Status of defect investigations in Si and SiC

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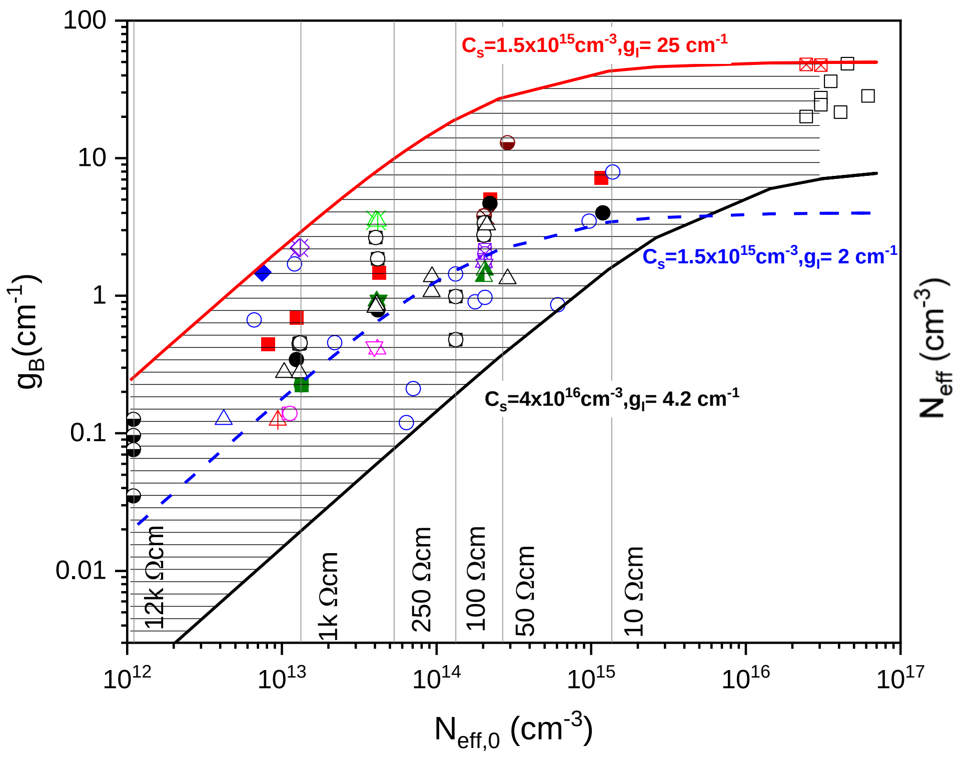
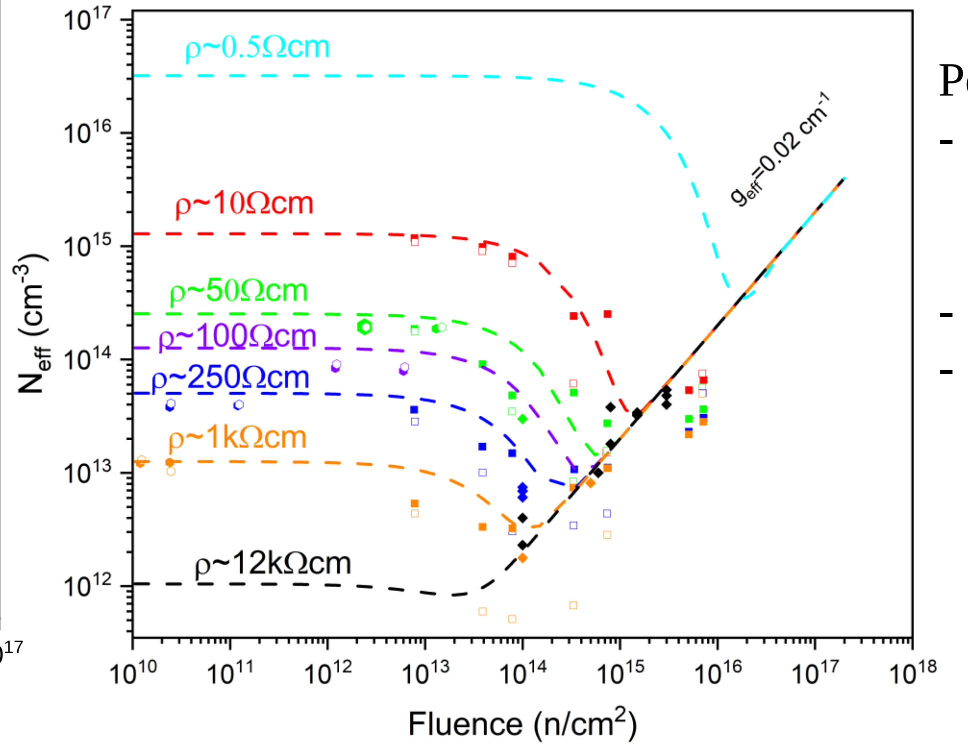
p-type Silicon diodes (Boron doped)

Motivation&*Aim*: Large spread in measured g_B making hard to develop reliable parametrization models to describe the radiation damage from low to high and extreme fluences - *understand the Acceptor Removal Process (Boron removal rate g_B and change in N_{eff}) in connection with impurity content*



Focus: on defects that can influence g_B and N_{eff}

$$N_{eff}(\Phi_{eq}) = g_{eff} \times \Phi_{eq} + N_{A,0} \times \exp(-g_B \times \Phi_{eq} / N_{A,0})$$



Experimental data compared to the parametrization model
Ferrero et al -https://doi.org/10.1016/j.nima.2018.11.121

Possible causes:

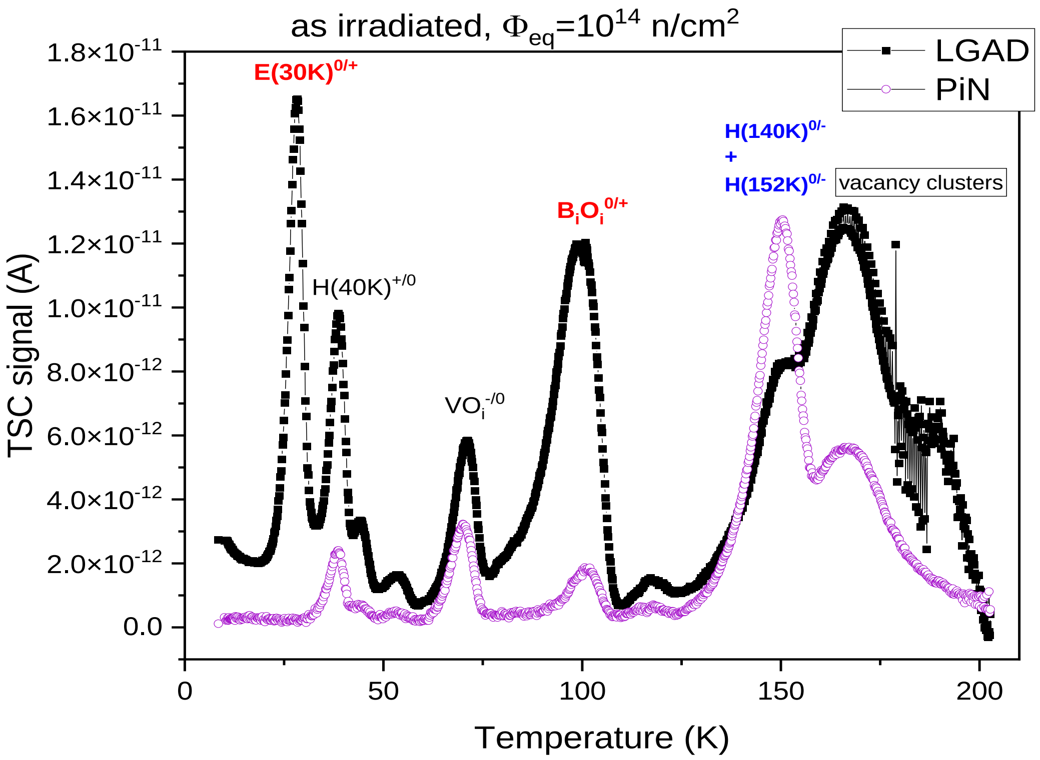
- Different impurity content (e.g. C, O but also B if P exist in the samples)
- Metastable defect states
- New defects at high fluences (2nd order) un-detected so far

DRD3

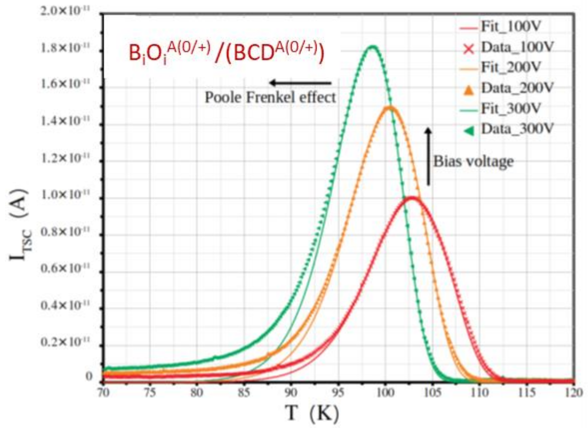
p-type Silicon diodes (Boron doped)

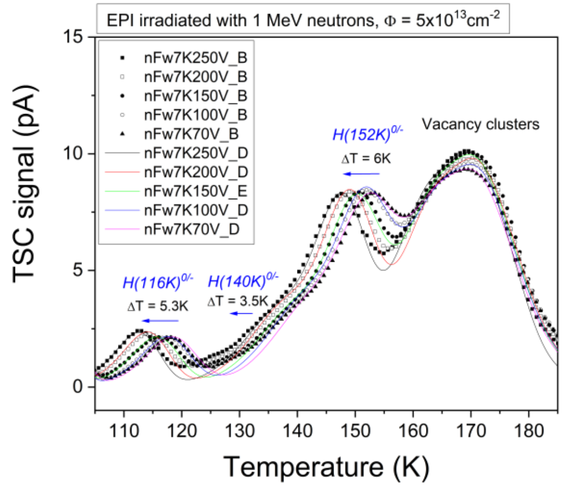
Defects that can be charged at room temperature (RT) of the sensors

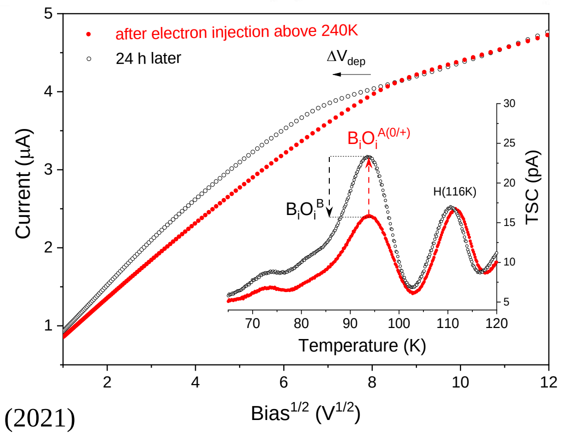
Typical TSC spectra in PiN and LGAD diodes
(filling of traps at 10K)



At RT donors with levels in the upper part of the bandgap are positively charged, acceptors with energy levels in the lower part of the gap are negatively charged, ***both*** showing the Poole Frenkel effect (their emission rate ~ exp (const.$F^{1/2}$) and have a direct impact on the device electrical properties[1-4]







B_iO_i (BCD) – bistable

Causes up to 70% variations variations in the calculated g_B in high resistivity diodes

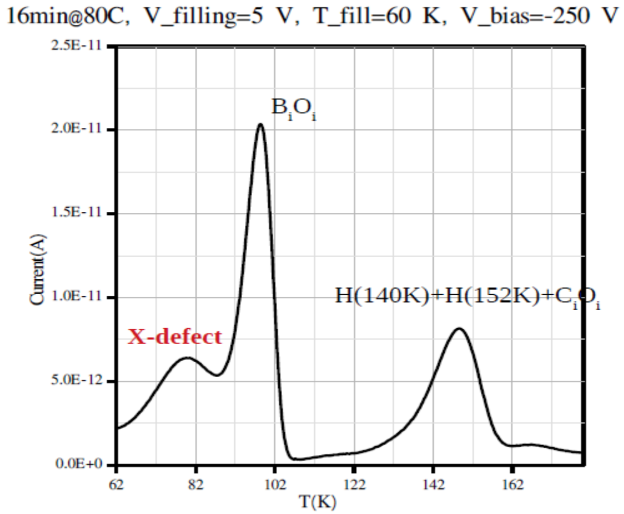
1. C. Liao et al., IEEE TRANSACTIONS ON NUCLEAR SCIENCE 69, 576-586 (2022)
2. I. Pintilie, E. Fretwurst, and G. Lindström, Appl. Phys. Lett., 92, 024101 (2008),
3. C. Besleaga et al, Nucl. Instrum.Methods Phys. Res. A, Accel. Spectrom. Detect. Assoc. Equip., 1017, 165809 (2021)
4. A. Nitescu et al, SENSORS 23, 5725 (2023)

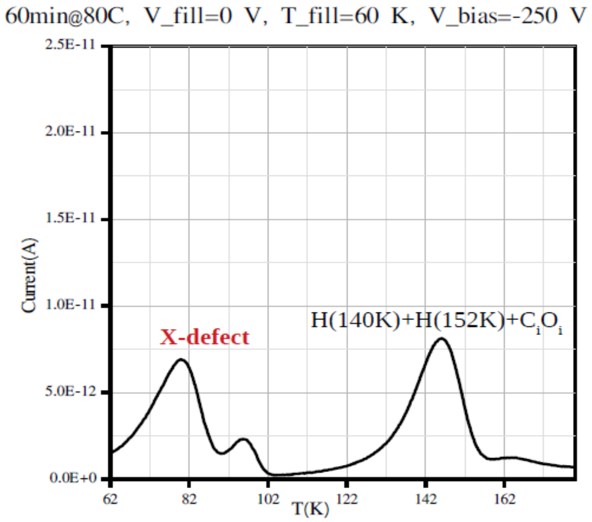
p-type Silicon diodes (Boron doped)

The X defect

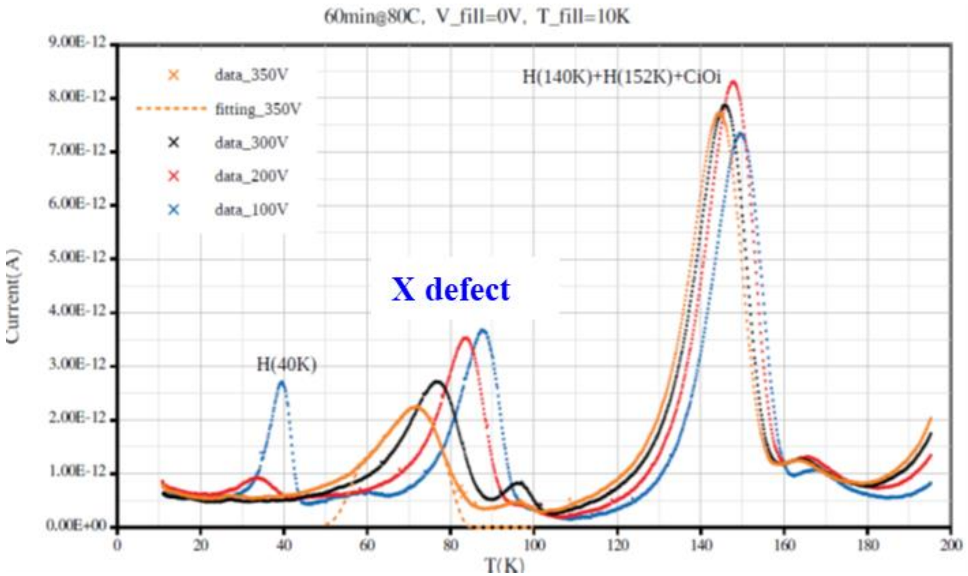
A hole trap detected first by TSC in low resistivity diodes (50 Ω cm)[1,5]

23 GeV protons, Φ_{eq}=4.28×10^{13} cm^{-2}

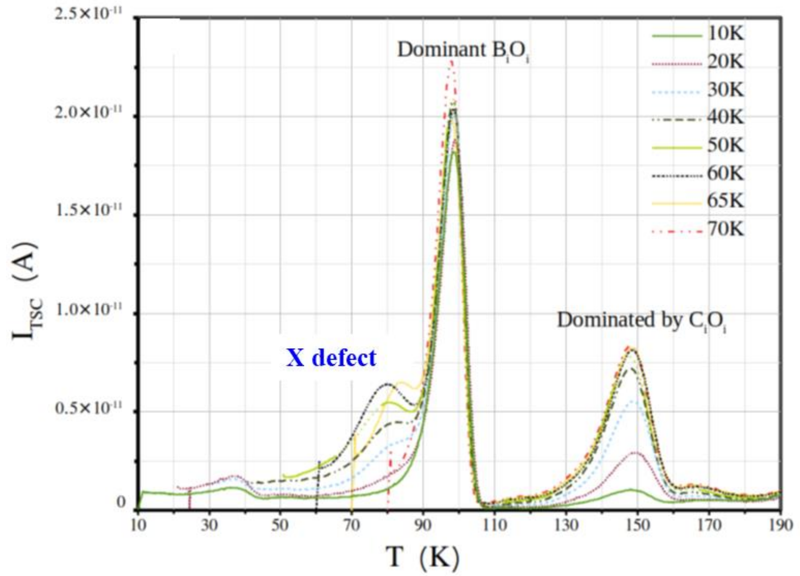




strong enhanced field emission



Temperature dependent capture cross section for holes (defect clearly detected when T_{fill} > 30 K)



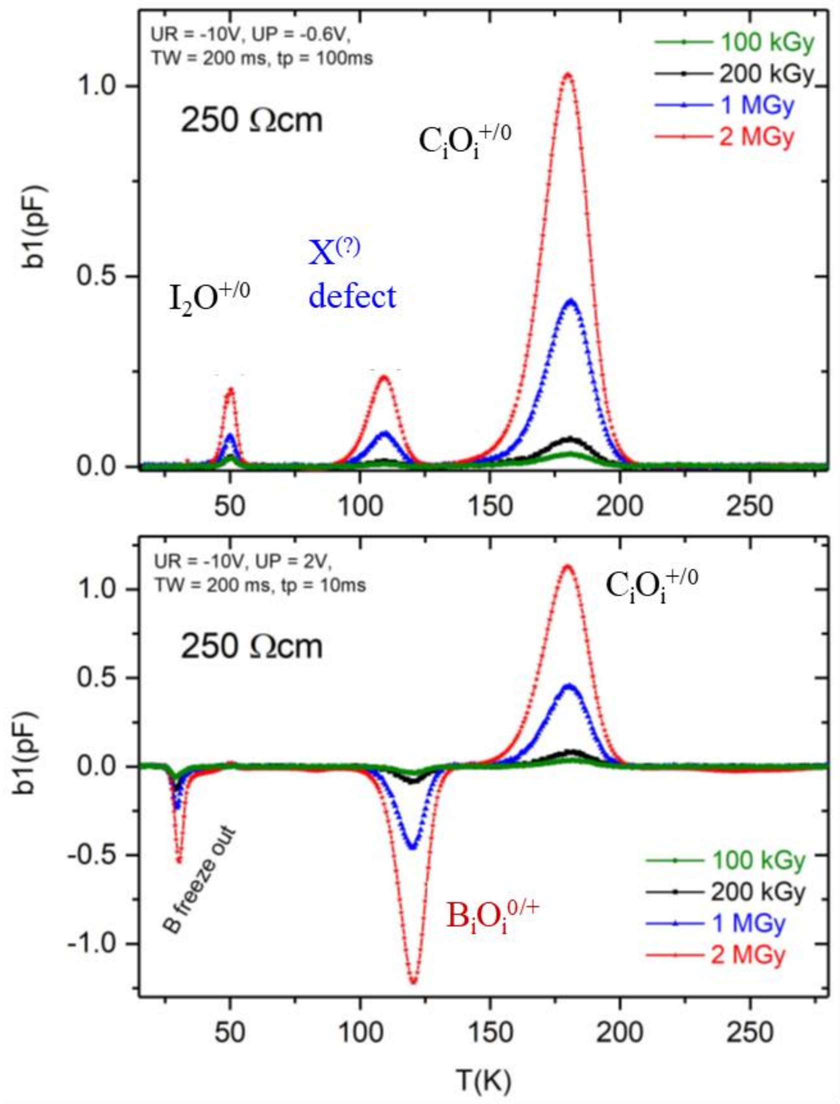
- **Is a defect with such properties detected also in diodes with larger resistivity ?**
- **What chemical structure may have and does it impact on the value of N_{eff} at RT?**

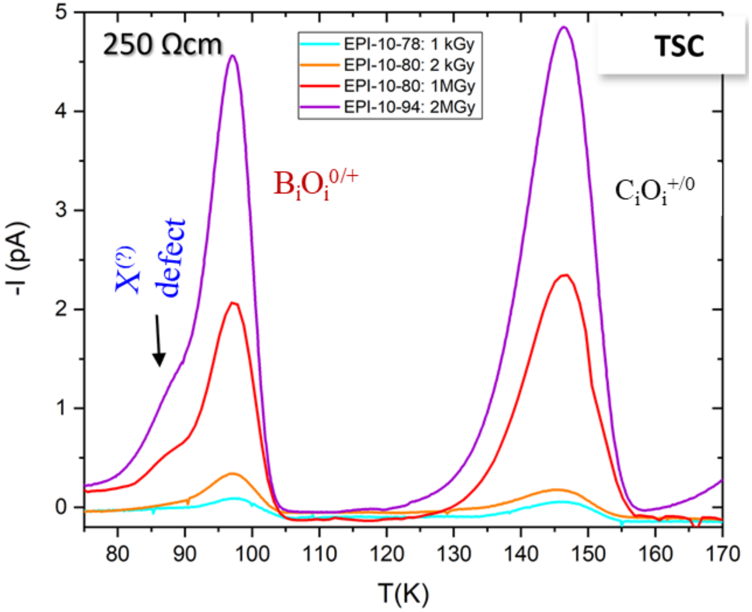
5. C. Liao et al., 37th RD50 Workshop, Zagreb, Croatia, 2020. Available: https://indico.cern.ch/event/896954

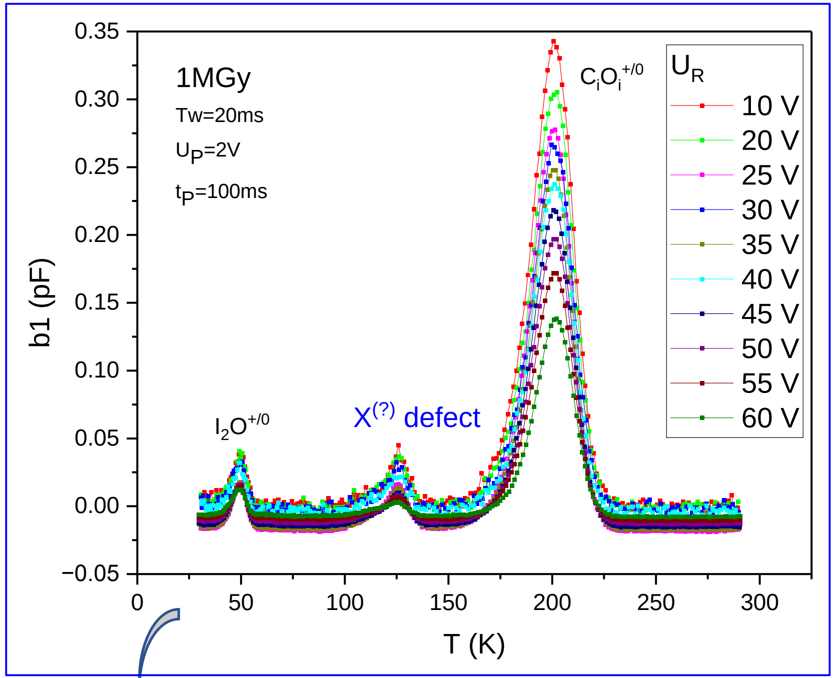
p-type Silicon diodes (Boron doped)

The X defect

DLTS and TSC on 250 Ω cm diodes irradiated with Co_{60}- γ







$I_2O^{+/0}$: Ev + 0.09 eV, $\sigma_p=2\cdot10^{-14}$ cm^2

X defect$^{(?)}$: Ev + 0.19 eV, $\sigma_p=4\cdot10^{-16}$ cm^2

$C_iO_i^{+/0}$: E_v + 0.36 eV, $\sigma_p=2\cdot10^{-15}$ cm^2

$B_iO_i^{0/+}$($BCD^{A(0/+)}$): E_c - 0.25 eV, $\sigma_n=6\cdot10^{-15}$ cm^2

No field enhanced emission in 250 Ω cm (no PF effect) !

X defect is not a coulombic center → $X^{+/0}$

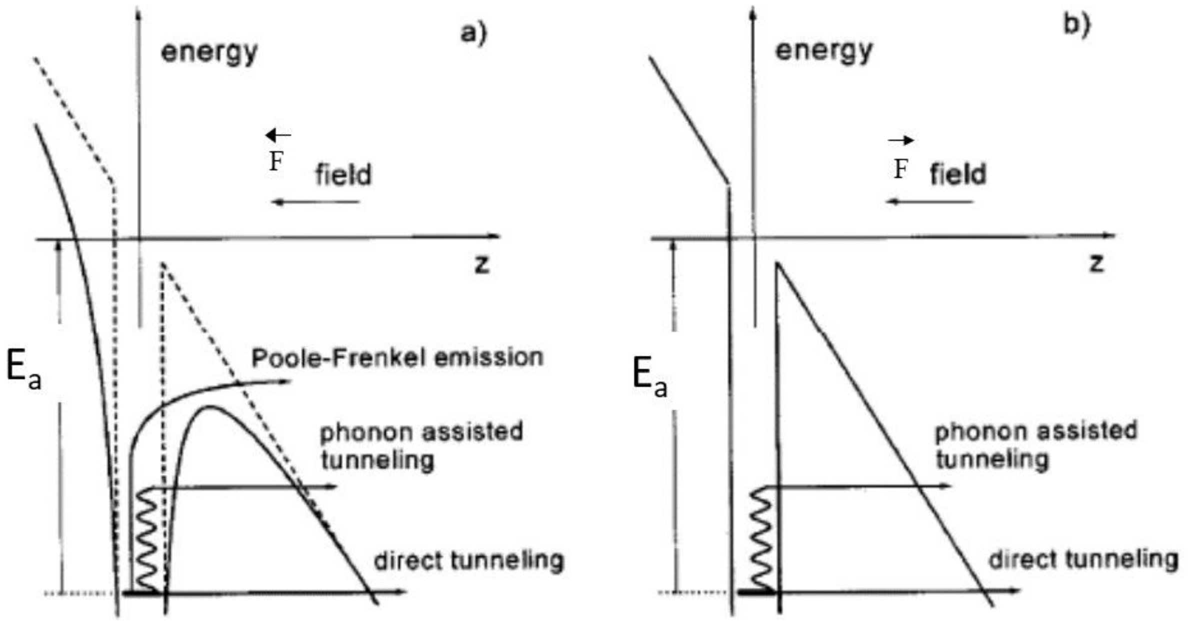
X defect has no impact on N_{eff}

p-type Silicon diodes (Boron doped)

The X defect – what possible chemical structure may have?

- E_a and σ_p similar to that of donor state of divacancy $V_2^{+/0}$
- Only in low resolution diodes the defect manifest a strong field enhanced emission

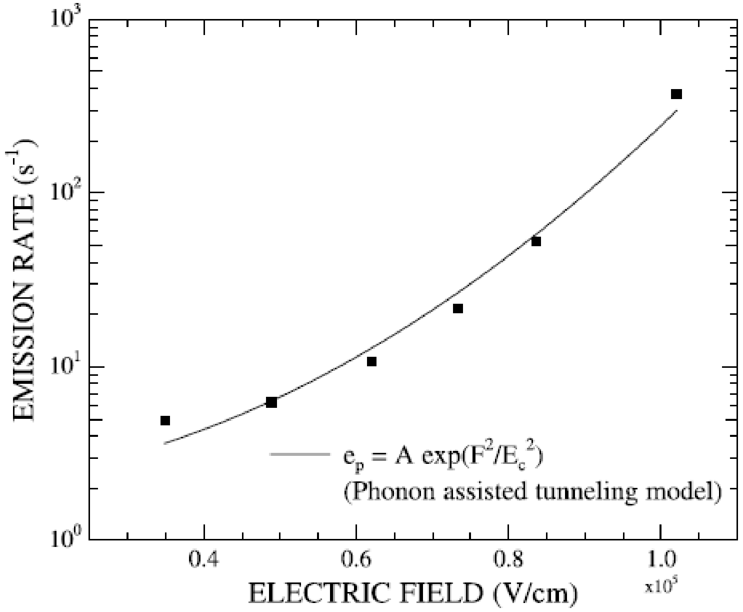
Potential barrier for the emission of an electron from a deep-level defect in external electric field for: a) charged impurities and b) neutral impurities.



PF emission rate ~ $\exp(\boldsymbol{F}^{1/2}/kT)$ PAT emission rate ~ $\exp(\boldsymbol{F}^2/E_c^2)$

6. S.D. Ganichev et al, Phys. Rev. B 61 (2000) 10 361.

The electric field effect on the emission rate of the $V_2^{(+/0)}$ fitted to the model for phonon assisted tunnelling for electric fields ***F*** **> 60 kV/cm**



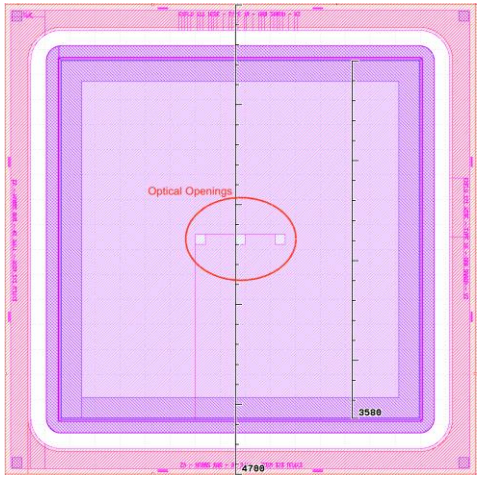
X defect can be associated with the donor state of divacancy $V_2^{(+/0)}$

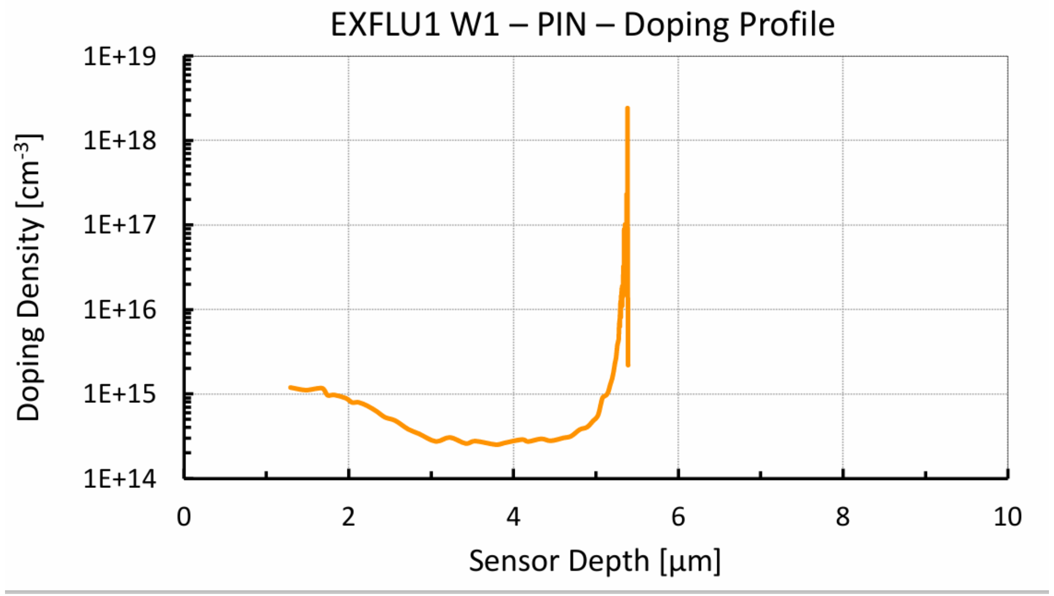
7. N. Zangenberg et al. / Nucl. Instr. and Meth. in Phys. Res. B 186 (2002) 71–77

DRD3

Carbon implanted diodes from the EXFLU1 batch

Wafer #	Thickness	C shield
1	45	
3	45	0.6
4	45	1.0





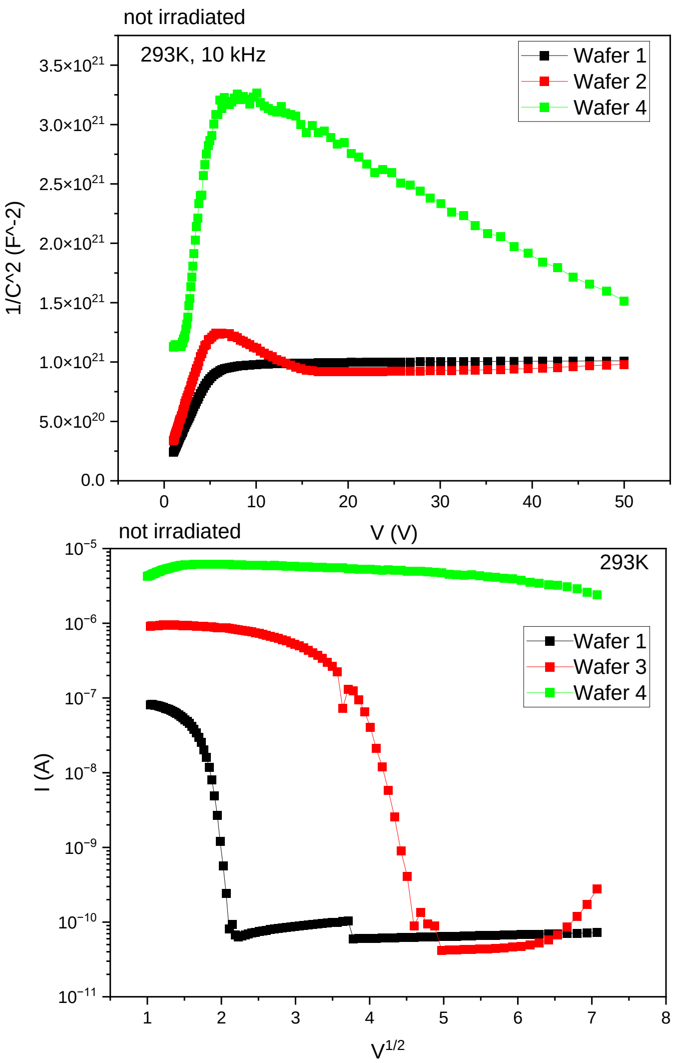
PIN sensors from the EXFLU1 batch: W1, W3, W4
900 Ωcm EPI thickness is 45 um – on 525 μm CZ substrates

Carbon spray deep implant – dose given in unit of FBK C dose

Measured before and after irradiation with $8x10^{14}$ n/cm^2
Available also 1.5E15 and 2.5E15 n_{eq}/cm^2
Annealing at 60°C for 80 minutes performed on the irradiated sensors

DRD3

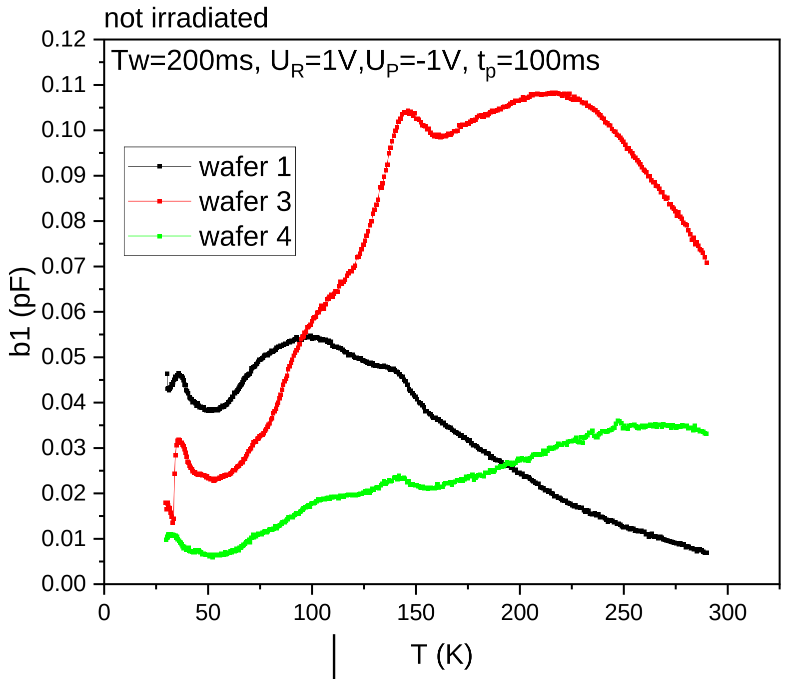
Carbon implanted diodes from the EXFLU1 batch



As processed diodes

Wafer #	Thickness	C shield
1	45	
3	45	0.6
4	45	1.0

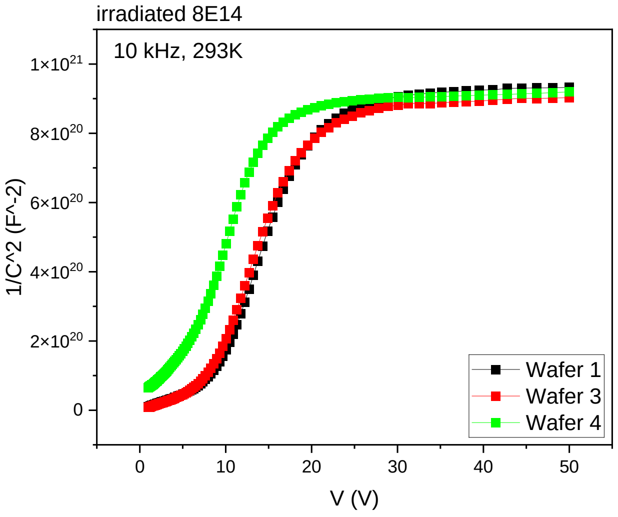
DLTS spectra
(injection successful only with Fw biasing)

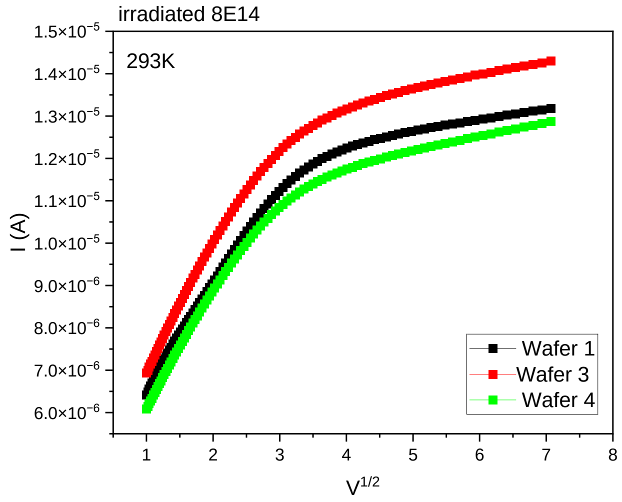


Strange C-Vs, I-Vs and large differences between the the as-processed samples

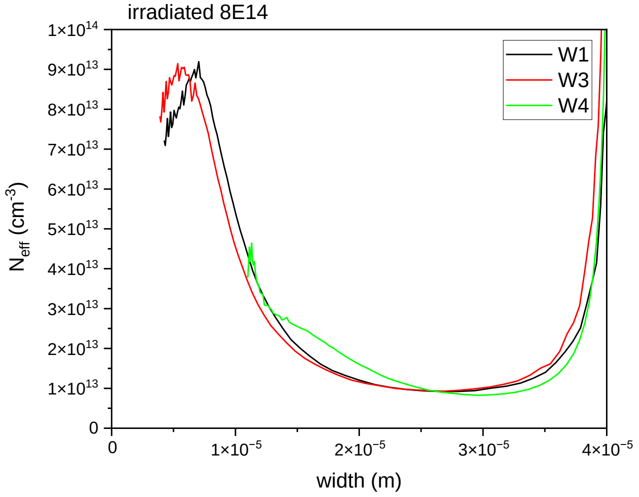
- A distribution of defects rather than point defects (most likely related to surface)
- For C implanted diodes (W3 and W4) the distribution moves to deeper energies, more defect states in W4 than in W3

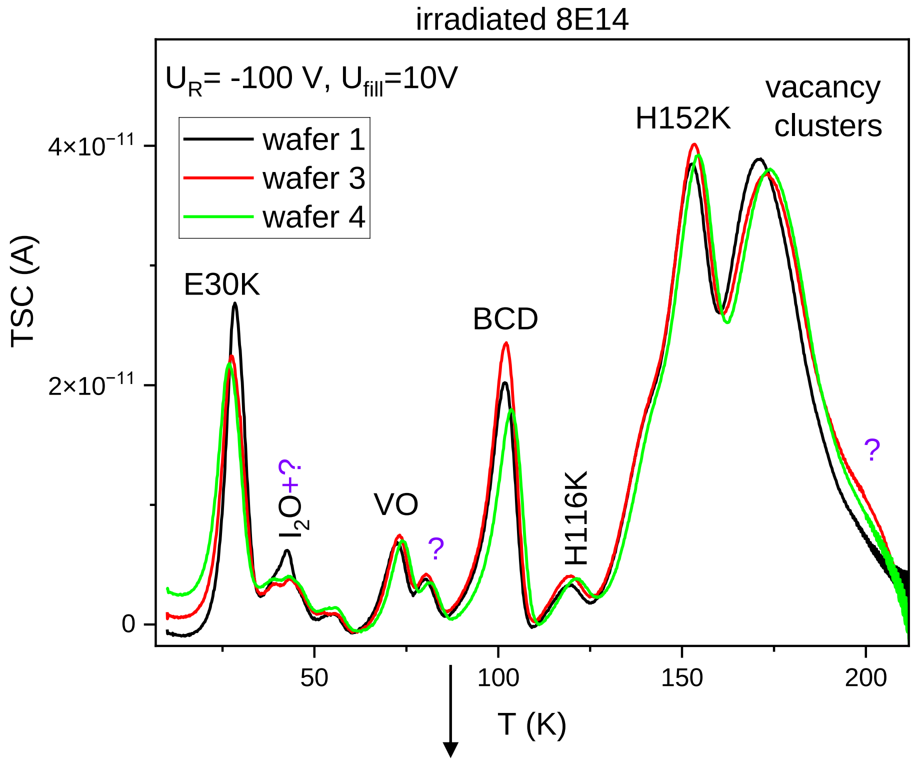
Carbon implanted diodes from the EXFLU1 batch – 8×10^{14} n/cm^2





Wafer #	Thickness	C shield
1	45	
3	45	0.6
4	45	1.0





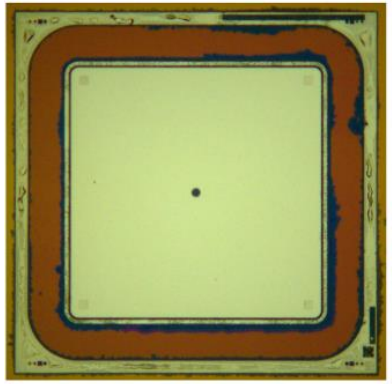
Strong nonhomogeneity in all of the samples

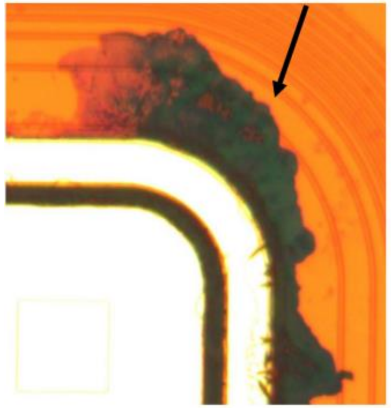
Similar defects, small variation in their concentration

n-type Silicon Carbide diodes (Nitrogen doped)

RD50 Common Project 4H-SiC LGADs, Planar Pad Diode Run & Status of Irradiation Campaign at CERN

- **CNM Run 17047 W2**
- n-type epitaxial 4H-SiC pad diodes
- 50µm EPI layer
- 3x3mm^2 area
- Outflow of Aluminium during processing
  →Broken guard ring structure
- More details in talk by Andreas Gsponer at 1st DRD3
- Irradiation campaign by SSD group at CERN
  - Irradiate with Protons, Neutrons and Gammas
  - Compare damage of different particle types
- Status of this project
  - Measured all diodes unirradiated (due to differences in processing)
  - Diodes send out to facilities, awaiting their return

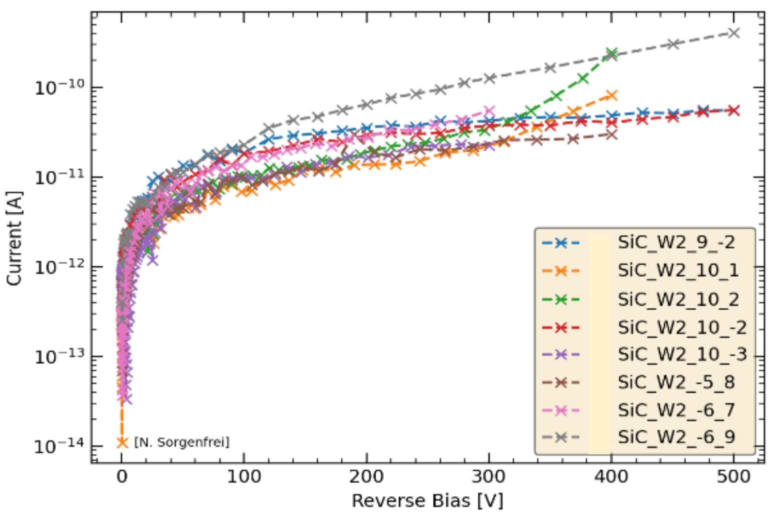


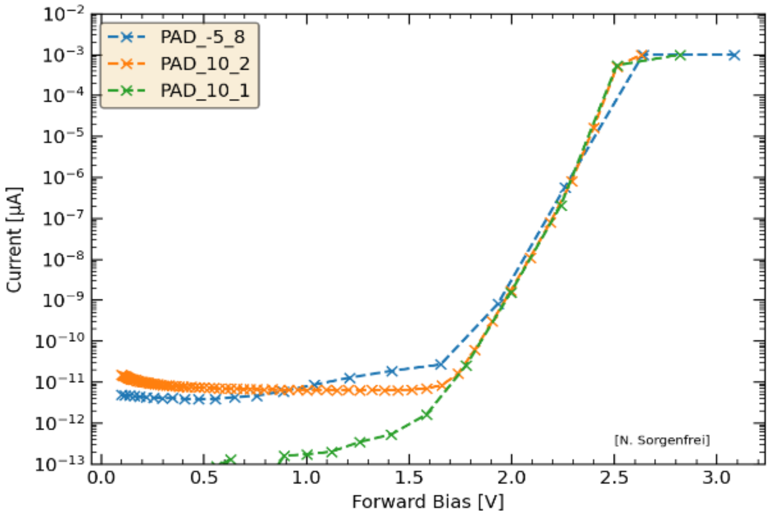


All results shown in the following are from **unirradiated diodes from the same wafer!**

Measurements on unirradiated diodes

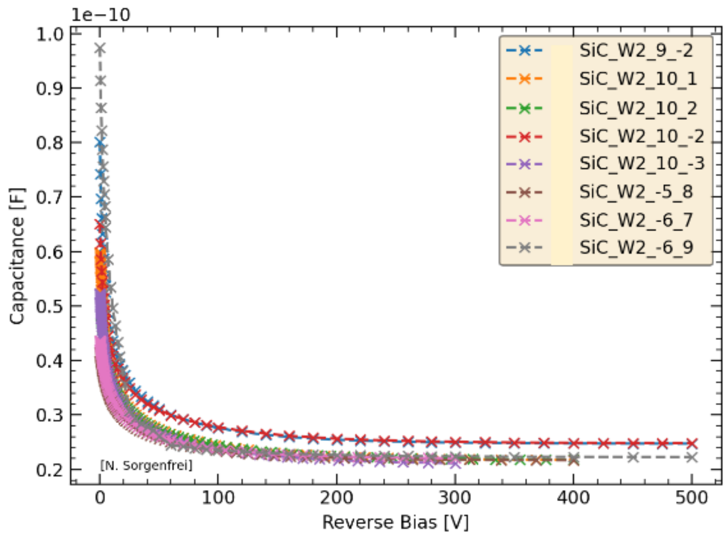
I-V

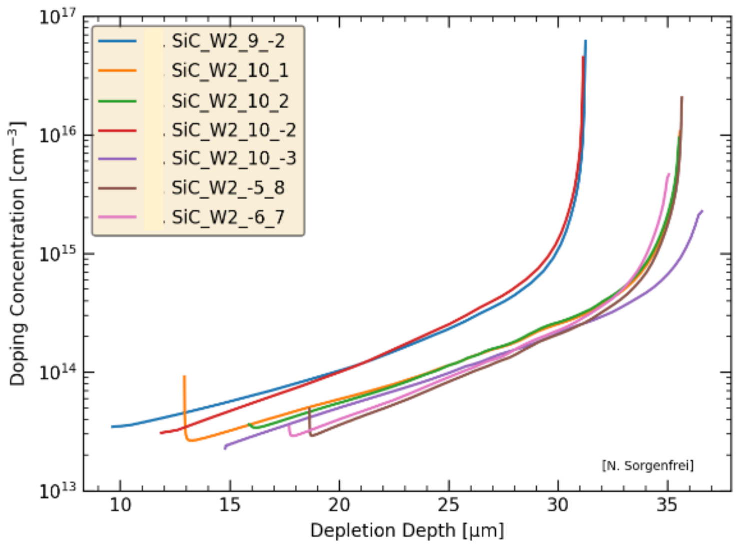




- Overall similar behaviour for both reverse and forward bias
- Only slight variations observed

C-V

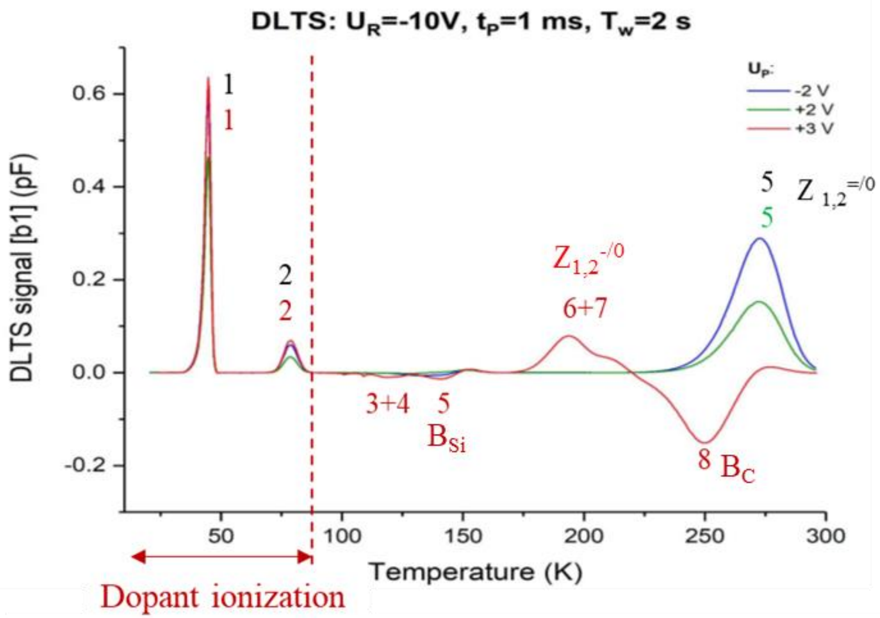


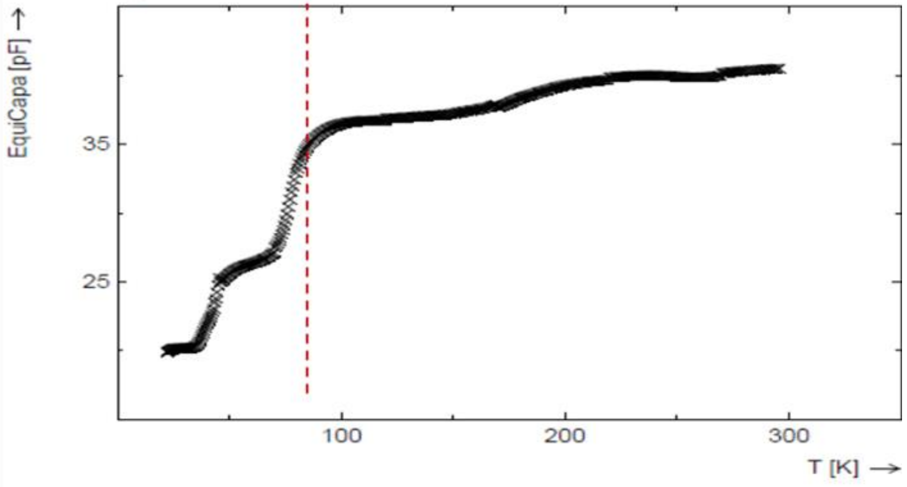


Differences observed in:

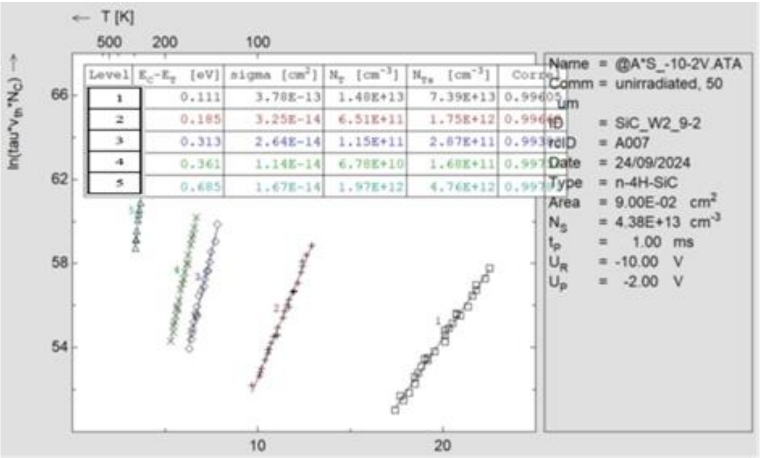
- Depletion depth
- Doping concentration profile
- Effective doping concentration
- Due to broken guard ring structure, large uncertainty on active area
  $\rightarrow$ Extracted values for doping are of indicative nature

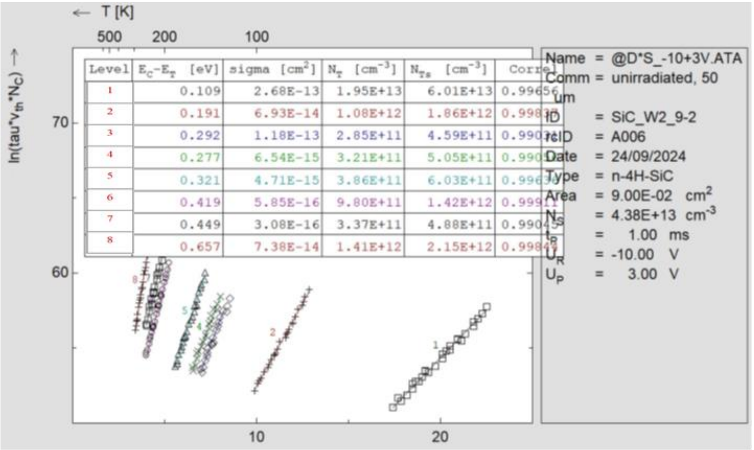
DLTS measurements on unirradiated diodes





W2 (17047, 50 um)





$Z_{1,2}$ defects

- electron traps with 2 energy levels in the bandga, exhibiting negative U behavior (capture/emission of the 2nd electron takes place faster than of the 1st electron) [7, 8]

- associated initially with a donor complex with Nitrogen dopant and interstitis Carbon on (h) and (k) sites [8,9] and lately with single and double acceptor levels of V_C (h)&V_C (k) (Carbon vacancy on hexagonal and cubic sites)[10]

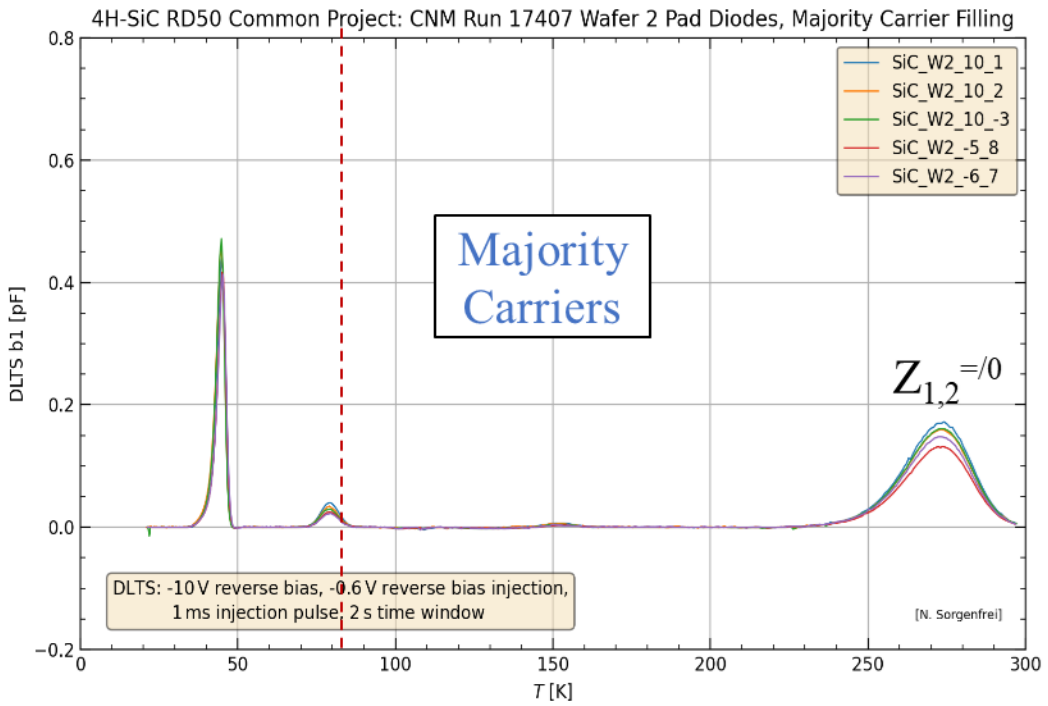
Peaks 5 and 6

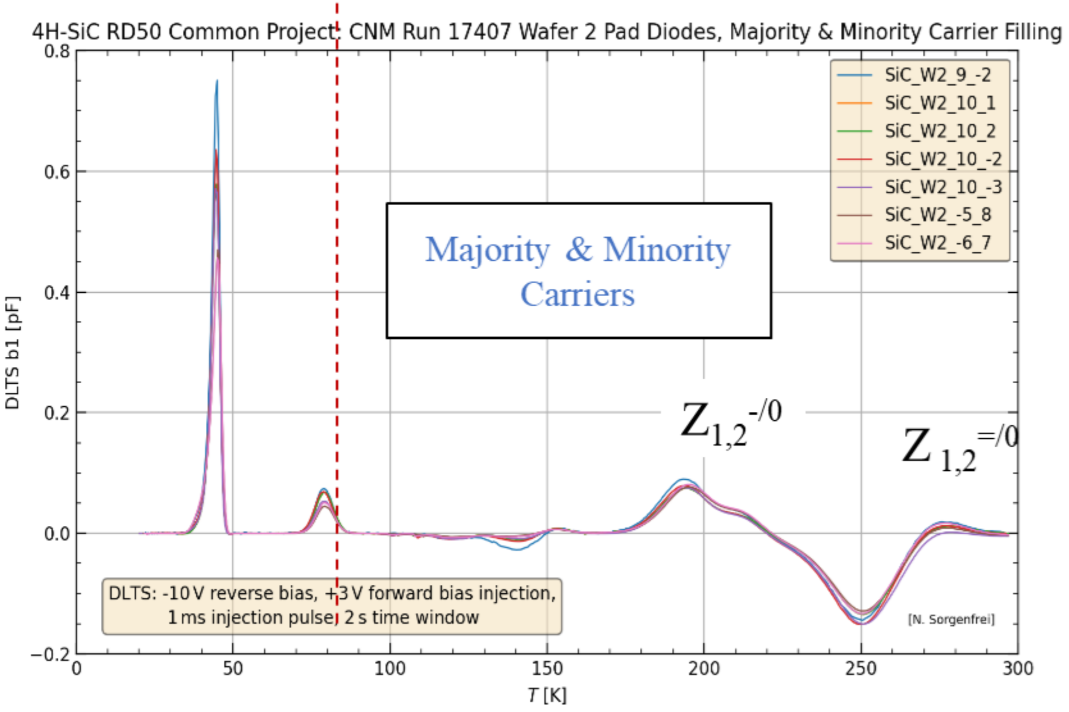
- Related to Boron incorporation on Silicon and Carbon sites (unintentional during CVD growth) [11-13]

Reliable DLTS evaluations only for T> 85K

7. C. Hemmingsson et al, Phys.Rev. B 58, R10119 (1998); ibid. 59, 7768 (E) (1999)
8. I. Pintilie et al, Appl. Phys. Lett., Vol. 81, No. 25, (2002)
9. T. A. G. Eberlein, R. Jones, and P. R. Briddon, Phys. Rev. Lett. 90, 225502 (2003)
10. N.T. Son et al, Phys. Rev. Lett. 109, 187603 (2012)
11. Vitor J. B. Torres et al, Phys.Rev. B 106, 224112 (2022)
12. Misagh Ghezellou et al, APL Mater. 11, 031107 (2023)
13. T. Knezevic et al, Materials 16, 3347 (2023)

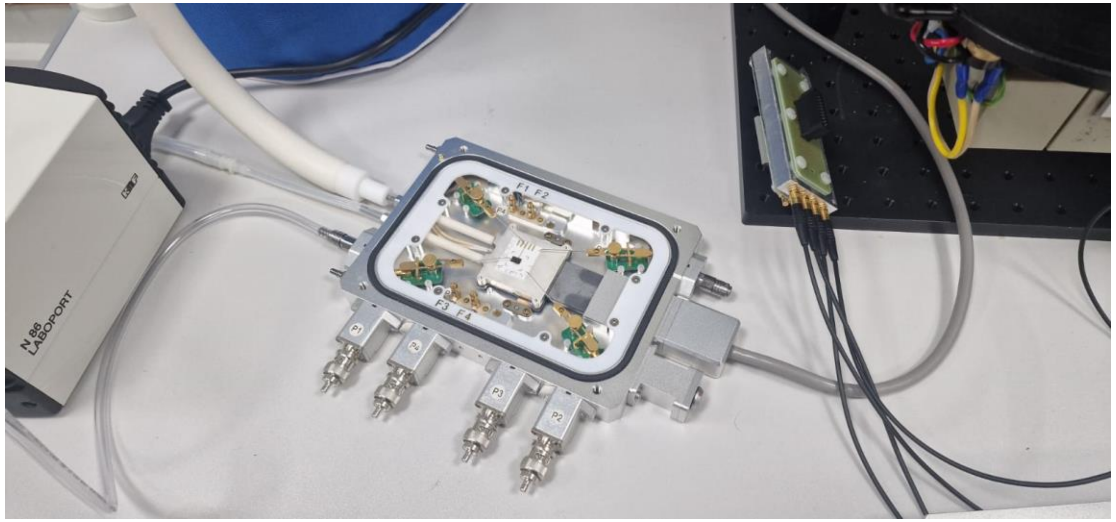
DLTS measurements on unirradiated diodes

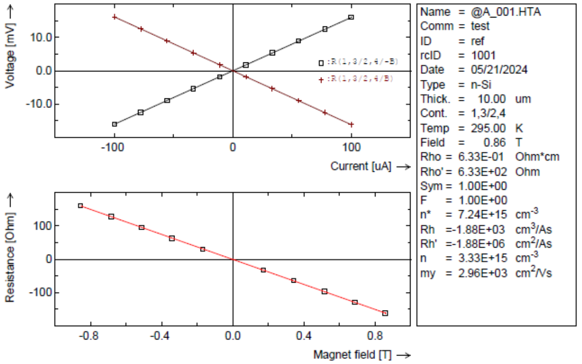


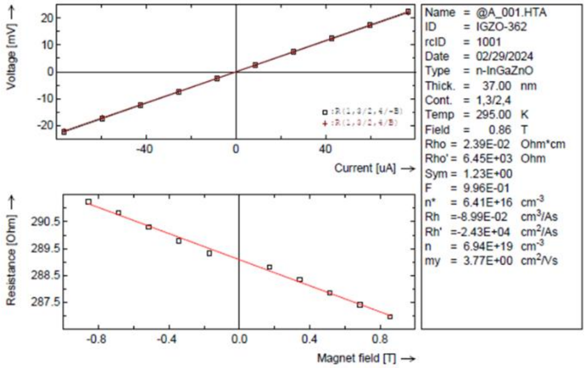


- Overall similar behaviour
- Same kind of defects observed in all samples with slight variations observed in defect concentration

First tests on high temperature set-up installed at NIMP

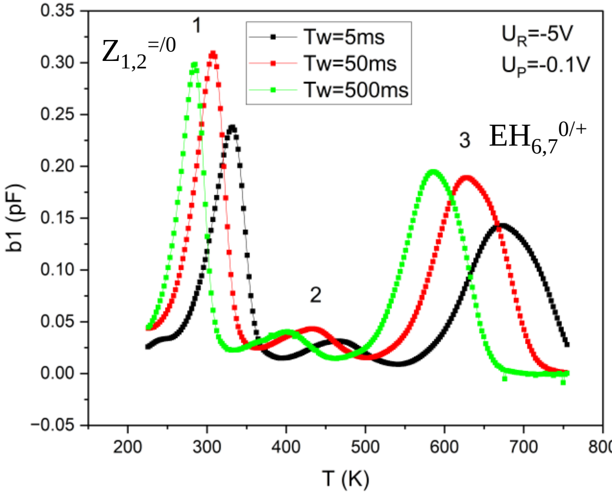


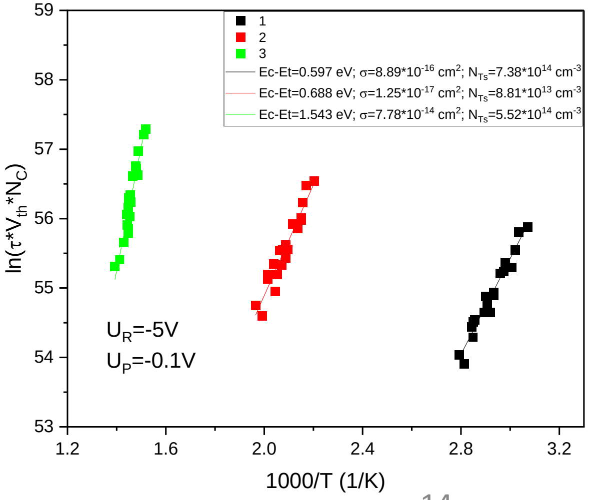




Hall System: n-type silicon (left): resistivity = 6.33x10^{-1} Ω cm, free carrier concentration = 3.33x10^{15}cm^{-3}, free carrier mobility = 2960 cm^2/Vs; **WBG semiconductor,** In:Ga:Zn oxide, Eg~3eV **(right)**: resistivity = 2.39x10^{-2} Ω cm; free carrier concentration = 6.94x10^{19}cm^{-3}; free carrier mobility = 3.77 cm^2/Vs.

EPI99 –irradiated with 6MeV electrons, $\Phi = 1.5\cdot10^{14}$ e/cm^2

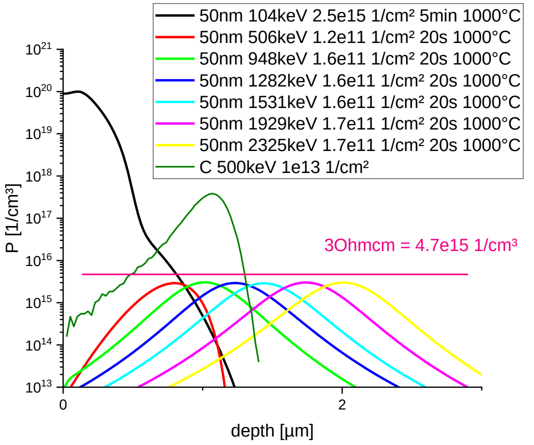




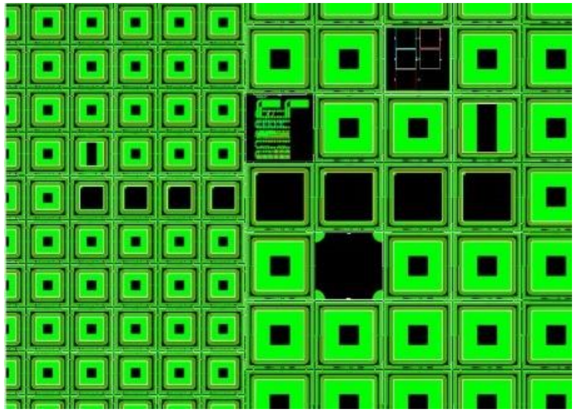
Future plans

Silicon – start measurements on *"Defect engineered diodes mimicking the gain layer in LGADs"* RD50 started project (18 differently defect engineered wafers with respect to B, O and C impurities as well as with P in compensated n^{++}-p^{+} diodes)

P and C implantations in compensated n^{++}-p^{+} diodes with 50 nm of oxide



layout design including samples for Hall measurements and diodes with fully transparent electrodes.



Expected results

- Reveal the microscopic radiation induced effects above 10^{15} n_{eq}/cm^2 and identify the reasons for losing the gain in LGADs.
- Reveal the role of O, C and P impurities in low resistivity B doped Si and of defects impacting on the gain layers in LGADs
- Detection and characterization of new defects induced by irradiation above 10^{15} n_{eq}/cm^2 (e.g. 2nd order defects)
- provide real inputs for modelling the radiation damage above 10^{16} n_{eq}/cm^2, allowing the development of accurate parametrization models validated on the entire range of fluences, from low to extreme;

Silicon Carbide – irradiate and start comprehensive defect investigations on the already fabricated devices

- n-type epitaxial 4H-SiC pad diodes (CNM Run 17047 W2)
- n-type 4H-SiC Schottky diodes at NIMP (< 15 µm EPI layers)

Expected results

- built up data set on defects induced by irradiation with different type of particles and fluence range from low to extreme
- establish the charge state of the detected defects and their impact on the device performance

Thank You!