DLTS studies on as irradiated PiN diodes of different resistivity

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Aim

Understand the acceptor removal process in Boron doped silicon and predict ways to control it:

- Detection and electrical characterization of defects induced by irradiation
- Determine the defect generation rate(s)
- Identify in which defects formation B is involved (e.g. B_iO_i defect) and evaluate the impact on the acceptor removal rate.

Investigated p-type Samples

PiN pads produced by CiS

50 µm thick P-type substrate:

- EPI, 50 ohm cm (4 samples)
- EPI, 250 ohm cm (4 samples)
- CZ, 100 ohm cm (4 samples)
- EPI, 1000 ohm cm (4 samples)
- FZ high resistivity (4 samples)

Irradiation

23 GeV protons:
(2 samples of each type, 2 fluences)

1MeV neutrons:
(2 samples of each type, 2 fluences)

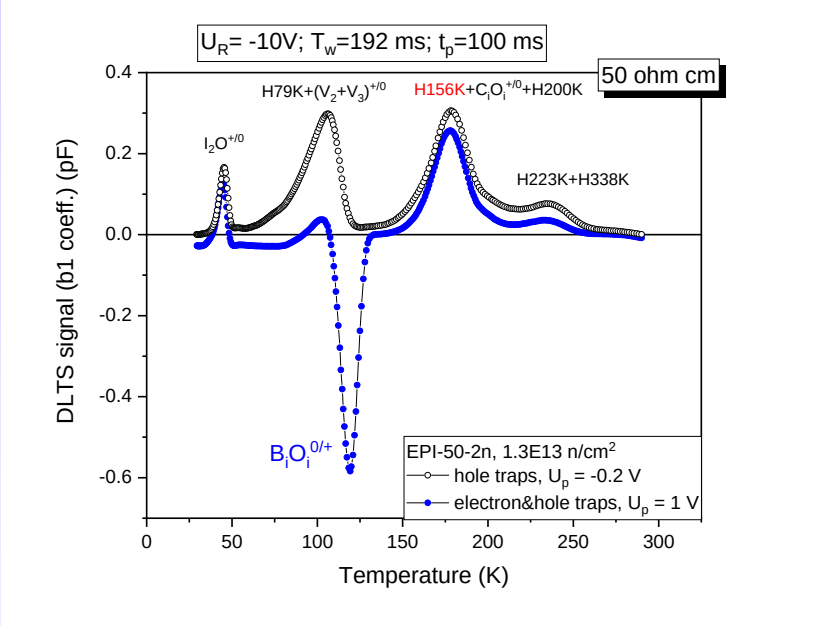
Investigated p-type, 50 µm thick, PiN Samples

Sample (identification No.)	Resistivity (ohm cm)	Irradiation	Fluence (cm^2) Φ / Φ_{eq}	N_{eff}^{293K} (cm^{-3}) (After irrad.)
EPI-50-1p (EPI-04-70)	50	23 GeV p	4E12 / **2.48E12**	2.61E14
EPI-50-1n (EPI-04-80)	50	1 MeV n	**2.4E12**	2.65E14
EPI-50-2n (EPI-04-83)	50	1MeV n	**1.3E13**	
EPI-250-1p (EPI-09-105)	250	23 GeV p	4E10 / **2.48E10**	4.95E13
EPI-250-2p (EPI-09-104)	250	23 GeV p	2E11 / **1.24E11**	4.85E13
EPI-250-1n (EPI-09-96)	250	1 MeV n	**2.4E10**	4.83E13
EPI-250-2n (EPI-09-99)	250	1 MeV n	**1.2E11**	4.57E13
EPI-1000-2p (EPI-15-95)	1000	p	4E10 / 2.**48E10**	1.05E13
EPI-1000-2n (EPI-15-92)	1000	n	**2.4E10**	1.62E13
CZ-100-1p (CZ-03-78)	100	p	2E12 / **1.24E12**	1.56E14
CZ-100-2p (CZ-03-79)	100	p	1E13 / **6.2E12**	1.41E14
CZ-100-1n (CZ-03-89)	100	n	**1.2E12**	1.65E14
CZ-100-2n (CZ-03-88)	100	n	**6E12**	1.47E14

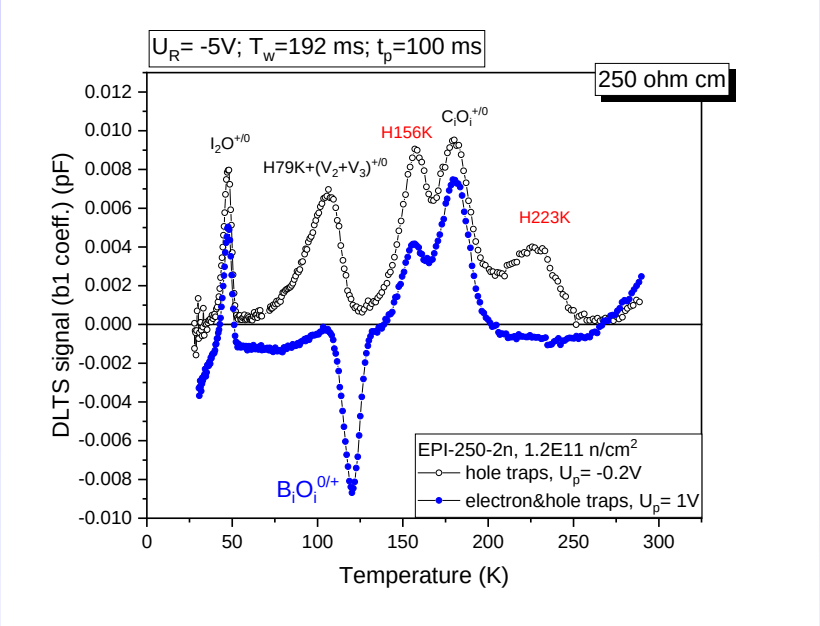
Typical DLTS spectra

EPI diodes, 50 µm thick diodes

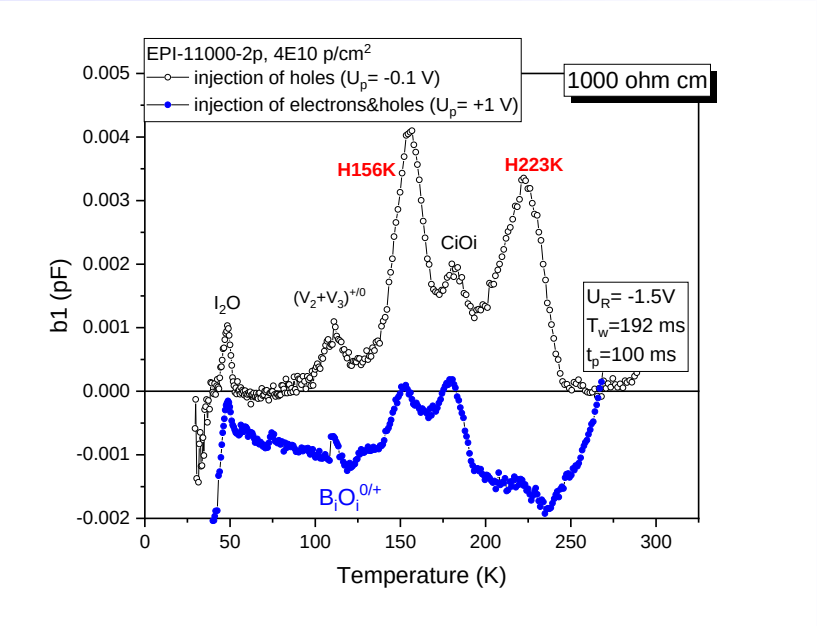
Low resistivity



Medium resistivity



High resistivity

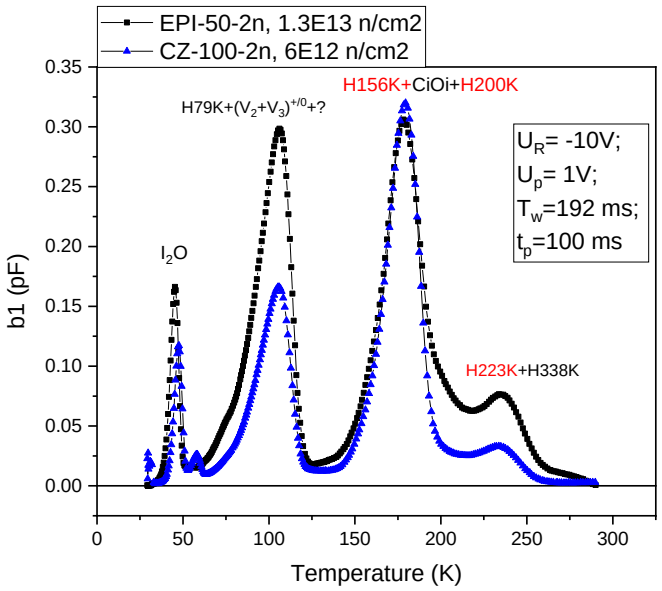


Several yet un-identified defects (traps for holes - H79K, H156K, H223K and H238K)

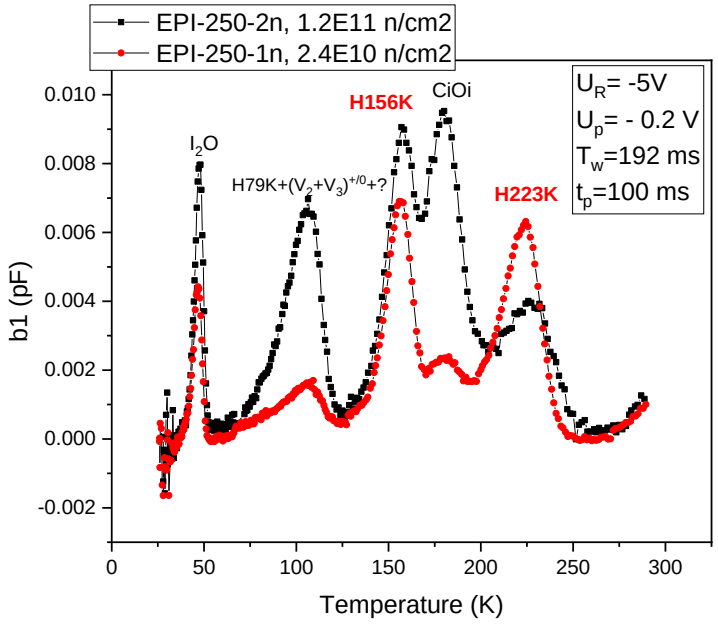
Trapping parameters

H156K and H223K – well seen in diodes of medium and high resistivity

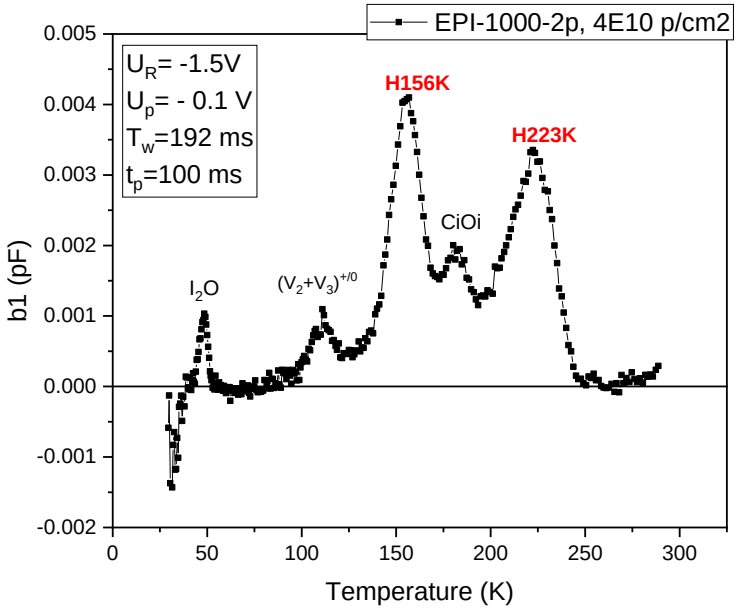
50 (EPI) and 100 ohm cm (CZ) diodes



250 ohm cm EPI diodes



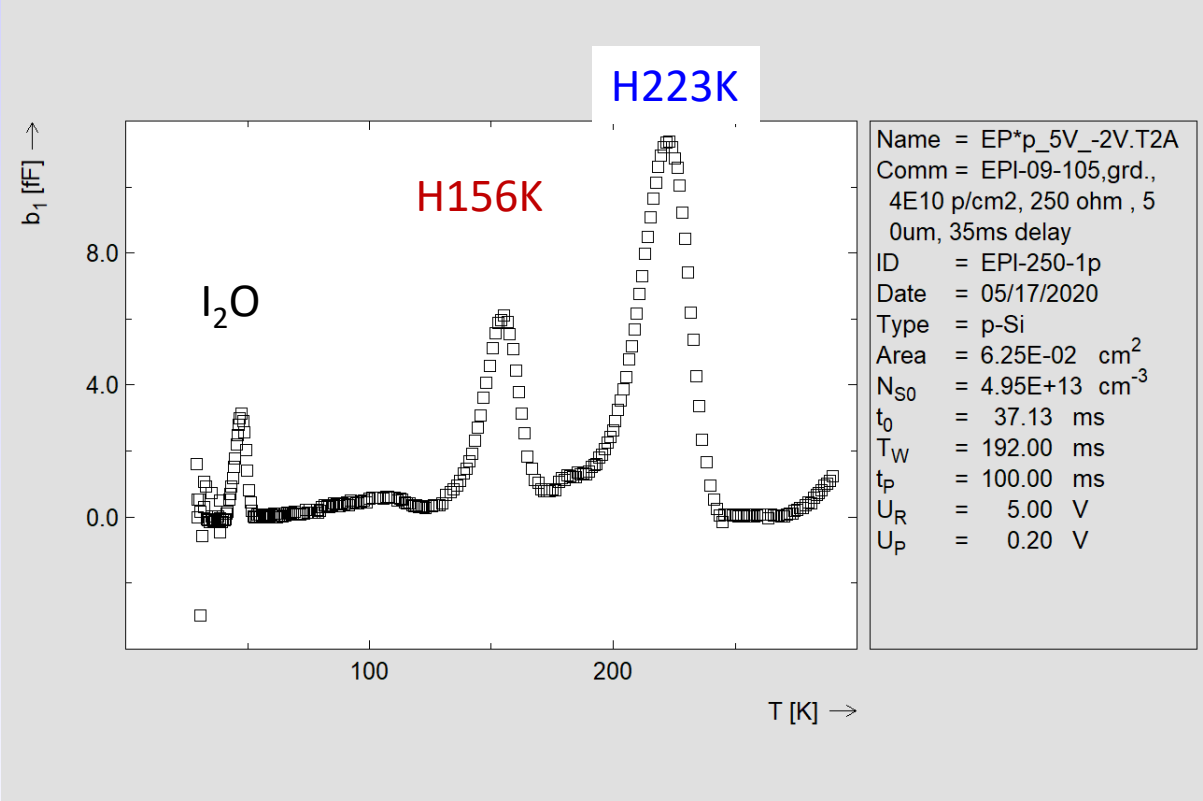
1000 ohm cm EPI diodes

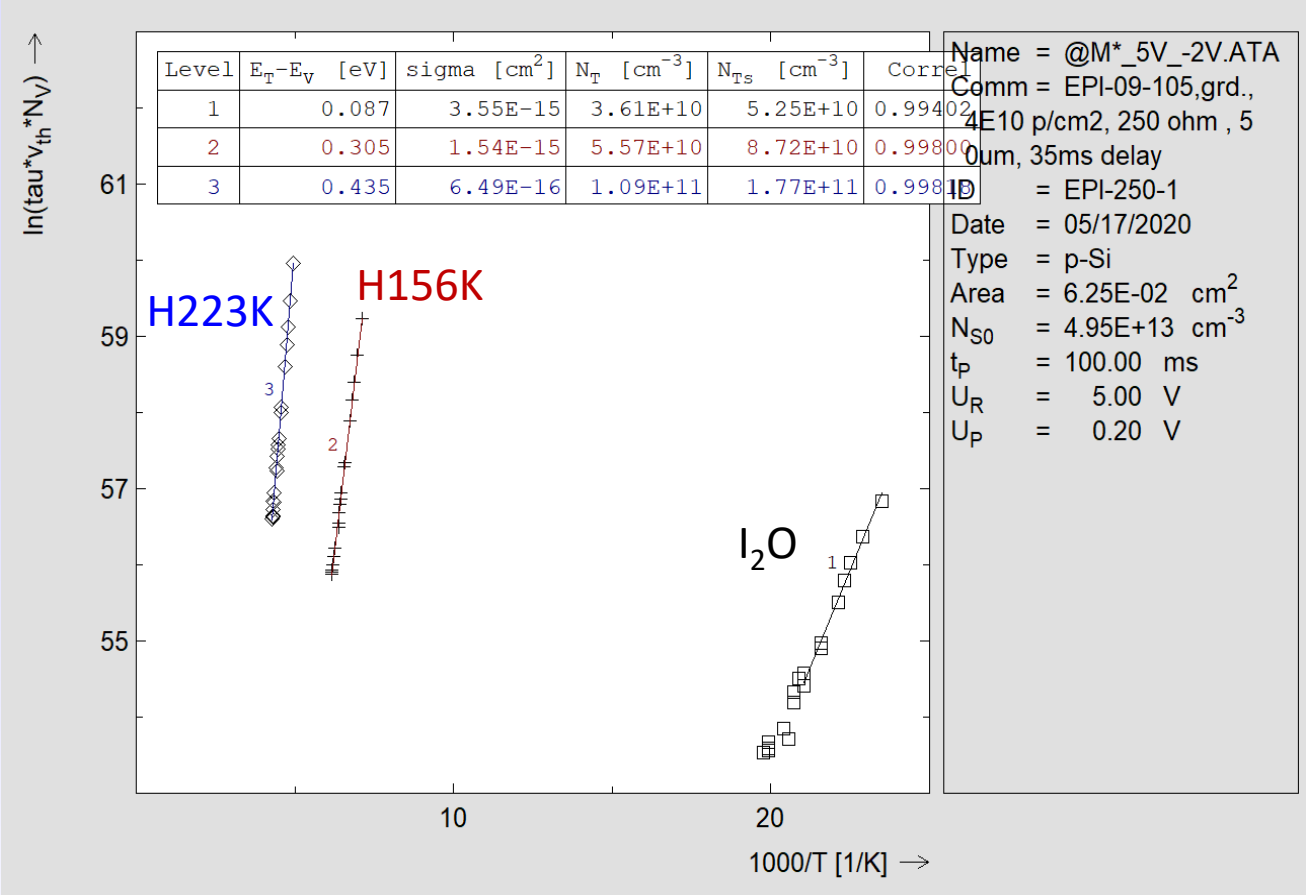


Trapping parameters

H156K and H223K – from **Arrhenius plots** (maxima analyses of DLTS spectra)

EPI-250-1p diode





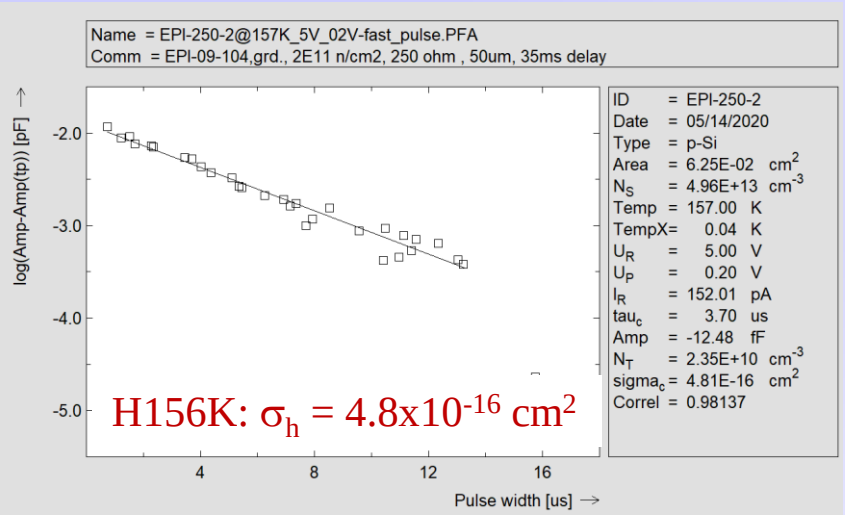
Level	E_T-E_V [eV]	sigma [cm^2]	N_T [cm^{-3}]	N_{Ts} [cm^{-3}]	Correl
1	0.087	3.55E-15	3.61E+10	5.25E+10	0.99402
2	0.305	1.54E-15	5.57E+10	8.72E+10	0.99800
3	0.435	6.49E-16	1.09E+11	1.77E+11	0.99813

H156K: E_a = Ev - 0.305 eV; σ_h = 1.5x10^{-15} cm^2

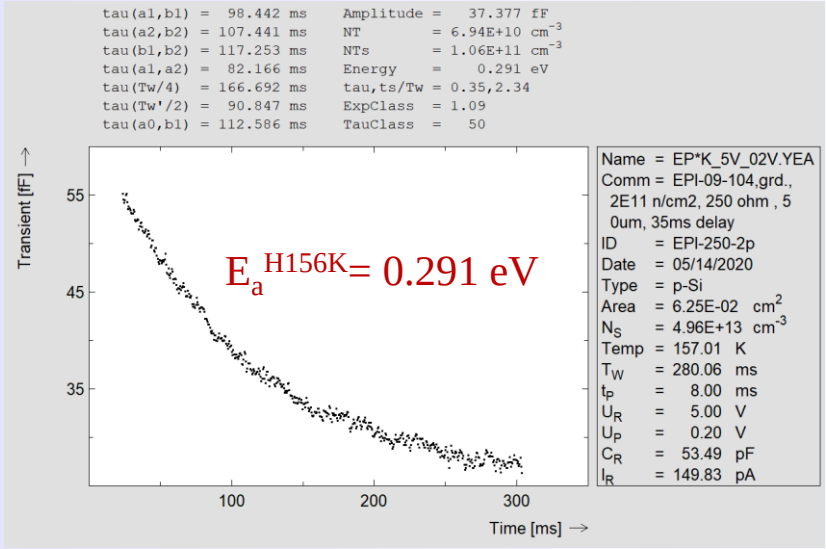
H223K: E_a = Ev - 0.435 eV; σ_h = 6.5x10^{-16} cm^2

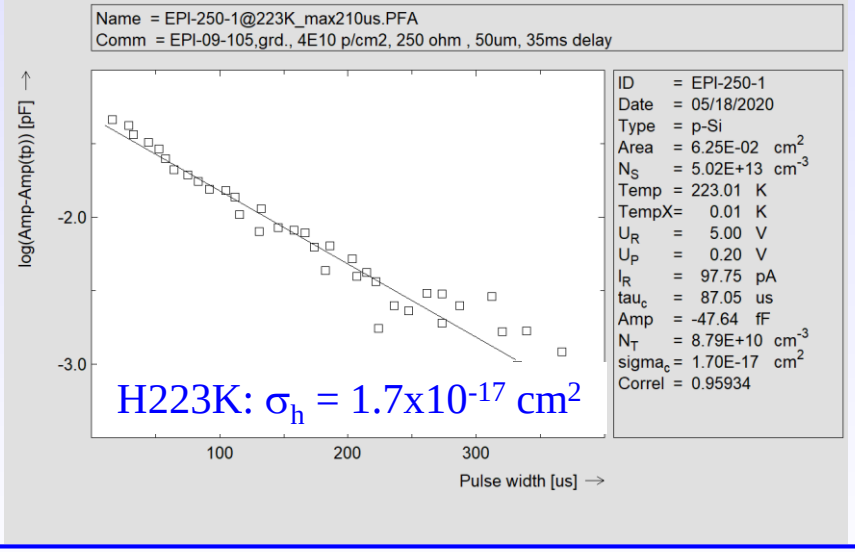
Trapping parameters

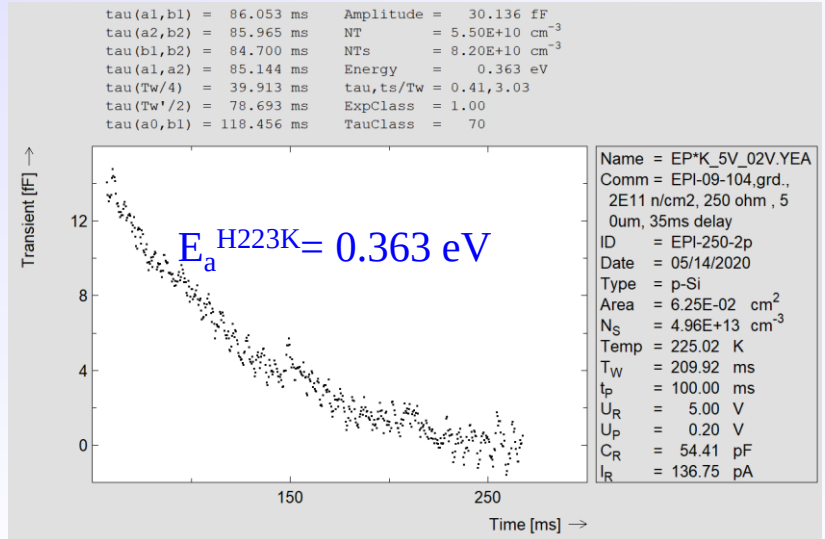
H156K and H223K – direct analyses of transients at constant temperature



EPI 250 ohm cm





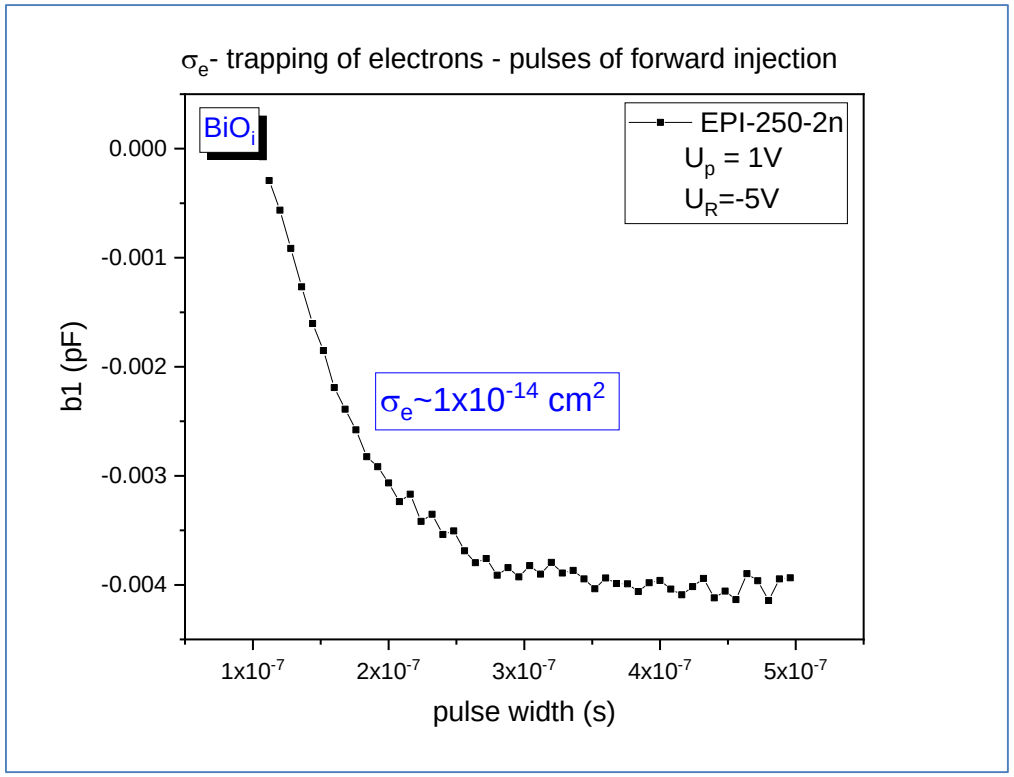


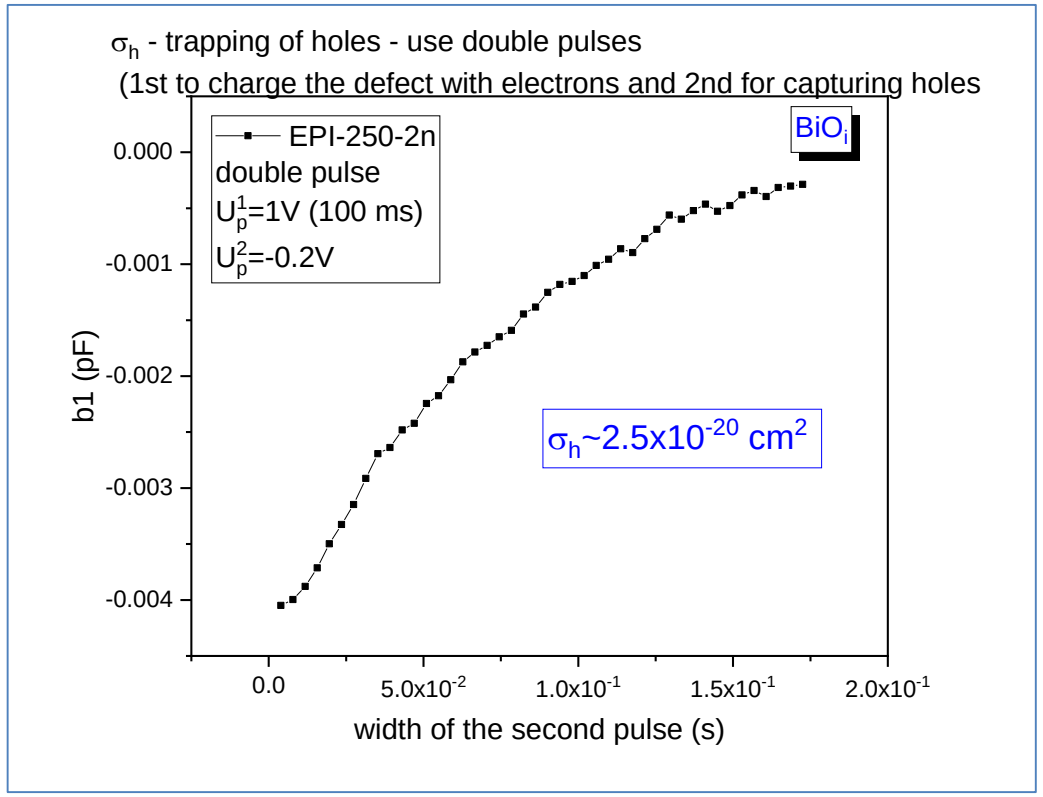
Trapping parameters

B_iO_i defect

Direct measurement of the capture cross sections (errors up to 20%)

- By measuring the amplitude of the emission transient as function of the filling pulse duration at constant temperature





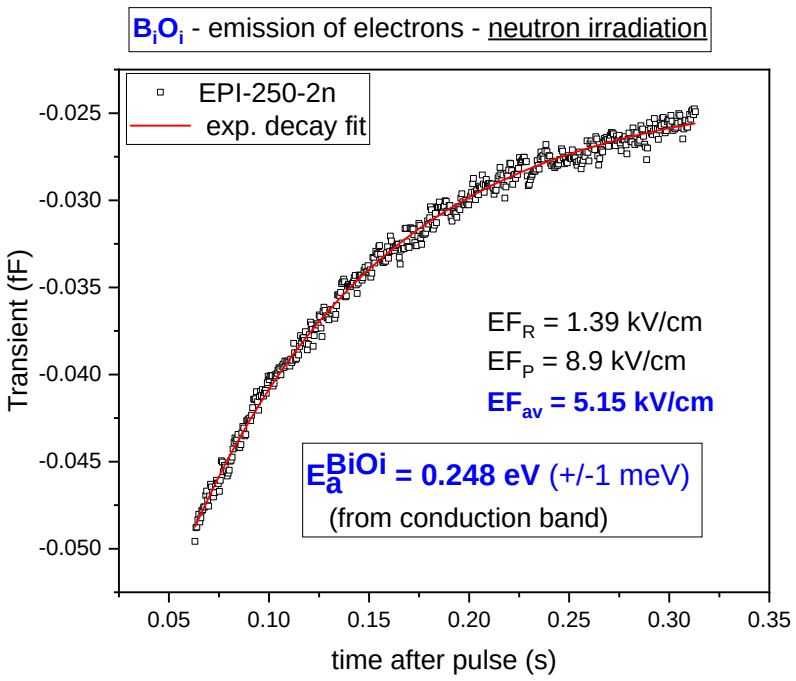
Trapping parameters

B_iO_i defect

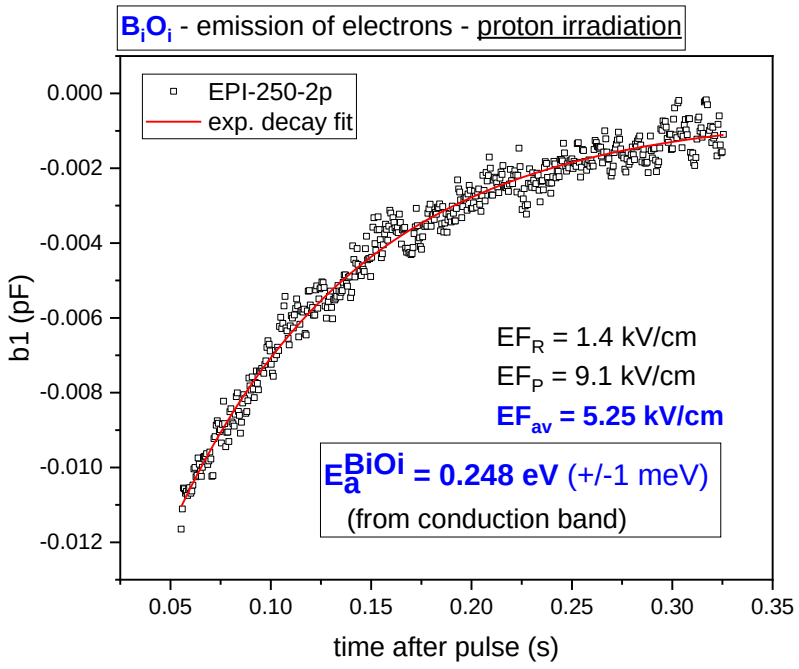
Activation energy (errors up to 5%)

– from direct analyses of transients at 120 K and exponential decay fit

(using as input the $\sigma_e=10^{-14}$ cm^2 value measured at the same temperature)



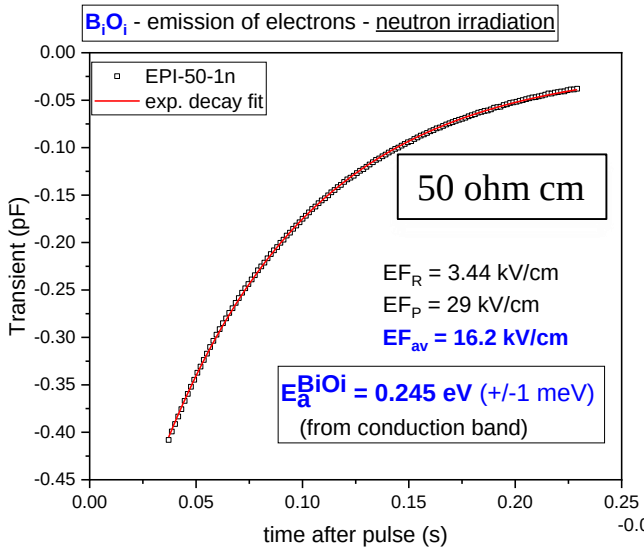
EPI – resistivity 250 ohm cm

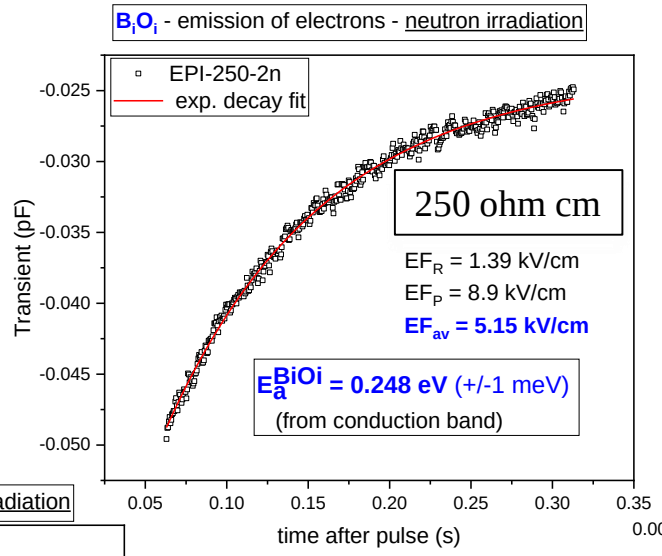


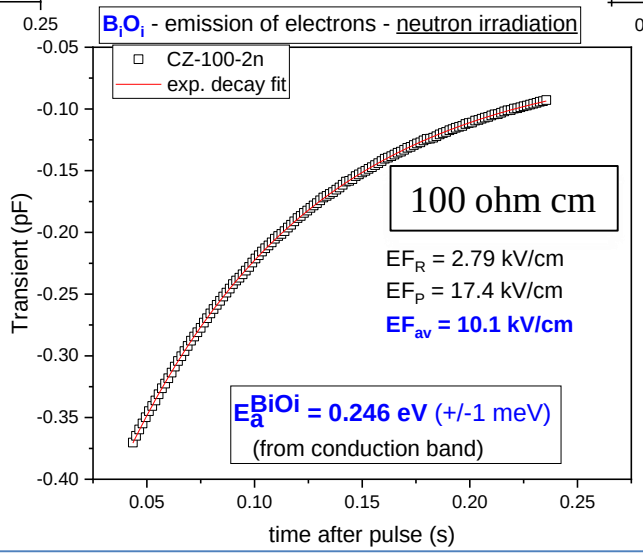
Same values for activation energy of BiOi in samples measured under similar electric fields

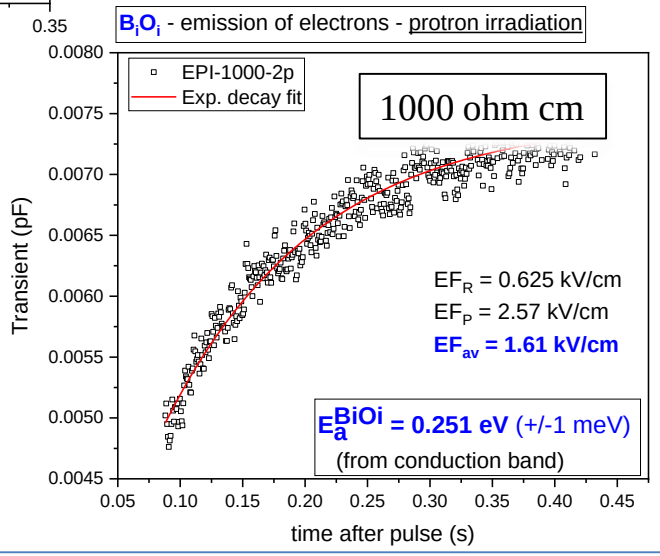
Trapping parameters

B_iO_i defect - Dependence of Ea on the electric field magnitude – Poole Frenkel effect for coulombic centers









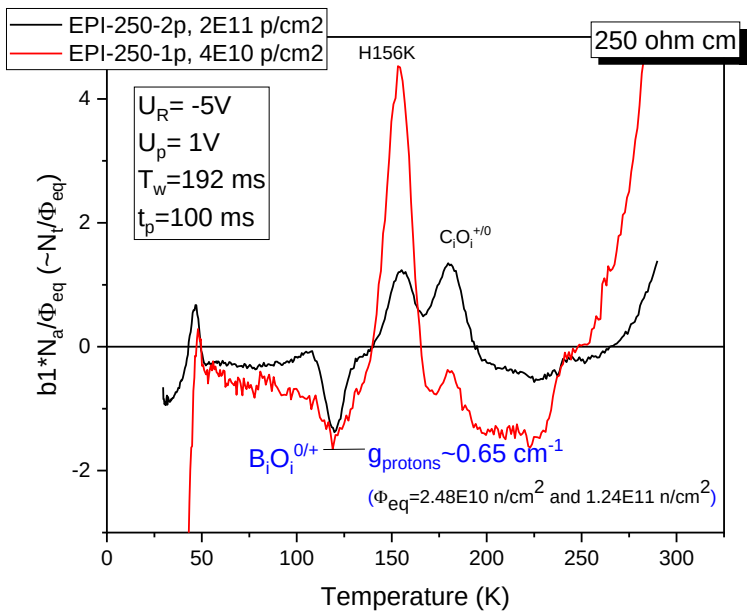
Enhanced field emission for BiOi defect – still more measurements needed for parametrizing the electric field dependence

B_iO_i generation rate(s)

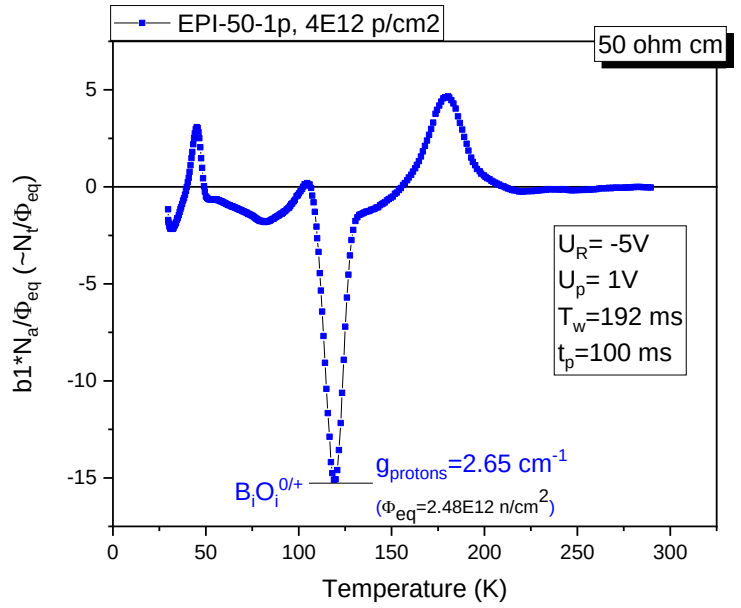
EPI diodes

23GeV proton irradiation

Medium resistivity/ fluences in the E10-E11 p/cm^2 range



Low resistivity/ fluences above E12 p/cm^2



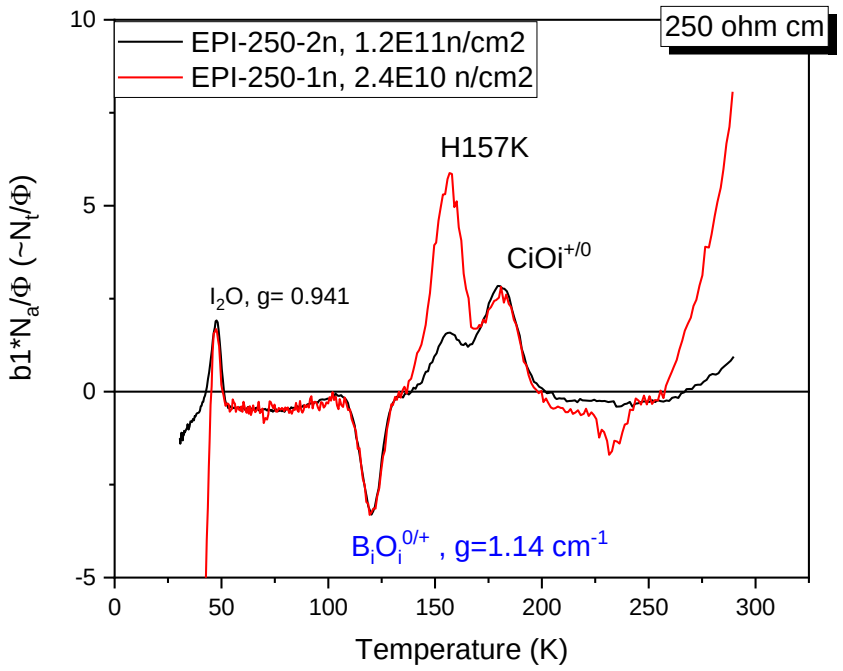
- The rate of BiOi defect generation in proton irradiated samples :
  - Increases when the material resistivity is lowered (as expected)
  - ~ constant for medium resistivity and fluences of E10-E11 p/cm^2
- H156K defect – may change in another in the E10-E11 cm^{-2} fluence range (to be investigated further)

B_iO_i generation rate(s)

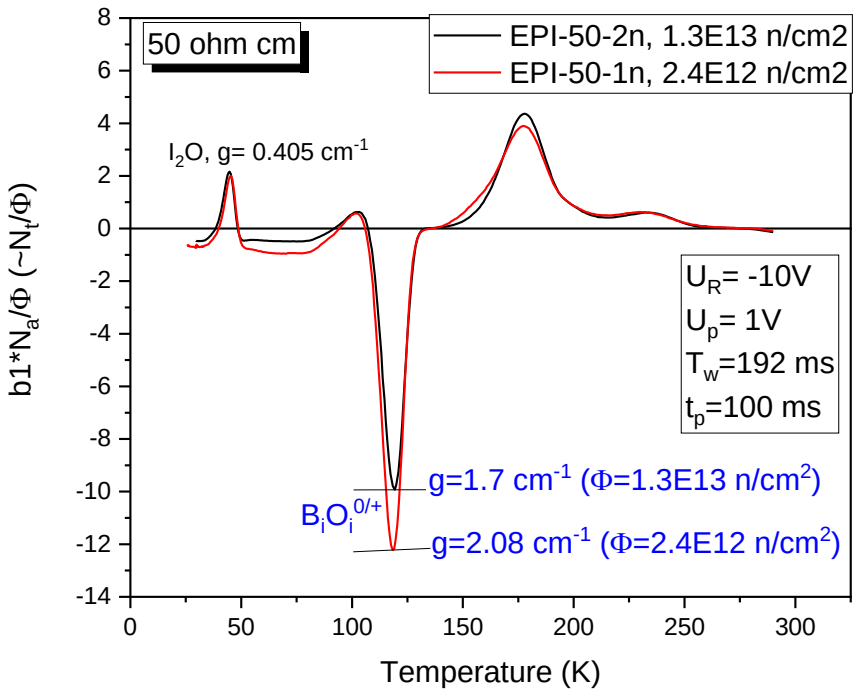
EPI diodes

1 MeV neutron irradiation

Medium resistivity/ fluences in the E10-E11 p/cm^2 range



Low resistivity/fluence in the E12-E13 n/cm^2 range

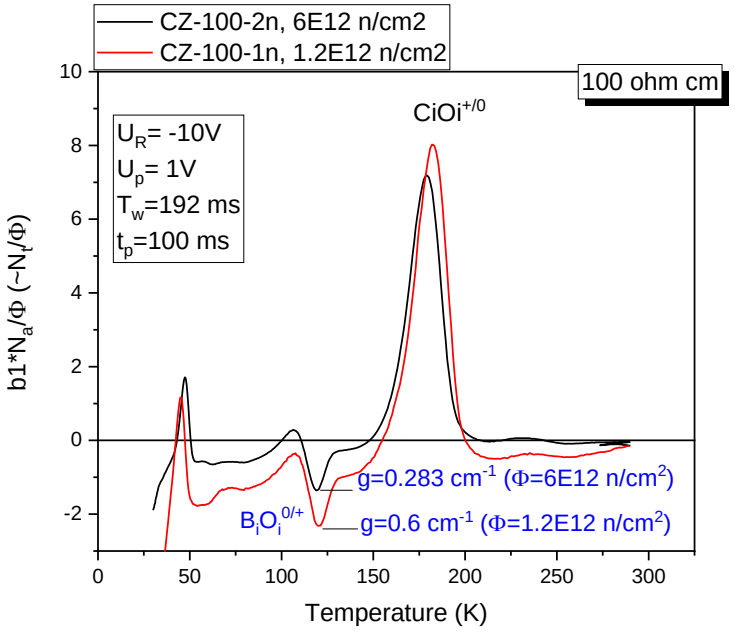


- The rate of BiOi defect generation in neutron irradiated samples:
  - Increases when the material resistivity is lowered (as expected)
  - Decreases with increasing the fluence above 10^{12} n/cm^2
- H156K defect – may change in another in the E10-E11 cm^{-2} fluence range (to be investigated further)

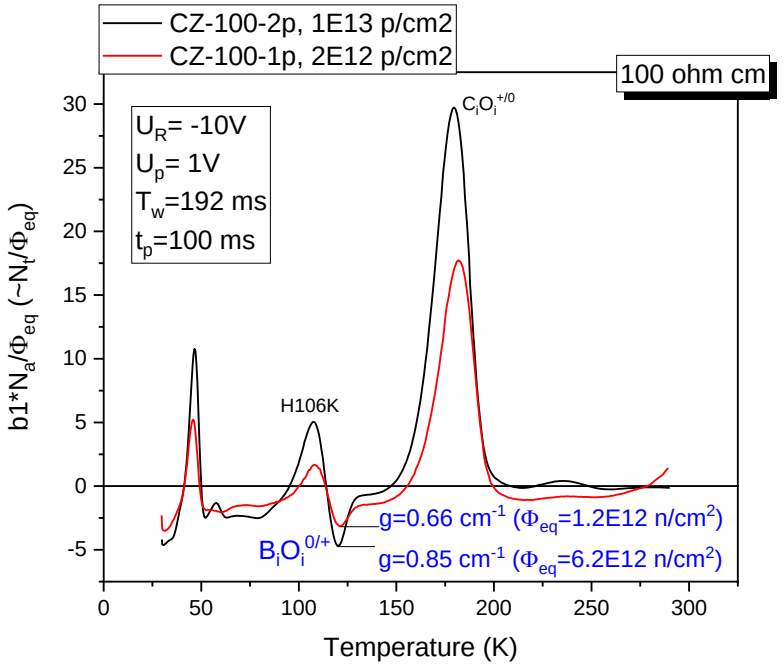
B_iO_i generation rate(s)

CZ diodes – low resistivity, **same equivalent fluences** for proton and neutron irradiation

1 MeV neutron irradiation



23GeV proton irradiation

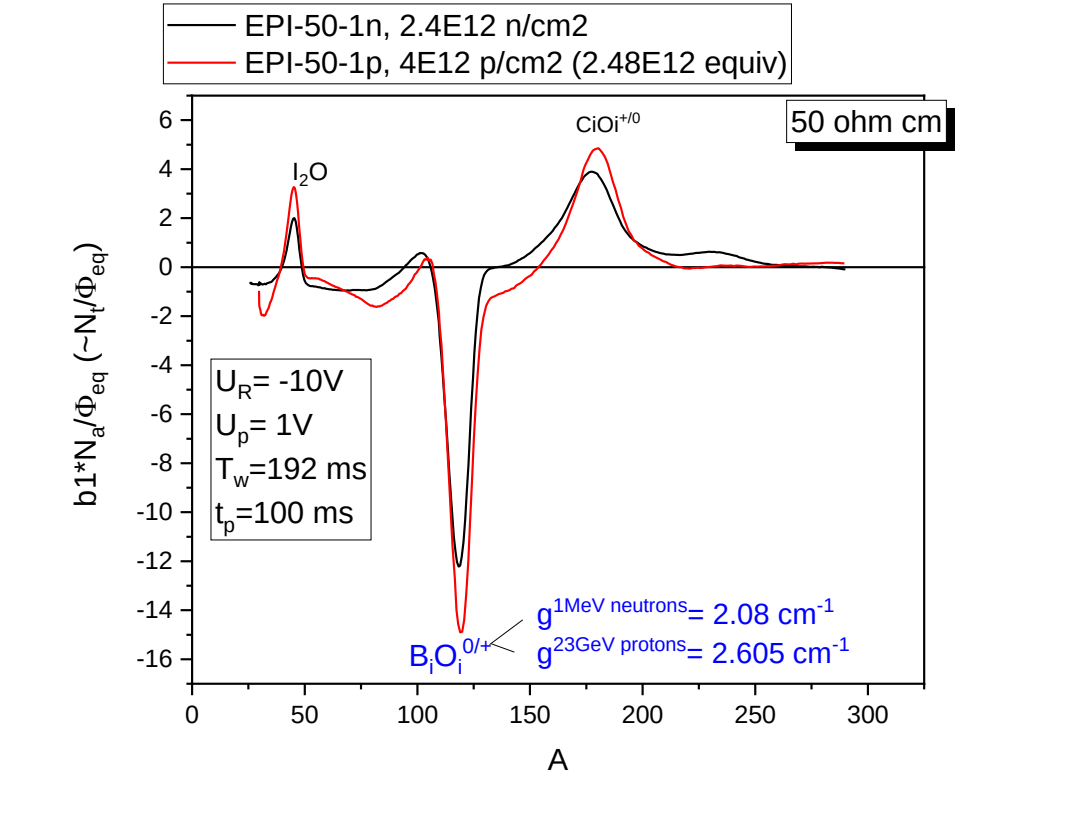


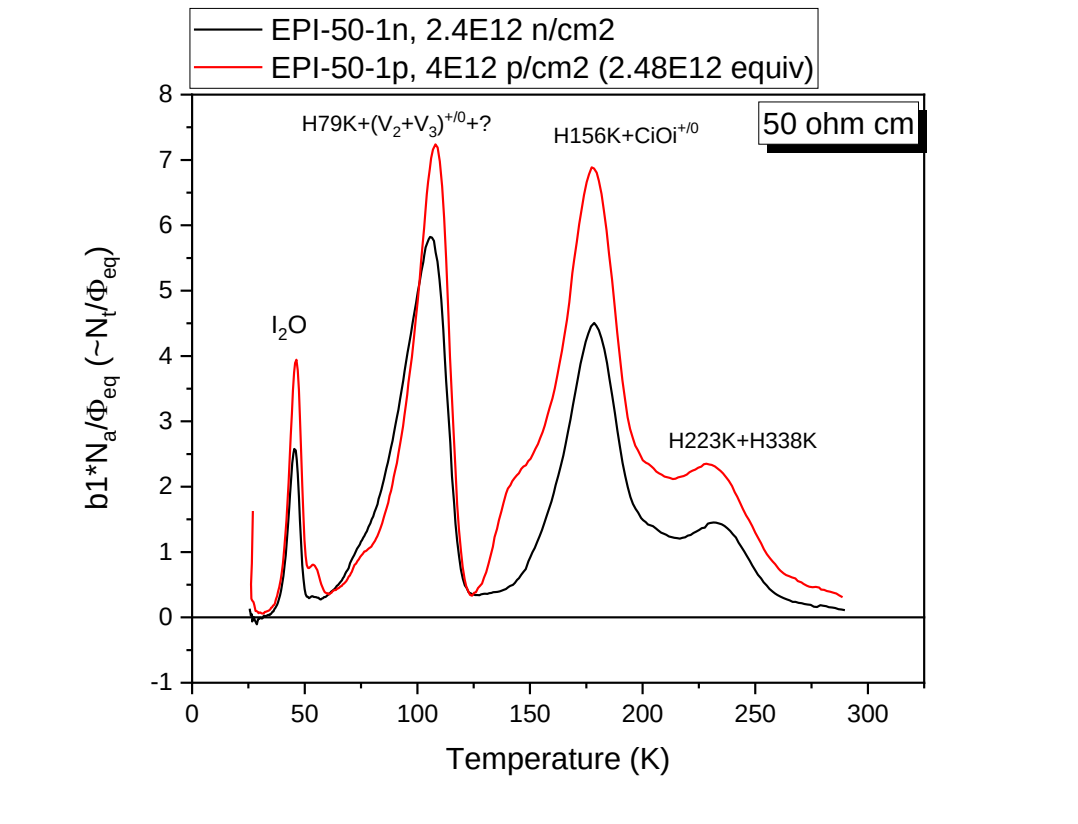
B_iO_i generation rate decreases with increasing the fluence (above 10^{12} /cm^2 !?) (with only a small decrease in the generation rate of CiOi)

BiOi generation rate increases with increasing the fluence (with a similar increase in the generation rate of CiOi)

Neutron versus Proton irradiation

Low resistivity **EPI** diodes

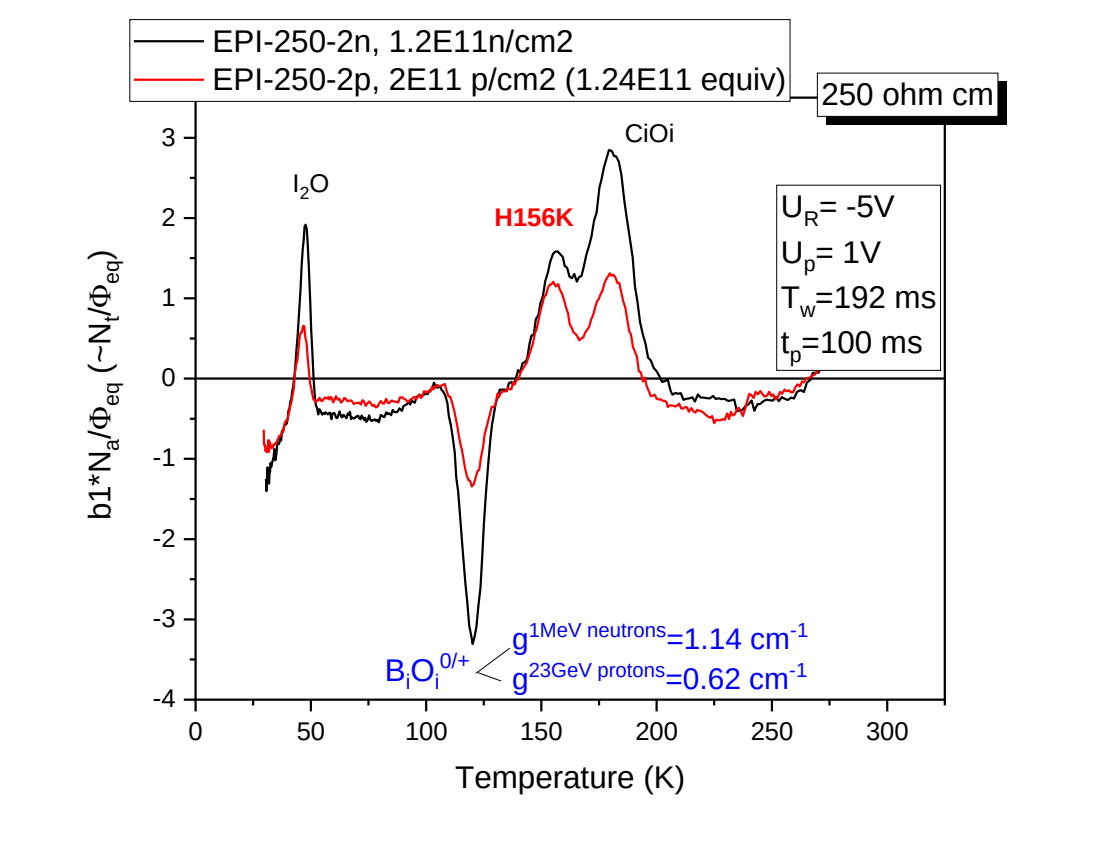


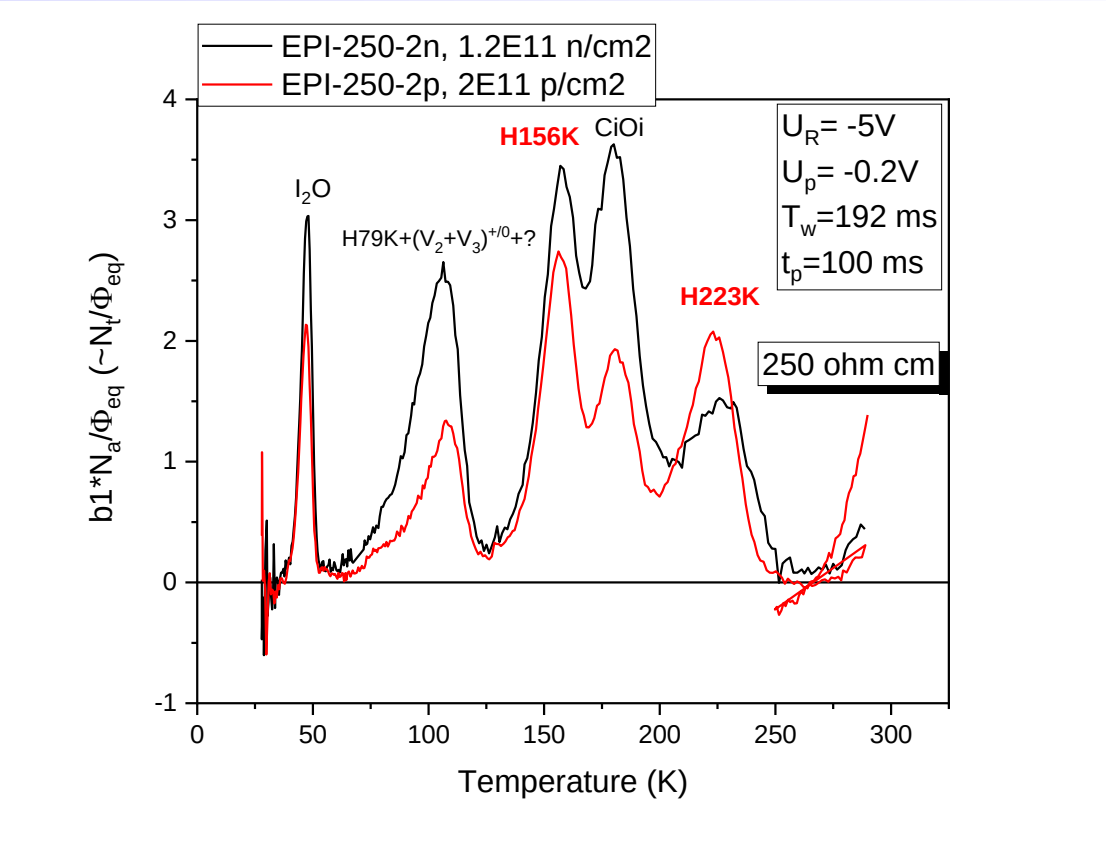


Proton irradiation induces **more** defects than **neutron** irradiation in low resistivity EPI diodes

Neutron versus Proton irradiation

Medium resistivity **EPI** diodes



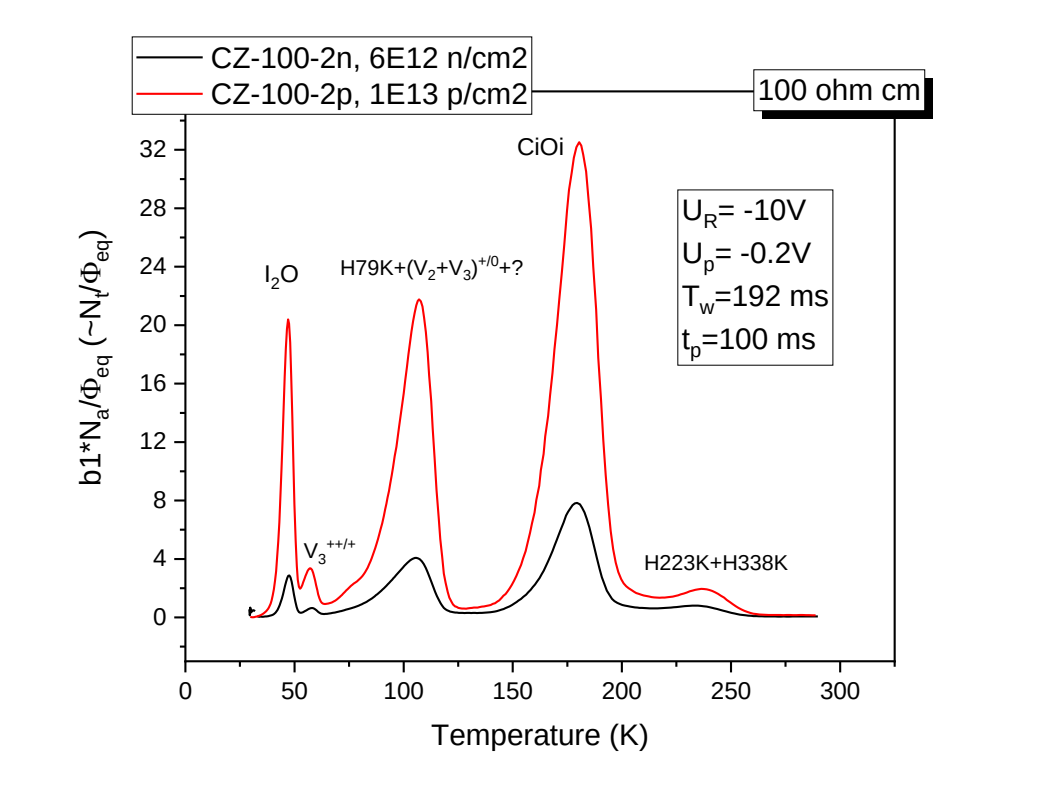


Proton irradiation induces **less** defects than **neutron** irradiation in medium resistivity EPI diodes

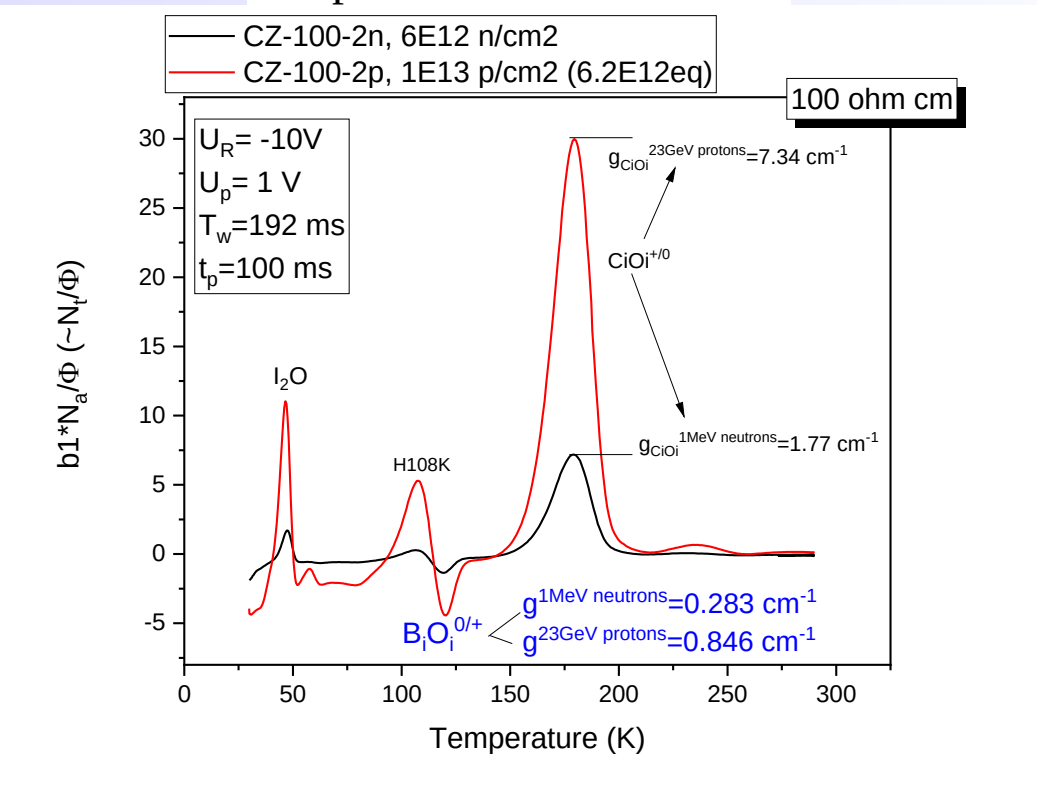
Neutron versus Proton irradiation

Low resistivity **CZ** diodes (with more O and C than EPI diodes)

Traps for holes



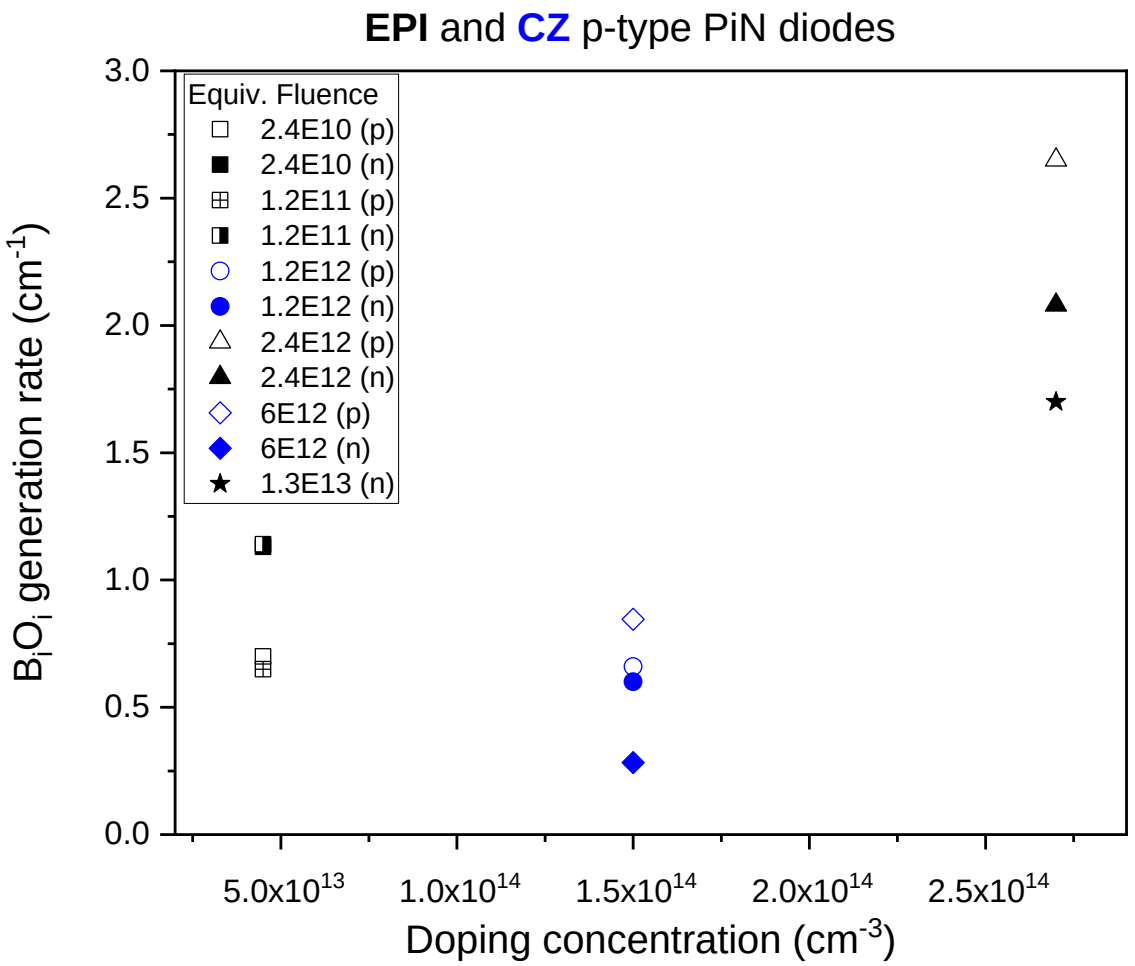
Traps for electrons&holes



For same equivalent fluences **Proton** irradiation induces **more** defects than **neutron** irradiation – similar to the case of low resistivity EPI diodes

B_iO_i generation rate – a real puzzle !

Dependence on doping



All the experiments done in same place, with the same set-up/procedures

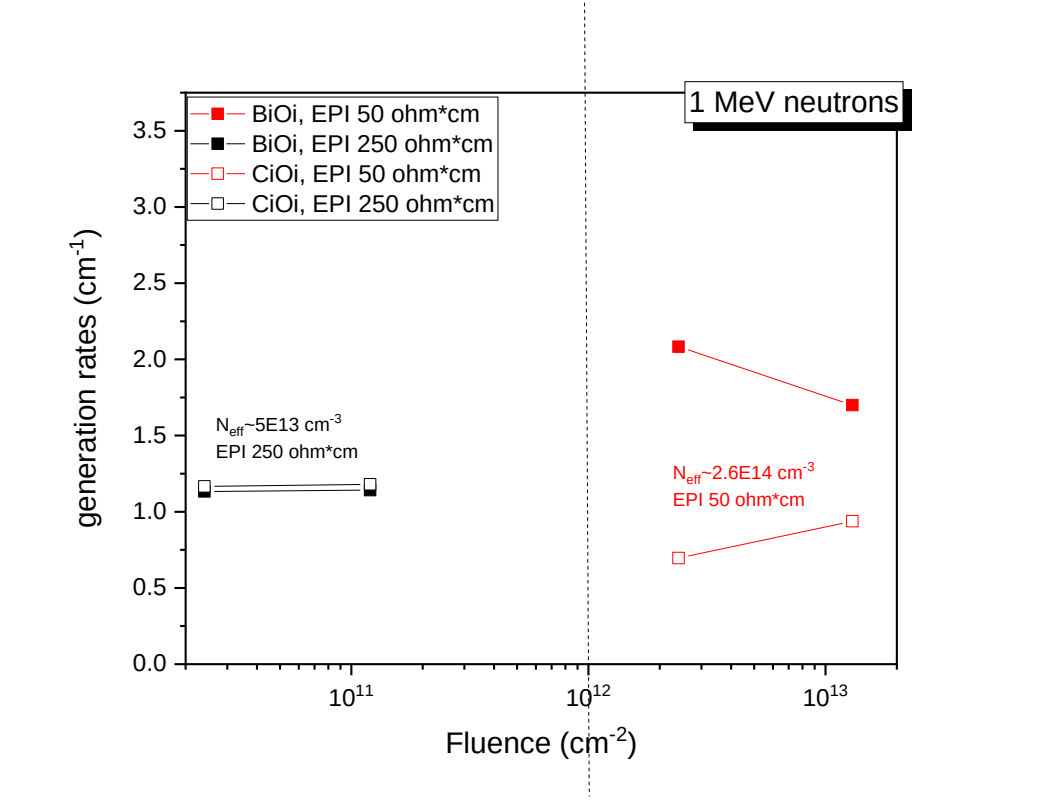
- Large differences between proton (open symbols) and neutron irradiation (filled symbols) for the same equivalent irradiation fluence and material (**EPI** and **CZ**) for fluences above 10^{12} cm^{-2}

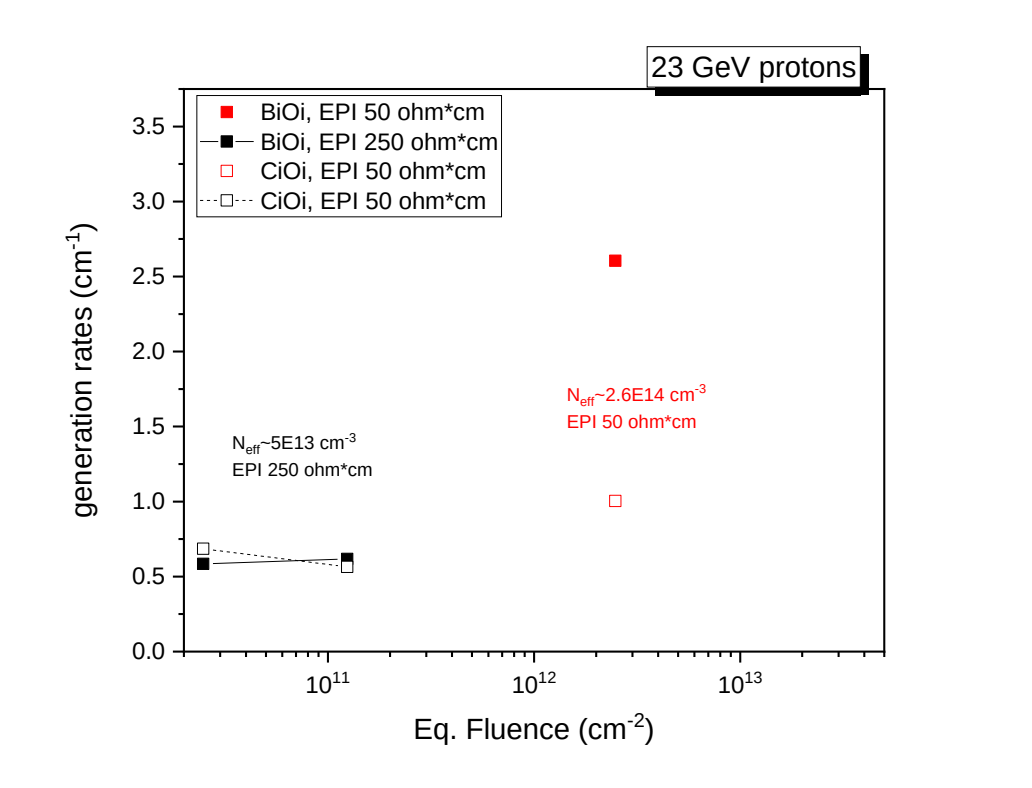
- The generation rate is also varying with the fluence (above 10^{12} cm^{-2}) for the same type of irradiation and material impurity content

BiOi generation rate – a real puzzle !

Dependence on fluence and type of irradiation

EPI material:





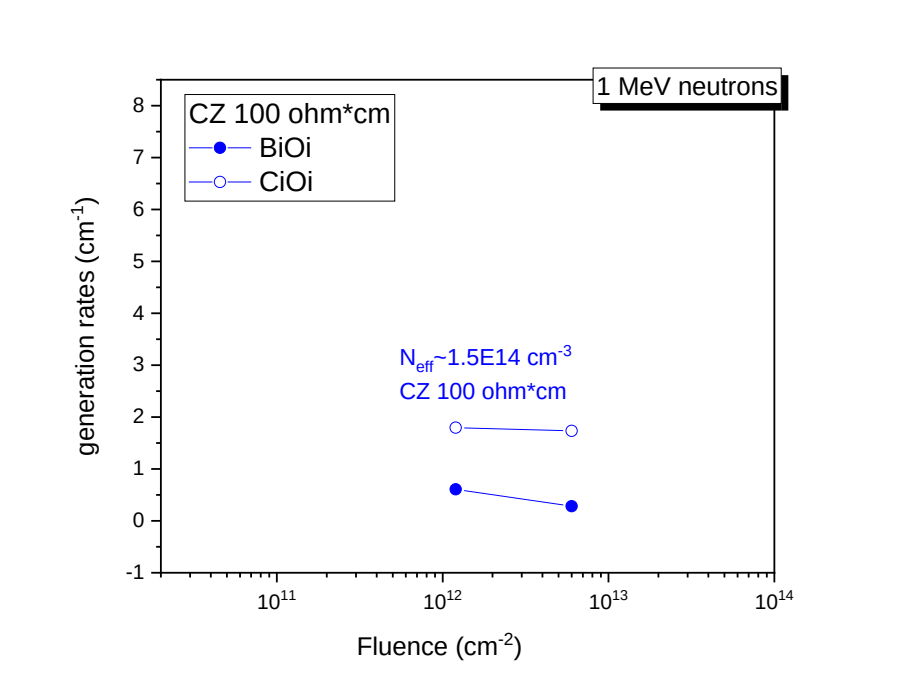
EPI material:

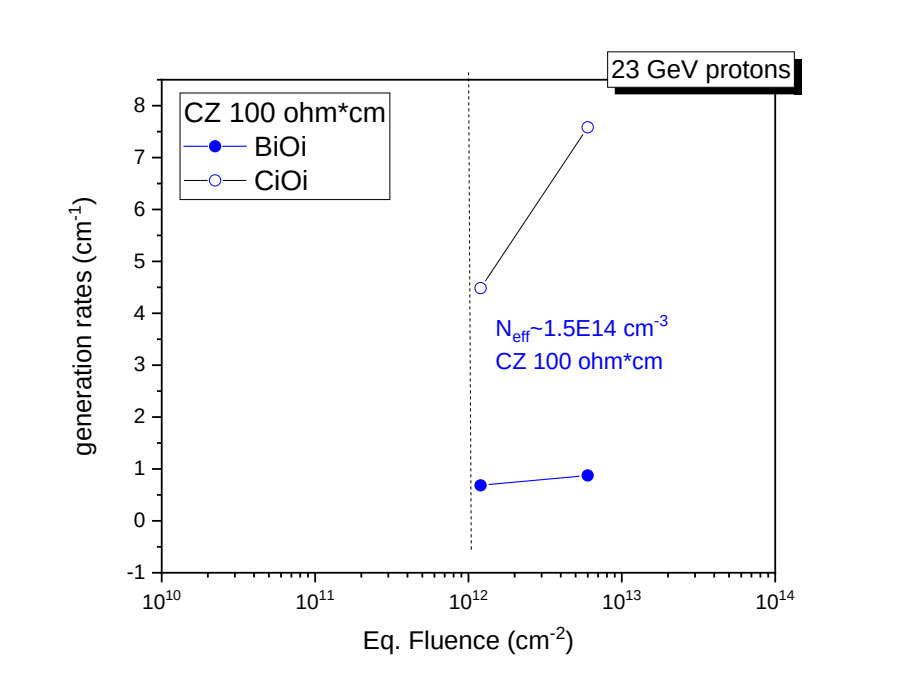
- **Low fluences&low B doping:** Similar **generation rates** for **B_iO_i and C_iO_i** defects for the same type of irradiation (more after neutrons than after protons)
- **Increasing the fluence (100 times)&B doping (5 times): gBiOi > gCiOi** (more after protons than after neutrons) for both type of irradiations

BiOi generation rate – a real puzzle !

Dependence on fluence and type of irradiation

CZ material





CZ material (at least 10 times more C and O in CZ than in EPI), irradiated with ½ fluences used for low resistivity EPI diodes:

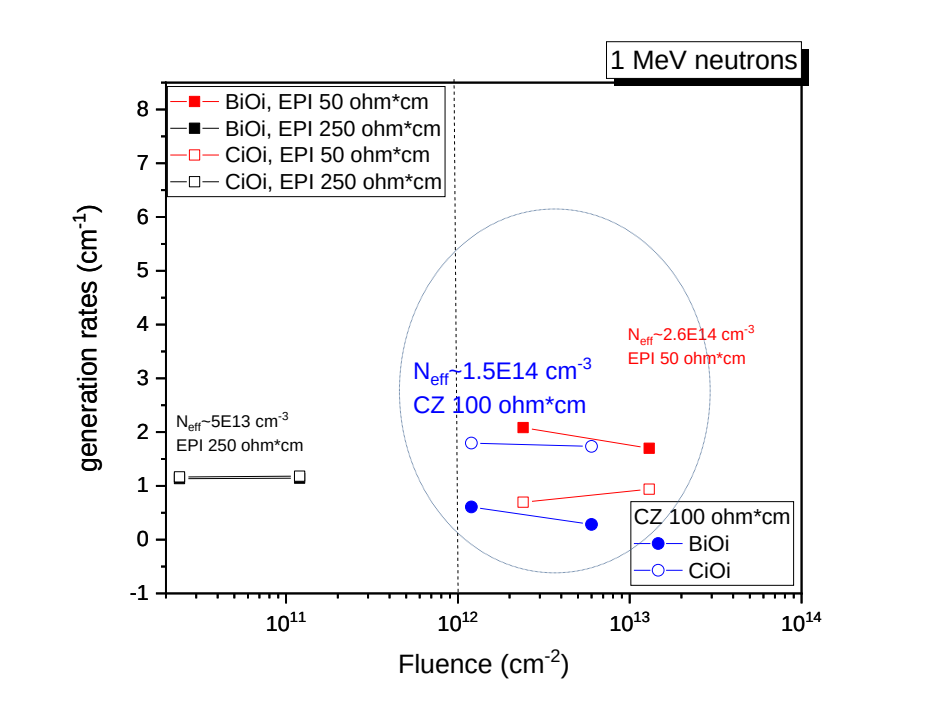
– **gBiOi < gCiO** for both type of irradiations (same equivalent fluence)

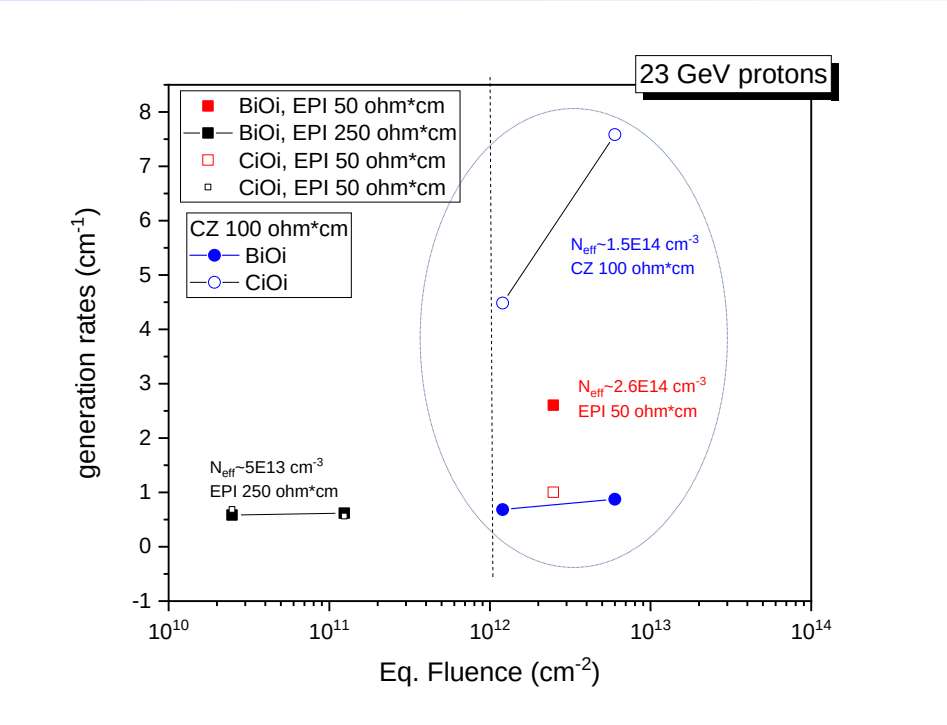
- different fluence dependence (for fluences 10^{12} – 10^{13} cm^2 gBiOi decreases after neutron irradiation and increases after proton irradiation) and **different generation rates after n or p irradiation** (larger after proton irrad), possible reason –interstitials trapped in the clusters generated by 1MeV neutron irradiation

BiOi generation rate – a real puzzle !

Dependence on the material (different C content in EPI and CZ materials)

- Fluence range 10^{12} – 10^{13} cm^{-2}

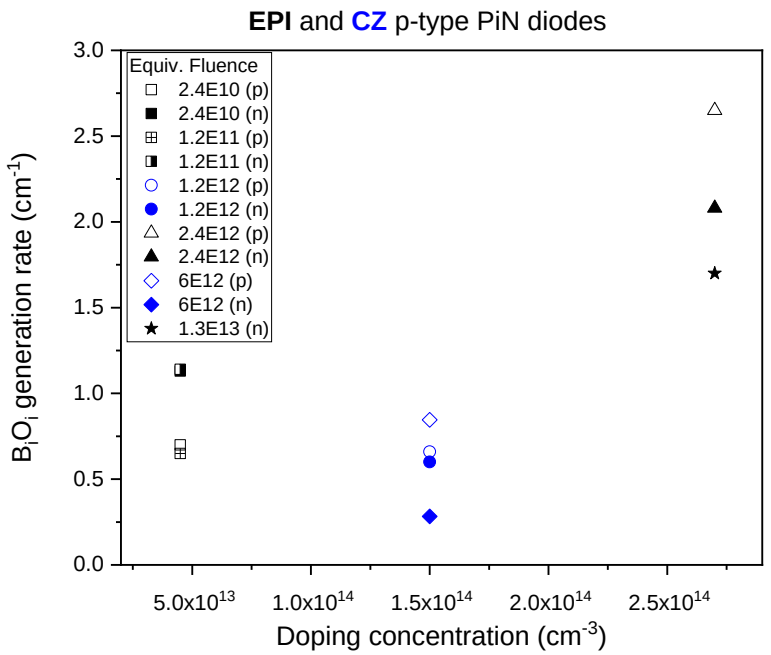




For similar fluences range and B doping – the generation rate of BiOi is larger in EPI than in CZ material (the opposite stands for the CiOi defect) for both types of irradiations – a result of the competition on interstitials between B and C

Summary and further work

- **Trapping parameters of several defects induced by irradiation**
  - Activation energy and capture cross sections (BiOi, H156K and H223K)
  - Concentrations and generation rates
- **The generation of BiOi defects depends on:**
  - **B doping –** the prime factor in generating the BiOi defect
  - **Impurity content (C and O content) –** Large differences between EPI and CZ of similar B doping
  - **type of irradiation -** Large differences between **p/n** irradiation even for the same equivalent fluence (above 10^{12} cm^{-2}) and impurity content (B, C and O) in the material
  - **irradiation fluence –** Large differences in the defect generation rates even when use the same type of irradiation and material



- **More diodes still to be measured in the RD50 Acceptor removal project**
- **Check the impurity content– is B content fully accounting for Na value or it is partly compensated during the growth process ?**
- **Annealing studies**
- **Different resistivity diodes (e.g. EPI 100 ohmcm, CZ 50, 250 ohmcm)?!**
- **LGAD diodes**

Thank you for your attention !