EP-DT-DD [1]
Detector Technologies
Detector Development

[2]

Universität Hamburg [3]
DER FORSCHUNG | DER LEHRE | DER BILDUNG

BELARUSIAN STATE UNIVERSITY [4]

Defect characterization in boron doped silicon sensors after exposure to protons, neutrons and electrons

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36th RD50 Workshop, June 3-5, 2020, Virtual meeting at CERN, Geneva

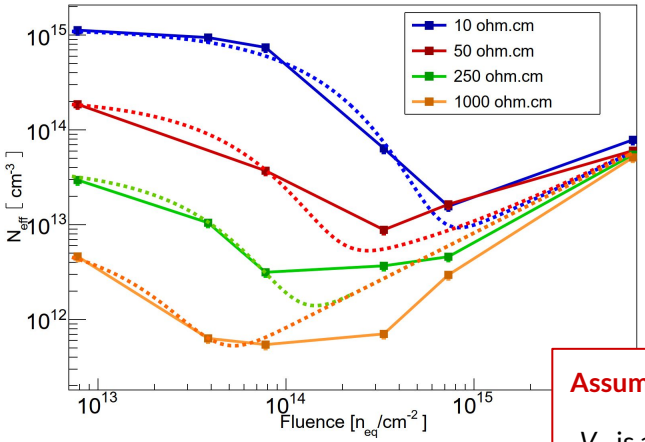
Acceptor removal: reminder

Macroscopic observation in Si detectors:

- mainly as a shift of V_{fd} obtained from CV measurements

$$V_{fd} = \frac{e_0 |N_{eff}| d^2}{2\epsilon\epsilon_0}$$

P. Almeida et al, 32nd RD50 workshop (2018)
+ few new data points added



Parametrization of N_{eff}:

$$|N_{eff}| = |N_{eff,0}| + g_c \Phi_{eq} - N_C[1 - \exp(-c\Phi_{eq})]$$

Assumptions:

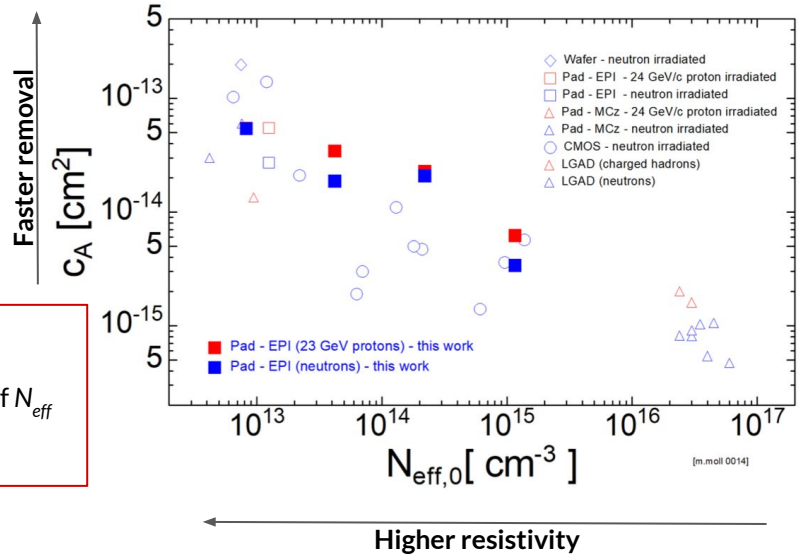
-V_{fd} is a valid parameter for evaluation of N_{eff}

-N_{eff}=const throughout the bulk

AR coefficients reported in literature

- C_A parameter drops with increasing N_{B0} (decreasing resistivity)
- Faster removal for higher resistivity if we take parametrization strict:

$$N_B = N_{B0} \exp(-c_A \Phi)$$



Acceptor removal: reminder

- Radiation induced removal of *B* from the substitutional lattice site, its deactivation as a shallow dopant leading to the change of V_{fd} and N_{eff} on the macroscopic level
- Originated from B_iO_i complex formation on the microscopic level
  - Most typical radiation induced reaction:

B_iO_i - donor in the upper part of E_g (contributes with '+' space charge)
For every removed Boron an acceptor is erased and a donor is created (factor of 2! in space charge)

Possible defect kinetics in Si: reminder

Assumption: [O]>>[B],[C]

- Boron can be removed by the reactions:

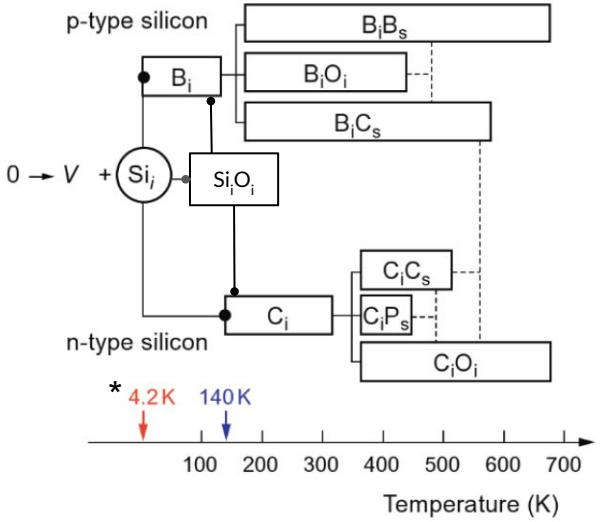
  $V + B_s \rightarrow VB$ (anneals out @T~0°C) - no role to play
  $\boldsymbol{I + B_s \rightarrow B_i \rightarrow B_i + O_i \rightarrow B_iO_i}$
  $\boldsymbol{B_i}$ - highly reactive!

- $\boldsymbol{Si_i}$ are shared between $\boldsymbol{B_s}$ & $\boldsymbol{C_s}$

Concurrent reaction channel: $I + C_s \rightarrow C_i \rightarrow C_i + O_i \rightarrow C_iO_i$
(Increasing C_s will protect B_s from removal)

- **Vs** : $V + O_i \rightarrow VO_i$ (remains more $\boldsymbol{Si_i}$ available)

Competing reactions with Si_i involving B, C and O



- Initial Boron removal rate
  (i.e. rate of BiOi formation at low fluence):

$$g_B = g_{BiOi} \approx g_I \left(1 + \frac{k_{IC}[C_s]}{k_{IB}[B_s]}\right)^{-1}$$

- Generation of interstitials (outside clusters): $g_I \approx 1\text{-}3\ cm^{-1}$ (high resitivity silicon)
- Sharing of interstitials between Bs and Cs: $k_{IB}/k_{IC} \approx 1\text{-}7$
- $[C_s] \approx 1 - 5 \times 10^{15}\ cm^{-3}$

*EPR studies of the lattice vacancy and low-temperature damage processes in Si by Watkins, G.D.

RD50 Acceptor Removal project

Dedicated defect and material characterization experiment

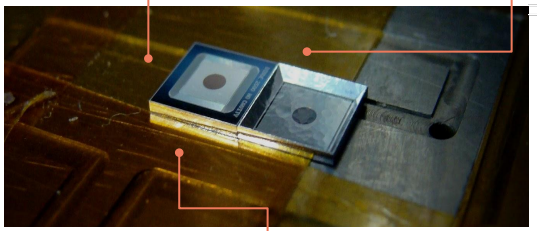
A large number of identical test structures with known B_s content:
- unify the list of the defects & their impact on sensor properties including introduction rates and annealing behaviour
- different irradiation particle types, materials, initial resistivities, O_s & C_s
- underlying reactions?
- is acceptor removal complete? Removal rate?

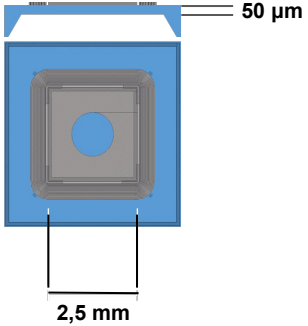
Test structure

Fz
>10 000 Ω·cm
100-285 µm

Cz
100 Ω·cm
100 or 285 µm

CiS Forschungsinstitut für Mikrosensorik GmbH





EPI
10, 50, 250 or 1000 Ω·cm
50 µm active layer

Irradiation

AIDA 2020

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

Electron irradiation

BELARUSIAN STATE UNIVERSITY

3.5-5.5 MeV

Neutron irradiation

Institut "Jožef Stefan" 50 let REAKTORJA TRIGA

Reactor neutrons

γ- irradiation

BGS IDEEN PLUS ENERGIE

^{60}Co

50 kGy, 200 kGy and 1 MGy

Proton irradiation

CERN IRRAD Proton Facility — 24 GeV /c

Boston General Hospital — 230 MeV

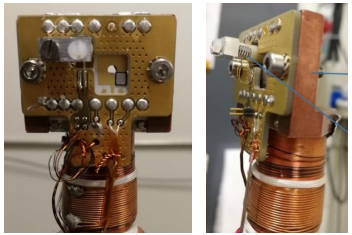
- clear signature for identification point and cluster defects

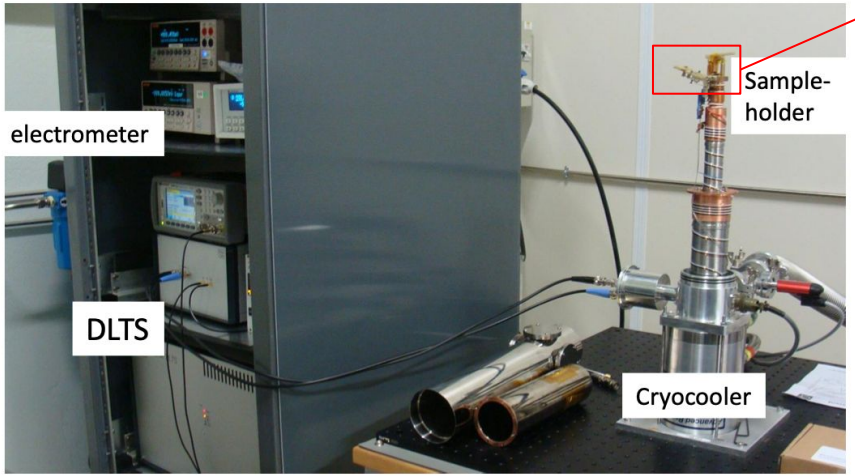
- identification of main defects responsible of radiation damage in Si and their formation kinetics

Setup for defect characterization

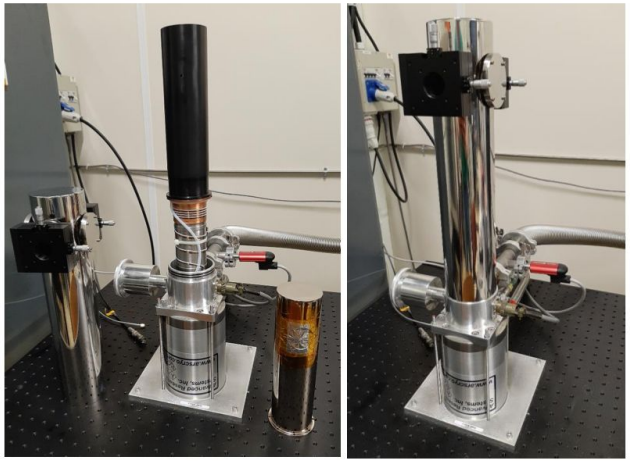
- Closed Cycle liquid Helium Cryocooler with cold head down to 8 K
- Vacuum ~10^{-6} mbar.
- Heating coil with temperature regulation for controlled warm-up
- **2 measurement techniques available:**
  - TSC: electrometer + Custom LabView DAQ
  - DLTS: Phystech commercial system (hardware, DAQ, analysis software)

Sample holder Version 2020

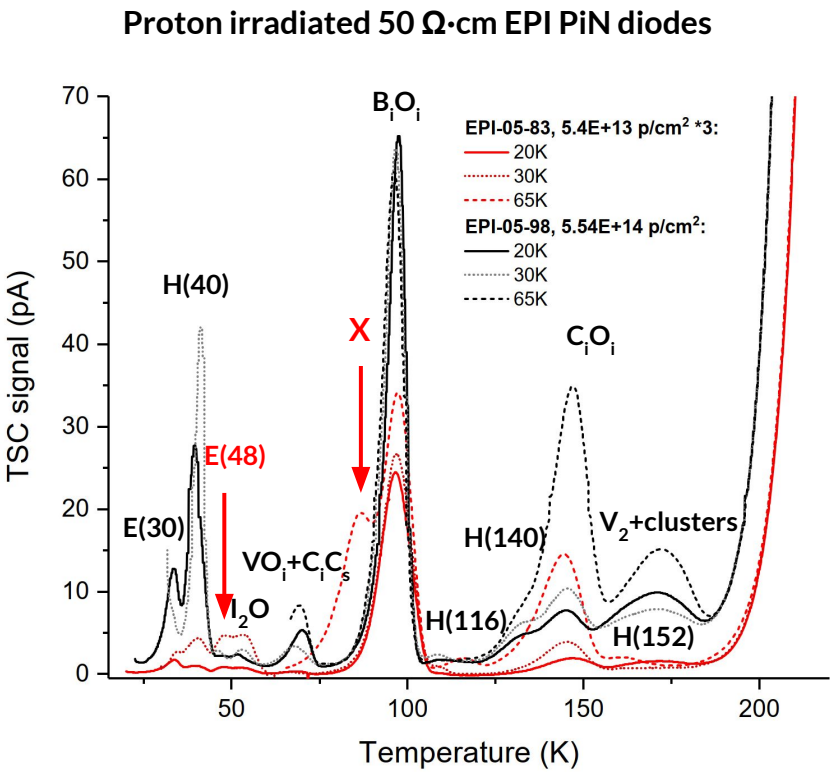




Work in progress on light injection option



TSC: fluence and T_{fill} dependence



- Several new defects are detected in proton irradiated with low fluences (2.4E+13 and 5.4E+13 p/cm^2) in low resistivity material
- Sensors are not fully depleted, T_{fill} dependence
- Before concentrations were found by integration over TSC peak introducing T threshold 'by eye'

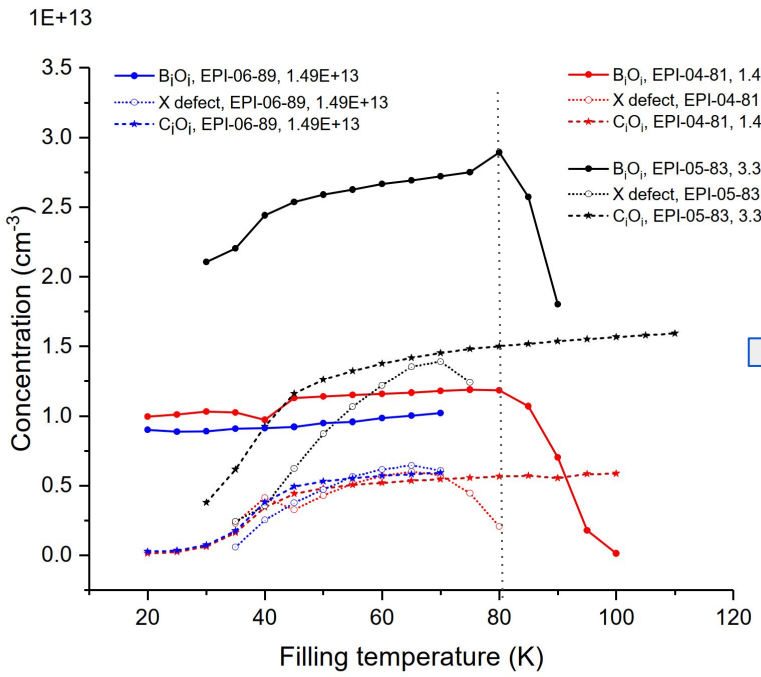
$$Q_t = \int dt I_{TSC}(t) \Rightarrow n_{t,0} = 2\frac{Q_t}{q_0 AW}$$

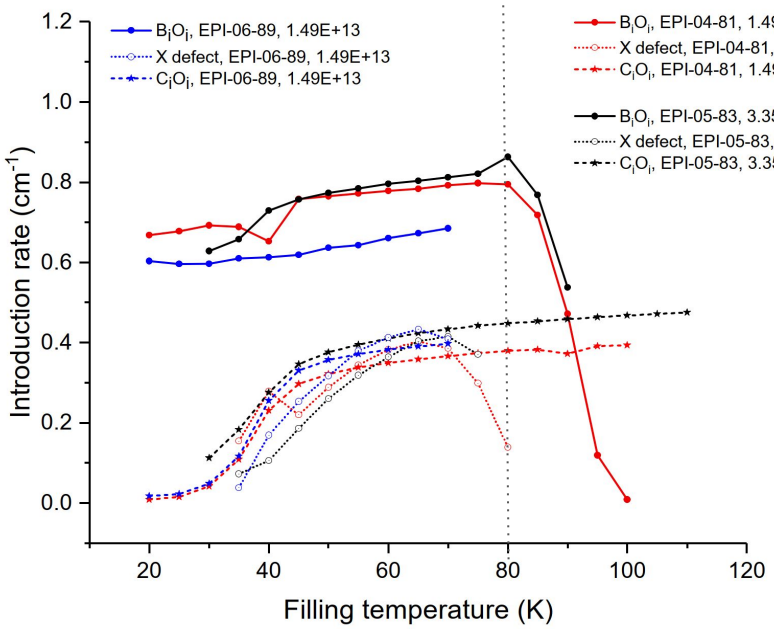
Measured n_t do not explained observed AR (missing factor of 2-4 in B_iO_i concentration)

- **New fitting** procedure is introduced in order to obtain E_a, σ and n_t from single TSC scan, works well for single point-like defects

TSC: defect concentrations and introduction rates via fitting

Fluence	Φ_{neq}/cm^2
2.4E+13	1.49E+13
5.4E+13	3.35E+13

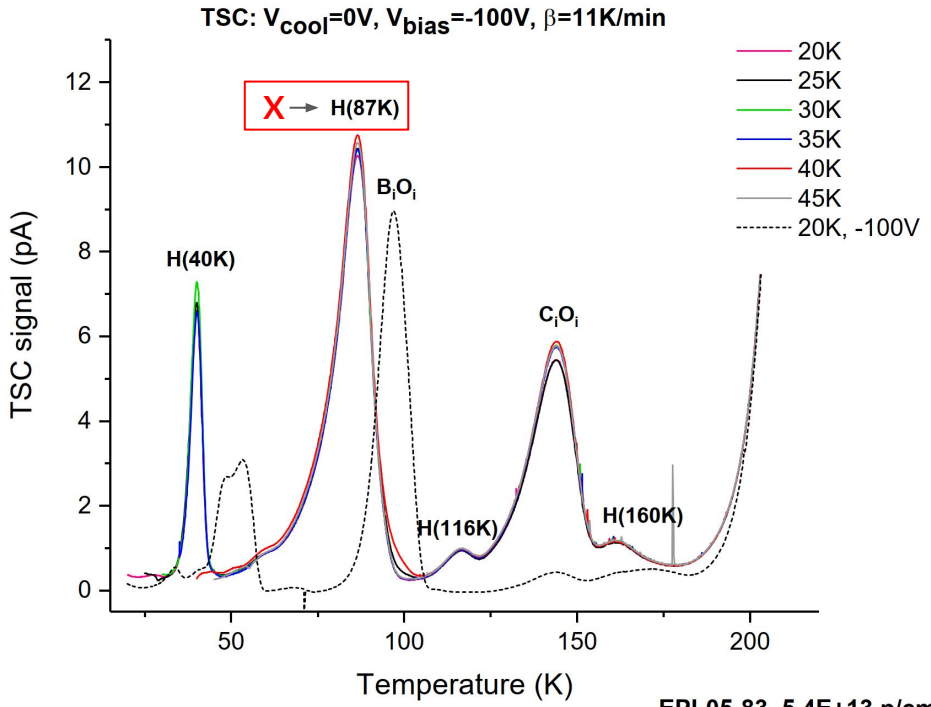




Sensors are not fully depleted → low introduction rate?

TSC: T_{fill} variation for 0 bias cooling

Example: proton irradiated 50 Ω·cm EPI PiN diode



EPI-05-83, 5.4E+13 p/cm²

<u>0 bias cooling</u> → filling only hole traps with majority carriers

⇒ X-defect - hole trap H(87K)
(proved by Hamburg group with light injection)

Integration over TSC peak (V_{bias}=-100V, T_{fill}=20K), Int.rate=n_t/Φ_{eq}

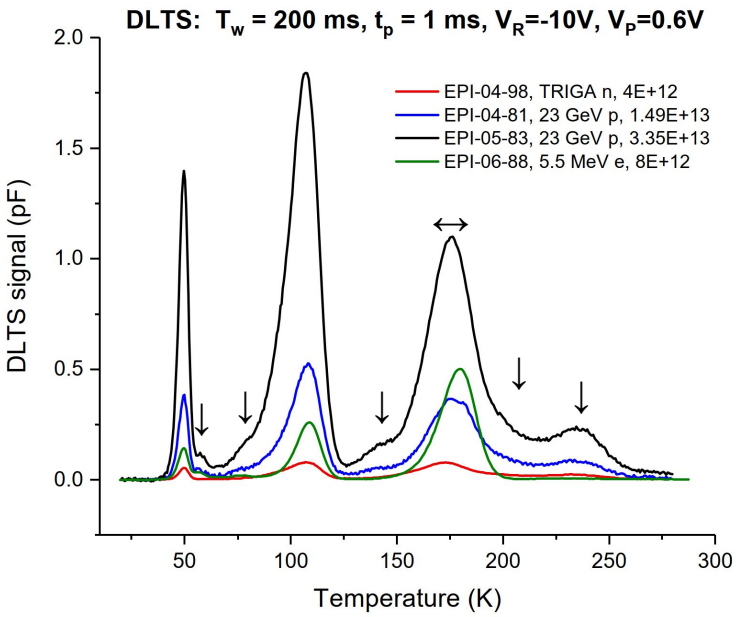
	EPI-04-81, 1.49E+13 n_{eq}/cm^2	EPI-05-83, 3.35E+13 n_{eq}/cm^2
H(40K)	0.08	0.09
H(87K)	0.35	0.41
H(116K)	0.03	0.03
C_iO_i	0.17	0.24
H(160K)	0.02	0.04

~0.4 by fitting

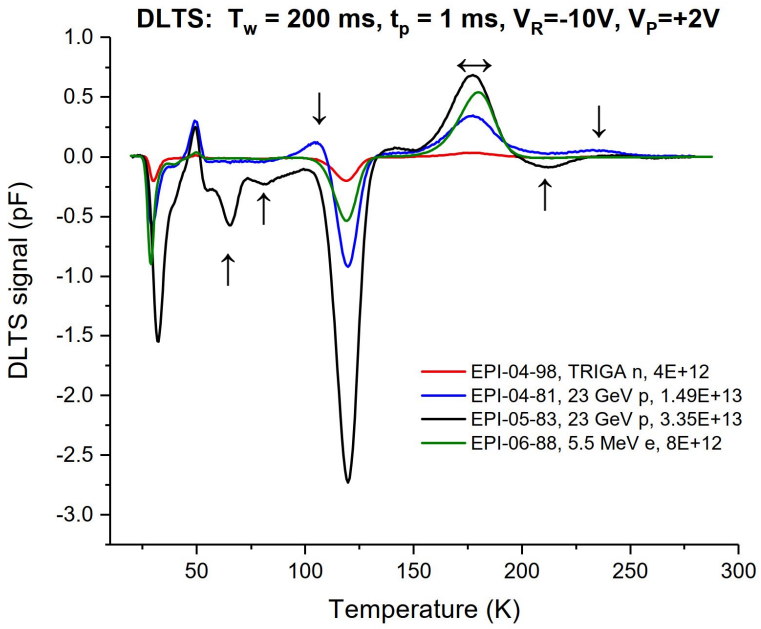
Fluence	Φ_{neq}/cm^2
2.4E+13	1.49E+13
5.4E+13	3.35E+13

DLTS data on e, p and n irradiated 50 Ω▪cm sensors

- holes injection (-10-2 V)



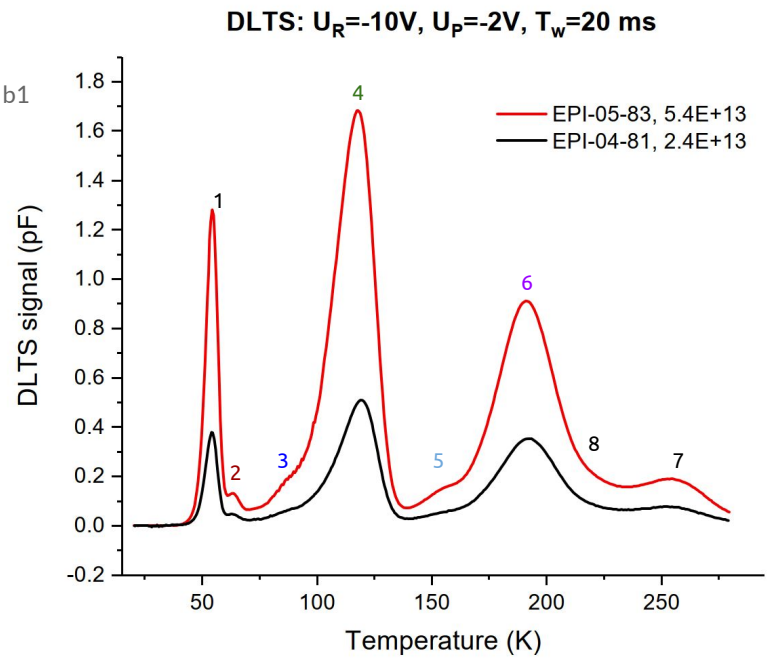
- both carrier types injection (-10+2 V)



Careful: peak heights do not correspond to N_T

Identification of the defects is ongoing. Further investigations with light injection and isochronal and isothermal annealing are planned in RD50 AR group

Arrhenius plots using correlator functions



Peak 1 - $C_iC_s^{+/0}$ <u>or</u> $I_2O^{+/0}$? Stability 225˚C <u>or</u> 50-100 ˚C

Peak 2 - $V_3^{0/+}$

Peak 3 -

Peak 4 - $V_2^{0/+}$+...

Peak 5 - B_iC_s Stability 400˚C

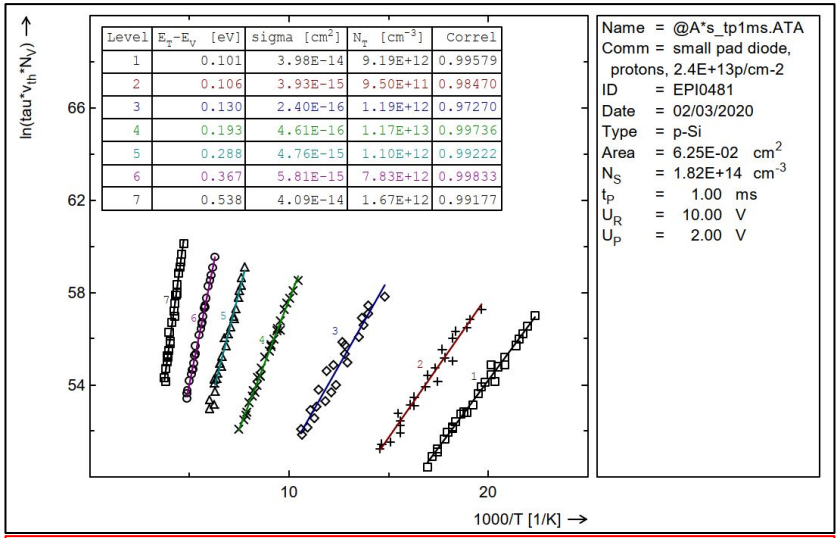
Peak 6 - $C_iO_i^{0/+}$ Stability 400˚C

Peak 7 - H_{255}

Peak 8 - H_{220}

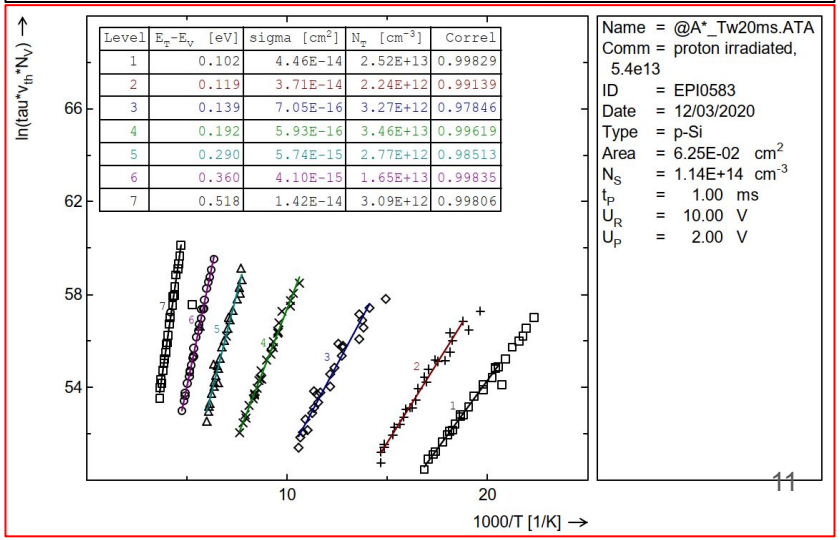
Annealing is planned

Arrhenius plot contains data obtained with correlator functions



Level	E_T-E_V [eV]	sigma [cm^2]	N_T [cm^{-3}]	Correl
1	0.101	3.98E-14	9.19E+12	0.99579
2	0.106	3.93E-15	9.50E+11	0.98470
3	0.130	2.40E-16	1.19E+12	0.97270
4	0.193	4.61E-16	1.17E+13	0.99736
5	0.288	4.76E-15	1.10E+12	0.99222
6	0.367	5.81E-15	7.83E+12	0.99833
7	0.538	4.09E-14	1.67E+12	0.99177

Name = @A*s_tp1ms.ATA
Comm = small pad diode, protons, 2.4E+13p/cm-2
ID = EPI0481
Date = 02/03/2020
Type = p-Si
Area = 6.25E-02 cm^2
N_S = 1.82E+14 cm^{-3}
t_P = 1.00 ms
U_R = 10.00 V
U_P = 2.00 V



Level	E_T-E_V [eV]	sigma [cm^2]	N_T [cm^{-3}]	Correl
1	0.102	4.46E-14	2.52E+13	0.99829
2	0.119	3.71E-14	2.24E+12	0.99139
3	0.139	7.05E-16	3.27E+12	0.97846
4	0.192	5.93E-16	3.46E+13	0.99619
5	0.290	5.74E-15	2.77E+12	0.98513
6	0.360	4.10E-15	1.65E+13	0.99835
7	0.518	1.42E-14	3.09E+12	0.99806

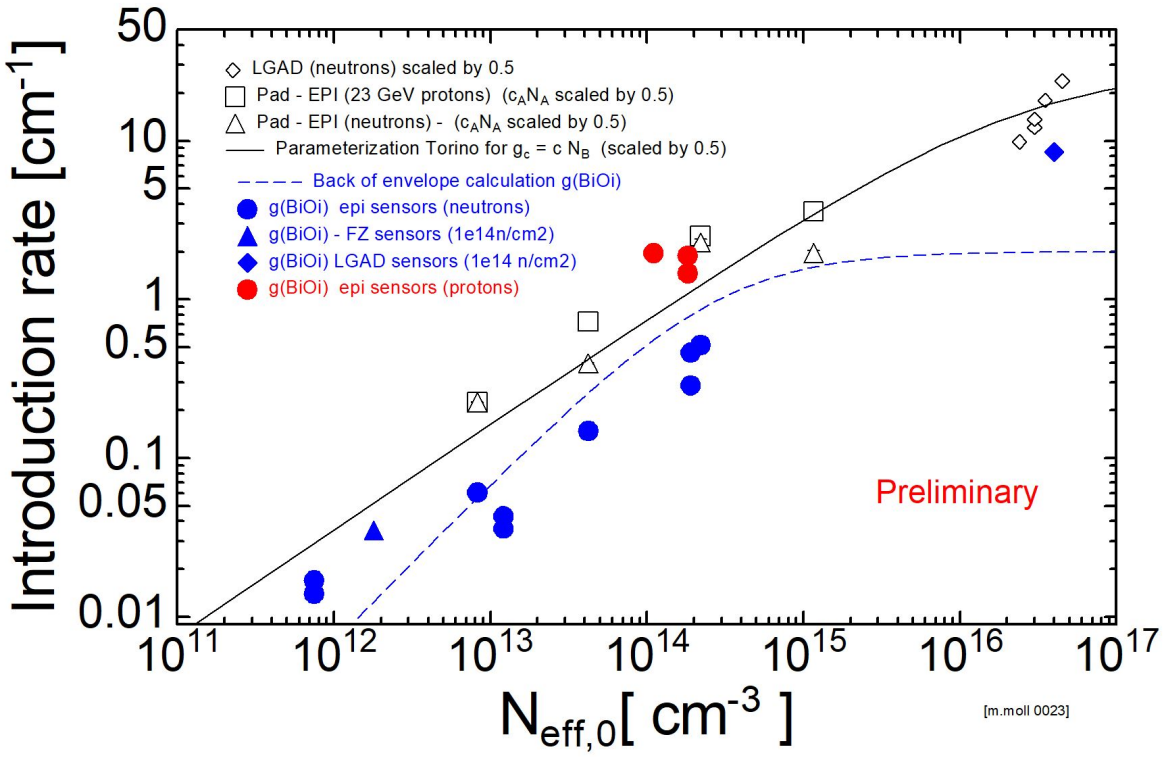
Name = @A*_Tw20ms.ATA
Comm = proton irradiated, 5.4e13
ID = EPI0583
Date = 12/03/2020
Type = p-Si
Area = 6.25E-02 cm^2
N_S = 1.14E+14 cm^{-3}
t_P = 1.00 ms
U_R = 10.00 V
U_P = 2.00 V

DLTS measurements results:

Sample	Resistivity (Ω·cm)	Particle type	Fluence	Φ_{neq}/cm^2	Annealing status	N_{eff} (cm^{-3}) CV@-20C	NT_{BiOi}/NTs_{BiOi}	Intr. rate B_iO_i	NT_{CiOi}/NTs_{CiOi}	Intr. rate C_iO_i
EPI-04-81	50	p	2.4E+13	1.49E+13	0 min	1.8E+14	2.18E+13/ 2.82E+13	1.46/ 1.89	7.83E+12/ 1.29E+13	0.53/0.87
EPI-05-83	50	p	5.4E+13	3.35E+13	0 min	1.1E+14	6.58E+13/ 1.15E+14	1.96/ 3.43	1.65E+13/ 2.72E+13	0.49/0.81
EPI-04-98	50	n	4E+12	4E+12	0 min	1.9E+14	1.15E+12/ 1.85E+12	0.29/ 0.46	3.70E+11/ 6.67E+11	0.09/0.17
EPI-08-83	250	n	5E+11	5E+11	0 min	3.3E+12	1.79E+10/ 2.17E+10	0.04/ 0.04	1.37E+10/ 2.22E+10	0.03/0.04
EPI-12-103	1k	n	1E+11	1E+11	0 min	7.5E+11	1.42E+09/ 1.73E+09	0.014/ 0.02	4.24E+09/ 6.69E+09	0.04/0.07
EPI-02-100	10	ē	5E+14	1.9E+13	RT	1.5E+15	4.34E+13/ 5.53E+13	2.28/ 2.91	1.05E+13/ 1.57E+13	0.81/0.83
EPI-02-105	10	ē	5E+14	1.9E+13	RT	1.4E+15	4.09E+13/ 5.21E+13	2.15/ 2.74	1.53E+13/ 2.16E+13	0.62/1.14
EPI-06-88	50	ē	2E+14	7.6E+12	RT	2E+14	1.32E+13/ 1.57E+13	1.74/ 2.07	6.44E+12/ 9.61E+12	0.85/1.26

B_iO_i - Introduction rates

Comparison of B_iO_i introduction rate to 'Acceptor Removal rate'



Conclusions

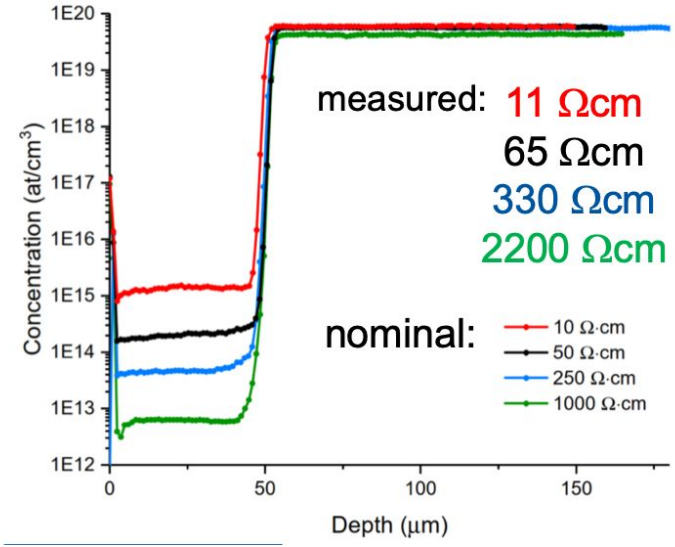
- TSC and DLTS were performed on 5.5 MeV electron, 23 GeV proton and reactor neutron irradiated sensors (10, 50, 250 and 1k Ω·cm)
- Defects observed after ē-irradiation have been also detected after proton and neutron irradiation with additional cluster-related ones
- Identification of defects ongoing, new defects are detected after low fluence proton irradiation in TSC
- Analysis on introduction rates is ongoing (table+see talk of Ioana)
- $gB_iO_i(n) < gB_iO_i(p) < gB_iO_i(e)$, Ω- and Φ-dependent
- Additional annealing study and optical injection are planned

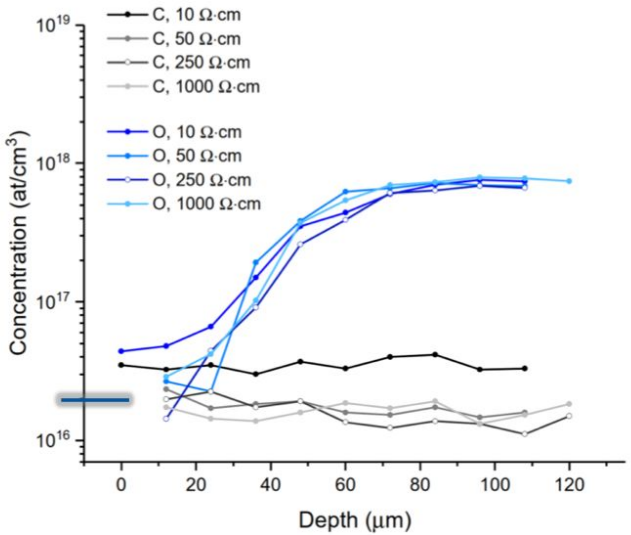
Microscopic understanding of acceptor removal remains incomplete, but we did several big steps forward

Spare slides

- All EPI wafers are produced in the same facility/process on same substrate (low resistivity CZ p-type Si) differing only in Boron content = resistivity of EPI layer
- All samples were irradiated together for each type of particles

Characterization on processed devises: SR (Spreading Resistance) and SIMS (Secondary Ion Emission Spectroscopy)





Displacement damage in Si

IEEE-TS Nucl. Sci. Vol. 56, No 6, Dec 2009, pp 3229-3235

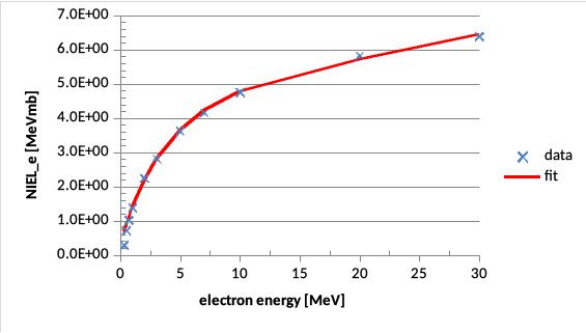
for actual use of this tabulation, please refer to:
A. Vasilescu and G. Lindstroem
Displacement damage in Silicon
on-line compilation: http://sesam.desy.de/~gunnar/Si-dfuncs

electron induced displacement damage in silicon
listed for kinetic energies between 300 keV and 200 MeV:
The only reliable data are from:
G.P.Summers et al., IEEE NS 40, No 6 (1993), 1372

Ekin [MeV]	D/95MeVmb
3,000E-01	3,182E-03
5,000E-01	7,998E-03
7,000E-01	1,139E-02
1,000E+00	1,543E-02
2,000E+00	2,489E-02
3,000E+00	3,126E-02
5,000E+00	3,979E-02
7,000E+00	4,558E-02
1,000E+01	5,160E-02
2,000E+01	6,241E-02
3,000E+01	6,780E-02
5,000E+01	7,344E-02
7,000E+01	7,634E-02
1,000E+02	7,870E-02
2,000E+02	8,106E-02

E_el (MeV)	NIEL (MeVcm²/g)	NIEL (MeVmb)
0.3	6.21E-06	2.897E-01
0.5	1.54E-05	7.183E-01
0.7	2.19E-05	1.022E+00
1	2.97E-05	1.385E+00
2	4.81E-05	2.244E+00
3	6.06E-05	2.827E+00
5	7.76E-05	3.620E+00
7	8.92E-05	4.161E+00
10	1.02E-04	4.758E+00

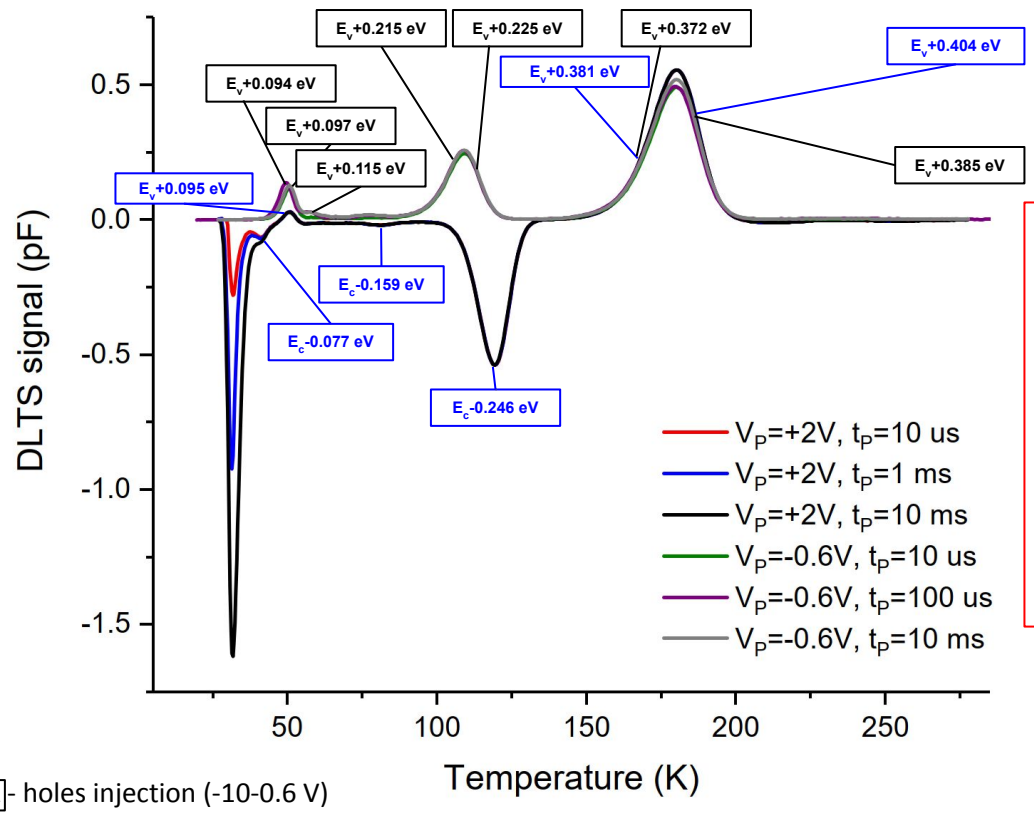
/95=0.038



Laplace: 5.5 MeV electron irradiated 50 Ω·cm EPI PiN diode

50 Ω·cm $N_{eff,\,0}$=~2E+14 at/cm^3

Results of transient measurements close to T_{peak}
+ direct evaluation of the data (by DLTFS method)
+ Laplace DLTS with variation of V_p and t_P



At least 2 levels are detected overlapping in DLTS spectra at 60K, 120K, 190K with majority carrier injection; several electron traps besides B_iO_i are found around 50K and 70K. Identification is not clear at the moment.
Further investigation with the light (minority carrier) injection, in low T region and annealing studies are planned.

Black - holes injection (-10-0.6 V)
Blue - both carrier types injection (-10+2 V)