

Summary:

Appearance of the X-defect in TSC measurements performed on Proton, neutron, electron & gamma-irradiated silicon diodes

A. Himmerlich, SSD weekly 02.09.2022

X-Defect in proton irradiated samples

23 GeV proton irradiated EPI Diodes investigated @ Hamburg:

Chuan Liao 37th RD50 WS Nov.2020
& C. Liao IEEE 69,3 (2022)

Label	EPI50P_01_DS_73	EPI50P_06_DS_71	EPI50P_09_DS_73	EPI50P_12_DS_74
Resistivity	10 Ωcm	50 Ωcm	250 Ωcm	2000 Ωcm
Irradiation	23 GeV proton, $\Phi_{eq} = 4.28E13 \text{ cm}^{-2}$			
Area	6.927E-2 cm ²			
Thickness	50 Ωcm:			

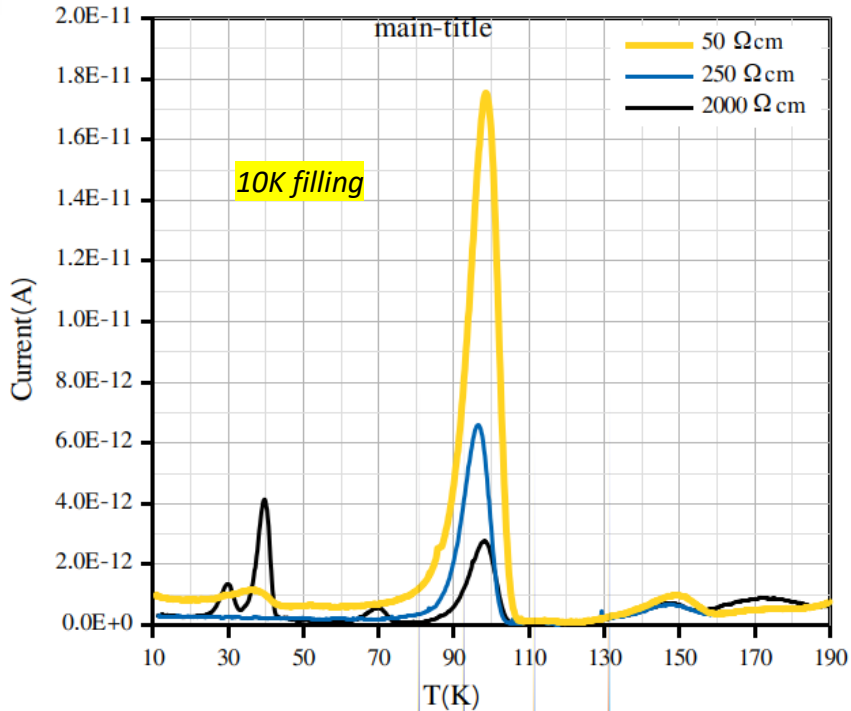


Fig 19. TSC spectra for diodes with different resistivity 50 Ωcm, 250 Ωcm and 2000 Ωcm

16min@80C, V_filling=5 V, T_fill=60 K, V_bias=-250 V

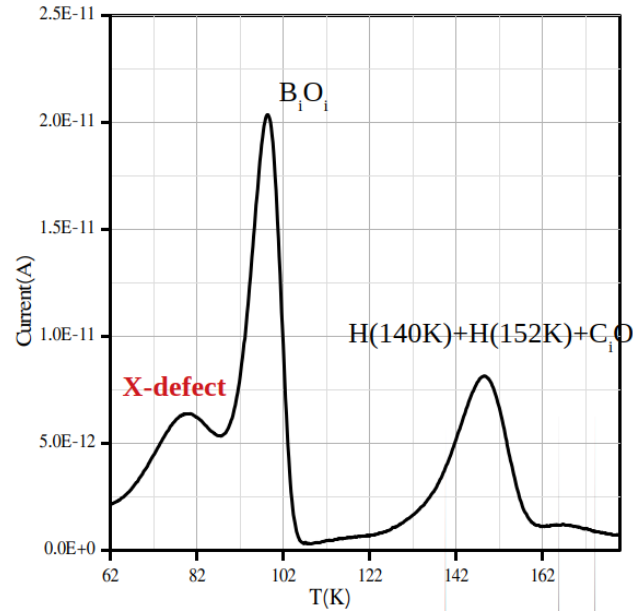


Fig 14. TSC spectrum of 50 Ωcm p-type diodes after filling at $T_{fill} = 60 \text{ K}$ with forward bias $V_{fill} = 5 \text{ V}$.

60min@80C, V_fill=0 V, T_fill=60 K, V_bias=-250 V

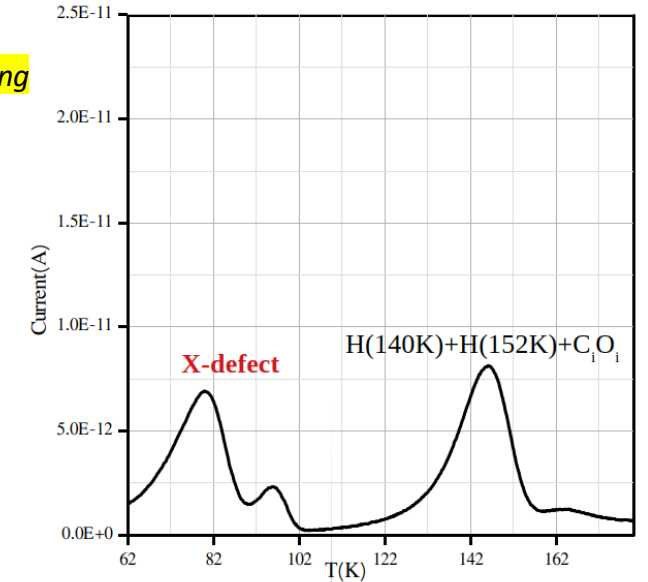


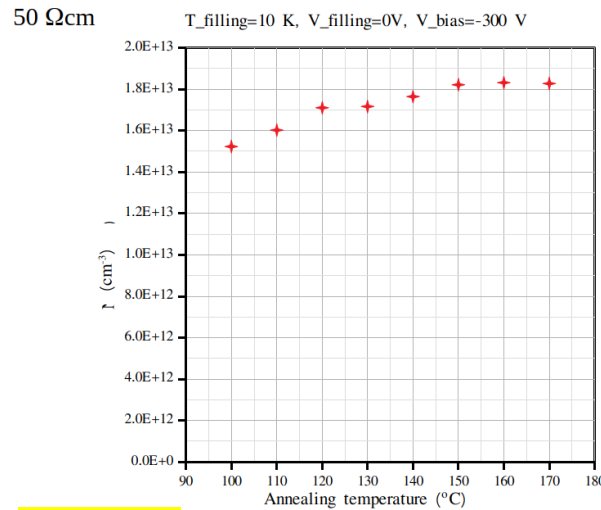
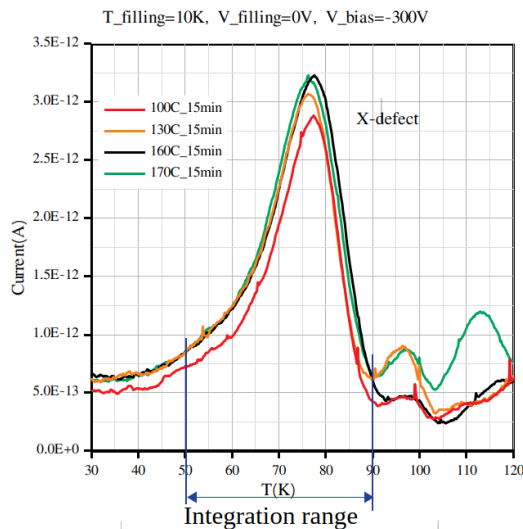
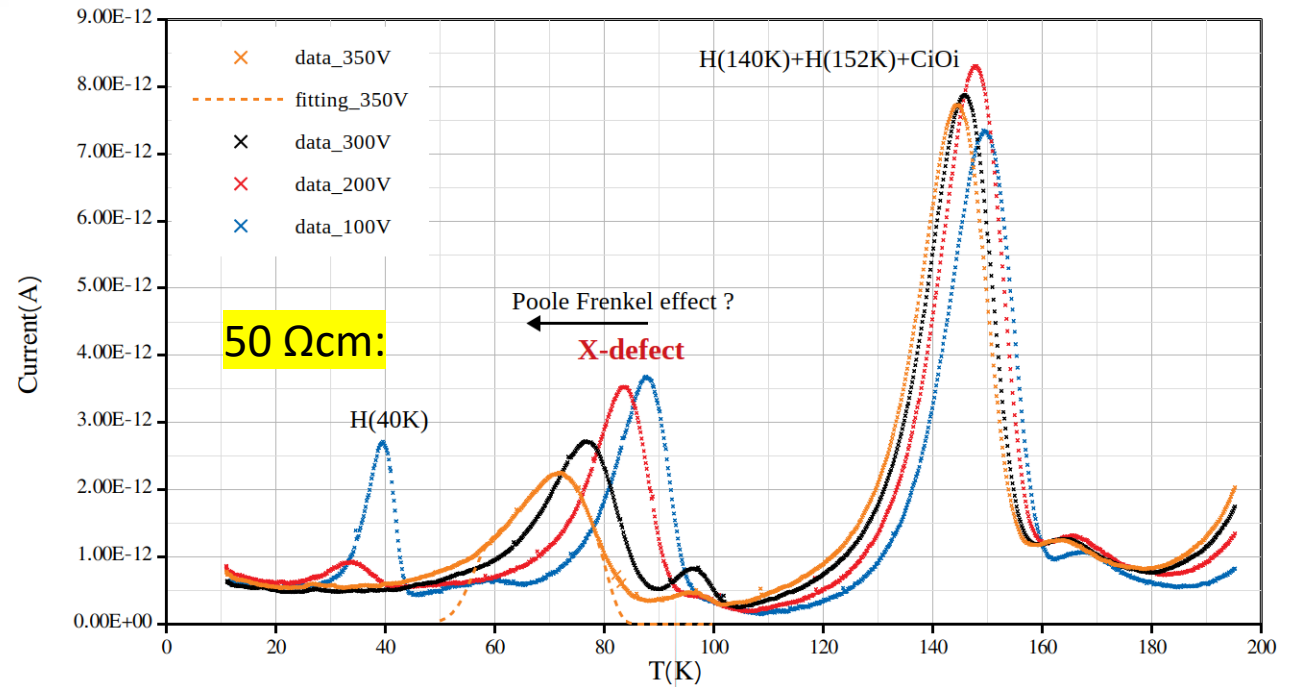
Fig 15. TSC spectrum for 0 V filling (majority carriers filling) and $T_{fill} = 60 \text{ K}$

23 GeV proton irradiated EPI Diodes investigated @ Hamburg:

Chuan Liao 37th RD50 WS Nov.2020
& C. Liao IEEE 69,3 (2022)

- capture cross section is strongly T dependent
- X-defect = hole trap
- PF-Effect
- Shallow acceptor: X(0/-), i.e. neutral when filled
- quite large T shift with bias
- Long tail at higher bias
- concentration slightly increase with annealing T

60min@80C, V_fill=0V, T_fill=10K

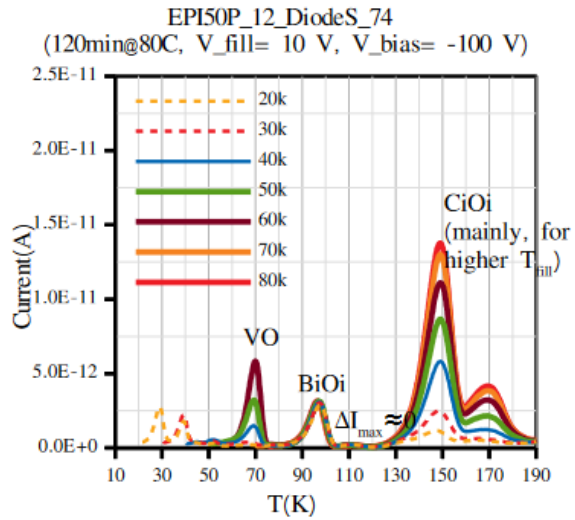


50 Ωcm:

23 GeV proton irradiated EPI Diodes investigated @ Hamburg:

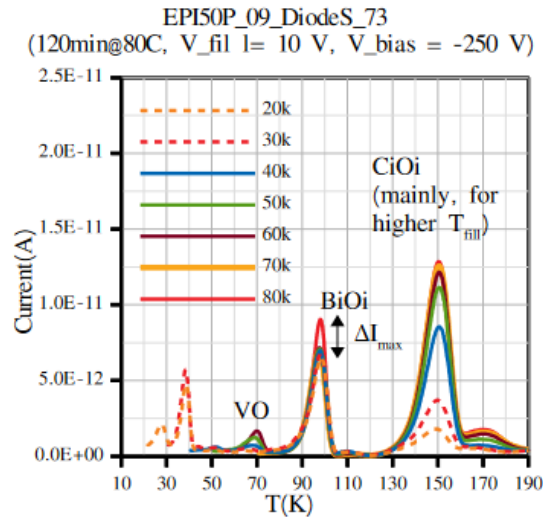
Chuan AR meeting 03.02.2021

2k Ωcm:



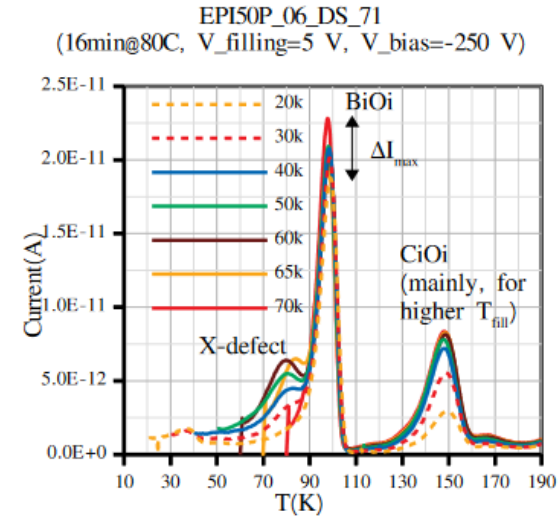
4.28E+13 neq/cm²

250 Ωcm:



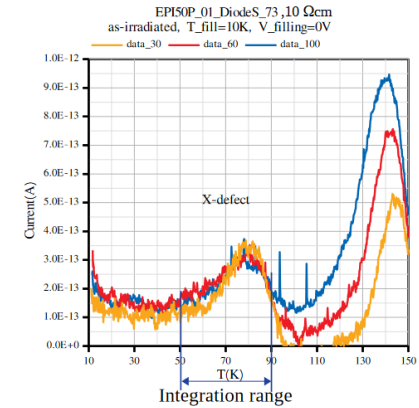
4.28E+13 neq/cm²

50 Ωcm:



4.28E+13 neq/cm²

10 Ωcm:



4.28E+13 neq/cm²

Dependence of the initial doping



The conclusion about X-defect:

1. X-defect is invisible at lower initial doping diodes;
2. Comparing three diodes with different resistivity, the increases of BiOi peak maximum for different T_{fill} (ΔI_{max}) are initial doping dependent. In principle, BiOi itself is not temperature dependent. So I think it's due to X-defect concentration is different for different initial doping diodes, and it might be indirectly proven whether the X-defect is boron related or not.

The conclusion about VO and CiOi:

Initial doping dependent.



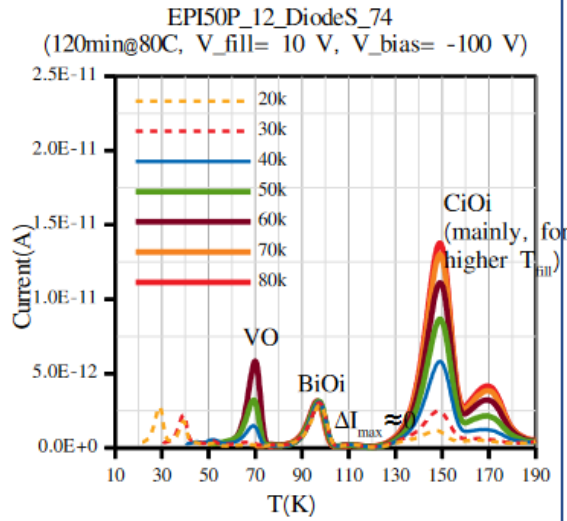
no x-defect

Chuan AR meeting 16.09.2022

23 GeV proton irradiated EPI Diodes investigated @ Hamburg:

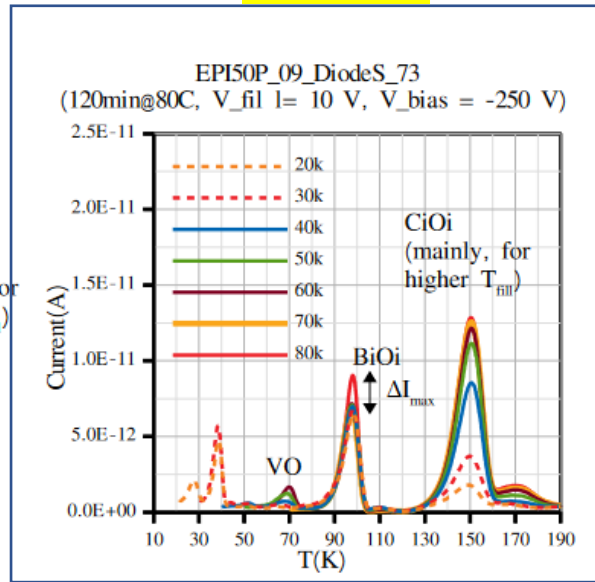
Chuan AR meeting 03.02.2021

2k Ωcm :



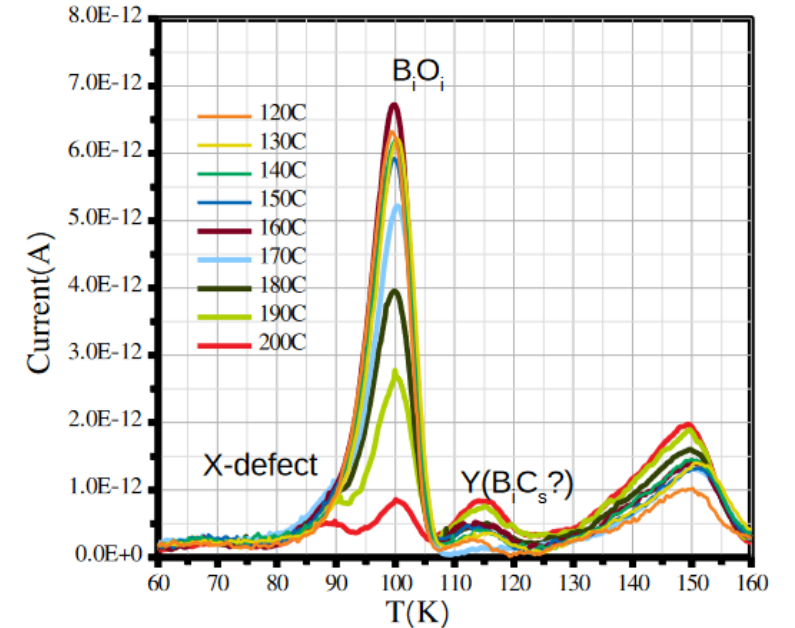
4.28E+13 neq/cm²

250 Ωcm :



4.28E+13 neq/cm²

Chuan AR meeting 27.04.2022
Annealing study



Is it really the same „X“-defect?

The conclusion about X-defect:

1. X-defect is invisible at lower initial doping diodes;
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The conclusion about VO and CiOi:

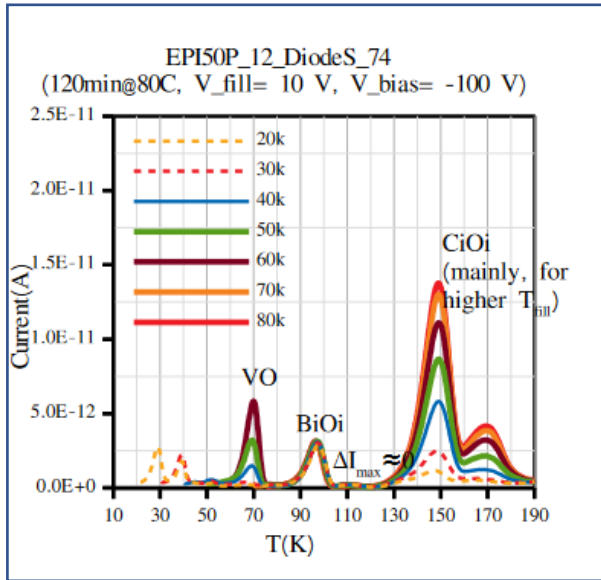
Initial doping dependent.

no x-defect

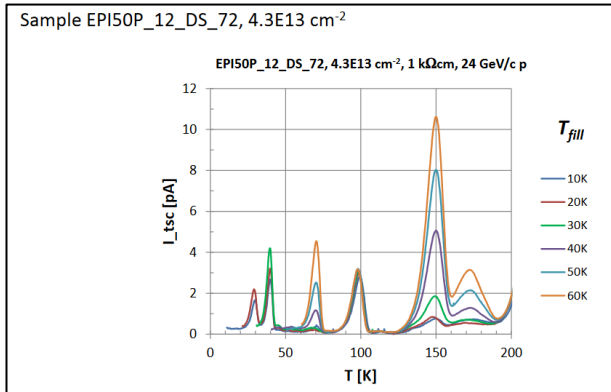
23 GeV proton irradiated EPI Diodes investigated @ Hamburg:

Chuan AR meeting 03.02.2021

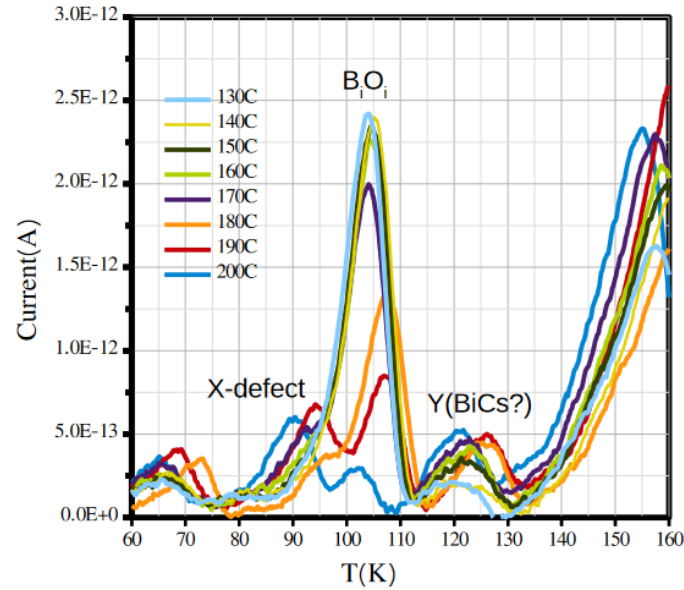
2k Ωcm :



4.28E+13 neq/cm²

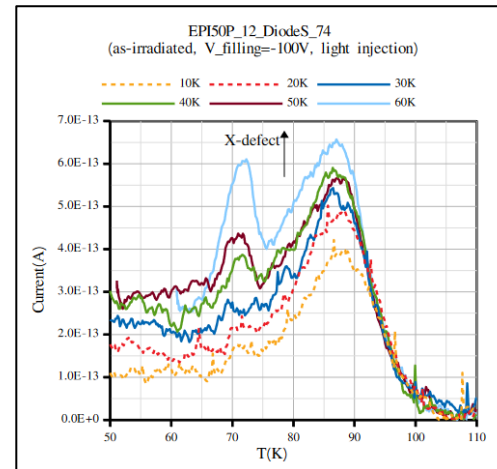


AR meeting 21.04.2020



Chuan AR meeting 27.04.2022
Annealing study

Is it really the same „X“-defect?



Chuan AR meeting 20.11.2020
Light injection
(no annealing)

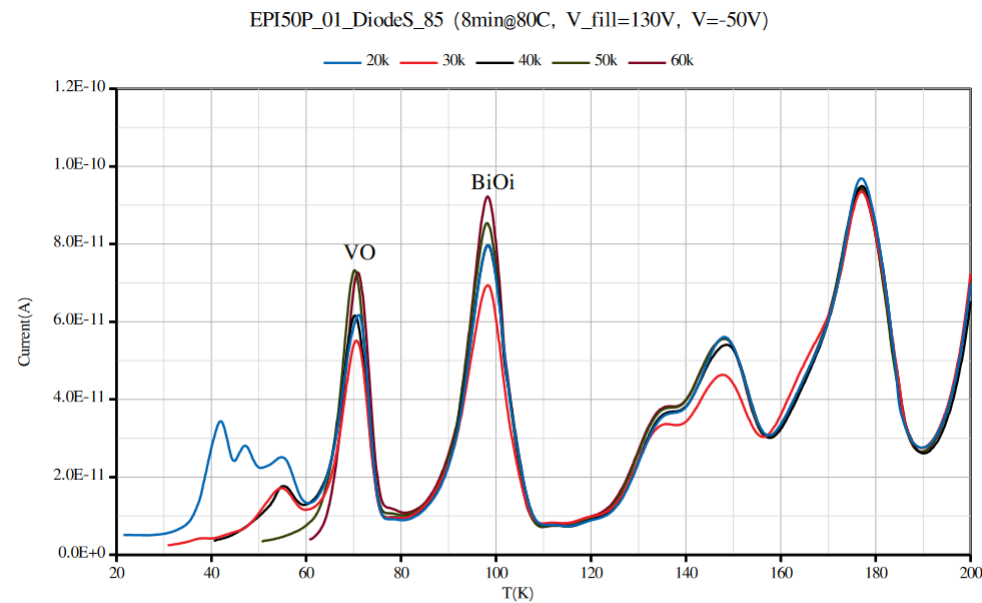
23 GeV proton irradiated EPI Diodes investigated @ Hamburg:

Chuan AR meeting 19.08.2020

10 Ωcm :

Higher fluence!

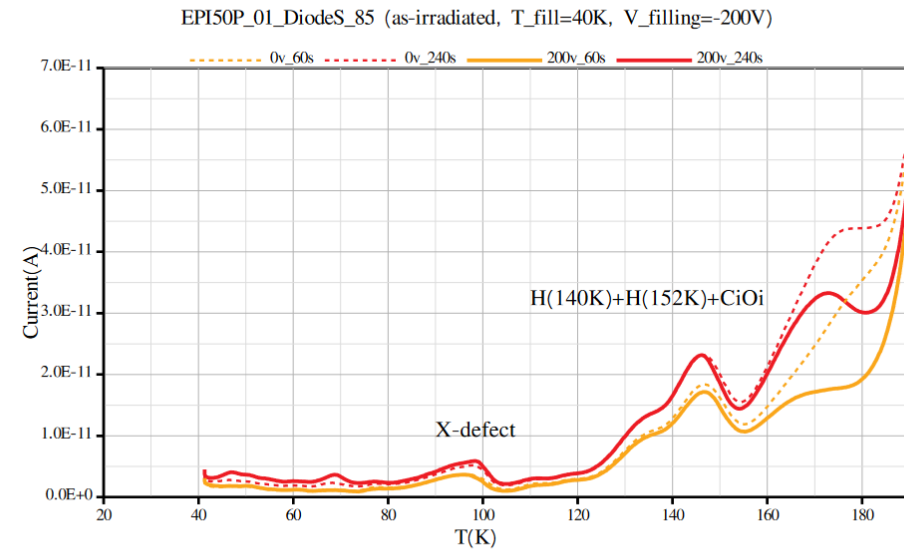
4.96E+15 neq/cm²



Complicated space charge and field distribution during heating up

NO X-defect

Light inject n⁺-electrode (hole injection)



Dotted line: 0V cooling down;
solid line: -200V cooling down;
Main difference for T > 160K.

Is it really the same „X“-defect?

23 GeV proton irradiated EPI Diodes investigated @ CERN

(data from 50 and 250 Ω cm sensors available)

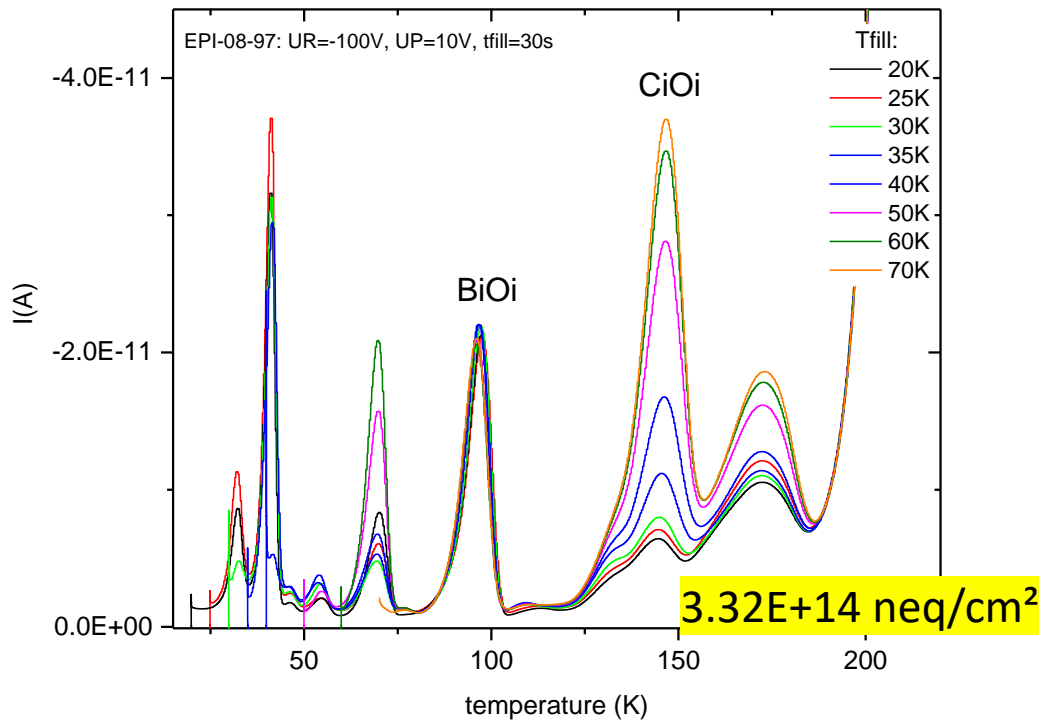
Jan. 2022

Sample	resistivity	fluence (p/cm ²)	fluence (n _{eq} /cm ²)	notes
EPI-01-103	10	1.22E+15	7.32E+14	<i>Neff annealing study</i>
EPI-05-99	50	1.22E+15	7.32E+14	<i>Neff annealing study</i>
EPI-08-98	250	1.22E+15	7.32E+14	<i>Neff annealing study</i>
EPI-12-98	1000	1.22E+15	7.32E+14	<i>Neff annealing study</i>
EPI-01-101	10	5.54E+14	3.32E+14	<i>TSC (Pedro)</i>
EPI-05-98	50	5.54E+14	3.32E+14	<i>TSC (Isidre)</i>
EPI-08-97	250	5.54E+14	3.32E+14	<i>TSC (Pedro)</i>
EPI-09-92	250	4.98E+14	2.99E+14	<i>TSC</i>
EPI-09-93	250	4.98E+14	2.99E+14	<i>TSC (Iza)</i>
EPI-09-94	250	4.98E+14	2.99E+14	<i>TSC (bad)</i>
EPI-09-79	250	1.91E+14	1.15E+14	<i>TSC</i>
EPI-09-80	250	1.91E+14	1.15E+14	<i>TSC (Iza)</i>
EPI-01-102	10	1.30E+14	7.80E+13	<i>TSC</i>
EPI-05-94	50	1.30E+14	7.80E+13	<i>TSC (Pedro)</i>
EPI-08-93	250	1.30E+14	7.80E+13	<i>TSC, I-DLTS =D</i>
EPI-12-93	1000	1.30E+14	7.80E+13	<i>TSC (Pedro)</i>
EPI-12-94	1000	6.44E+13	3.86E+13	<i>(TSC)</i>
EPI-05-83	50	5.40E+13	3.35E+13	<i>TSC, DLTS =D</i>
EPI-02-96	10	1.30E+13	7.80E+12	<i>(TSC.txt)</i>
EPI-05-104	50	1.30E+13	7.80E+12	<i>(TSC.txt, DLTS-transient)</i>
EPI-08-95	250	1.30E+13	7.80E+12	<i>(TSC.txt)</i>
EPI-12-95	1000	1.30E+13	7.80E+12	<i>(TSC.txt)</i>
EPI-04-81	50	2.44E+13	1.49E+13	<i>TSC, DLTS =D</i>
EPI-06-89	50	2.44E+13	1.49E+13	<i>TSC</i>
EPI-04-69	50	4.00E+12	2.48E+12	<i>TSC, DLTS (Ioana bro.)</i>
EPI-09-103	250	2.00E+11	1.20E+11	<i>(DLTS)</i>

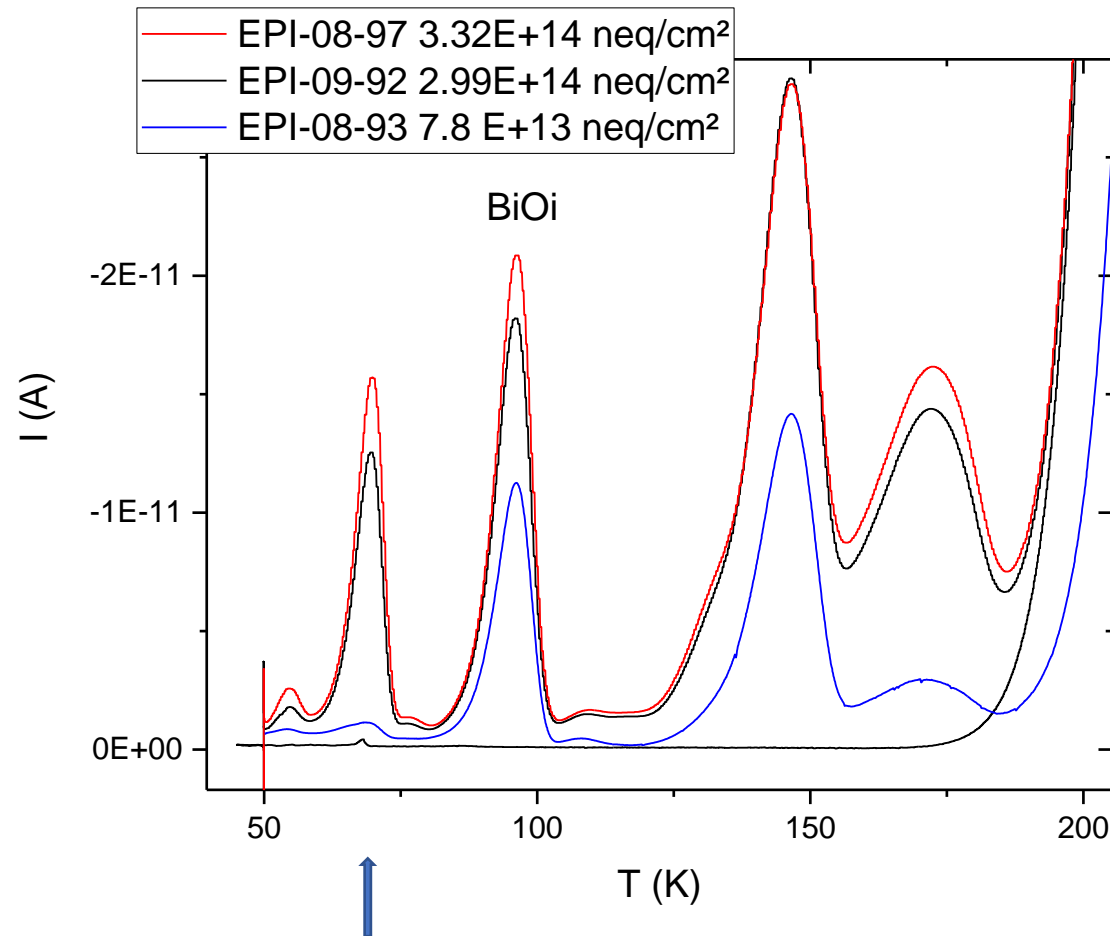
23 GeV proton irradiated EPI Diodes investigated @ CERN

(data from 50 and 250 Ωcm sensors available)

EPI 250 Ωcm:



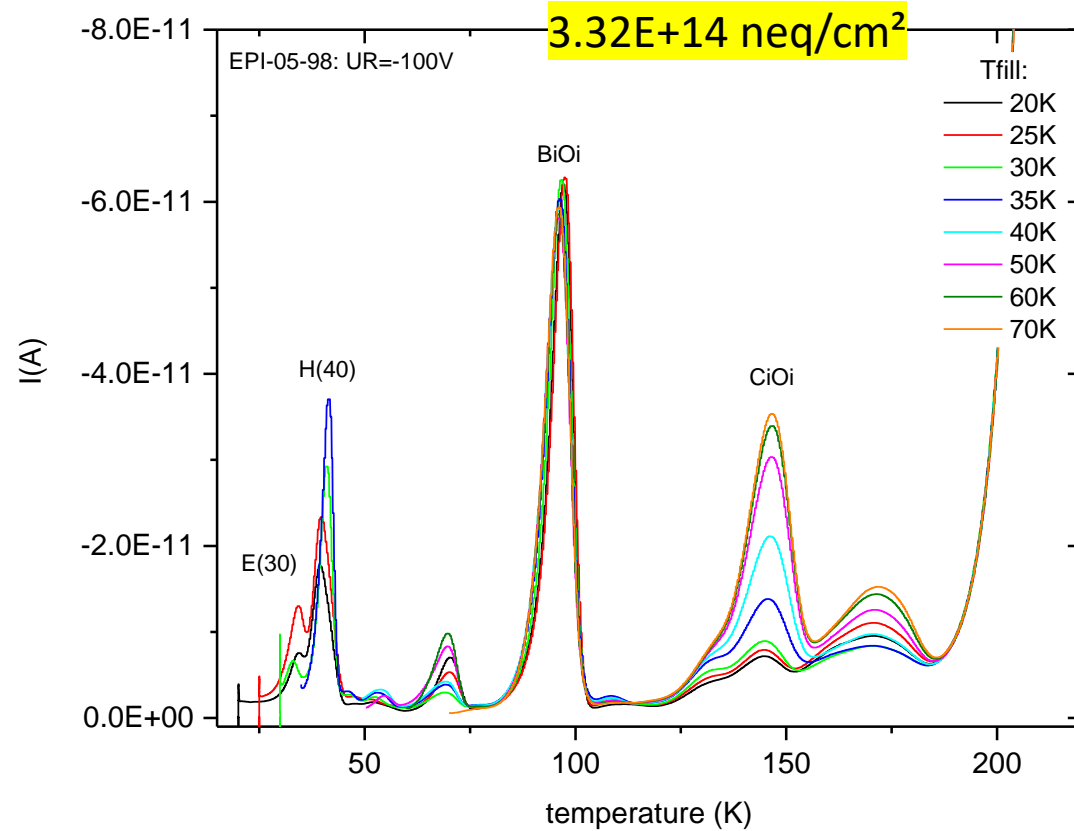
no X-defect in the 250 Ωcm sensors
BUT: lowest fluence measured for this resistivity: $7.8 E+13 \text{ neq/cm}^2$!!!



Gurinskaya et al. NIMA 2020
 VOi+CiCs

23 GeV proton irradiated EPI Diodes investigated @ CERN (data from 50 and 250 Ωcm sensors available)

EPI 50 Ωcm:

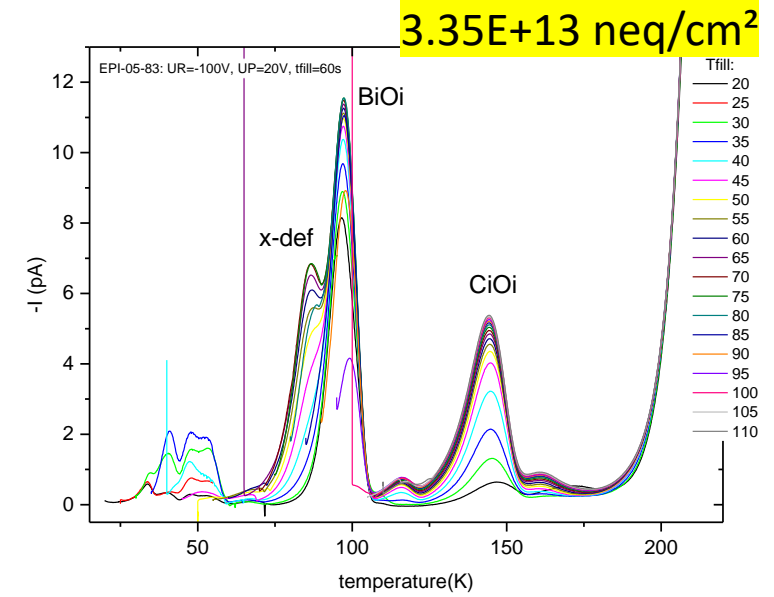
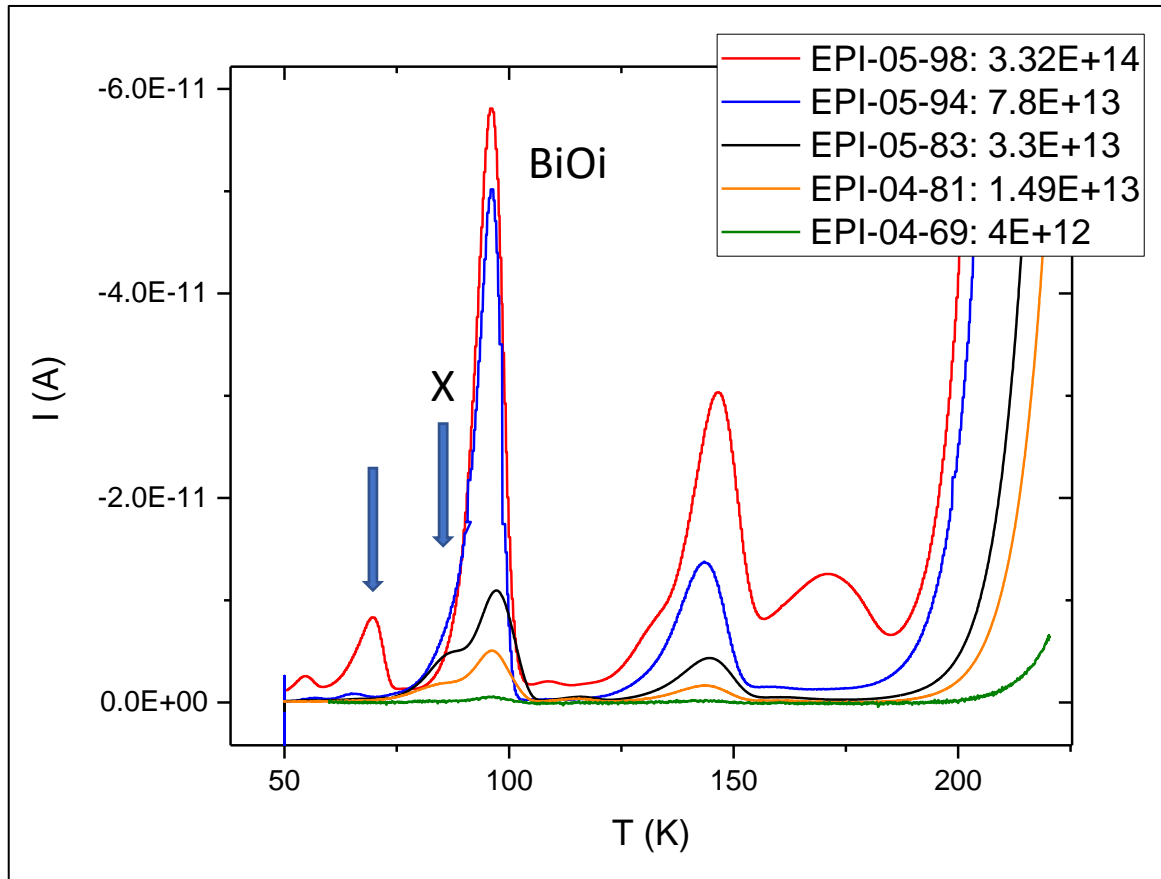


no X-defect

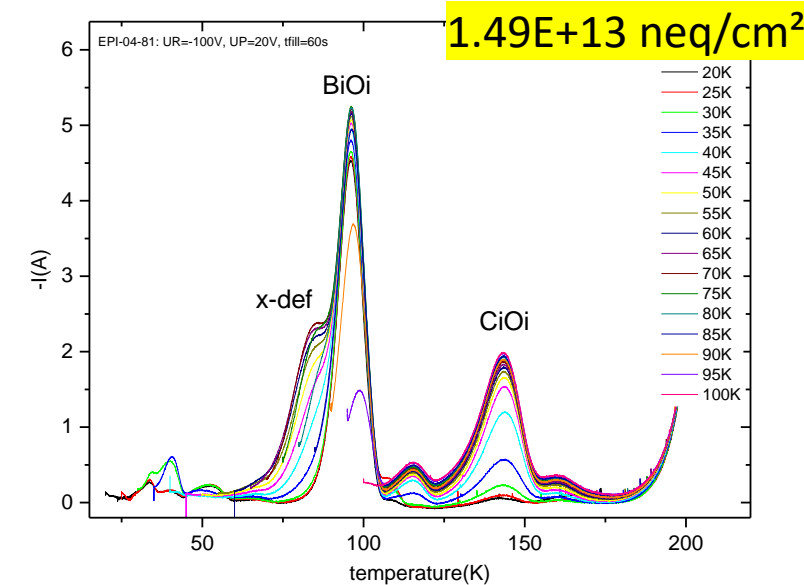
(Chuan: 4.28E+13 neq/cm² => x-defect visible in 50 Ωcm)

23 GeV proton irradiated EPI Diodes investigated @ CERN (data from 50 and 250 Ωcm sensors available)

EPI 50 Ωcm:



appearance of the X-defect for lower fluences

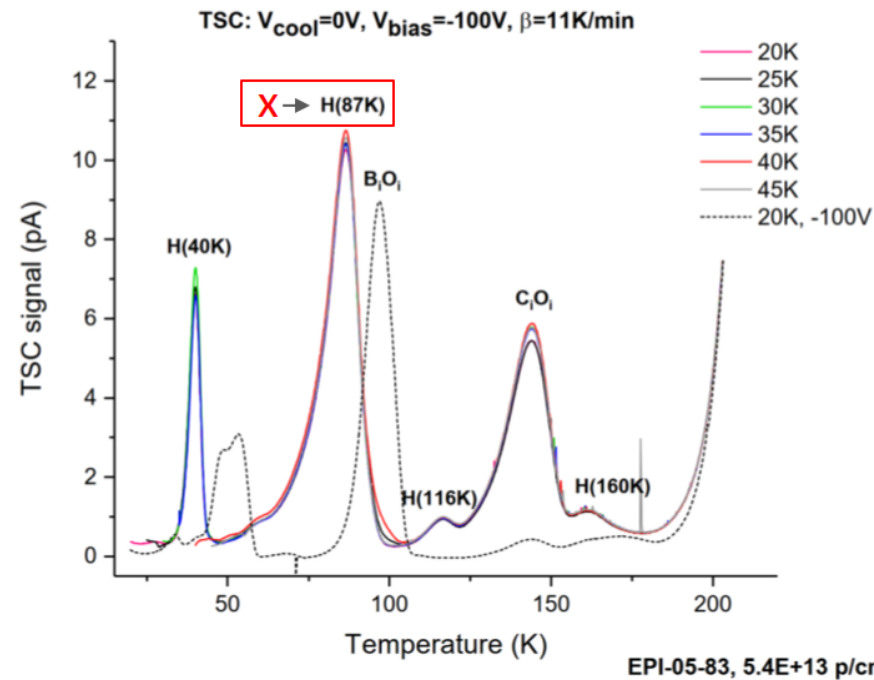


23 GeV proton irradiated EPI Diodes investigated @ CERN (data from 50 and 250 Ωcm sensors available)

YANA 36th RD50 WS 2020

TSC: T_{fill} variation for 0 bias cooling

Example: proton irradiated 50 Ω·cm EPI PiN diode



0 bias cooling → filling only hole traps with majority carriers

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

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

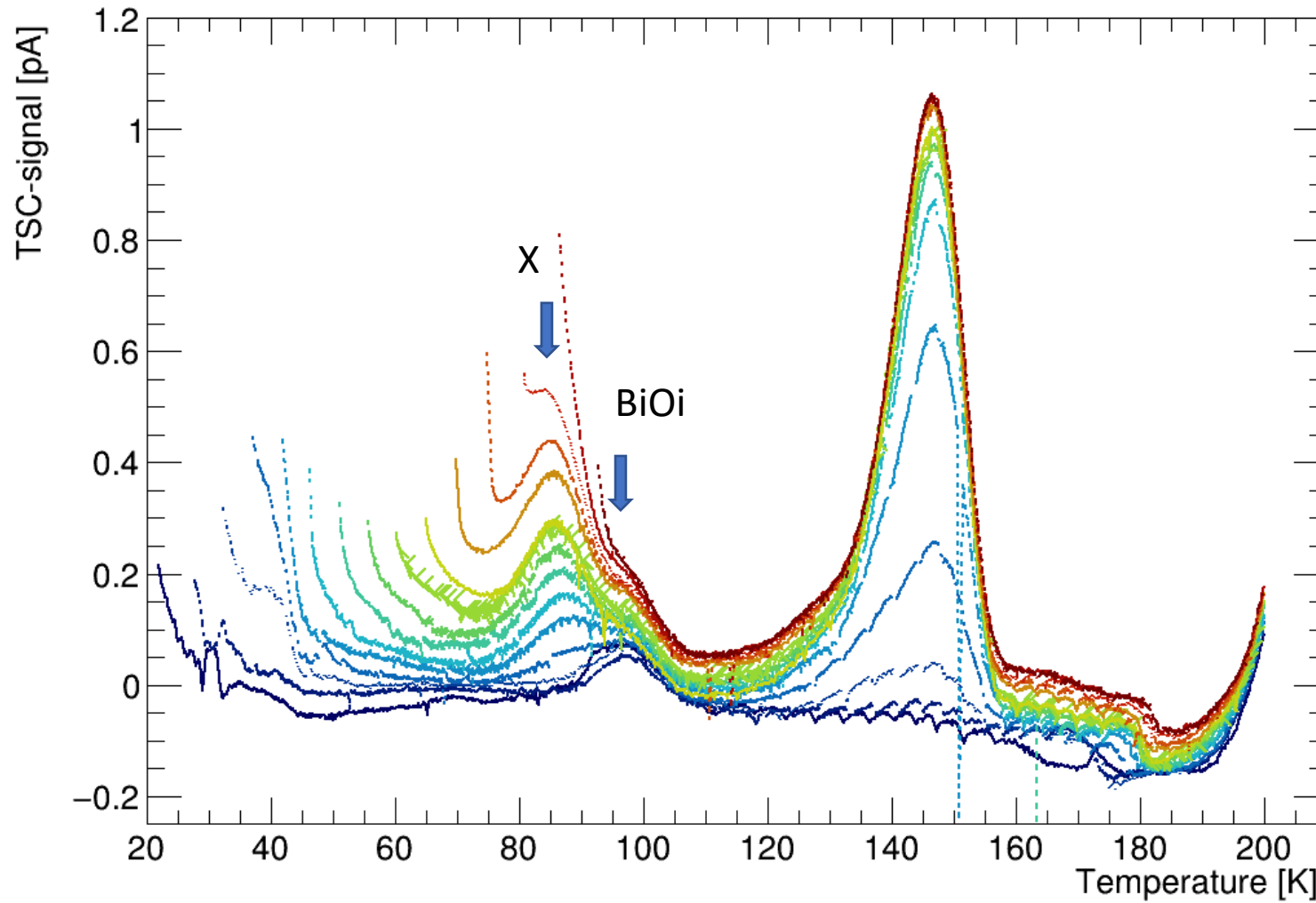
	EPI-04-81, $1.49E+13 n_{eq}/cm^2$	EPI-05-83, $3.35E+13 n_{eq}/cm^2$	
H(40K)	0.08	0.09	
H(87K)	0.35	0.41	~0.4 by fitting
H(116K)	0.03	0.03	
C_iO_i	0.17	0.24	
H(160K)	0.02	0.04	

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



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

CIS16-Cz-03-100-DS-105 (100 Ωcm, 41 μm, proton irradiated, 4.02E+12 p/cm²)

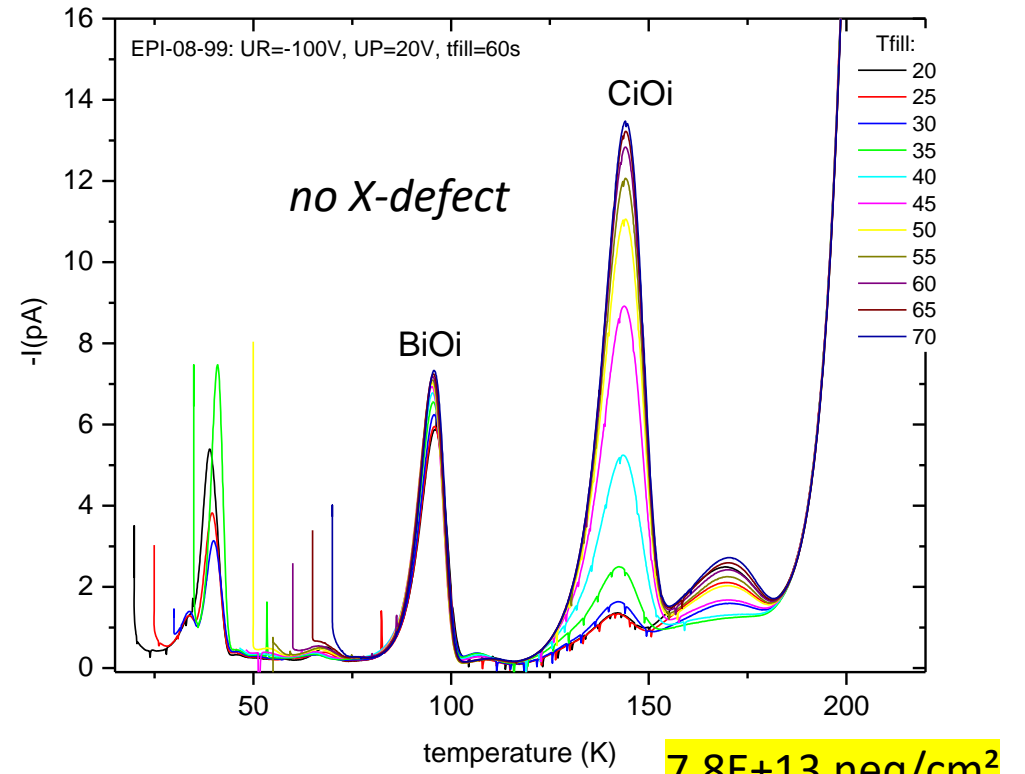


X-Defect in neutron irradiated samples

Neutron irradiated EPI Diodes investigated @ CERN

Sample	resistivity	fluence (n/cm ²)	notes
EPI-01-100	10	3.32E+14	TSC (Isidre)
EPI-04-102	50	3.32E+14	TSC (Isidre)
EPI-08-100	250	3.32E+14	TSC (Isidre)
EPI-12-99	1000	3.32E+14	TSC (Isidre)
EPI-01-98	10	7.80E+13	TSC (Isidre)
EPI-04-101	50	7.80E+13	TSC (Isidre) =D
EPI-08-99	250	7.80E+13	TSC (2018 & 2021), DLTS, IDLTS
EPI-12-96	1000	7.80E+13	TSC (Isidre)
EPI-01-80	10	1.2 E+13	DLTS,
EPI-04-94	50	1.2 E+13	TSC, DLTS
EPI-04-98	50	4.00E+12	DLTS, no TSC
EPI-04-DB-41	50	4.00E+12	TSC (Isidre) not analysed
EPI-04-82	50	2.4E+12	DLTS, TSC (not possible)
EPI-08-DB-41	250	5.00E+11	TSC (no signal)
EPI-08-83	250	5.00E+11	DLTS, TSC (verrauscht)
EPI-12-DB-41	1000	1.00E+11	TSC (no signal)
EPI-12-103	1000	1.00E+11	DLTS, TSC

no Tfill dependent measurements

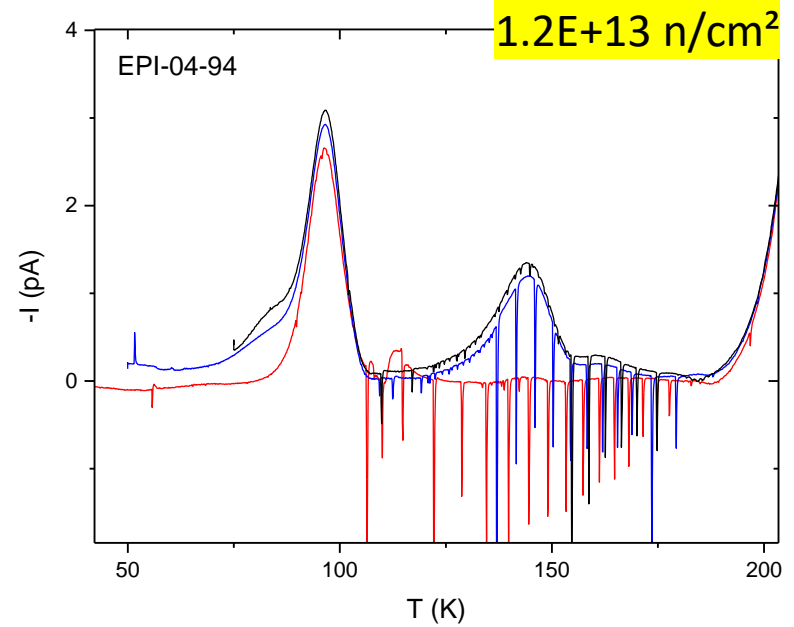


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EPI-08-83	250	5.00E+11	DLTS, TSC (verrauscht)
EPI-12-DB-41	1000	1.00E+11	TSC (no signal)
EPI-12-103	1000	1.00E+11	DLTS, TSC

no Tfill dependent measurements

no x-defect
no Tfill dependent measurements



Neutron irradiated EPI Diodes investigated @ CERN

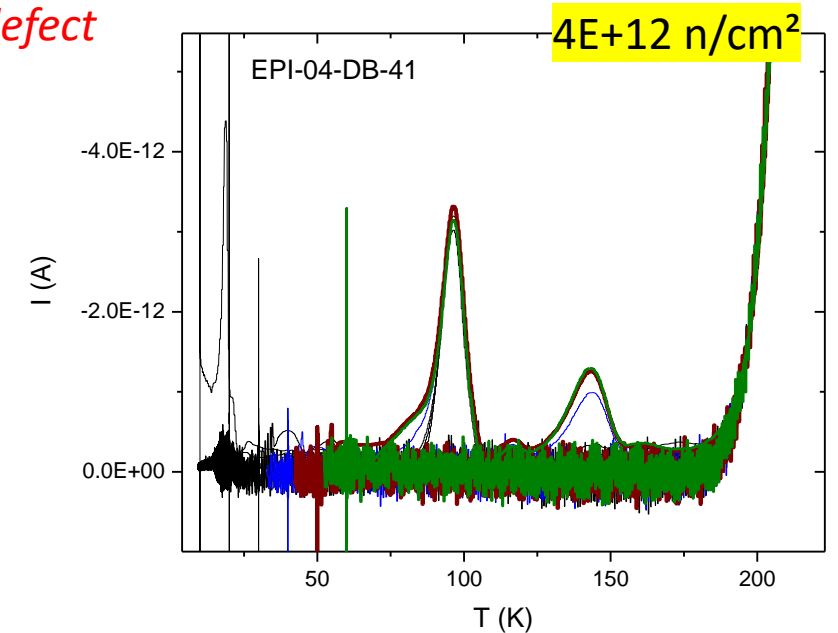
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EPI-04-98	50	4.00E+12	DLTS, no TSC
EPI-04-DB-41	50	4.00E+12	TSC (Isidre) not analysed
EPI-04-82	50	2.4E+12	DLTS, TSC (not possible)
EPI-08-DB-41	250	5.00E+11	TSC (no signal)
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no T_{fill} dependent measurements

no x-defect

no T_{fill} dependent measurements

x-defect



Neutron irradiated EPI Diodes investigated @ CERN

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EPI-12-103	1000	1.00E+11	DLTS, TSC

no Tfill dependent measurements

no x-defect

no Tfill dependent measurements

x-defect

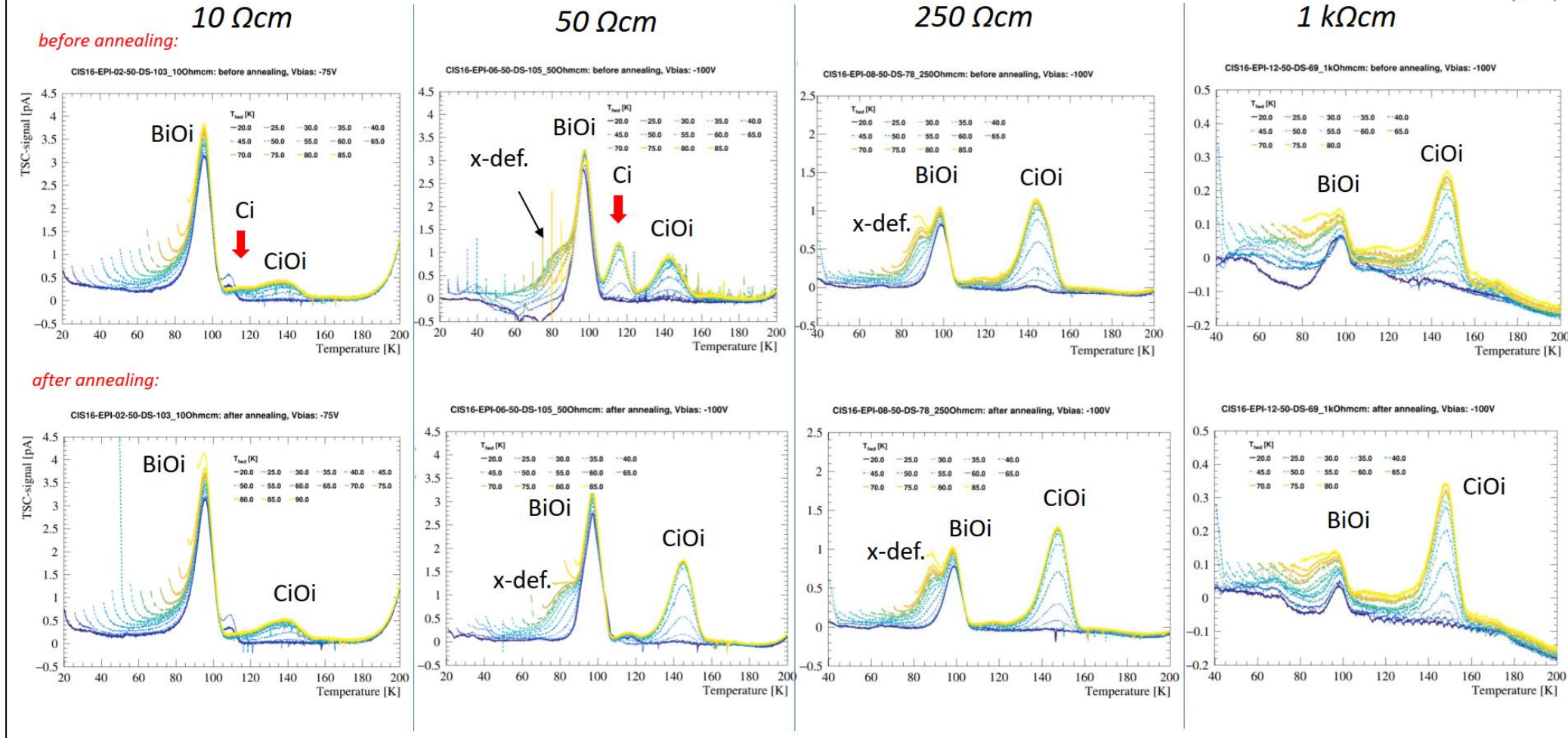
x-defect

low/bad TSC signals

- X-defect seems fluence dependent
- Dependency on the resistivity cannot be specified due to a lack of data

X-Defect in electron irradiated samples

TSC (before & after annealing 10 min @ 60°C)



3.87E+13 neq/cm²

7.14E+12 neq/cm²

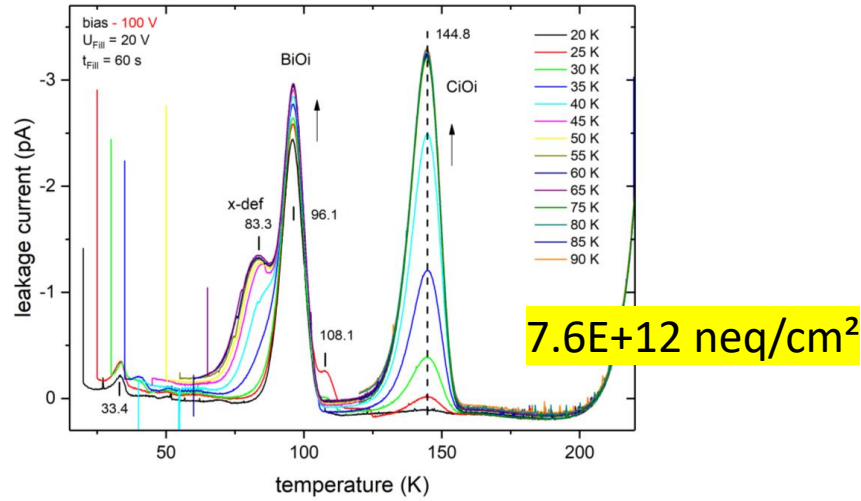
2.36E+12 neq/cm²

1.19E+12 neq/cm²

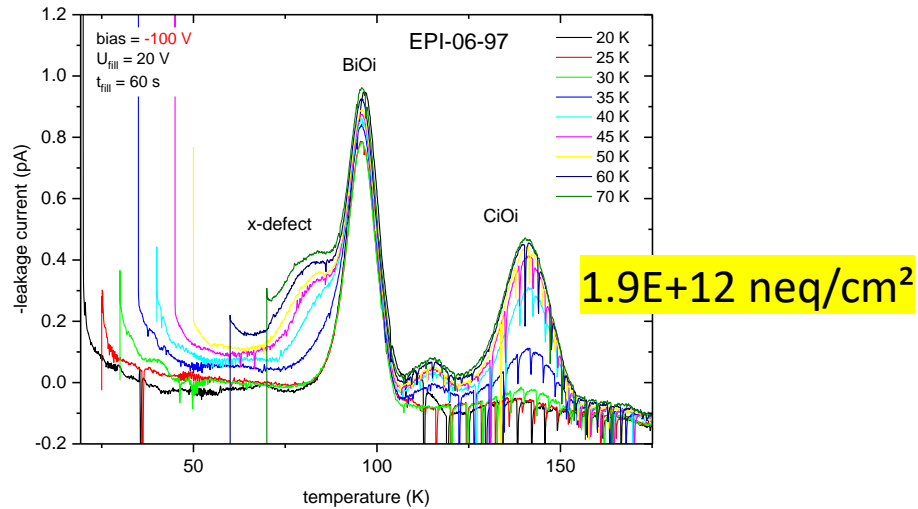
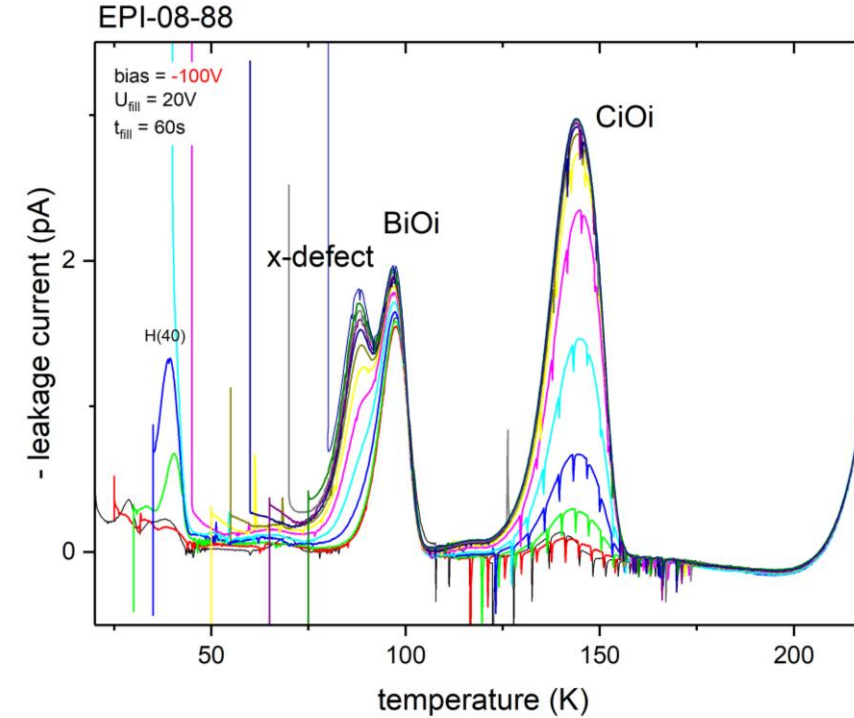
5.5 MeV electron irradiated EPI Diodes investigated @ CERN

50 Ωcm:

EPI-06-88 (50 Ωcm, 5.5 MeV electrons, $7.6e+12$ neq/cm²)



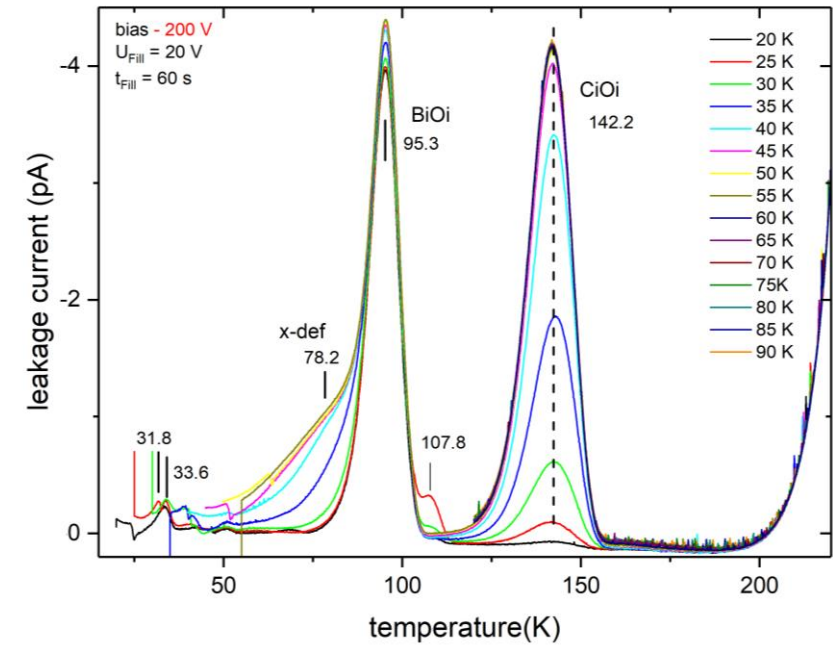
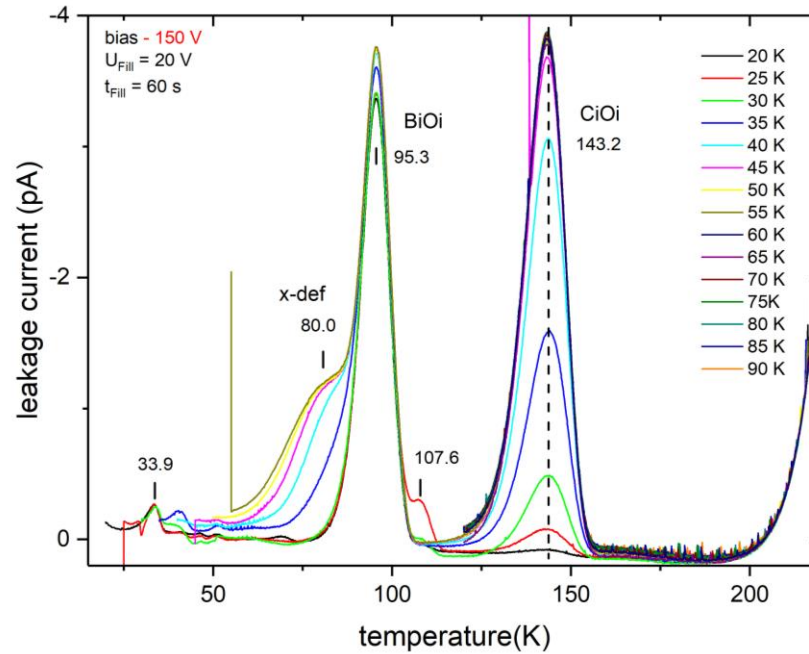
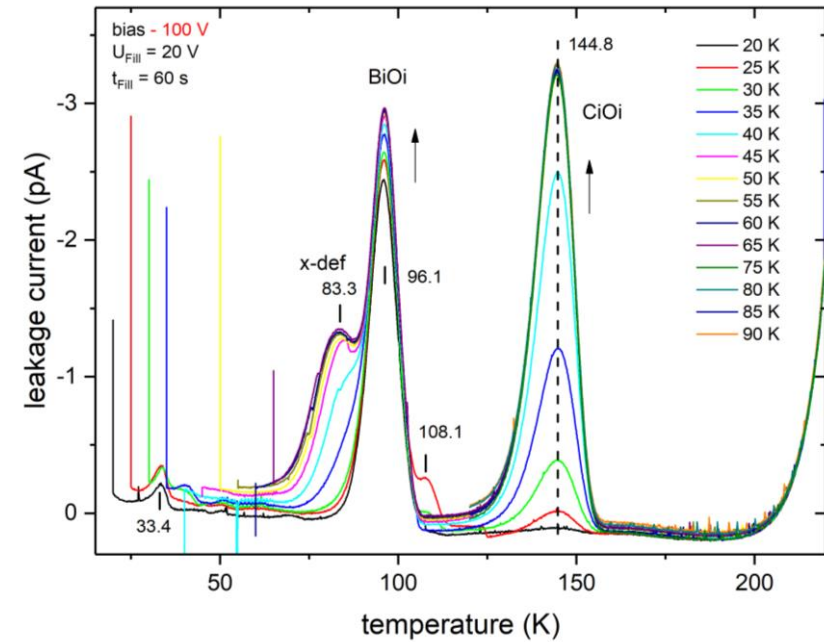
250 Ωcm:



3.8E+12 neq/cm²

5.5 MeV electron irradiated EPI Diodes investigated @ CERN

bias dependence of the x-defect:



EPI-06-88 (50 Ωcm , 5.5 MeV electrons, $7.6e+12 \text{ n}_{eq}/\text{cm}^2$)

6 MeV electron irradiated EPI Diodes investigated @ Hamburg

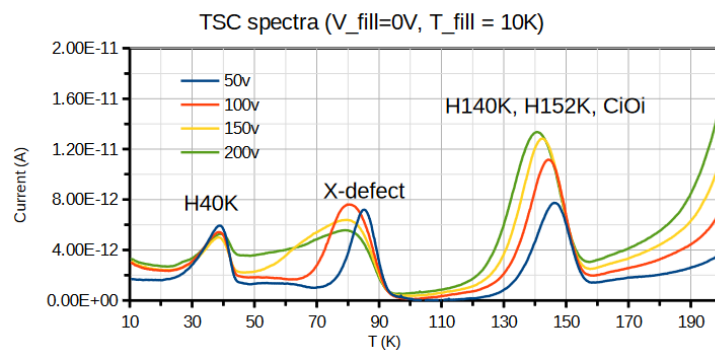
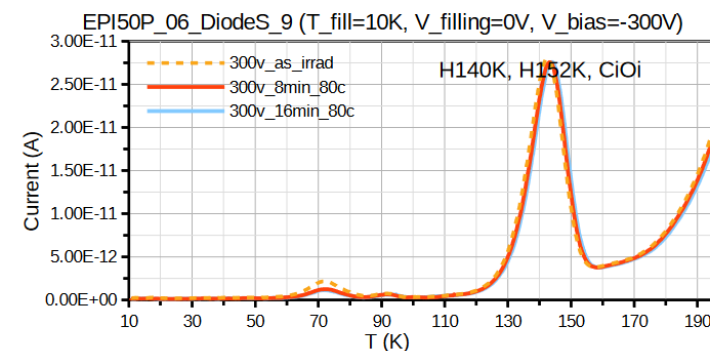
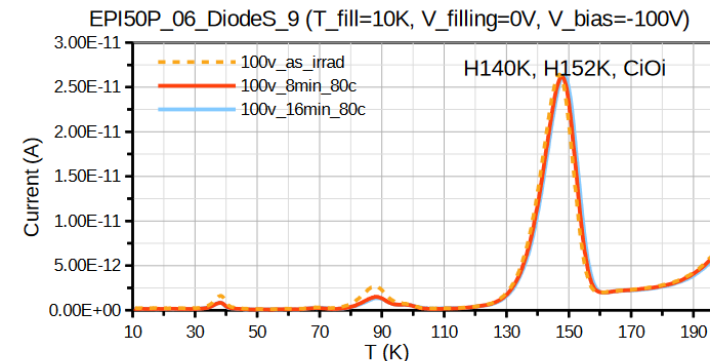
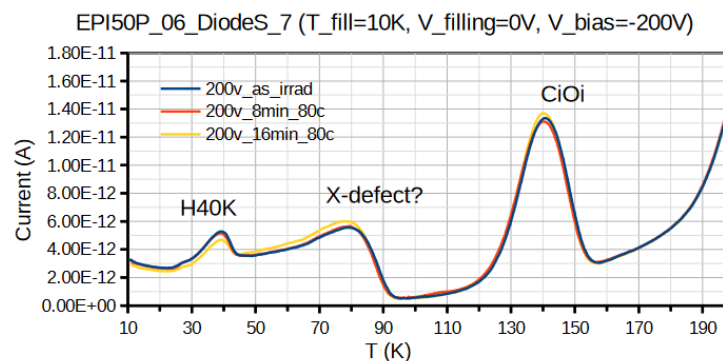
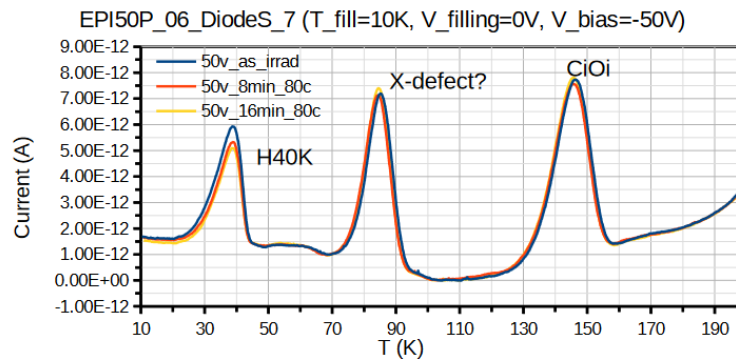
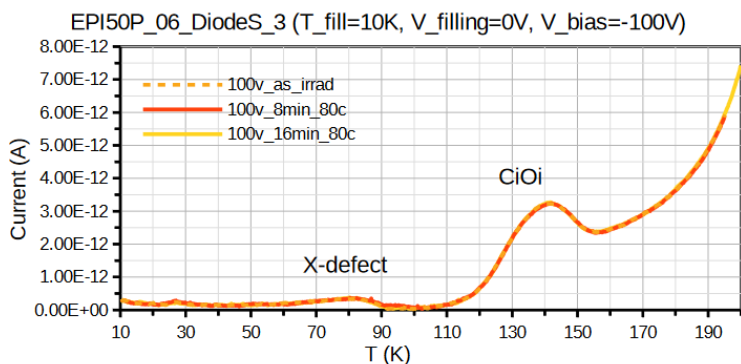
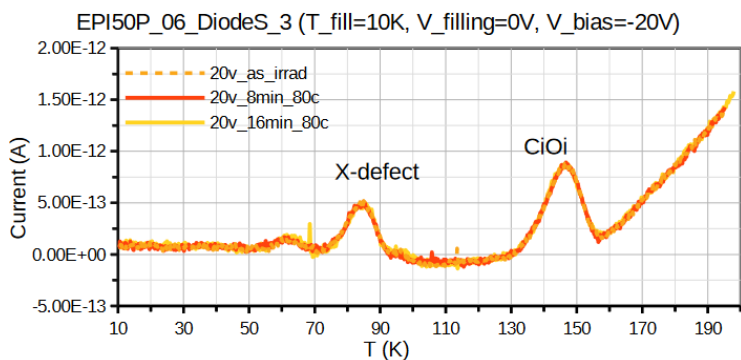
Chuan, AR meeting
09.06.21 & 19.05.21):

10 Ωcm:

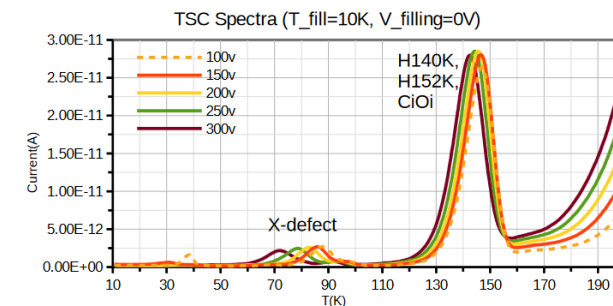
1.59E+14 neq/cm²

2.39E+14 neq/cm²

3.98E+13 neq/cm²



X-defect ??



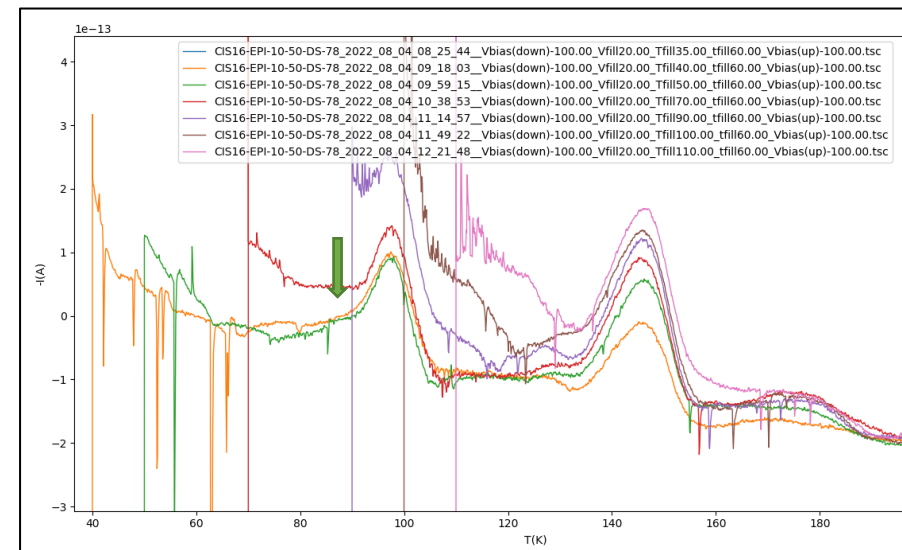
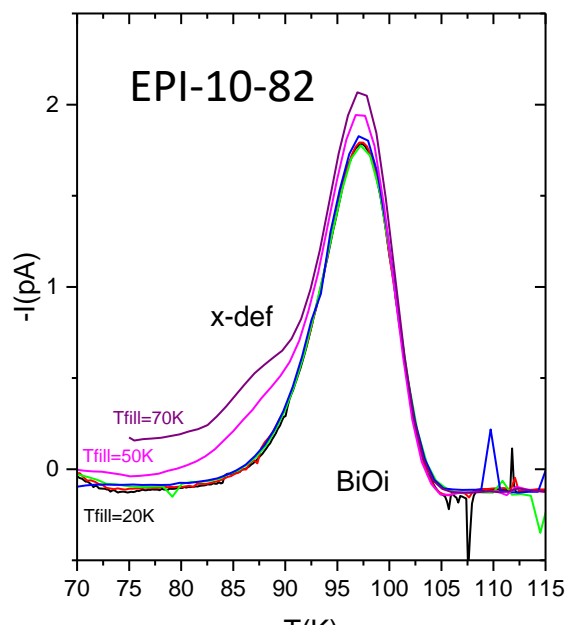
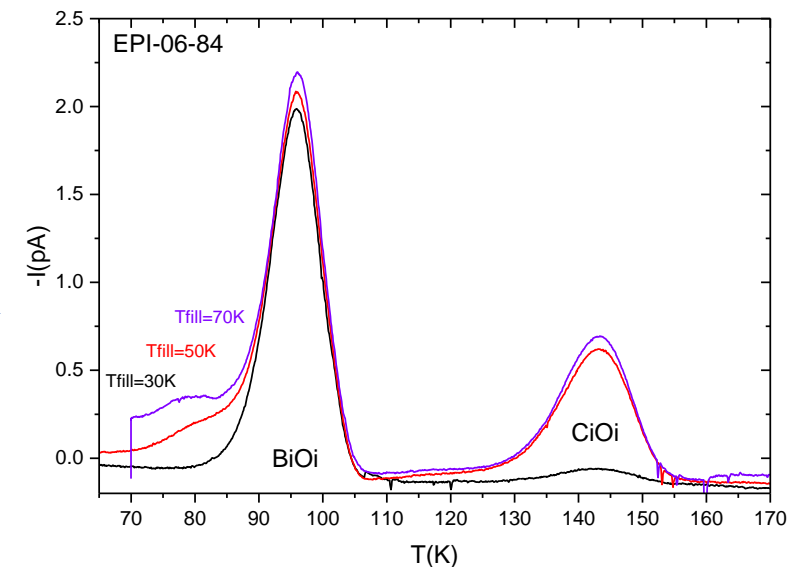
- X-defect for 6 MeV electrons also at higher fluences compared to 200 MeV

X-Defect in gamma irradiated samples

^{60}Co Gamma irradiated EPI Diodes investigated @ CERN

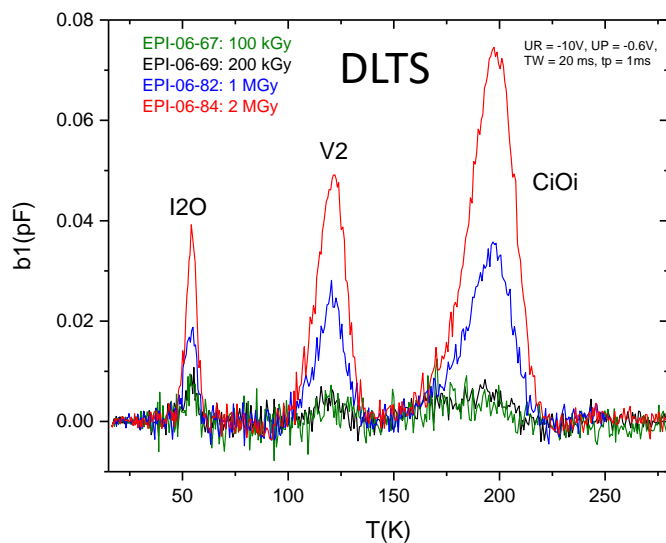
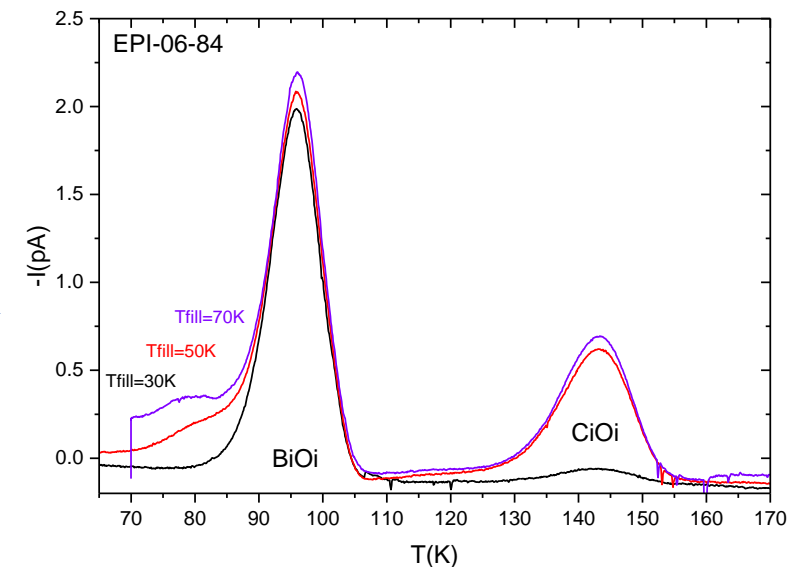
Sample	resistivity (Ωcm)	dose (Mrad)	dose (MGy)	
EPI-06-DS-67	50	10	0.1	not annealed
EPI-06-DS-69 ¹⁾	50	20	0.2	not annealed
EPI-06-DS-82 ¹⁾	50	100	1	not annealed
EPI-05-DS-73 ²⁾	50	100	1	several month @ RT
EPI-06-DS-84 ¹⁾	50	200	2	not annealed

EPI-10-78	250	10	0.1	not annealed
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 (DLTS) & annealed (DLTS)
EPI-08-DS-79 ²⁾	250	100	1	several month @ RT

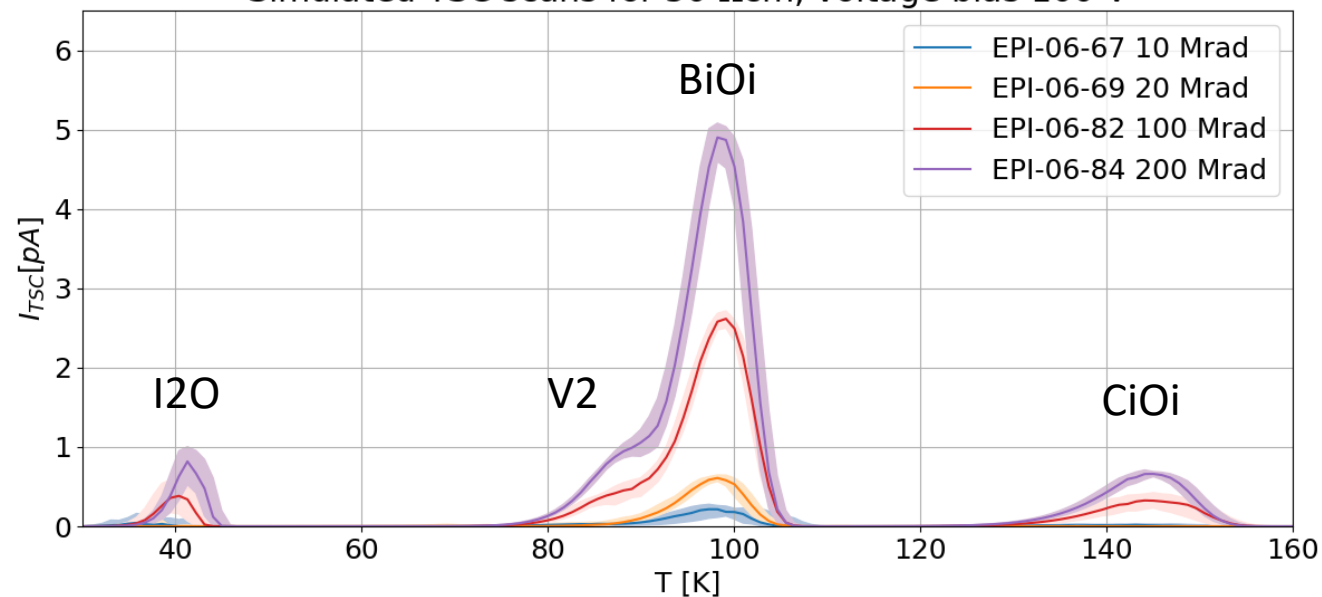


^{60}Co Gamma irradiated EPI Diodes investigated @ CERN

Sample	resistivity (Ωcm)	dose (Mrad)	dose (MGy)	
EPI-06-DS-67	50	10	0.1	not annealed
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-06-DS-84 ¹⁾	50	200	2	not annealed
EPI-10-78	250	10	0.1	not annealed
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 (DLTS) & annealed (DLTS)
EPI-08-DS-79 ²⁾	250	100	1	several month @ RT



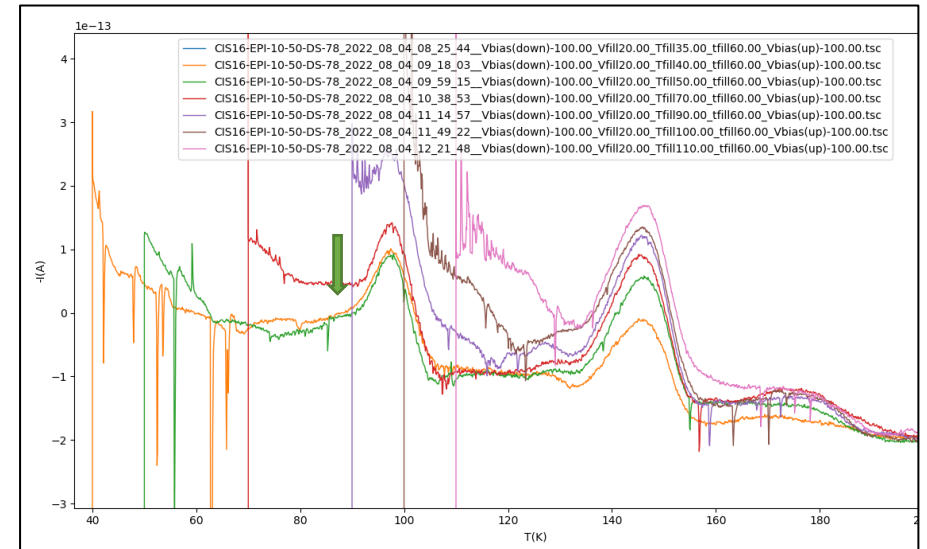
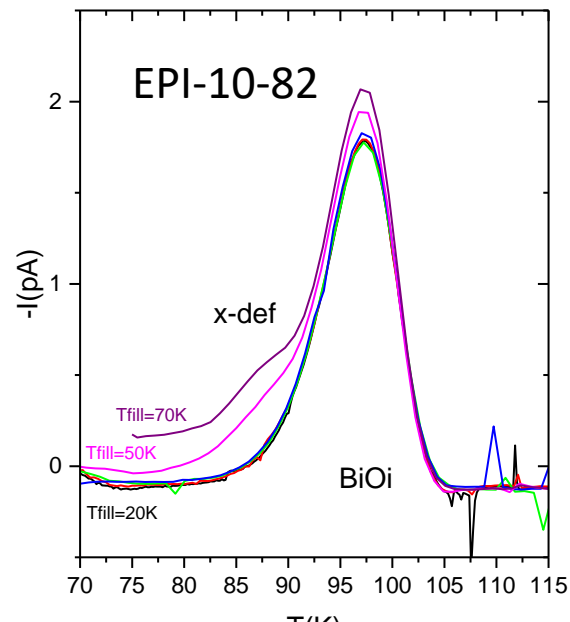
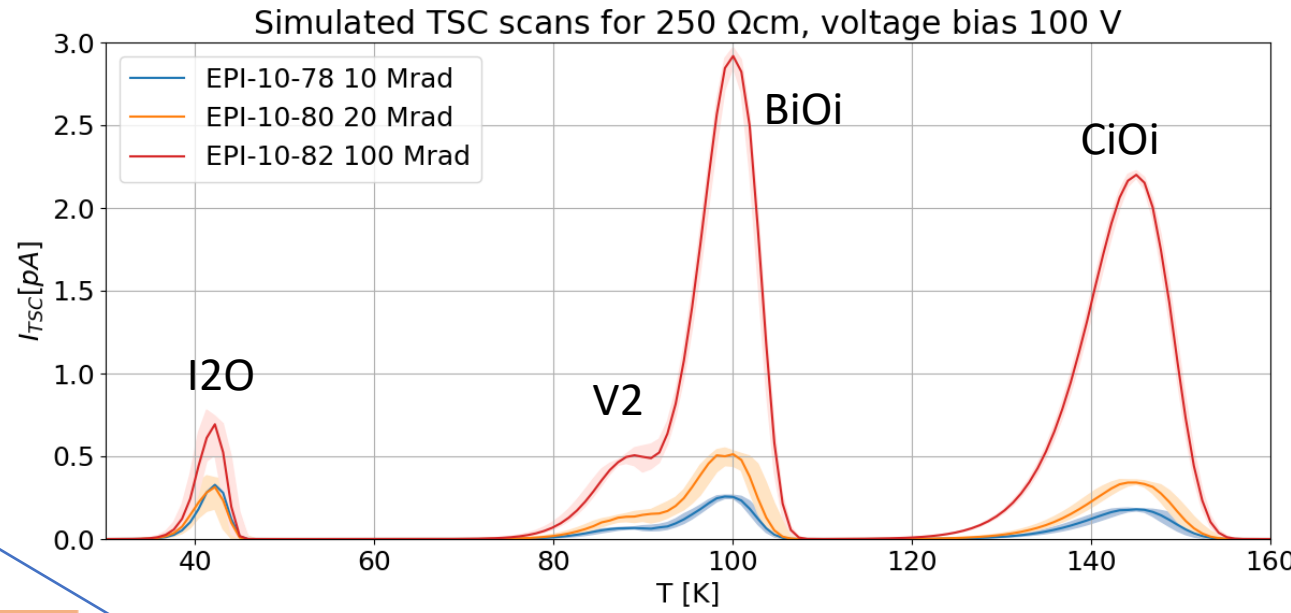
Simulated TSC scans for 50 Ωcm , voltage bias 100 V



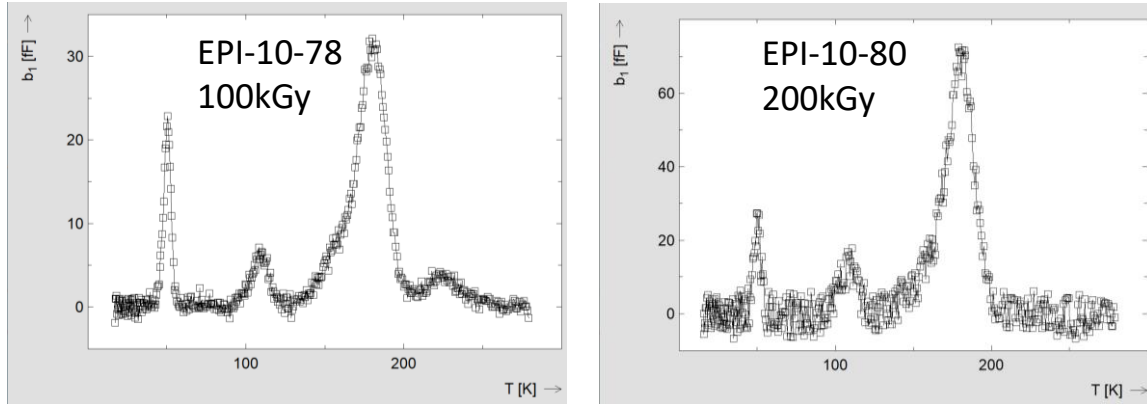
^{60}Co Gamma irradiated EPI Diodes investigated @ CERN

Sample	resistivity (Ωcm)	dose (Mrad)	dose (MGy)	
EPI-06-DS-67	50	10	0.1	not annealed
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-06-DS-84 ¹⁾	50	200	2	not annealed

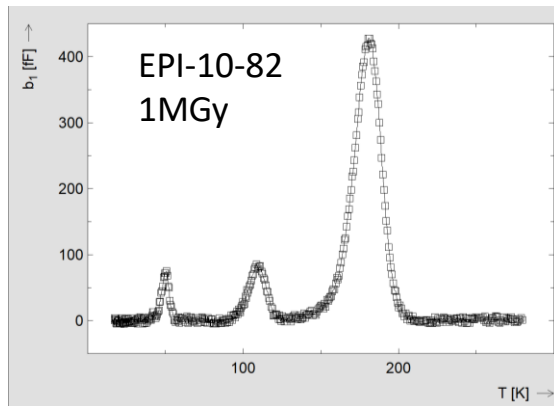
EPI-10-78	250	10	0.1	not annealed
EPI-10-DS-80 ¹⁾	250	20	0.2	not annealed
EPI-08-DS-80 ²⁾	250	20	0.2	unknown
EPI-10-DS-82 ¹⁾	250	100	1	not annealed (DLTS) & annealed (DLTS)
EPI-08-DS-79 ²⁾	250	100	1	several month @ RT



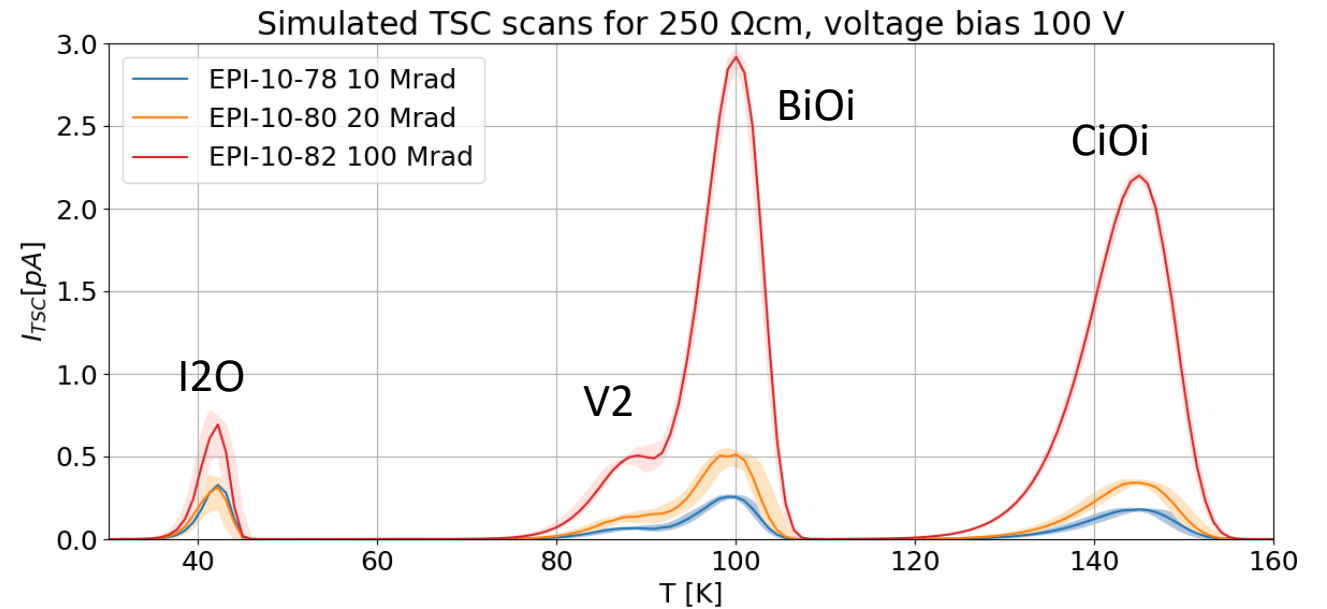
250 Ωcm EPI diode



DLTS



- X-defect also for the highest doses observed



Summary

Chuan, AR meeting 16.09.2020:
EPI (10 Ωcm) **4.28E+13 /cm²**
⇒ **Yes**

Chuan, AR meeting 19.08.20:
EPI (10 Ωcm) **4.96E+15 /cm²**
⇒ **No**
⇒ Yes (light injection) ??

Dependence on the particle type or error of the fluence ??

resistivity [Ωcm]	Protons		Neutrons		Electrons (200 MeV)		Electrons (5 MeV)	
10 (EPI)	no data		no data		= 4.18E+13	no	no data	
50 (EPI)	≥ 7.8E+13	no						
	≤ 4.28E+13	yes	≤ 1.2E+13	yes	= 7.14E+12	yes	≤ 7.6E+12	yes
100 (CZ)	= 2E+12	yes	no data		no data		no data	
250 (EPI)	≥ 7.8E+13	no	= 7.8E+13	no				
	≤ 7.8E+13	(no data)	no data		= 2.36E+12	yes	= 3.8E+12	yes
1000 (EPI)	no data		no data		= 1.19E+12	yes	no data	

Chuan, AR meeting 09.06.21:
EPI (10 Ωcm), **6 MeV electrons**
2.39E+14 /cm² => yes ??
1.59E+14 /cm² => yes ??
3.98E+13 /cm² => yes

Dependence on the particle energy??

Chuan, AR meeting 03.02.21/ 27.04.22:
EPI (250 Ωcm) **4.28E+13 /cm²**
⇒ **No (before annealing)**
⇒ Yes (after annealing)

Chuan, AR meeting 03.02.21/ 27.04.22:
EPI (2k Ωcm) **4.28E+13 /cm²**
⇒ **No (before annealing)**
⇒ Yes (before annealing, light injection) ??
⇒ Yes (after annealing)

→ *Indicates resistance dependence & fluence dependence*

Summary

Chuan, AR meeting 16.09.2020:
EPI (10 Ωcm) **4.28E+13 /cm²**
⇒ **Yes**

Chuan, AR meeting 19.08.20:
EPI (10 Ωcm) **4.96E+15 /cm²**
⇒ **No**
⇒ Yes (light injection) ??

Dependence on the particle type or error of the fluence ??

resistivity [Ωcm]	Protons		Neutrons		Electrons (200 MeV)		Electrons (5 MeV)	
10 (EPI)	no data		no data		= 4.18E+13	no	no data	
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	≤ 4.28E+13	yes	≤ 1.2E+13	yes	= 7.14E+12	yes	≤ 7.6E+12	yes
100 (CZ)	= 2E+12	yes	no data		no data		no data	
250 (EPI)	≥ 7.8E+13	no	= 7.8E+13	no				
	≤ 7.8E+13	(no data)	no data		= 2.36E+12	yes	= 3.8E+12	yes
1000 (EPI)	no data		no data		= 1.19E+12	yes	no data	

Chuan, AR meeting 09.06.21:
EPI (10 Ωcm), **6 MeV electrons**
2.39E+14 /cm² => yes ??
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3.98E+13 /cm² => yes

Dependence on the particle energy??

Chuan, AR meeting 03.02.21/ 27.04.22:
EPI (250 Ωcm) **4.28E+13 /cm²**
⇒ **No (before annealing)**
⇒ Yes (after annealing)

Chuan, AR meeting 03.02.21/ 27.04.22:
EPI (2k Ωcm) **4.28E+13 /cm²**
⇒ **No (before annealing)**
⇒ Yes (before annealing, light injection) ??
⇒ Yes (after annealing)

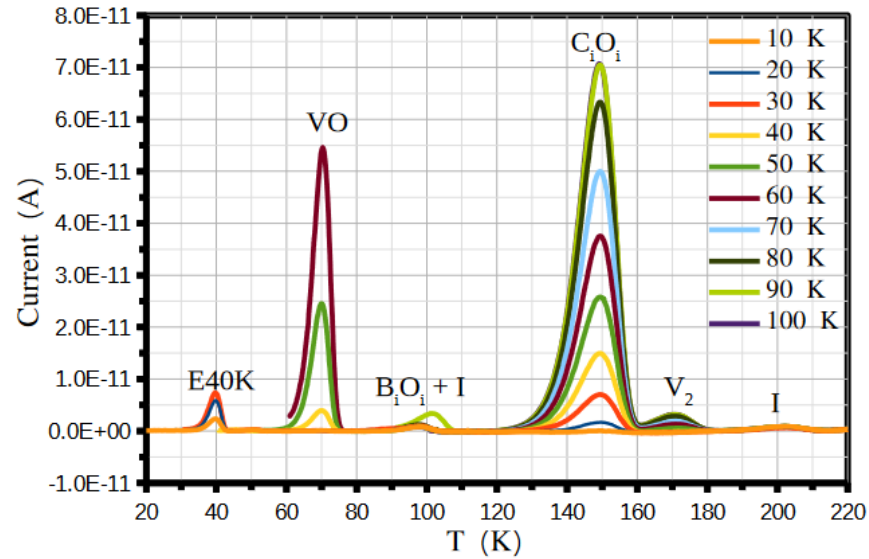
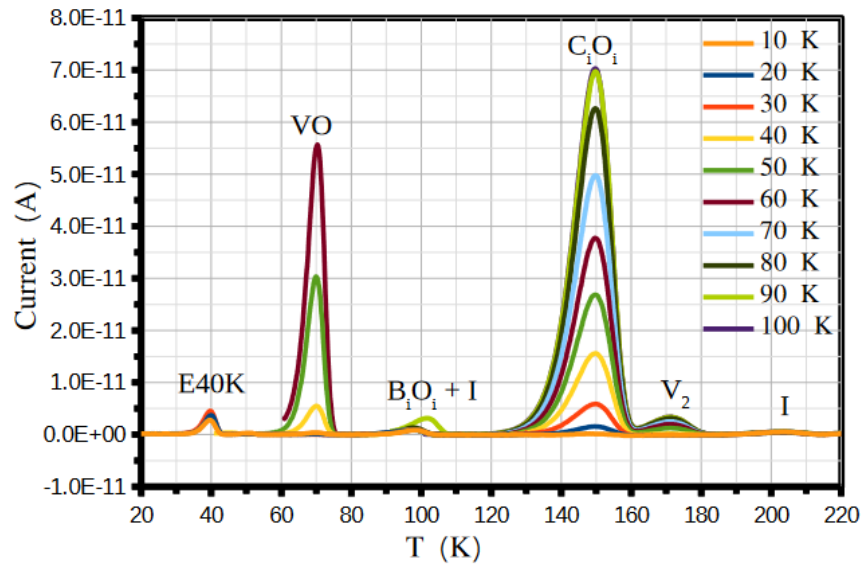
→ *Indicates resistance dependence (!) & fluence dependence*

X-defect:

- **Not visible at high fluences (fluence dependence)**
- Resistance dependence (?): higher doping x-defect still visible at higher fluences
- particle energy dependence (?): low energy particles produce X-defect
- seen in all Gamma-irrad. Samples (!)

=> Point defect that disappears when cluster formation increases ??

Chuan AR meeting 21.06.2022

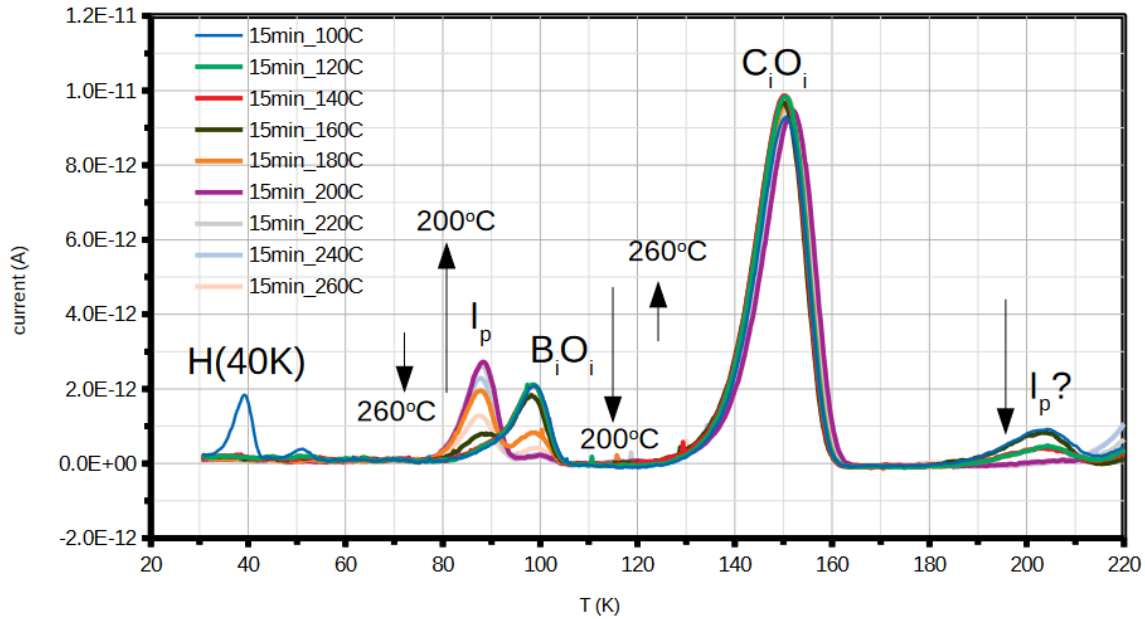


- P-stop diode, 100 Mrad (left) / P-spray diode, 100 Mrad (right)
- Same experimental parameters but with different T_{fill}
- The amplitude of E40K, VO, C_1O_1 , V_2 appeared strongly temperature dependent

^{60}Co Gamma irradiated FZ Diodes investigated @ Hamburg

Chuan AR meeting 16.08.2022

200 Mrad, $T_{\text{fill}} = 30\text{K}$, $V = -300\text{V}$
 Annealing study



100 Mrad, $T_{\text{anneal}} = 170^\circ\text{C}$
 bias dependence

no poole frenkel effect

