Current Deep Level Transient Spectroscopy (I-DLTS) technique applied to p-type silicon diodes for Acceptor Removal studies

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Session Classification: Defect and Material Characterization – Acceptor removal studies

21st of june, 2021

RD50 - Acceptor removal project

Dedicated defect and material characterization experiment

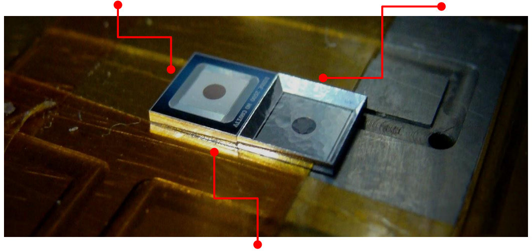
- pursue the “acceptor removal project” to understand defect kinetics mechanisms;
- measure the ratio of point to cluster defects for various particle irradiations;
- compare microscopic defect formation to macroscopic effects on silicon sensors

EP-DT-DD
Detector Technologies
Detector Development

Universität Hamburg
DER FORSCHUNG | DER LEHRE | DER BILDUNG

IFCA
Instituto de Física de Cantabria

BELARUSIAN STATE UNIVERSITY

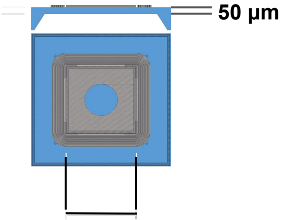


Fz
>10 000 Ω·cm
100-285 µm

Cz
100 Ω·cm
100 or 285 µm

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

CiS Forschungsinstitut für Mikrosensorik GmbH



2,6 mm

Electron irradiation

5.5 MeV BELARUSIAN STATE UNIVERSITY

200 MeV vesper clear

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**

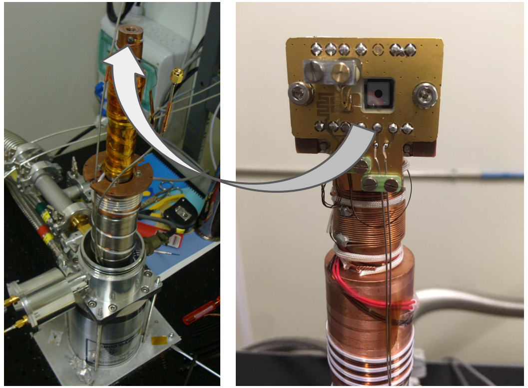
Boston General Hospital **230 MeV**

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

Microscopic Damage: N_{BiOi} / Φ_{neq}

TSC

I-DLTS



C-DLTS

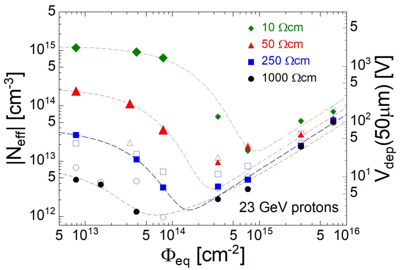
See previous talk by Anja Himmerlich

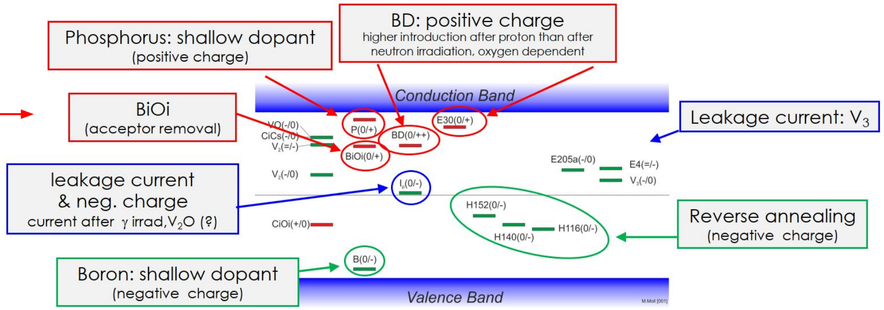
TS-Cap

See next talk by Chuan Liao

I-DLTS looks into the current transient by carrier emission in a time scale of milliseconds (TSC - seconds, different filling procedure). TSC and I-DLTS can be complementary to each other by means of defect identification. Both - current-based microscopic defect analysis methods.

Defects mapping





Phosphorus: shallow dopant
(positive charge)

BD: positive charge
higher introduction after proton than after neutron irradiation, oxygen dependent

BiOi
(acceptor removal)

Leakage current: V_3

leakage current
& neg. charge
current after γ irrad, V_2O (?)

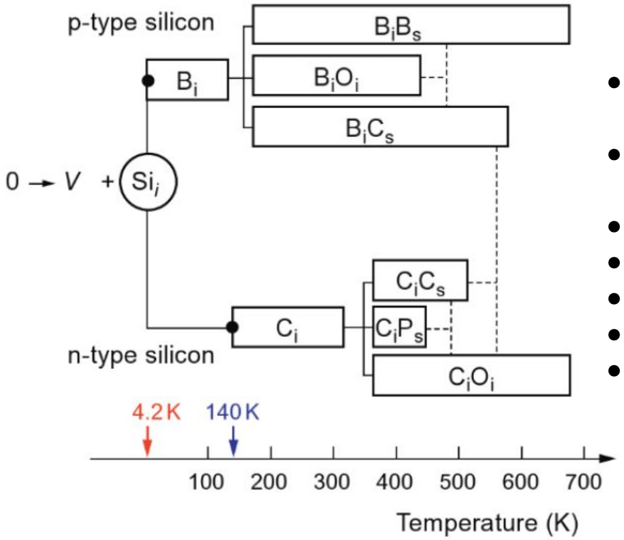
Reverse annealing
(negative charge)

Boron: shallow dopant
(negative charge)

Find the microscopic origin of the macro effects of radiation damage such as I_{leak}, trapping and doping

Defect kinetics and stability

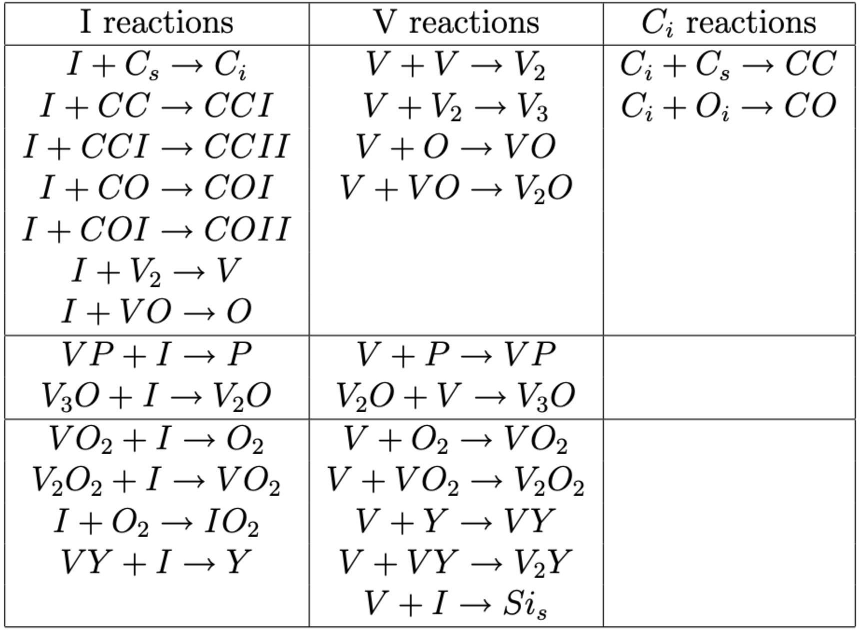
Simplification



Burdens:

- Reaction is not complete
- Not electrically active
- Several levels
- bistability
- negative-U
- PF
- T-dependent CCS

‘Reality’



I reactions	V reactions	C_i reactions
$I + C_s \rightarrow C_i$ $I + CC \rightarrow CCI$ $I + CCI \rightarrow CCII$ $I + CO \rightarrow COI$ $I + COI \rightarrow COII$ $I + V_2 \rightarrow V$ $I + VO \rightarrow O$	$V + V \rightarrow V_2$ $V + V_2 \rightarrow V_3$ $V + O \rightarrow VO$ $V + VO \rightarrow V_2O$	$C_i + C_s \rightarrow CC$ $C_i + O_i \rightarrow CO$
$VP + I \rightarrow P$ $V_3O + I \rightarrow V_2O$	$V + P \rightarrow VP$ $V_2O + V \rightarrow V_3O$	
$VO_2 + I \rightarrow O_2$ $V_2O_2 + I \rightarrow VO_2$ $I + O_2 \rightarrow IO_2$ $VY + I \rightarrow Y$	$V + O_2 \rightarrow VO_2$ $V + VO_2 \rightarrow V_2O_2$ $V + Y \rightarrow VY$ $V + VY \rightarrow V_2Y$ $V + I \rightarrow Si_s$	

Defect kinetics according to the Davies Model [Dav87] (first part). MacEvoy extension [Mac95] (second part). Oxygen dimer extension [Kra03] (third part).

- B and C competing for interstitials
- High ρ Si: O ≫ C ≫ B leading to the production of mainly C_iO_i

Initial impurity content

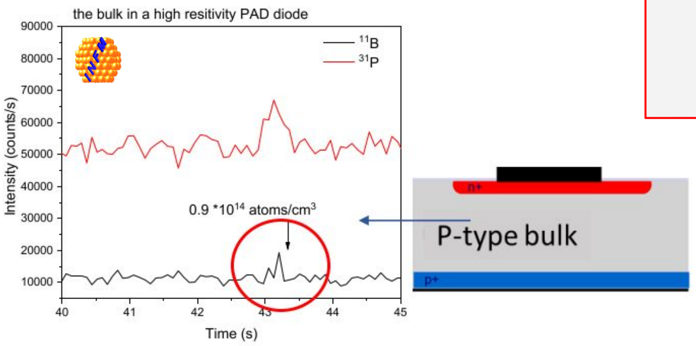
- **SR (a) and SIMS (b): ITME and ITE, Warsaw, Poland**

  $[B_s]$ content could be detected by SIMS only in EPI diodes with $\rho < 50\ \Omega \cdot \mathrm{cm}$

  Similar C content in EPI and CZ material $\sim 1.3 \cdot 10^{16}\ \mathrm{cm}^{-3}$, for FZ $\sim 10^{15}\ \mathrm{cm}^{-3}$

- **LA-ICP-MS: NIMP, Bucharest-Magurele, Romania**

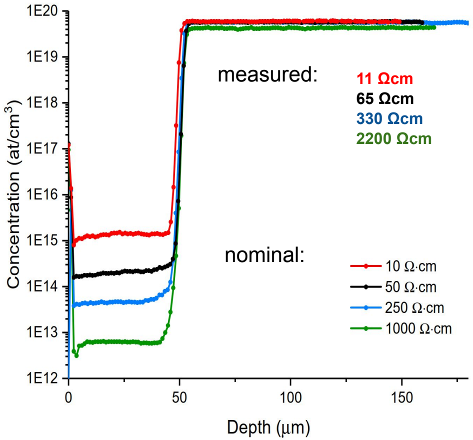
Stefan Neatu et al., 37th RD50 Workshop, 2020



Looking for new techniques and facilities...

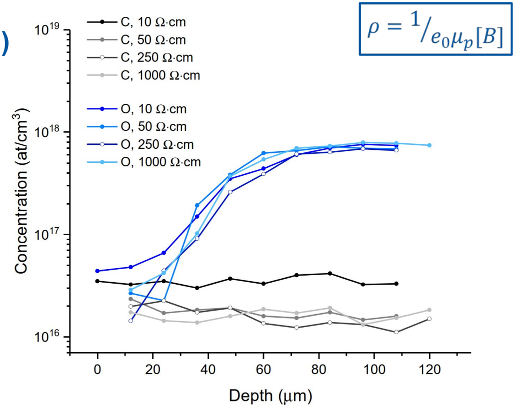
Both P and B are detected in Si bulk

a)



b)

$$\rho = {}^{1}\!/_{e_0 \mu_p [B]}$$

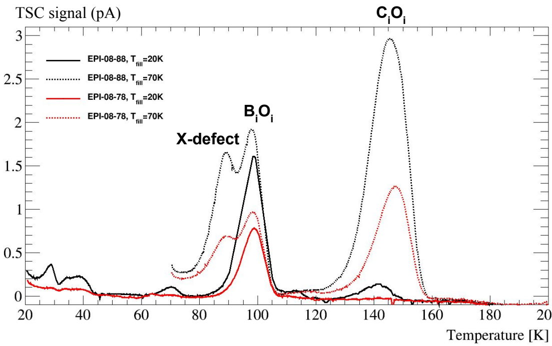


Detection limit of SIMS > $10^{14}\ \mathrm{cm}^{-3}$

TSC

Max V_{bias} 250V

TSC: U_R=-100V, I_{inj}=1mA, t_{inj}=60sec, T_{fill}=20K, 70K



2 EPI pad diodes [250Ω·cm] irradiated with electrons

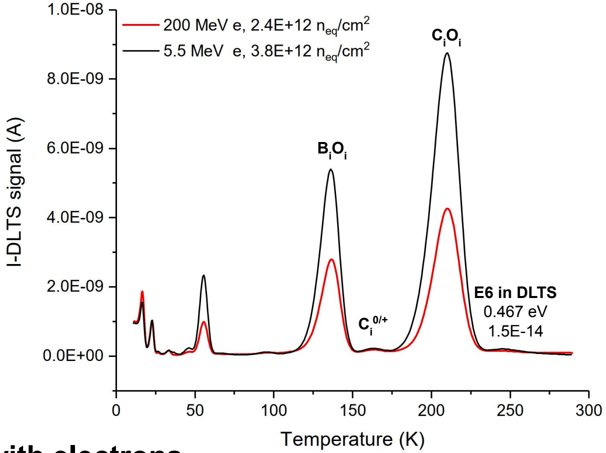
👍
- Bias voltage up to 300V;
- Presence of the shoulder (X-defect) by T_{fill} variation
- ‘Full’ concentrations

👎
- Noise
- High I_{leak} from 220K

I-DLTS

Max V_{bias} 100V

I-DLTS: U_R=-100V, U_P=+1.5V, T_w=10ms, t_p=10ms



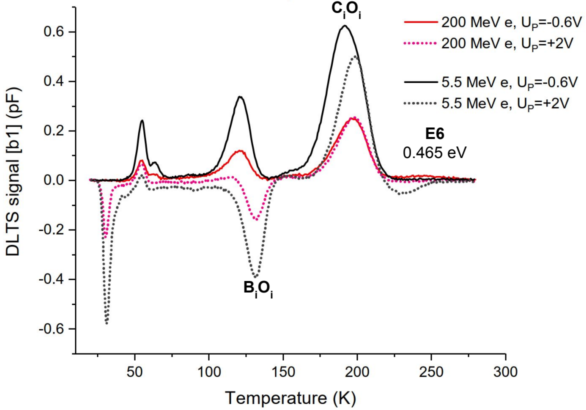
👍
- Can detect shallow defect levels - at least 11 in total;
- Arrhenius in one T-scan
- Separate type of carriers

👎
- Amplitude of transient is T-dependent

C-DLTS

1 MHz AC signal
Max V_{bias} 100V

DLTS: U_R=-10V, t_p=1 ms, T_w=20 ms

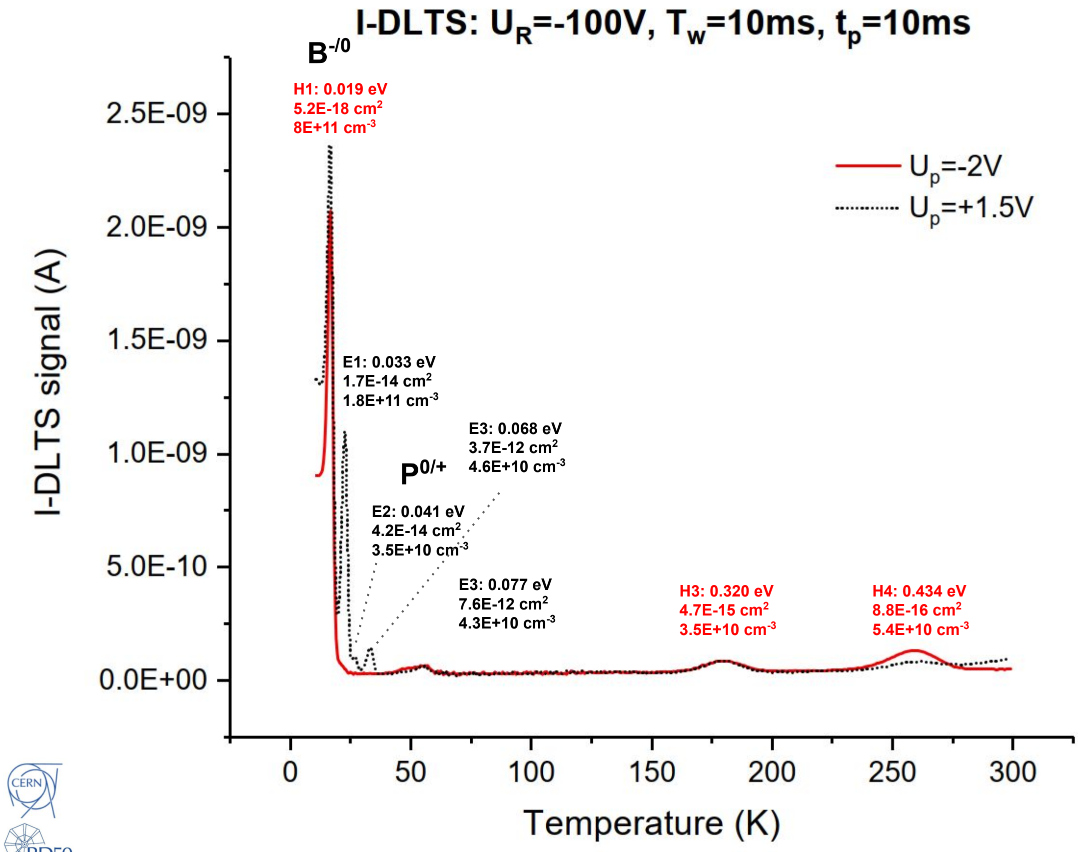


👍
- Terrific sensitivity, at least 10 defect levels in total;
- No need to fully deplete device
- Separate type of carriers

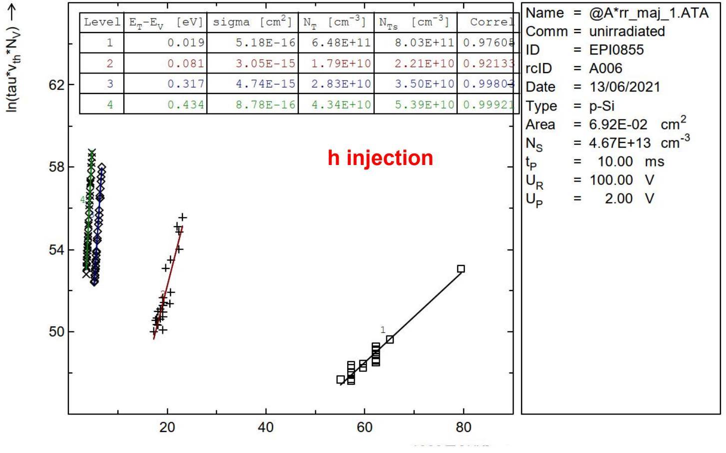
👎
- Limitation: $N_T \ll N_S$
- Carrier freeze-out

I-DLTS on <u>unirradiated</u> 250 Ω·cm EPI pad diode

$$\ln(\tau_e v_{th,n,p} N_{C,V}) = -\ln(\boxed{\sigma_{n,p}}) + \frac{\boxed{E_a}}{k_B T}$$

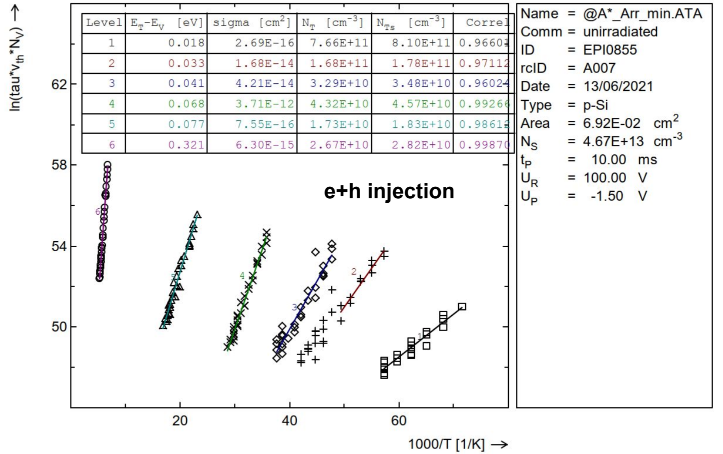


I-DLTS: U_R=-100V, T_w=10ms, t_p=10ms



Level	E_T-E_V [eV]	sigma [cm^2]	N_T [cm^{-3}]	N_{Ts} [cm^{-3}]	Correl
1	0.019	5.18E-16	6.48E+11	8.03E+11	0.97605
2	0.081	3.05E-15	1.79E+10	2.21E+10	0.92133
3	0.317	4.74E-15	2.83E+10	3.50E+10	0.9980
4	0.434	8.78E-16	4.34E+10	5.39E+10	0.99921

Name = @A*rr_maj_1.ATA
Comm = unirradiated
ID = EPI0855
rcID = A006
Date = 13/06/2021
Type = p-Si
Area = 6.92E-02 cm^2
N_S = 4.67E+13 cm^{-3}
t_P = 10.00 ms
U_R = 100.00 V
U_P = 2.00 V

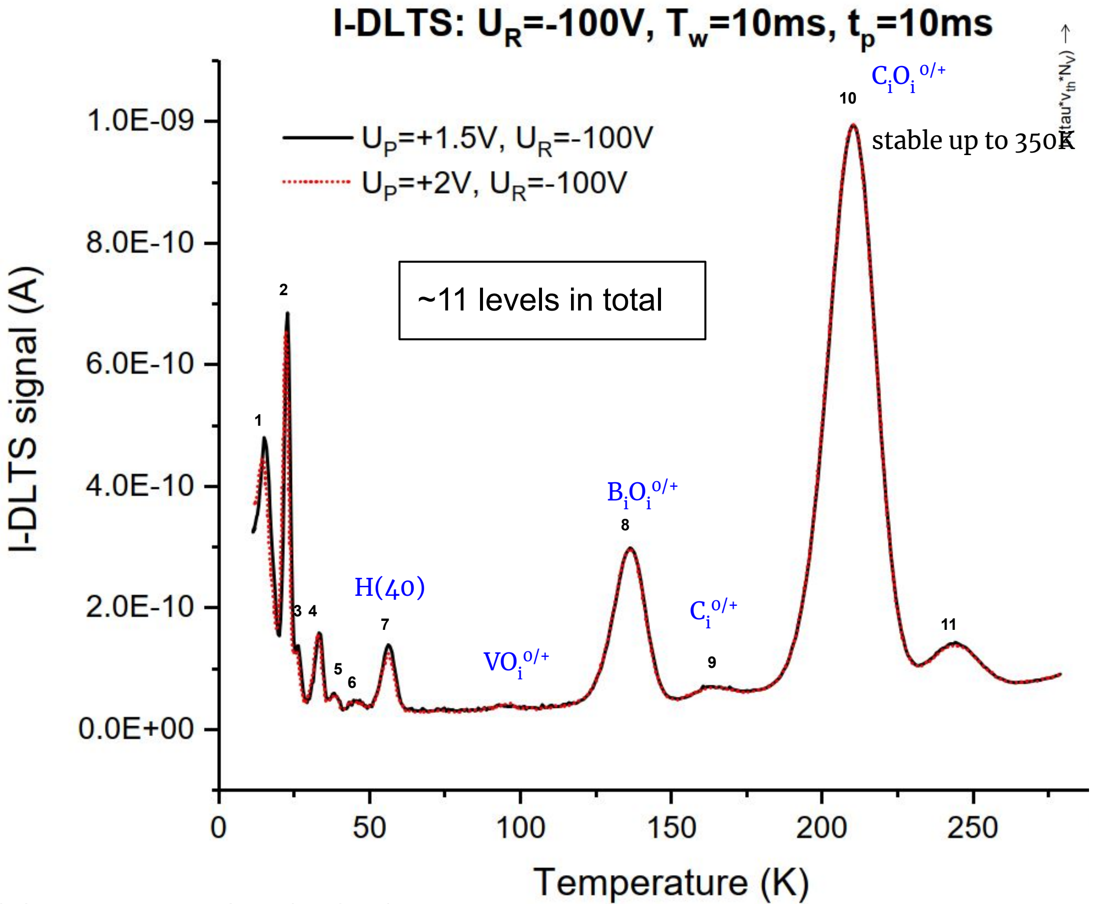


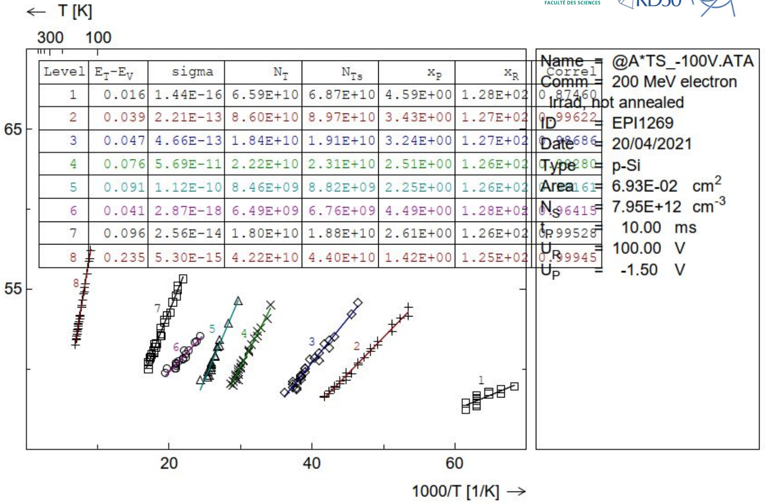
Level	E_T-E_V [eV]	sigma [cm^2]	N_T [cm^{-3}]	N_{Ts} [cm^{-3}]	Correl
1	0.018	2.69E-16	7.66E+11	8.10E+11	0.9660
2	0.033	1.68E-14	1.68E+11	1.78E+11	0.97112
3	0.041	4.21E-14	3.29E+10	3.48E+10	0.9602
4	0.068	3.71E-12	4.32E+10	4.57E+10	0.99266
5	0.077	7.55E-16	1.73E+10	1.83E+10	0.9861
6	0.321	6.30E-15	2.67E+10	2.82E+10	0.99870

Name = @A*_Arr_min.ATA
Comm = unirradiated
ID = EPI0855
rcID = A007
Date = 13/06/2021
Type = p-Si
Area = 6.92E-02 cm^2
N_S = 4.67E+13 cm^{-3}
t_P = 10.00 ms
U_R = 100.00 V
U_P = -1.50 V

If ρ~330Ω·cm we expect to have 4E+13 of B_s

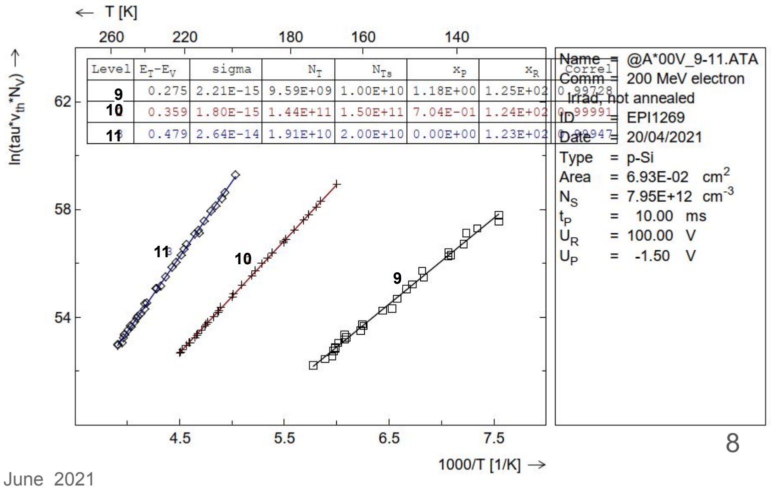
Optimal I-DLTS conditions for irradiated high-resistivity material:





Level	E_T-E_V	sigma	N_T	N_{Ts}	x_P	x_R	Correl
1	0.016	1.44E-16	6.59E+10	6.87E+10	4.59E+00	1.28E+02	0.87460
2	0.039	2.21E-13	8.60E+10	8.97E+10	3.43E+00	1.27E+02	0.99622
3	0.047	4.66E-13	1.84E+10	1.91E+10	3.24E+00	1.27E+02	0.98686
4	0.076	5.69E-11	2.22E+10	2.31E+10	2.51E+00	1.26E+02	[illegible]280
5	0.091	1.12E-10	8.46E+09	8.82E+09	2.25E+00	1.26E+02	[illegible]161
6	0.041	2.87E-18	6.49E+09	6.76E+09	4.49E+00	1.28E+02	0.96415
7	0.096	2.56E-14	1.80E+10	1.88E+10	2.61E+00	1.26E+02	0.99528
8	0.235	5.30E-15	4.22E+10	4.40E+10	1.42E+00	1.25E+02	0.99945

Name = @A*TS_-100V.ATA
Comm = 200 MeV electron
Irrad, not annealed
ID = EPI1269
Date = 20/04/2021
Type = p-Si
Area = 6.93E-02 cm^2
N_S = 7.95E+12 cm^{-3}
t_P = 10.00 ms
U_R = 100.00 V
U_P = -1.50 V



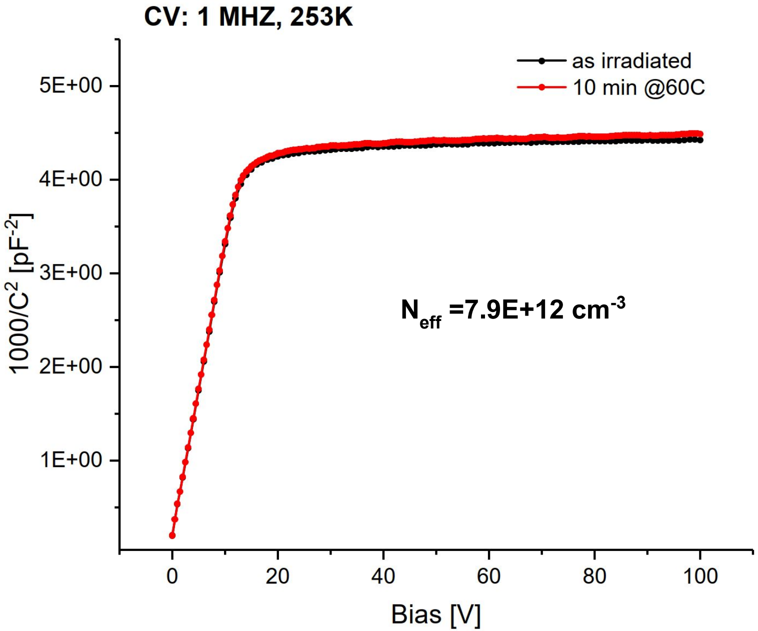
Level	E_T-E_V	sigma	N_T	N_{Ts}	x_P	x_R	Correl
9	0.275	2.21E-15	9.59E+09	1.00E+10	1.18E+00	1.25E+02	0.99728
10	0.359	1.80E-15	1.44E+11	1.50E+11	7.04E-01	1.24E+02	0.99991
11	0.479	2.64E-14	1.91E+10	2.00E+10	0.00E+00	1.23E+02	0.99947

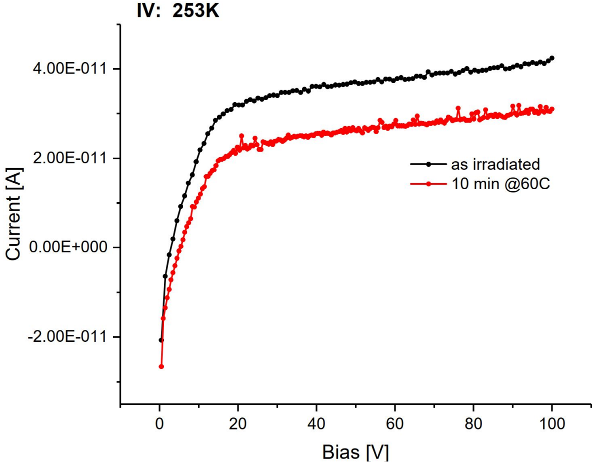
Name = @A*00V_9-11.ATA
Comm = 200 MeV electron
Irrad, not annealed
ID = EPI1269
Date = 20/04/2021
Type = p-Si
Area = 6.93E-02 cm^2
N_S = 7.95E+12 cm^{-3}
t_P = 10.00 ms
U_R = 100.00 V
U_P = -1.50 V

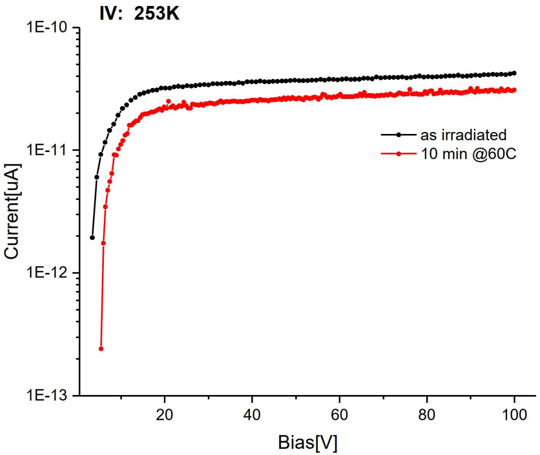
CIS16-EPI-12-50-DS-69 (1 kΩcm)
-- 200 MeV electrons, 1.2E+12 n_{eq}/cm^2

CIS16-EPI-12-50-DS-69 (1 kΩcm)
-- 200 MeV electrons, 1.2E+12 n_{eq}/cm^2

Annealing behaviour of macroscopic properties



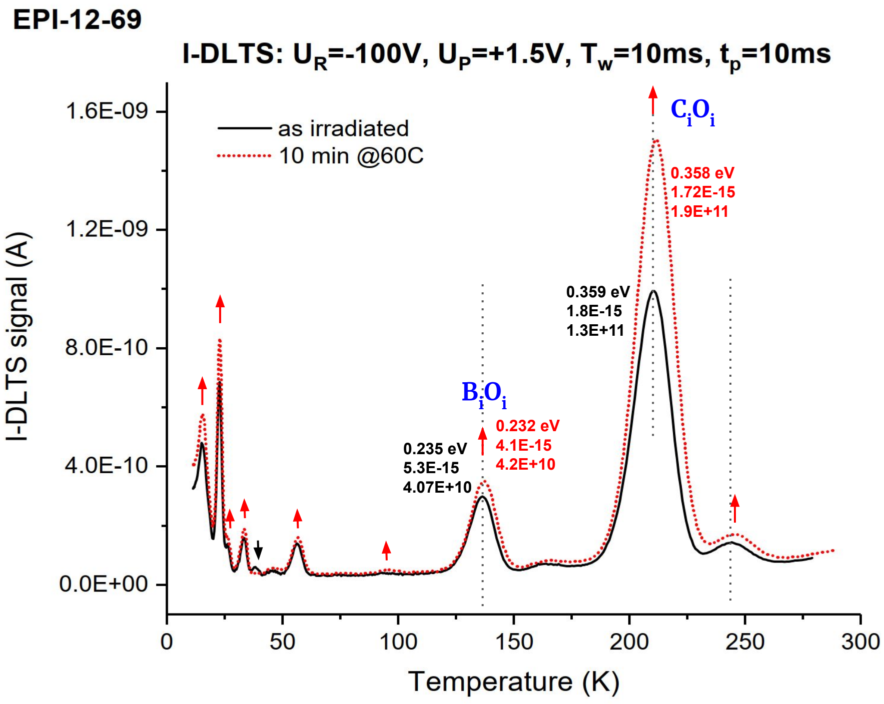




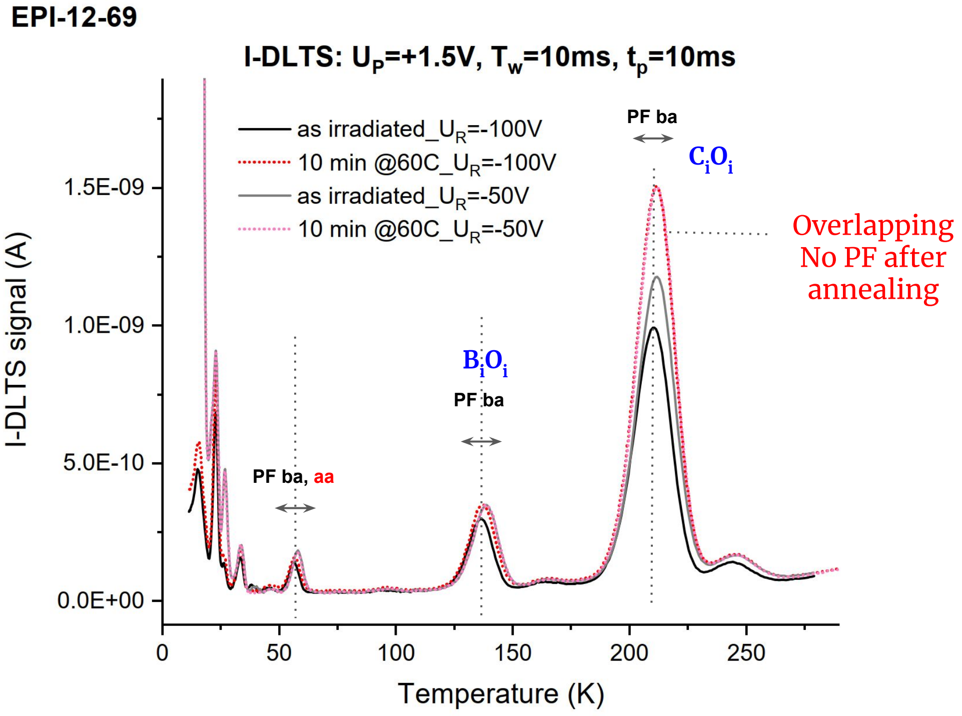
1^{st} annealing step (10 min, 60°C) causes <u>no</u> change in V_{dep} (1MHz) → N_{eff} but pronounced change in I_{leak}

CIS16-EPI-12-50-DS-69 (1 kΩcm)
-- 200 MeV electrons, 1.2E+12 n_{eq}/cm^2

Annealing behaviour of I-DLTS spectra


EPI-12-69

I-DLTS: U_R=-100V, U_P=+1.5V, T_w=10ms, t_p=10ms


EPI-12-69

I-DLTS: U_P=+1.5V, T_w=10ms, t_p=10ms

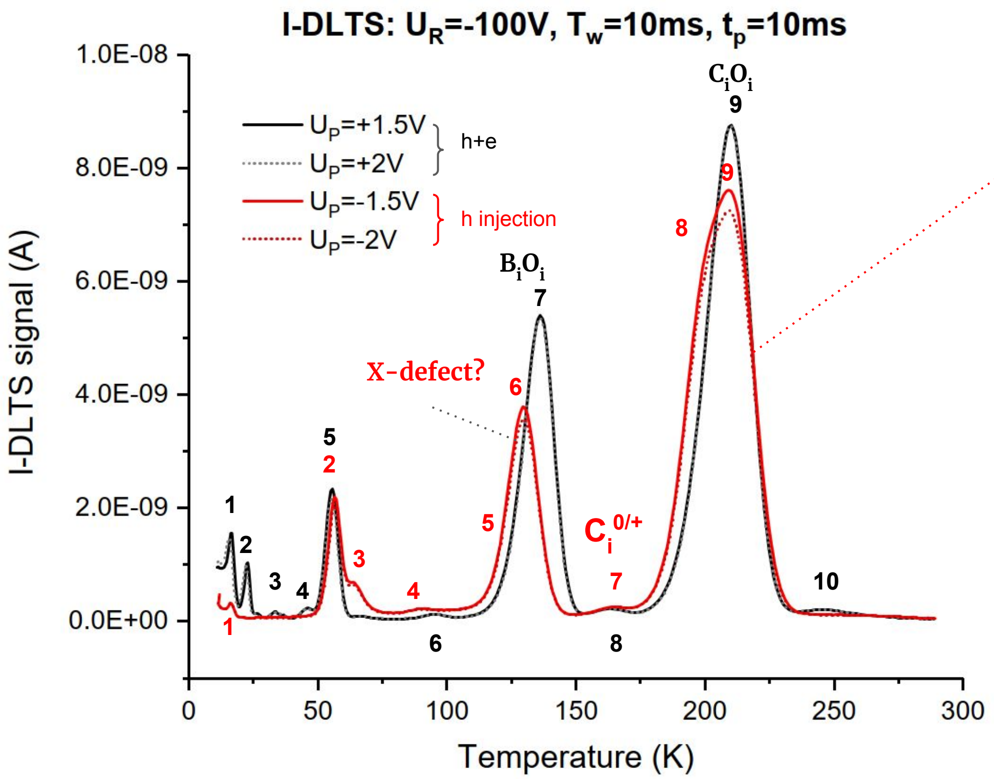
Overlapping
No PF after
annealing

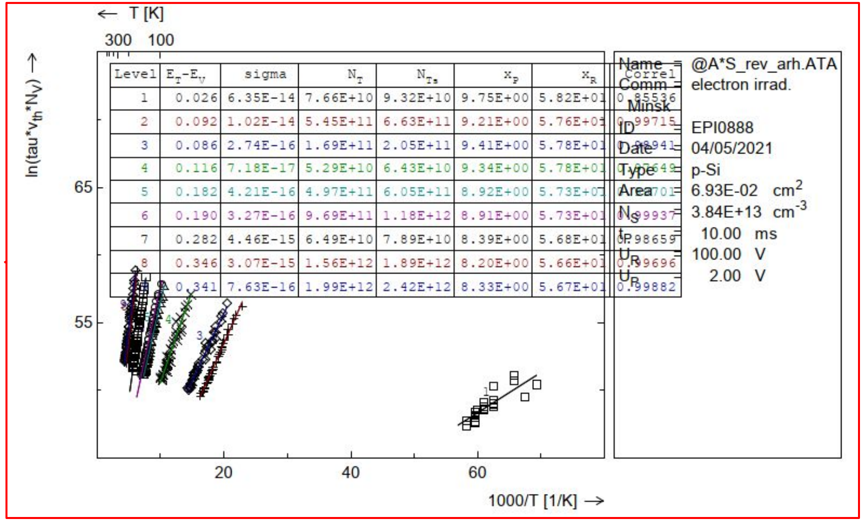
Sink for electrically inactive C ?

Seems that C_iO_i changes configuration to ‘stable’ with annealing

L.Makarenko *et al.*, JAP 123, 161576 (2018)

Injection dependence in I-DLTS spectra





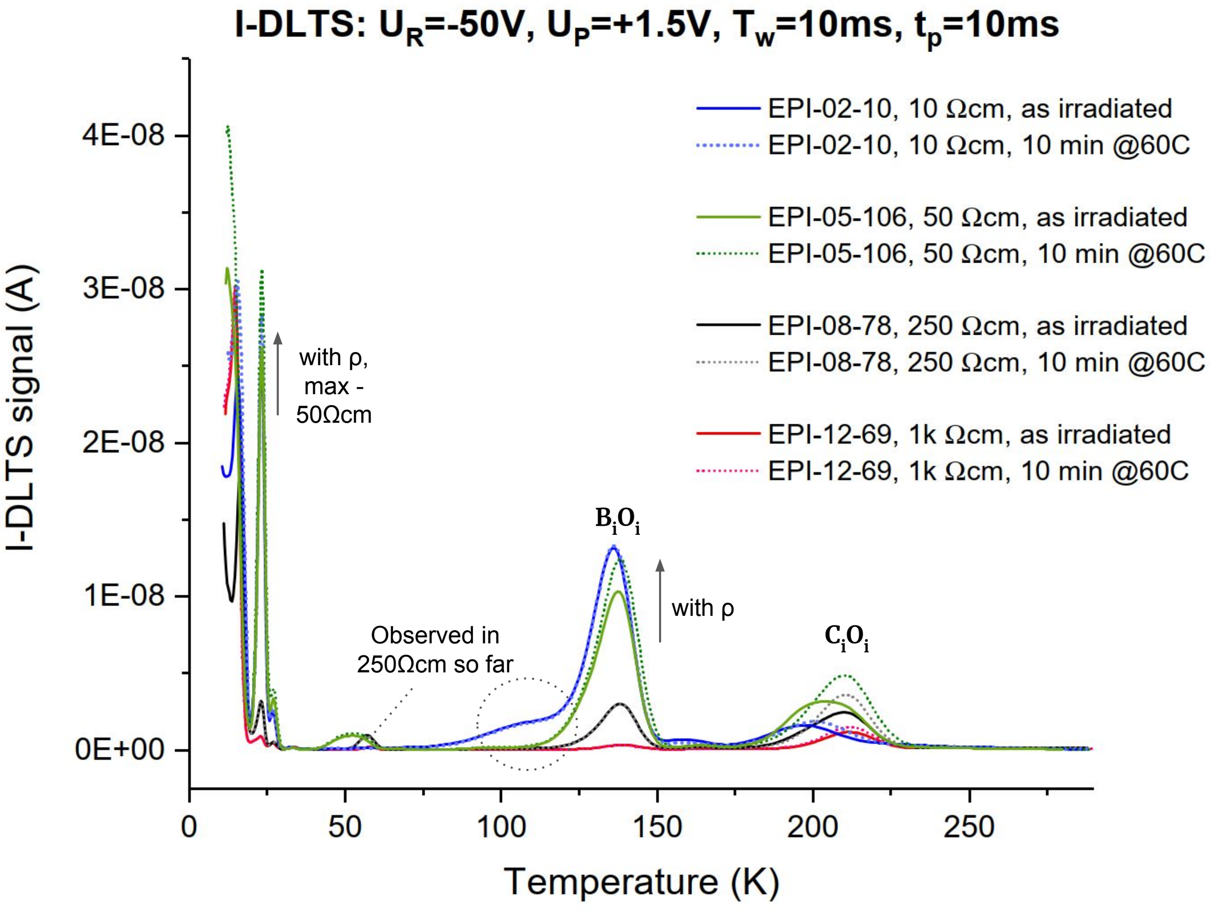
Level	E_T-E_V	sigma	N_T	N_{Ts}	x_P	x_R	Correl
1	0.026	6.35E-14	7.66E+10	9.32E+10	9.75E+00	5.82E+01	0.85536
2	0.092	1.02E-14	5.45E+11	6.63E+11	9.21E+00	5.76E+01	0.99715
3	0.086	2.74E-16	1.69E+11	2.05E+11	9.41E+00	5.78E+01	0.98941
4	0.116	7.18E-17	5.29E+10	6.43E+10	9.34E+00	5.78E+01	[illegible]
5	0.182	4.21E-16	4.97E+11	6.05E+11	8.92E+00	5.73E+01	[illegible]
6	0.190	3.27E-16	9.69E+11	1.18E+12	8.91E+00	5.73E+01	0.99937
7	0.282	4.46E-15	6.49E+10	7.89E+10	8.39E+00	5.68E+01	0.98659
8	0.346	3.07E-15	1.56E+12	1.89E+12	8.20E+00	5.66E+01	0.99696
[illegible]	0.341	7.63E-16	1.99E+12	2.42E+12	8.33E+00	5.67E+01	0.99882

Name = @A*S_rev_arh.ATA
Comm = electron irrad.
Minsk
ID = EPI0888
Date = 04/05/2021
Type = p-Si
Area = 6.93E-02 cm^2
N_S = 3.84E+13 cm^{-3}
t = 10.00 ms
U_R = 100.00 V
U_R = 2.00 V

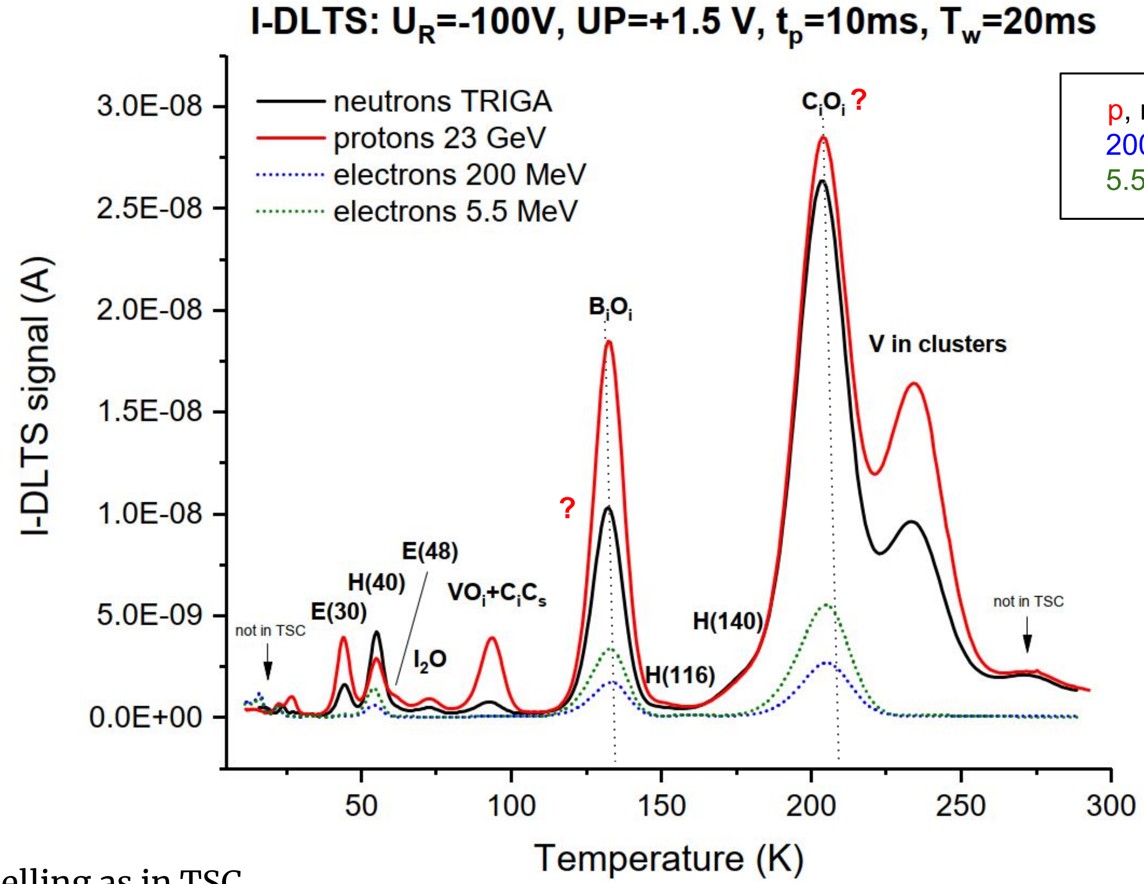
Was kept at RT, need to perform annealing to catch C_i kinetics

CIS16-EPI-08-50-DS-88 (250 Ωcm)
-- 5.5 MeV electrons, 3.8E+12 n_{eq}/cm^2

p-Si pad diodes, 200 MeV electron irradiation



250 Ωcm pad diodes – different irradiation

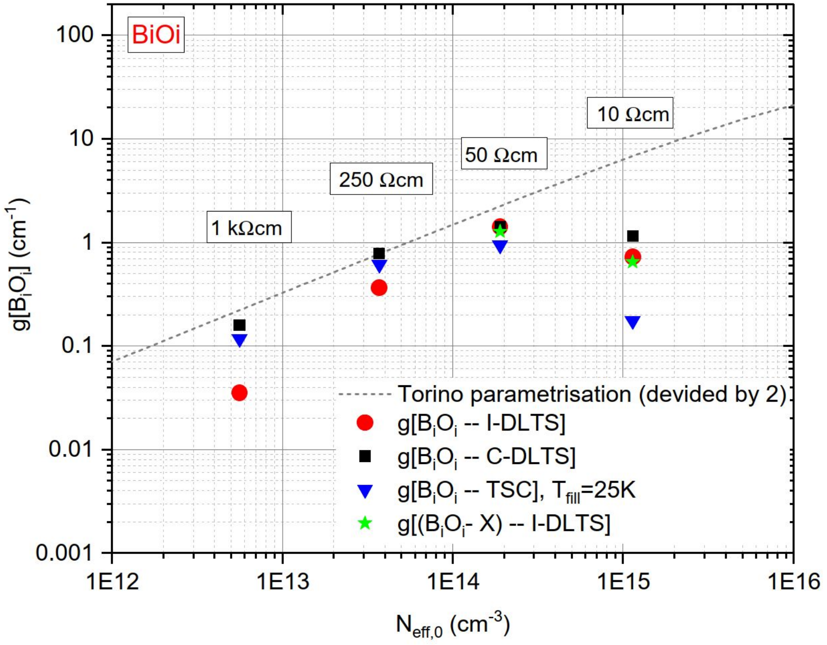


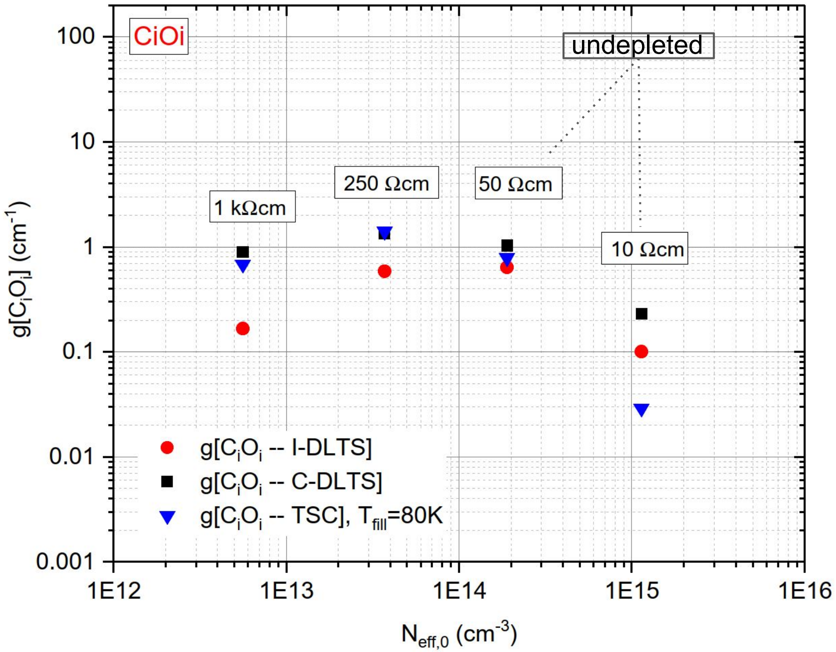
p, n	7.6E+13
200MeV e	2.4E+12
5.5MeV e	3.8E+12

If we use same labelling as in TSC

Introduction rates of 2 defects of main interest – B_iO_i and C_iO_i

200 MeV e





EPI-02-103 [11Ω · cm] : 3.9E+13 n_{eq}/cm^2
EPI-06-105 [65Ω · cm] : 7.1E+12 n_{eq}/cm^2
EPI-08-78 [330Ω · cm] : 2.4E+12 n_{eq}/cm^2
EPI-12-69 [2200Ω · cm] : 1.2E+12 n_{eq}/cm^2

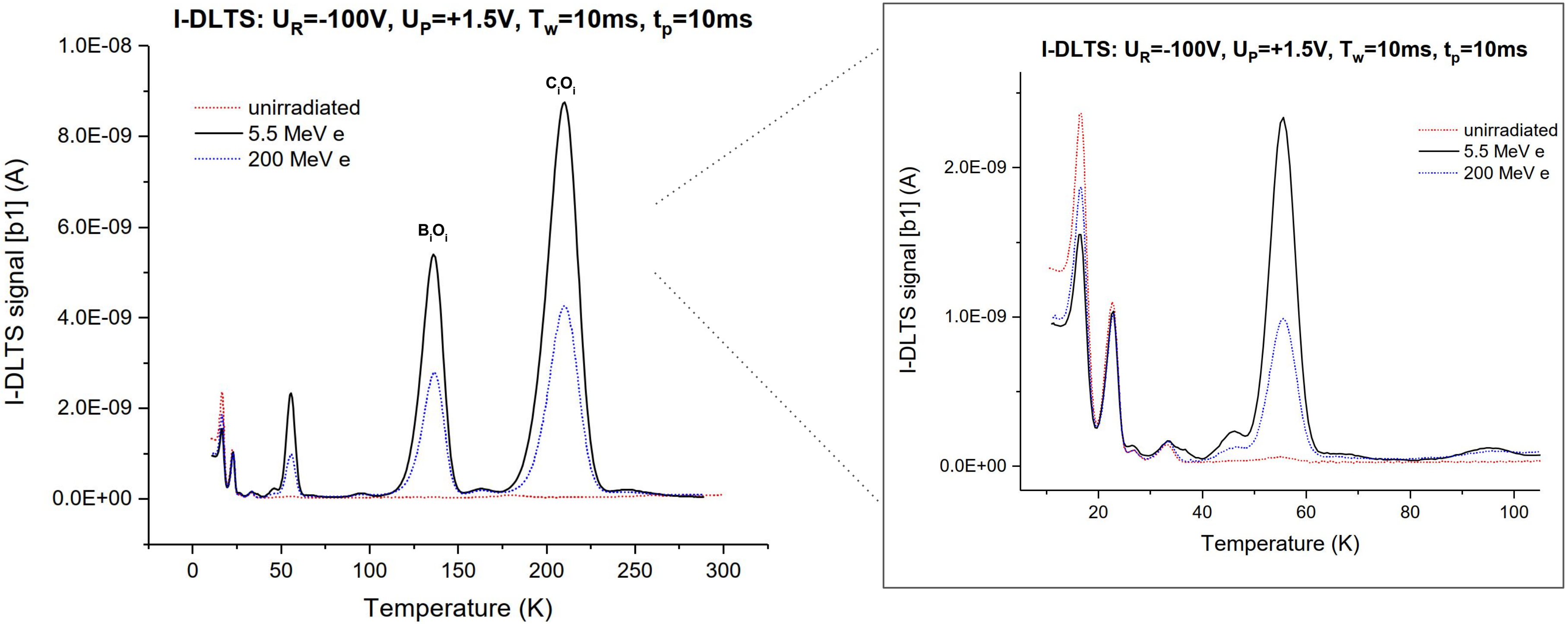
Summary

- It has been shown that I-DLTS is sensitive technique for surveying deep and shallow levels able to discover traps that have been overlooked in C-DLTS and TSC; but it has some limitations
- We shall certainly add I-DLTS to the measurements protocol especially for high resistivity devices and high fluence irradiations when C-DLTS is not possible
- Optical injection should be implemented to overcome the drawback of uncertainties in traditional voltage pulse filling with forward bias I_{fill} in both I-DLTS and TSC
- Optimal filling conditions at the saturation for defect levels with a special attention to B_iO_i, C_iO_i and X-defect are the key for a success measurements campagne

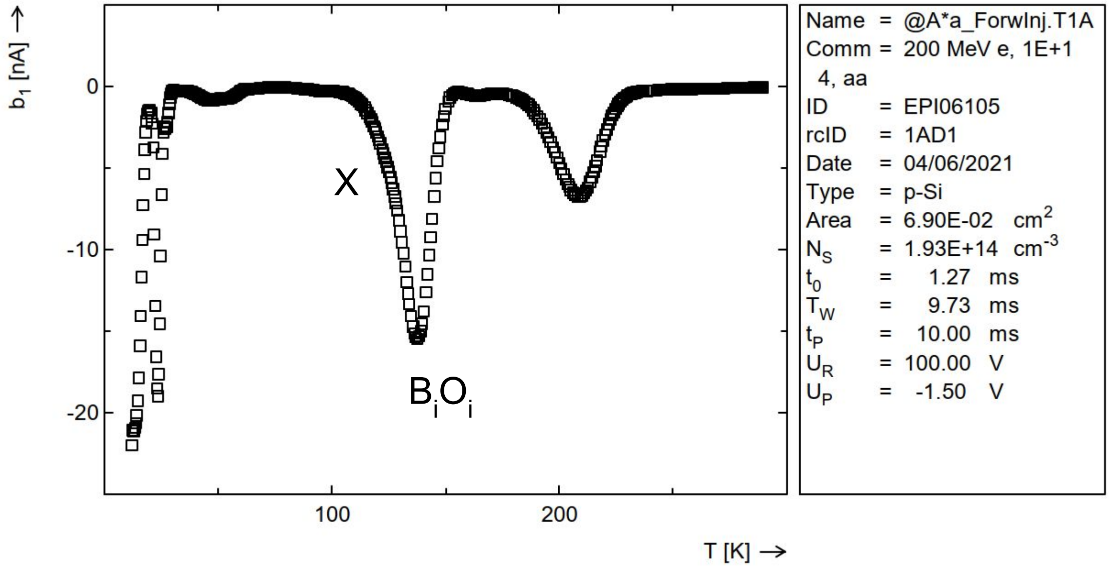
Thank you!

Spare slides

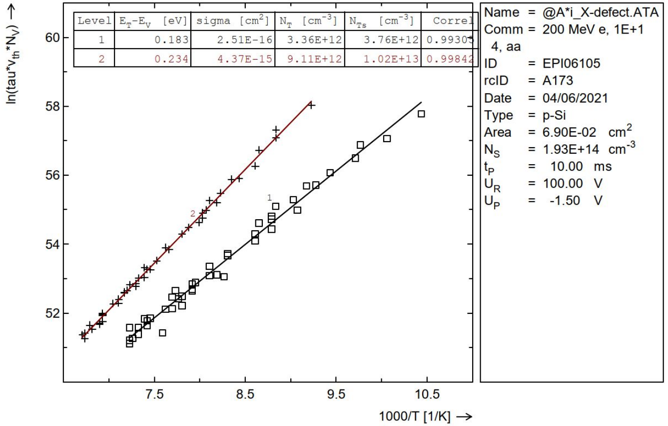
Comparison of I-DLTS for unirradiated and e-irradiated 250 ohm.cm EPI diodes



Arrhenius for X-defect and B_iO_i in 50 ohm.cm EPI diode



Name = @A*a_ForwInj.T1A
Comm = 200 MeV e, 1E+1
4, aa
ID = EPI06105
rcID = 1AD1
Date = 04/06/2021
Type = p-Si
Area = 6.90E-02 cm^2
N_S = 1.93E+14 cm^{-3}
t_0 = 1.27 ms
T_W = 9.73 ms
t_P = 10.00 ms
U_R = 100.00 V
U_P = -1.50 V



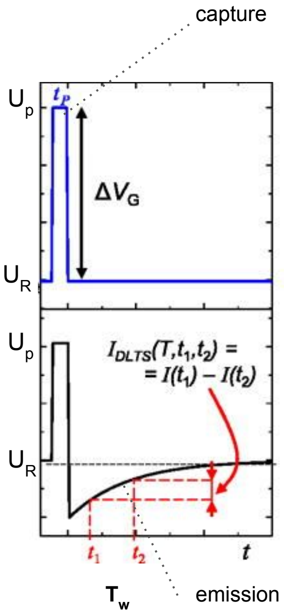
Level	E_T-E_V [eV]	sigma [cm^2]	N_T [cm^{-3}]	N_{Ts} [cm^{-3}]	Correl
1	0.183	2.51E-16	3.36E+12	3.76E+12	0.99305
2	0.234	4.37E-15	9.11E+12	1.02E+13	0.99842

Name = @A*i_X-defect.ATA
Comm = 200 MeV e, 1E+1
4, aa
ID = EPI06105
rcID = A173
Date = 04/06/2021
Type = p-Si
Area = 6.90E-02 cm^2
N_S = 1.93E+14 cm^{-3}
t_P = 10.00 ms
U_R = 100.00 V
U_P = -1.50 V

- **I-DLTS spectrum** is obtained from transients measured at different temperatures

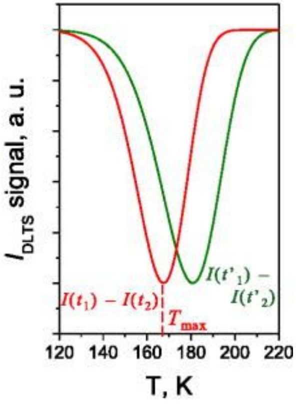
I-DLTS

Correlator functions → Arrhenius



sampling time constant

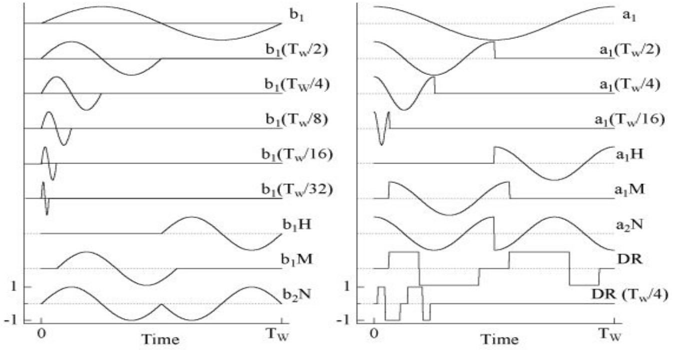
$$\tau_e(T_{max}) = \frac{t_2 - t_1}{ln\left(\frac{t_1}{t_2}\right)}$$

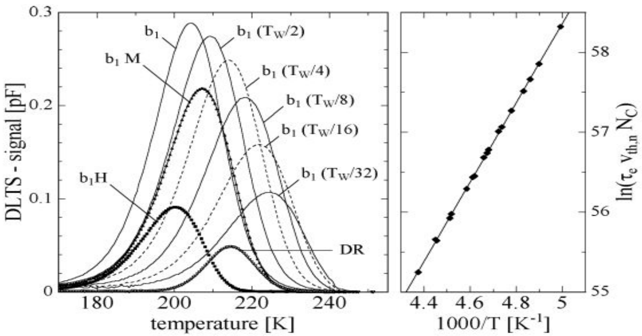


γ=dT(t)/dt=0.1 K/s

$$e_{n,p} = \frac{1}{\tau_e} = \sigma_{n,p} \cdot v_{th,n,p} \cdot N_{C,V} \cdot exp\left(-\frac{E_a}{k_B T}\right)$$

$$\boxed{I(t) - I_R = \frac{1}{2} q S w_R N_T \frac{1}{\boxed{\tau_e}} e^{-t/\boxed{\tau_e}}}$$





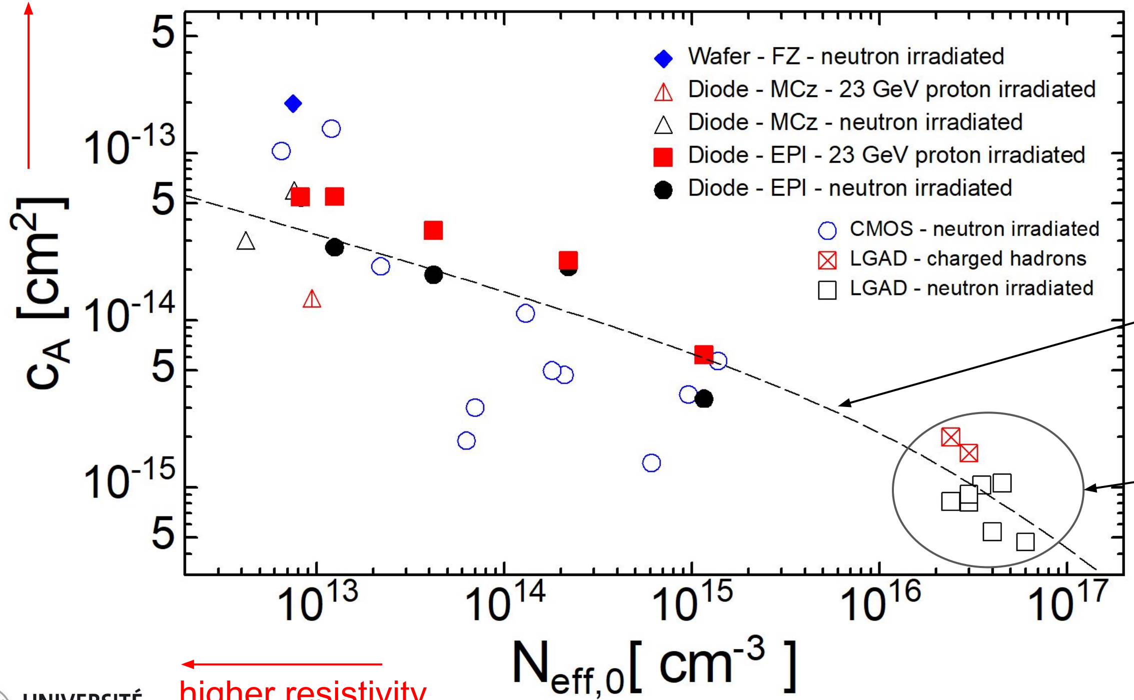
Amplitude of I-transient (trap concentration) is T-dependent, important to find good conditions (T_W, V_R, t_P)

Acceptor removal coefficient *c*

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

As reported in literature + our data (different measurements techniques used, different devices, different Si material ([C], [O], [B]) → strong scattering of the data

‘faster removal’



higher resistivity

“Torino parameterization”

M.Ferrero et al., Radiation resistant LGAD design, 2019

LGADs

Acceptor removal: reminder

- Radiation induced removal of B_s 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:

$Si_i + B_s \rightarrow B_i$

$B_i + O_i \rightarrow B_iO_i$

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

$\mathbf{I+B_s \rightarrow B_i \rightarrow B_i+O_i \rightarrow B_iO_i}$

B_i - highly reactive!

- **Si_i** are shared between **B_s** & **C_s**

Concurrent reaction channel: $I+C_s \rightarrow C_i \rightarrow C_i+O_i \rightarrow C_iO_i$

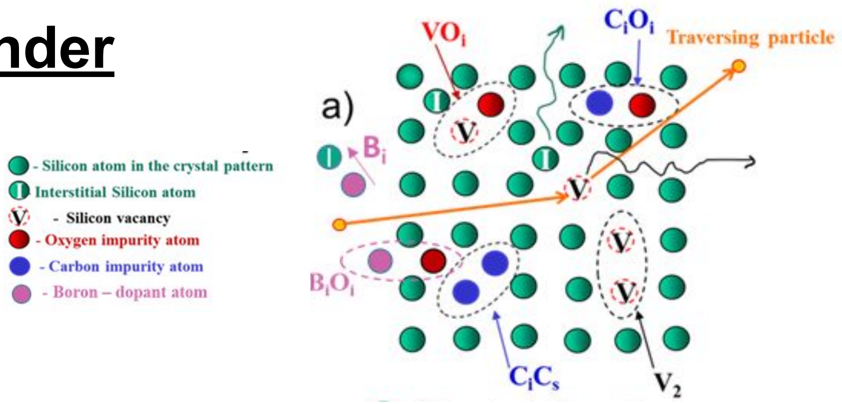
(Increasing C_s will protect B_s from removal)

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

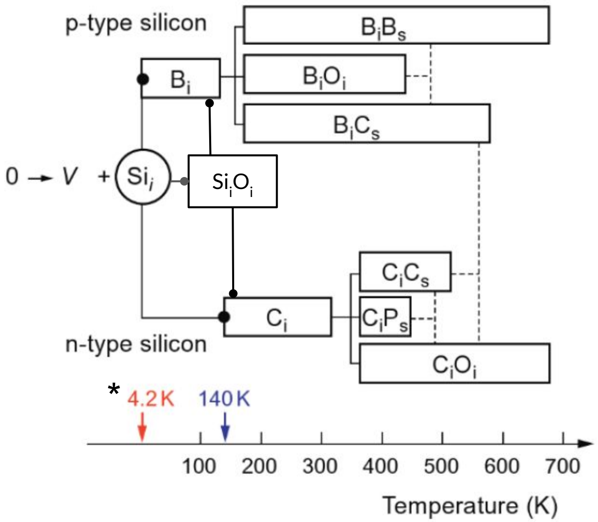
- Initial Boron removal rate (i.e. rate of BiOi formation at low fluence):

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

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



Competing reactions with Si_i involving B, C and O



*Watkins, G.D., Lattice defects in semiconductors, 1974

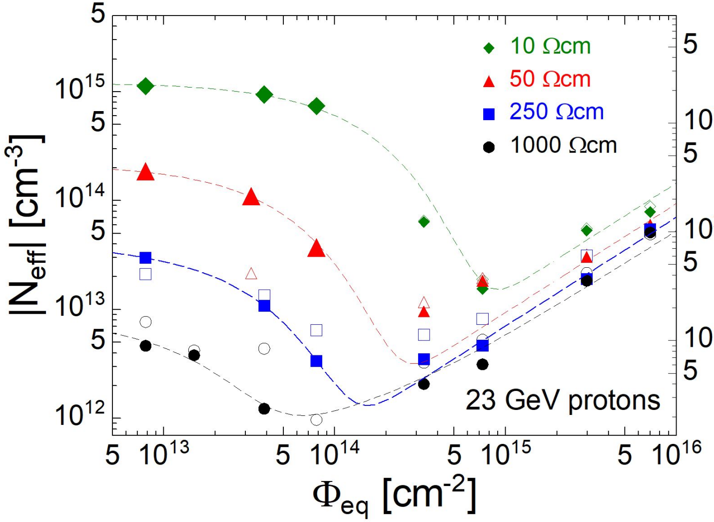
Macroscopic Damage: N_{eff}

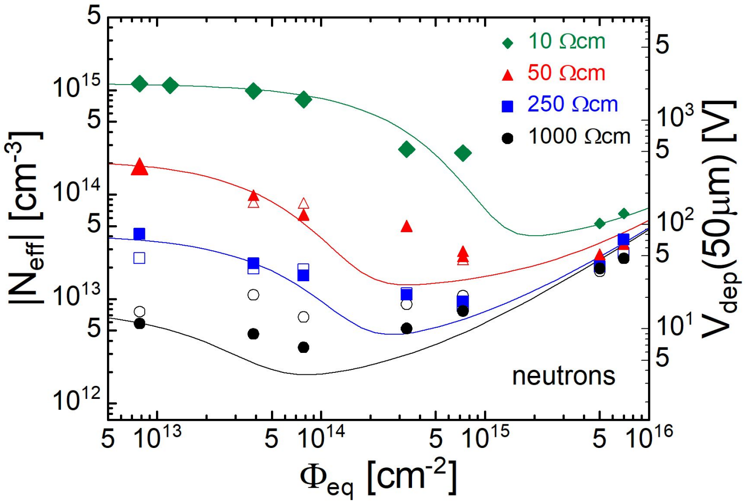
Assumptions:

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

- N_{eff}=*const* throughout the bulk

- N_{eff} extracted from CV measurements (10 kHZ, -20C)
- can be affected by errors for lower and higher irradiated sensors!





Pedro Almeida et al., 31st RD50 Workshop, 2017

M.Moll et al., Characterization of radiation induced acceptor removal in boron doped epitaxial silicon pad diodes (to be published)

- Samples initially differing by more than 2 orders of magnitude in resistivity behave very similar after very high radiation levels
- Very complex behavior after proton irradiation (“type inversion” ← TCT measurements)
- Parameterization of the data gives ***c*** - *“removal coefficient”* for each resistivity

$$N_{eff}(\Phi_{eq}) = N_{eff,0} \cdot \exp(-c\Phi_{eq}) + g_c\Phi_{eq}$$