPI diode

Majority carrier injection:



red & black graph: samples not annealed

Defect concentration in dependency of the pulse time:

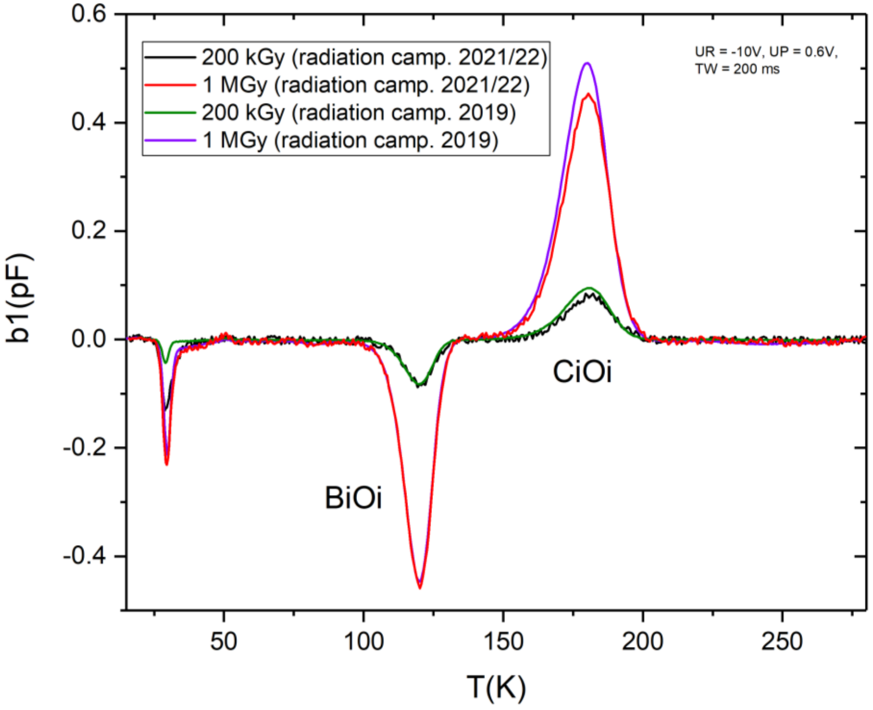


- I2O shows dependence on the annealing status of the sample
- Ratio of the averaged concentration values: I2O = 2.5 and V2 = 4.2

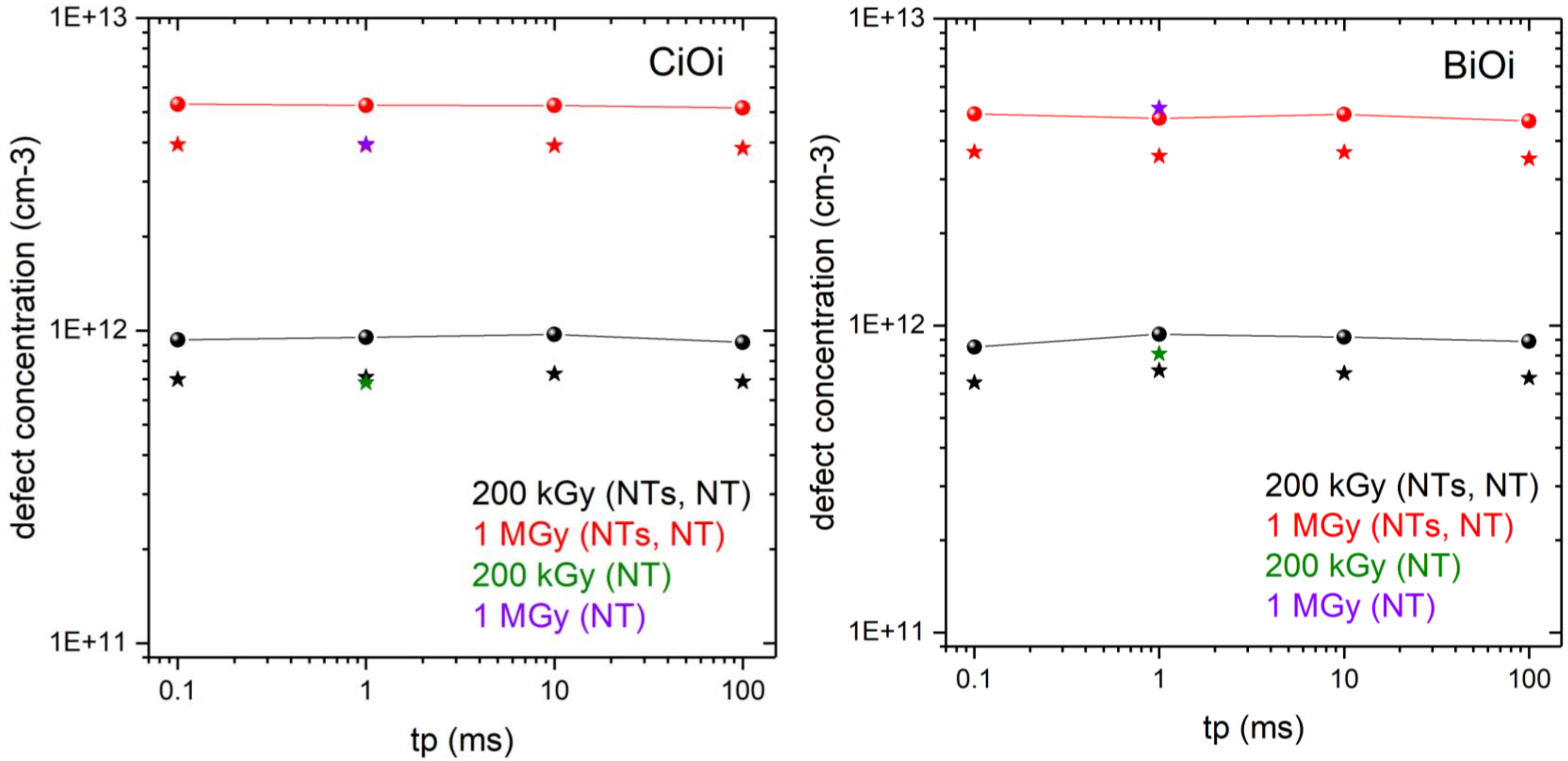
NT: approximated trap concentration
NTs: trap concentration calculated by taking the scr into consideration

Defect characterization (DLTS) – 250 Ωcm EPI diode

Majority & minority carrier injection:



Defect concentration in dependency of the pulse time:

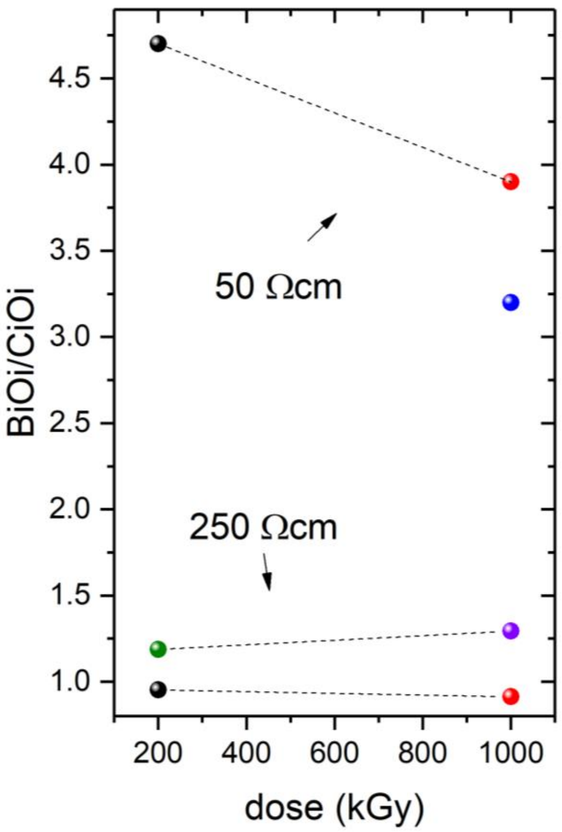


- Ratio of the averaged concentration values: CiOi = 5.5 and BiOi = 5.3
- BiOi concentration ≈ CiOi concentration

NT: approximated trap concentration
NTs: trap concentration calculated by taking the scr into consideration

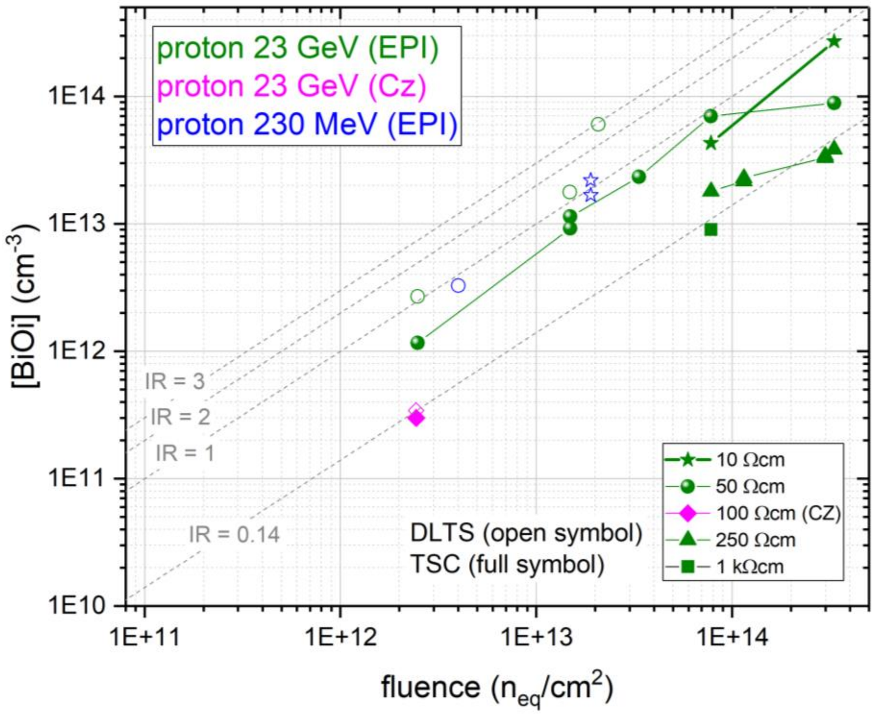
Defect characterization (DLTS) – EPI diodes

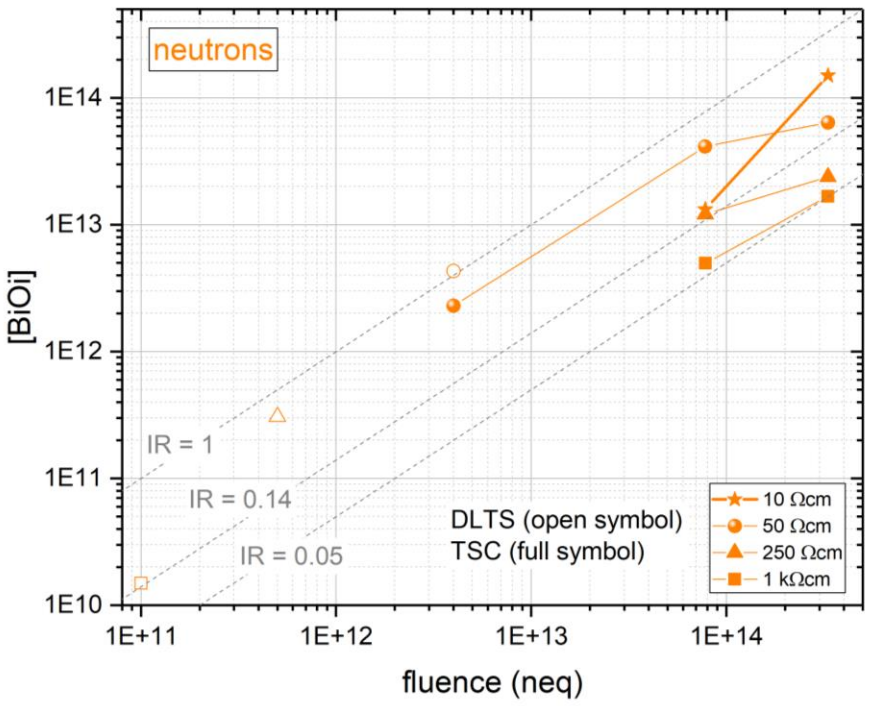
BiOi to CiOi ratio:



- 250 Ωcm: BiOi/CiOi ratio dose independent ≈ 1
- 50 Ωcm: more BiOi compared to CiOi
- 50 Ωcm: dose dependence → for higher dose: less BiOi relative to CiOi (comparable to *proton & neutron irradiation*)

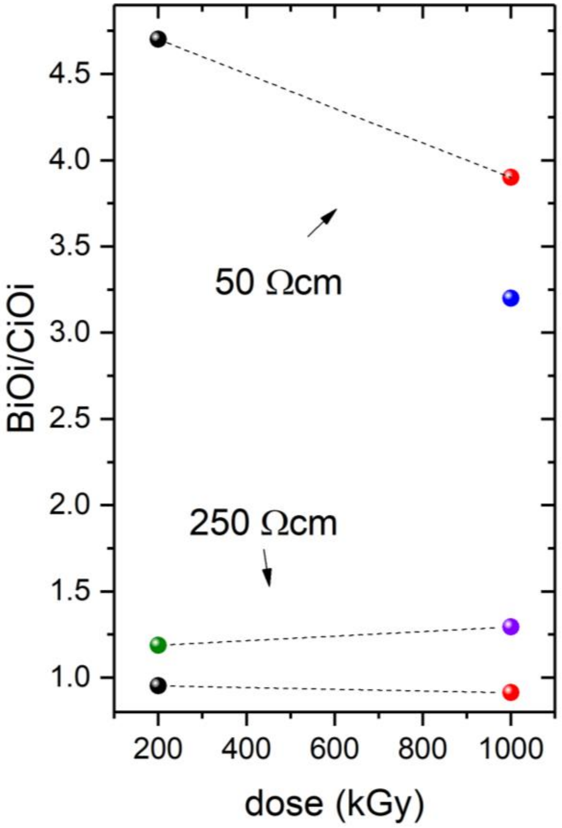
!! Needs to be verified by ongoing measurements



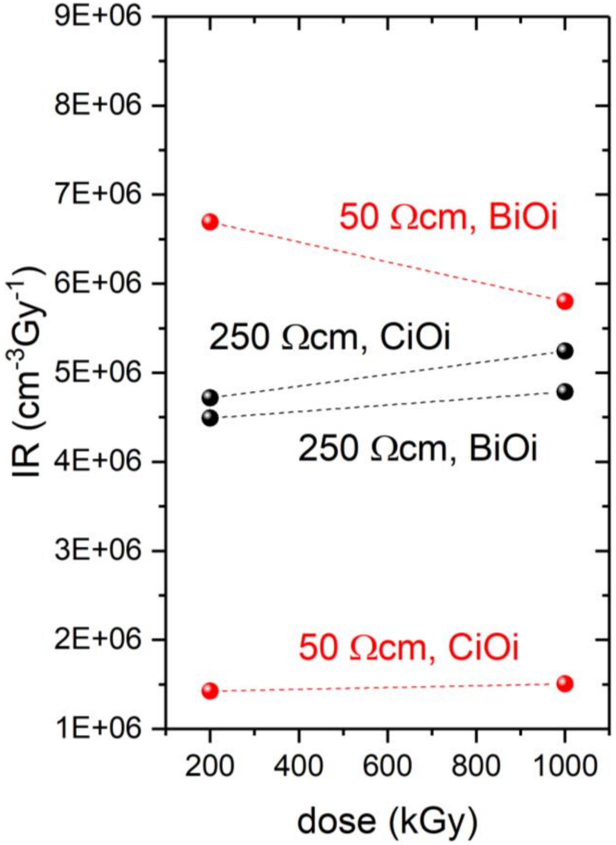


Defect characterization (DLTS) – EPI diodes

BiOi to CiOi ratio:

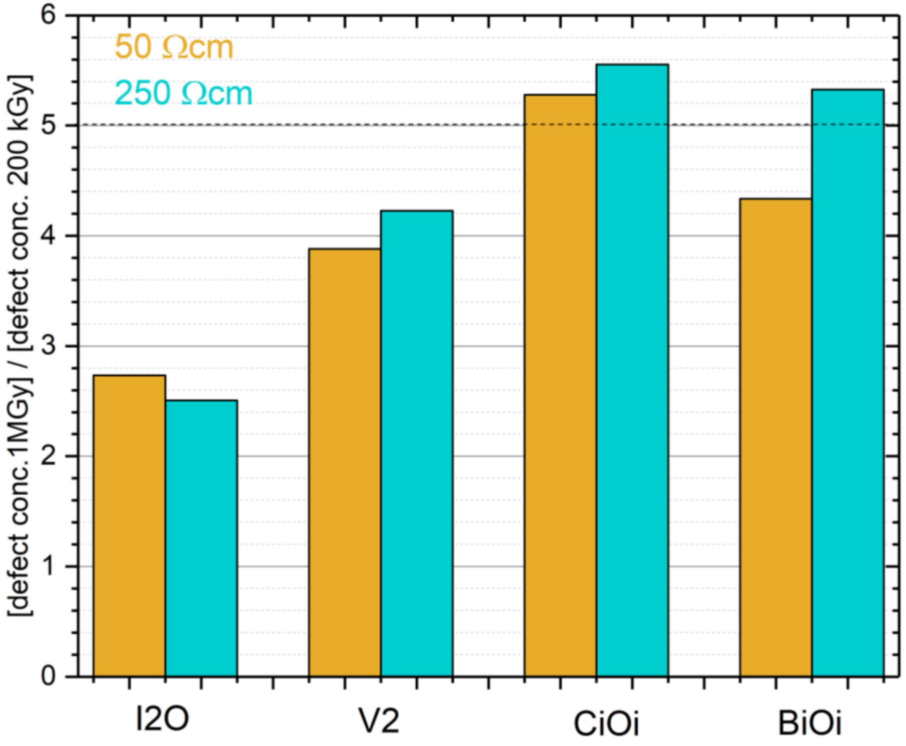


BiOi & CiOi introduction rate:



- 250 Ωcm: BiOi-IR and CiOi-IR almost equal
- 50 Ωcm: BiOi-IR higher than CiOi-IR

Defect ratio 1 MGy to 200 kGy

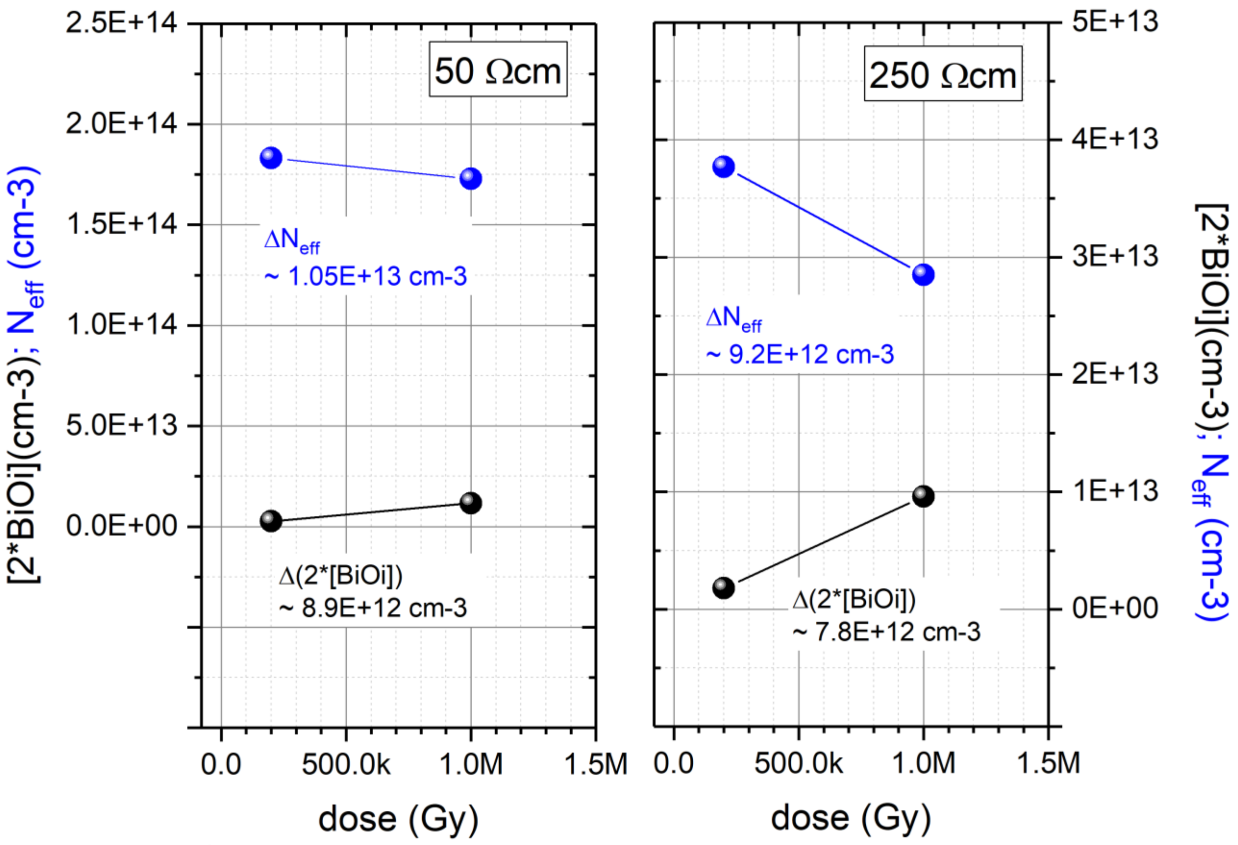


- I2O & V2: ratio < 5
- CiOi: ratio around 5
- BiOi: doping dependence

!! Needs to be verified by ongoing measurements

Defect characterization (DLTS) – EPI diodes

Correlation between changes in the effective doping concentration and the BiOi concentration



N_{eff} *(cv: 1MHz, T ~ 120K)*

- Change in Neff correlates with change in the BiOi concentration
- $\Delta N_{eff}/\Delta BiOi \approx 2.35$

Expected:

- One BiOi deactivates 2 active B atoms

Speculation:

→ B deactivation not fully covered by the BiOi formation

→ other B-related defect (like the electrical inactive BiBs with concentration in the range of 10^{11} cm^{-3}) ?

→ BiOi instability ?

!! Needs to be verified by ongoing measurements

see: 40th RD50 Workshop talk of A. Nitescu: "On the bistability of the Boron related donor associated with the acceptor removal process in irradiated p-type silicon " 21.06.2022

Summary and Outlook

Conclusion:

- Defect characterization on ^{60}Co – gamma irradiated Si pad diodes
- Identify and characterize the main defects I2O, V2, BiOi and CiOi
- BiOi defect:
  - Donor type defect level in the upper part of the band gap that deactivates 2 active boron atoms
  - Correlates with a factor of about 2 with the changes in the effective space

Outlook:

- Ongoing defect characterization of the full set of gamma-irradiated sensors (100kGy – 2MGy; EPI & Fz) & annealing experiments to further verify the presented results

- Further focus on the understanding of the high B-deactivation rates of LGADs
  - → A new wafer production planned with dedicated carbon & boron concentrations

- Get deeper insight into the properties of the „BiOi" defect
  - Bistability of the BiOi *(Besleaga et al. NIMA 1017, 165809 (2021))*
  - $B_{Si}Si_i$ instead of BiOi *(Lauer et al. Phys. Stat. Sol. A 2022 (https://doi.org/10.1002/pssa.202200177))*

see: I. Pintilie: "RD50 Project proposal: Defect engineering in PAD diodes mimicking the gain layer in LGADs"
40th RD 50 workshop 21.06.2022 ⟹ 12h00

Thank you for your attention!

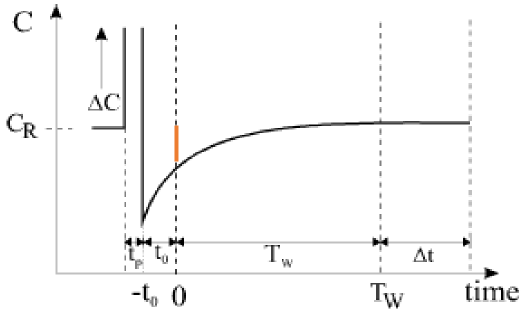
Backup slides

DLTS: N_T <--> N_{Ts}
TRAP concentration

DLTS – Transients (C-DLTS)

Change in the capacitance $\Delta C_0 = C(t = 0) - C_R$

(Calculation from the Poisson equation, Moll thesis Appendix A.3)



$$\boxed{\Delta C_0 = -C_R \frac{N_{Ts}}{2N_D} \frac{L_R^2 - L_P^2}{W_R^2}}$$

Trap concentration „calculated with the space charge region“

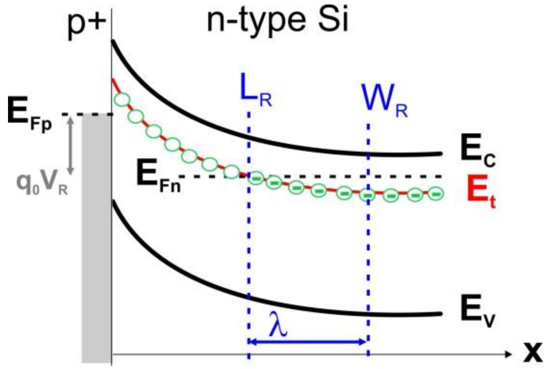
$$\boxed{N_{Ts} = -2N_D \frac{\Delta C_0}{C_R} \frac{W_R^2}{L_R^2 - L_P^2}}$$

CV curves during the tempscan for the CR and CP values

„approximated“ trap concentration
(… if you select the reverse bias and pulse voltage in such kind that $L_P \approx 0$ und $\lambda << W_R$)

$$\boxed{N_T \approx -2N_D \frac{\Delta C_0}{C_R}}$$

Standard calculation of N_T
not effected by CP



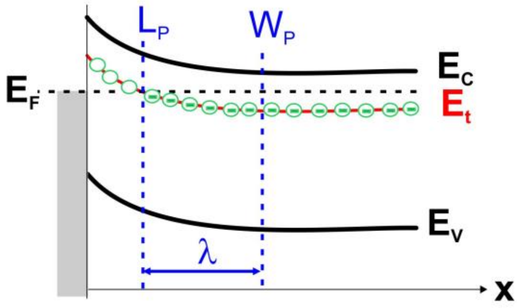
at reverse bias in equilibrium

$$L_R = W_R - \lambda = x_R$$

Transition region λ: *defined by the point where the trap level crosses the quasi-Fermi-level*

$$\lambda = \sqrt{\frac{2\varepsilon(E_F - E_T)_0}{q^2 n_0}}$$

(Program takes here energy value from the Arrhenius plot or from sample parameter,
n_0: free carrier concentration)

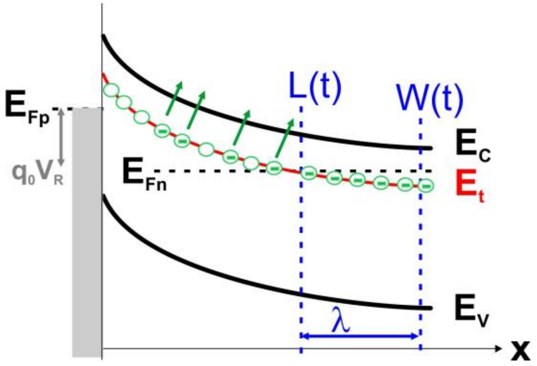


at pulse voltage

$$L_P = W_P - \lambda = x_P$$

Calculated via CR or CP

CR: reverse bias capacitance (measured)
CP: capacitance during the pulse (measured or calculated)



after end of pulse

$$L(t) = W(t) - \lambda$$

Nt approximation: $L_P \approx 0$ und $\lambda << W_R$

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