TSC measurements on 200µm pad diodes irradiated with 23 MeV protons

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Universität Hamburg
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PHYSICS AT THE TERA SCALE
Helmholtz Alliance

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02-04/12/2015

Outline

- Framework:

- R&D studies of Si-sensors for future HEP experiments
- focus on proton-induced bulk-damage
- **goal**: radiation-damage model based on microscopic measurements

- IV/CV and TSC Measurements on thin Float Zone diodes:

- after irradiation with 23 MeV protons, $\Phi=(0.3 – 1.0) \cdot 10^{14}$ neq/cm^2
- isothermal annealing
- the new analysis tool for defect investigation

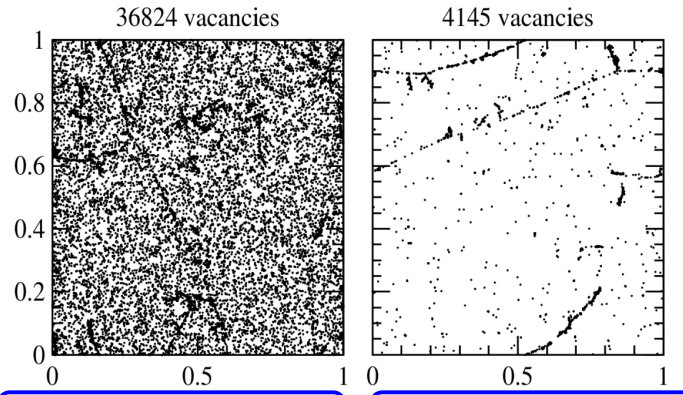
- Summary and Outlook

Introduction

Future HEP experiments:
- NIEL ~ $2 \cdot 10^{16}$ neq/cm^2
- IEL ~ 5 MGy

This work:
1) understand the properties of proton-induced defects
   in n-type and p-type Si
   in the energy range (MeV – GeV)
2) develop a radiation-damage model
   based on microscopic measurements

[10^{14} neq in 1 um^3, `M. Huhtinen NIM A 491(2002)]



10 MeV protons
Mainly POINT DEFECTS

24 GeV/c protons
Mainly CLUSTERS

Introduction

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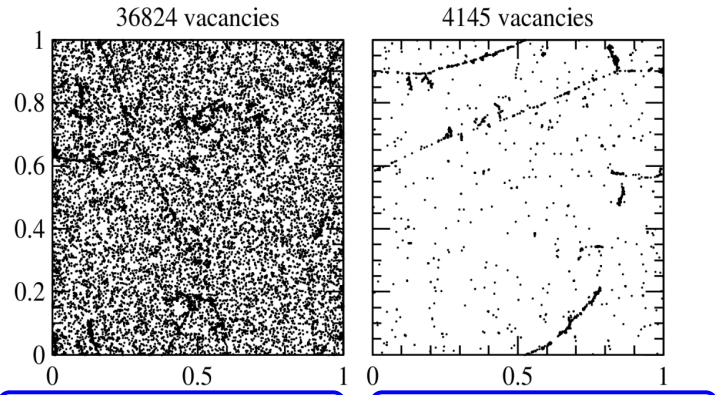
   based on microscopic measurements

This presentation:
- p- and n-type Float Zone (FZ) diodes
  (deep diffused, active thickness ~200µm)

- samples irradiated with 23 MeV protons
- fluence range: $(0.3\text{-}1) \cdot 10^{14}$ neq/cm^2

- measurements:
  IV/CV and TSC measurements for
  different annealing steps @80ºC

[10^{14} neq in 1 um^3, `M. Huhtinen NIM A 491(2002)]



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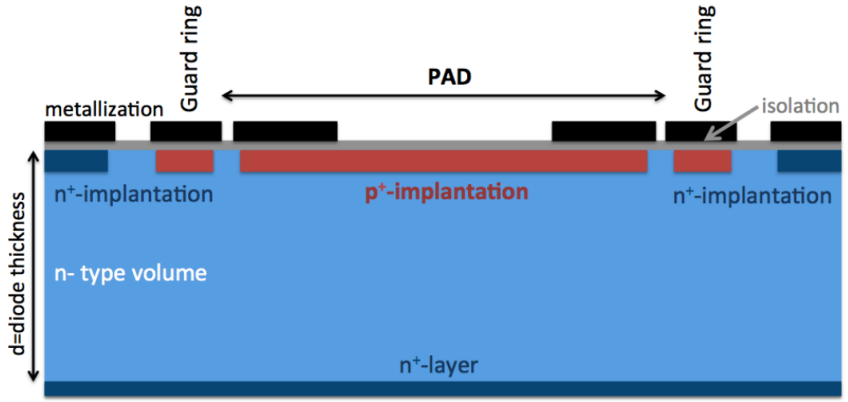

DIODES (5x5mm²)	N	P
Thickness (µm)	~ 220	~210
Neff (cm^{-3})	$2.9 \cdot 10^{12}$	$2.5 \cdot 10^{12}$

Experimental procedure

IV/CV

macroscopic

- before and after irradiation
- after **isothermal annealing**

- IV/CV in reverse bias,
at three temperatures:
T = + 20ºC (10 kHz)
T = 0ºC (1 kHz)
T = -20ºC (455 Hz)

Sensor properties (and limits)
- Vdep, Neff, leakage current, ...

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TSC

microscopic

1) COOLING @ reverse bias

2) TRAP FILLING @ T = 10K
forward bias, *with free charge carriers*
→ *majority & minority carriers*

3) RECORDING OF CHARGE EMISSION
@ reverse bias, β = 11K/min

4) LEAKAGE CURRENT

Defect properties (and impact)
$\Delta E_{n,p}$, concentration, (capture cross-section)

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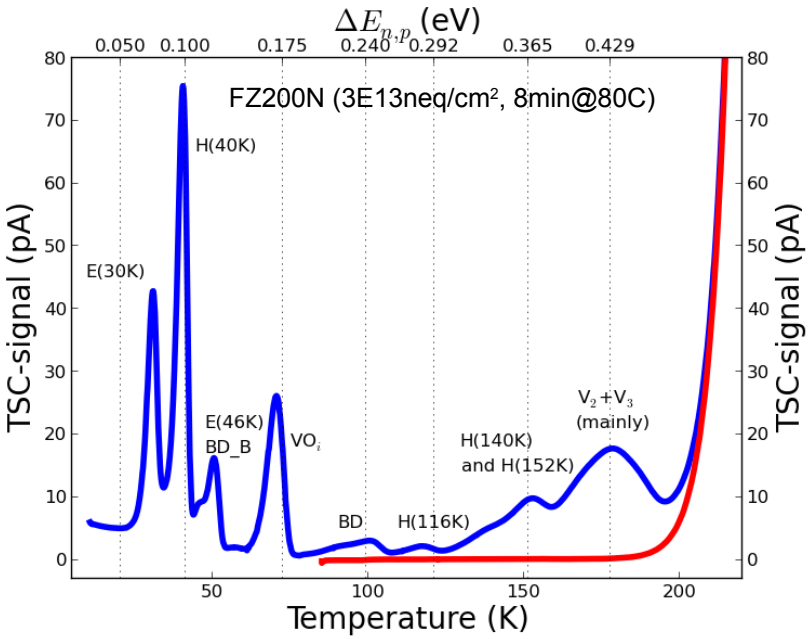
Sensor properties (and limits)
- Vdep, Neff, leakage current, ...

Defect properties (and impact)
$\Delta E_{n,p}$, concentration, (capture cross-section)

1) search for defects with an impact on the macroscopic diode parameters
2) aim: the results will be used as input for TCAD simulations

Analysis of TSC spectra



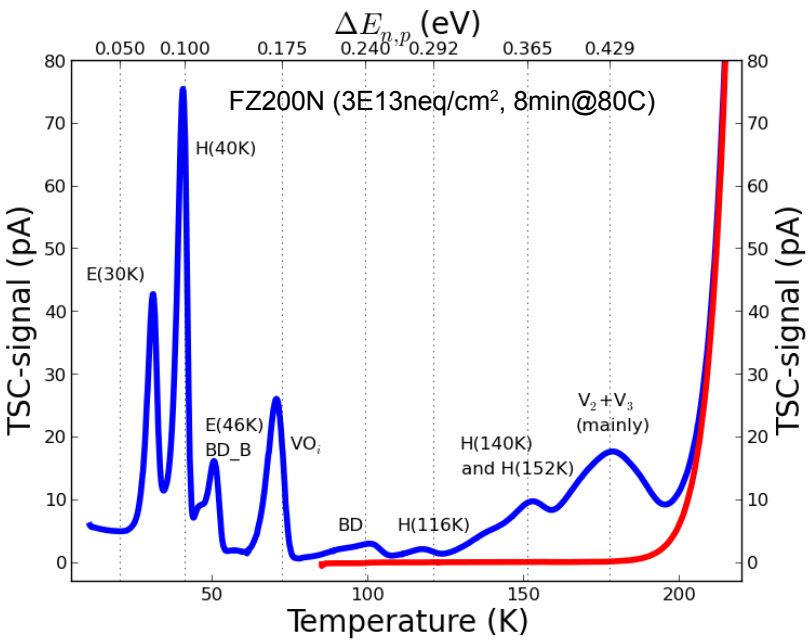
- **TSC spectrum** (10K, 290K)
- typical filling current ~ 1mA

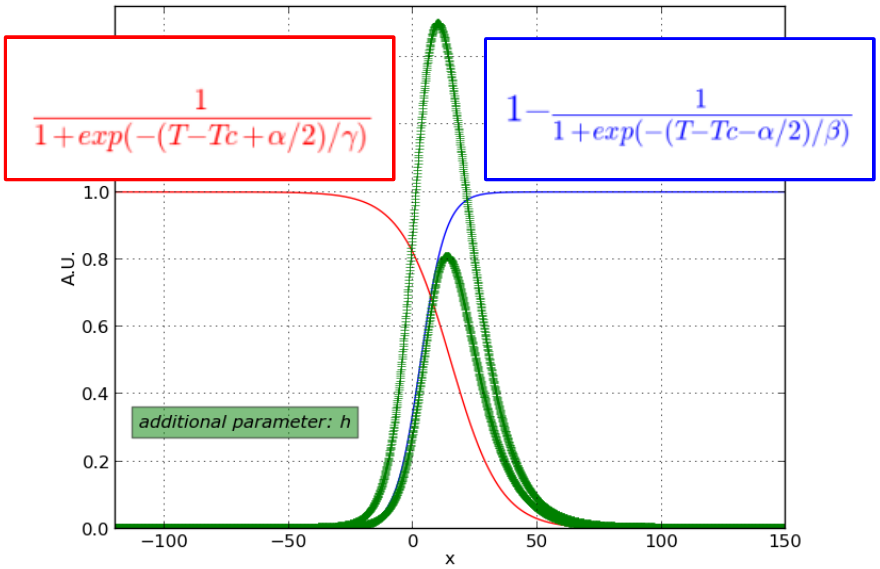
$$\Delta E_{n,p} = \pm\left(E_{C,V} - E_t\right)$$

- **LEAKAGE current**
- subtraction (80K, 290K)

$$I_{leakage} \propto \exp\left(\frac{-\Delta E_a}{k_B T}\right)$$

Analysis of TSC spectra





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- PEAK FITTER (5 parameters/peak):
constrained multivariate
least-squares optimization
- A = peak amplitude
- Tc = peak center
- α → temperature shift
- β → falling edge
- γ → rising edge

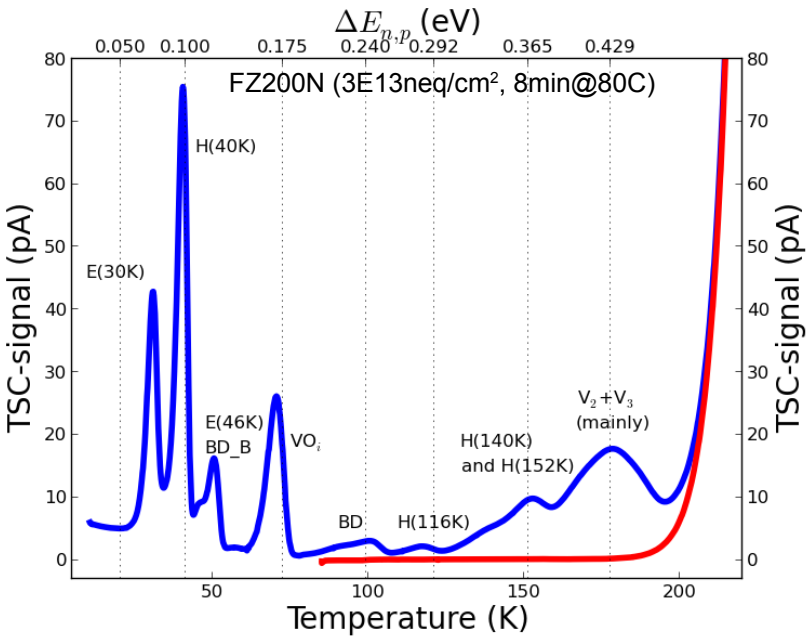
+ constraints (on par. and fitting range)

GOAL:

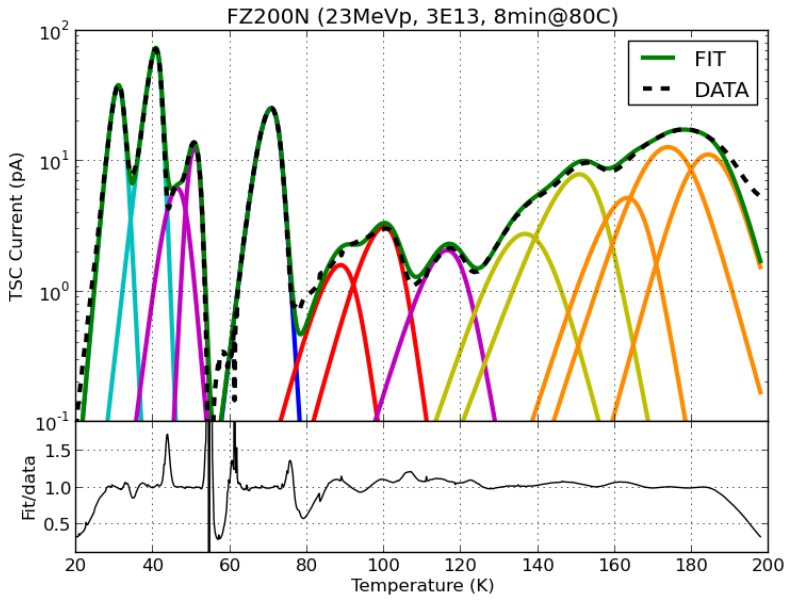
- *concentration* N_t
- *activation energy* $\Delta E_{n,p}$

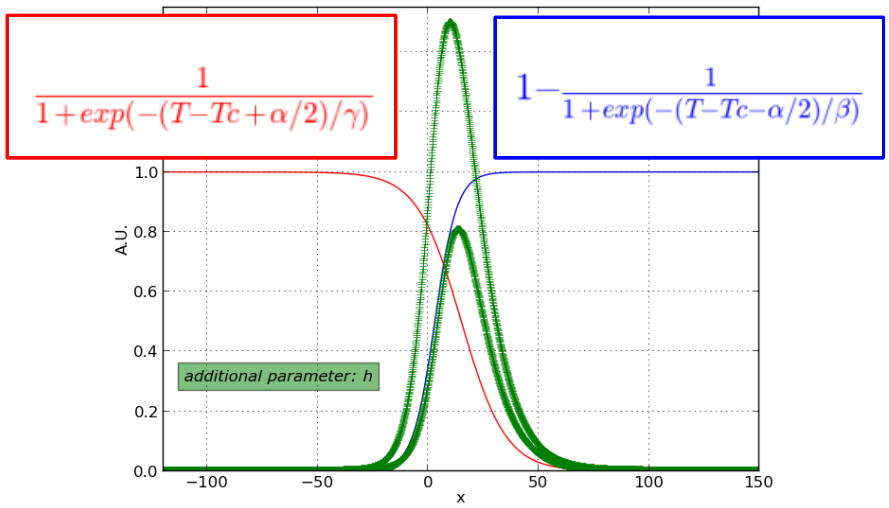
$$N_t = \frac{2 \cdot Area_{peak}}{q_0 \cdot Volume}$$

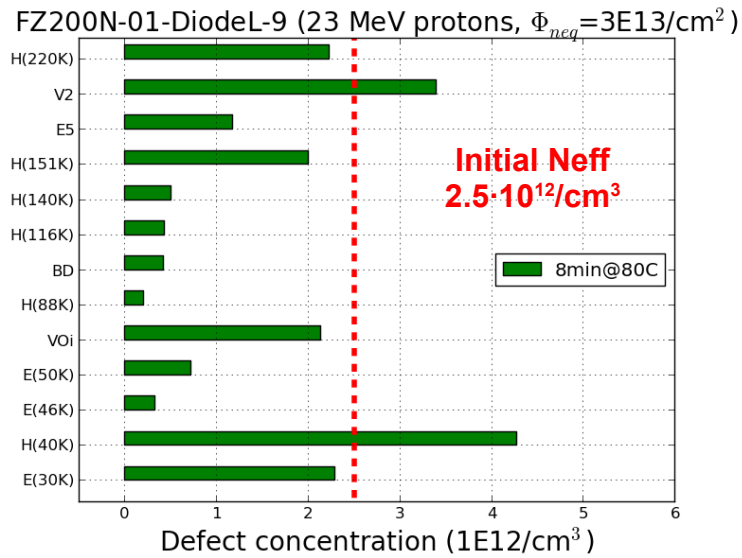
Analysis of TSC spectra



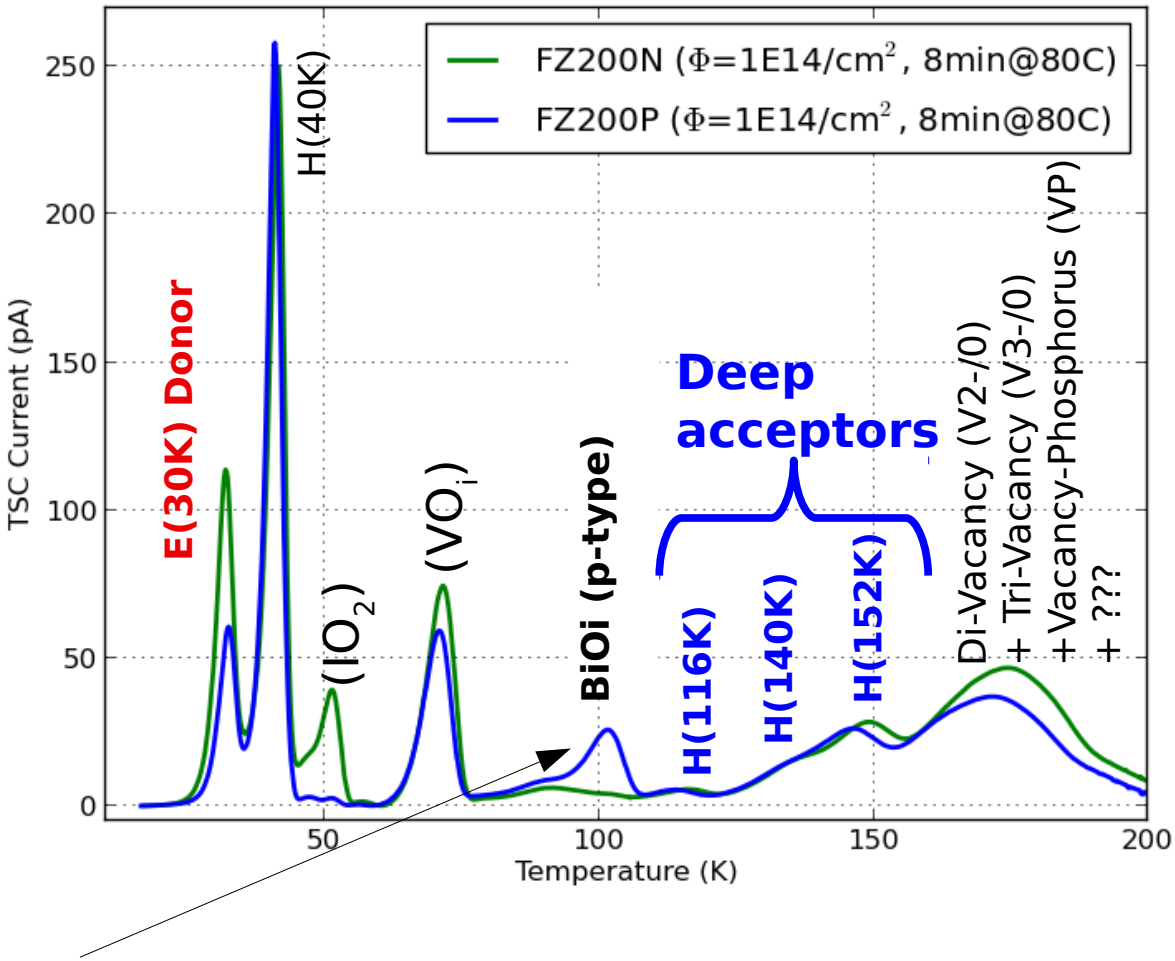
FIT







Comparison between n-type and p-type sensors



Boron-oxygen? in p-type?

- main defects with impact on SC:
  E(30K): +SC
  deep acceptors: -SC
- introduction rates for deep acceptors: similar in n- and p-type

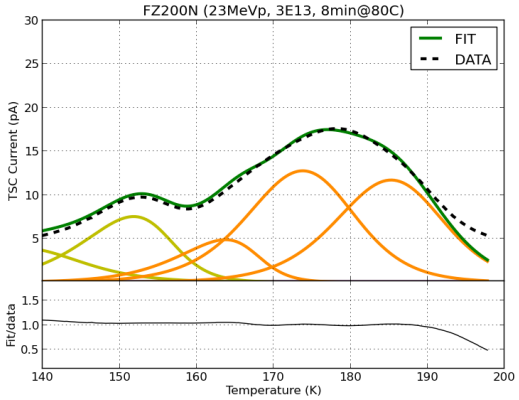
- T=100K: B_iO_i ?
- investigations on properties and annealing of B_iO_i are needed
- less information available for **p-type devices**

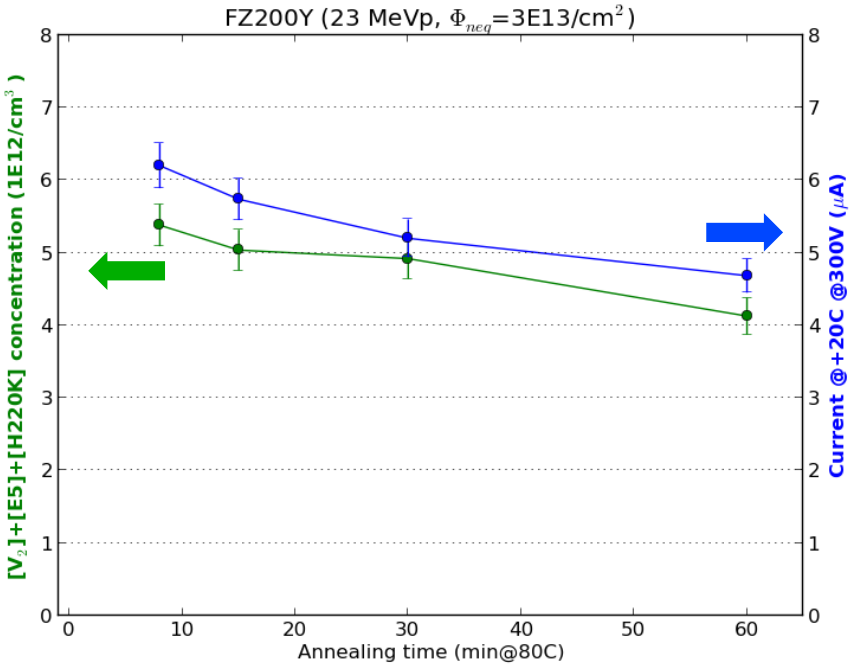
→ better understanding of radiation tolerance of boron-doped Si-devices

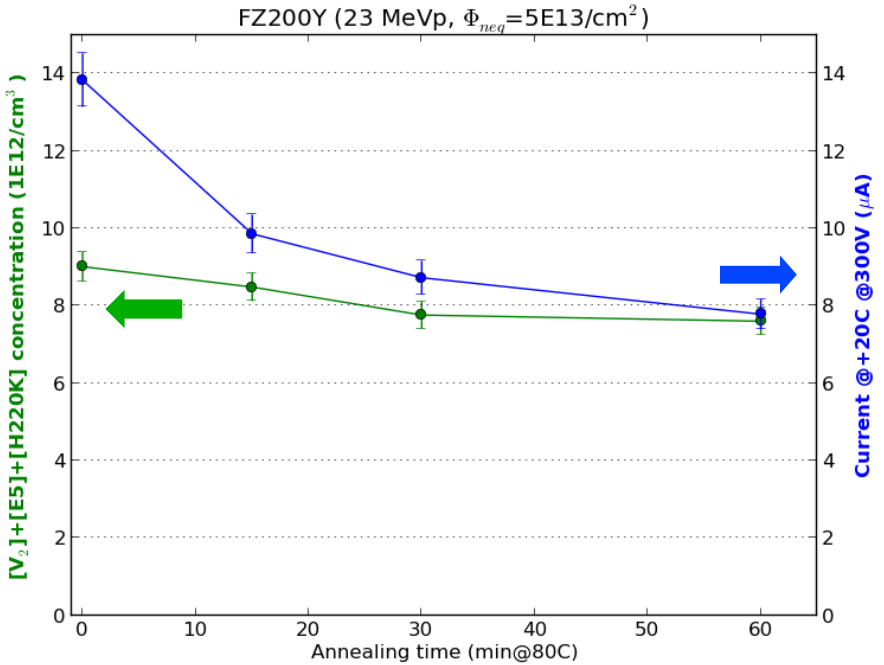
→ **information from:**
- IV + TSC → leakage current
- CV + TSC → Neff
- Front illumination → e^-/h^+ traps

IV ↔ TSC for p-type sensors

Qualitative correlation:
- **V2, E5, H(220K) concentration** from TSC (Vh=300V)
- **leakage current** from IV (@+20C, @300V)

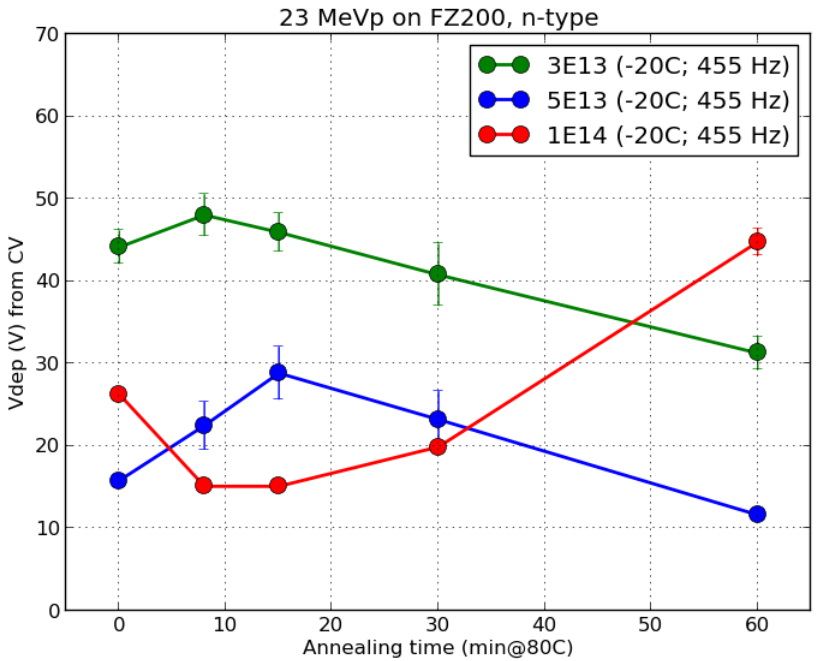


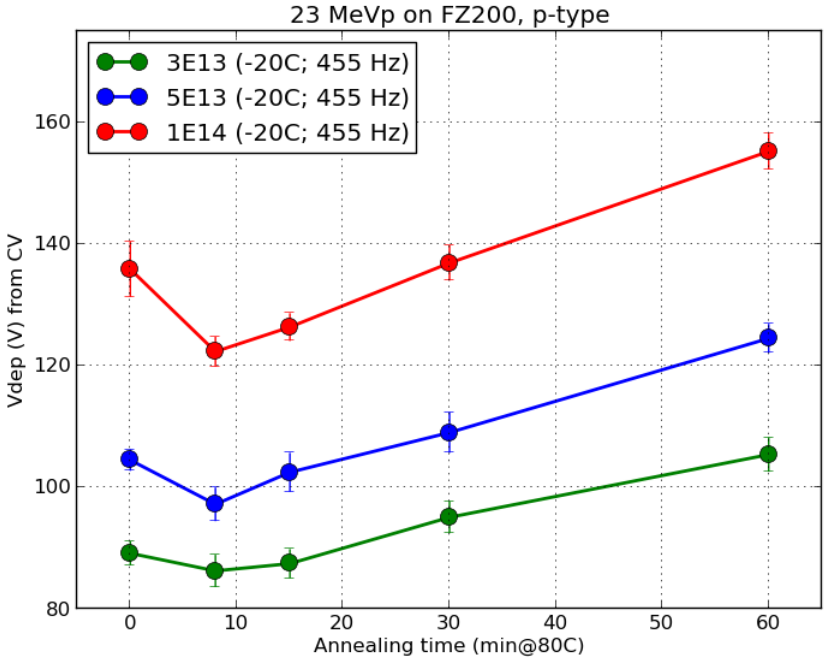




CV measurements

- **Vdep** from CV measurements
- 23 MeV protons on FZ200 n-type → space charge (SC) sign inversion after Φ_{neq}=1E14/cm^2
- 23 MeV protons on FZ200 p-type → no space charge (SC) sign inversion.
- **Vdep from CV characteristic→ Neff**



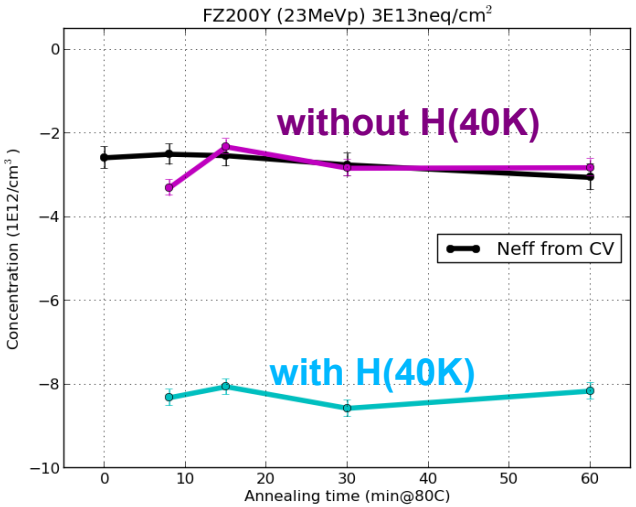


Error bars are multiplied by 2 to make them visible

Neff (CV) ↔ TSC for p-type FZ

- 23 MeVp on FZ200 p-type → no space charge (SC) sign inversion
- impact of defects on SC:

- Neff(0)	+ [BiOi]	+ [E(30K)]	- [H(116K)] - [H(140K)] - [H(152K)]	- [H(40K)]
- Neff(0)	+ [BiOi]	+ [E(30K)]	- [H(116K)] - [H(140K)] - [H(152K)]	
	Boron removal	**+ SC**	**- SC**	



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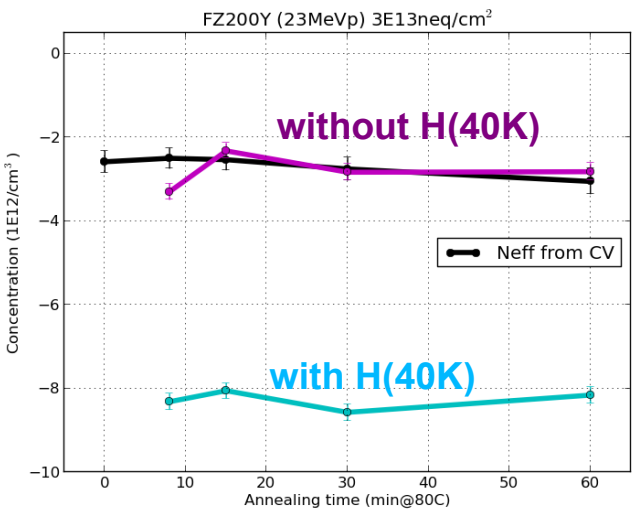
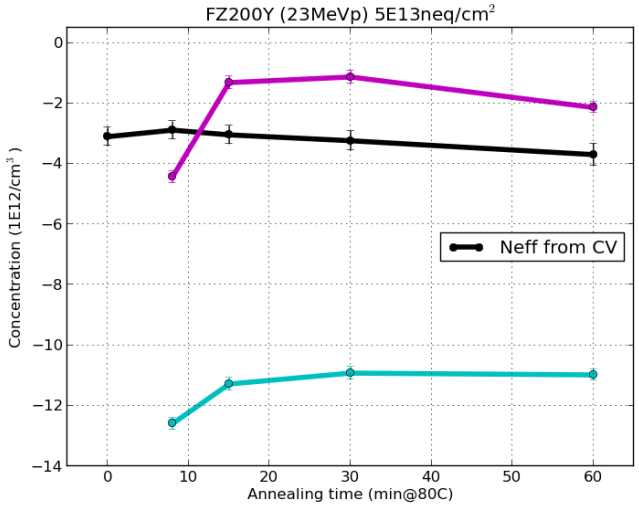
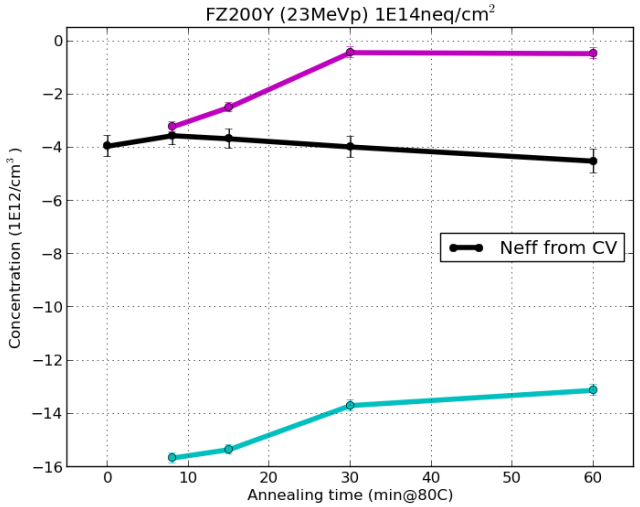






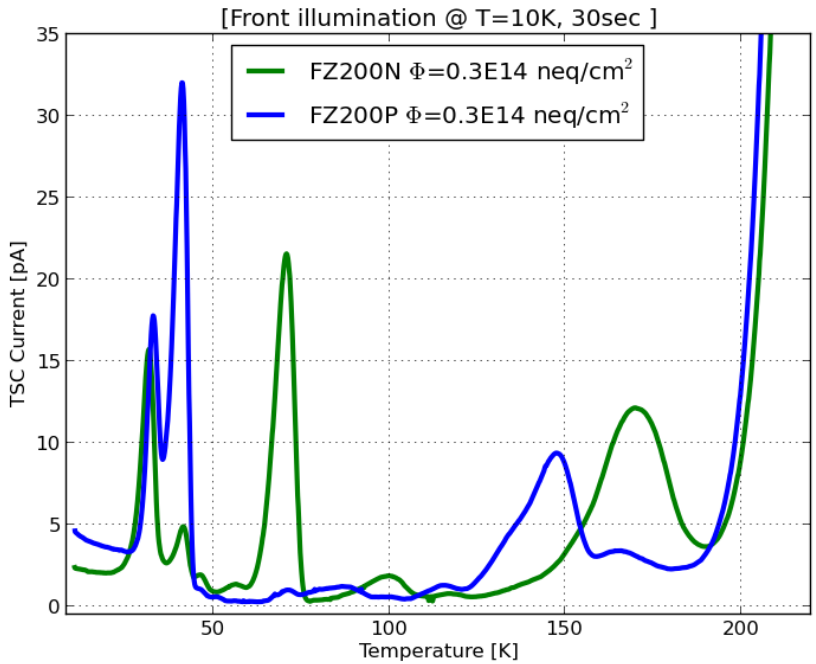
1) H(40K) has NO impact on SC
2) E(30K) too large contribution @ $\Phi_{eq} \geq 5 \cdot 10^{13}$ /cm²

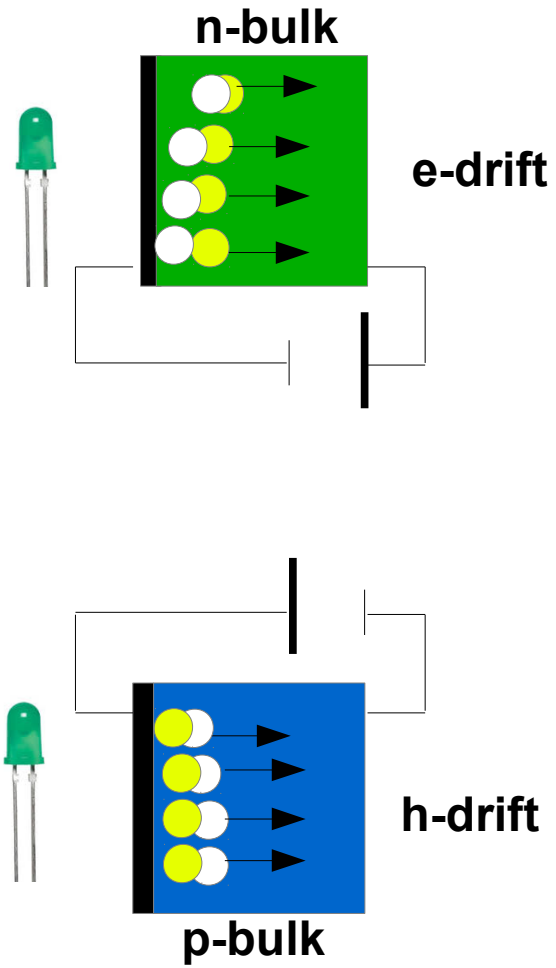
Front side illumination

(on n- and p-type diodes)

FZ200 n- and p-type:
- front side illumination (520nm, 30sec, @ T=10K)
- illumination + reverse bias → majority carriers

- overestimation of E(30K) in p-type material due to a shallow hole trap?
- boron removal





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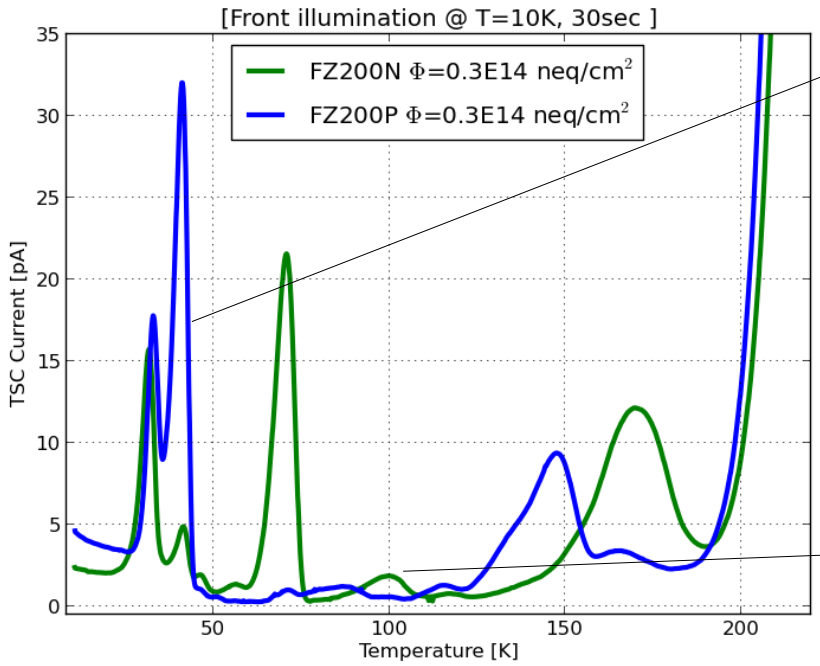

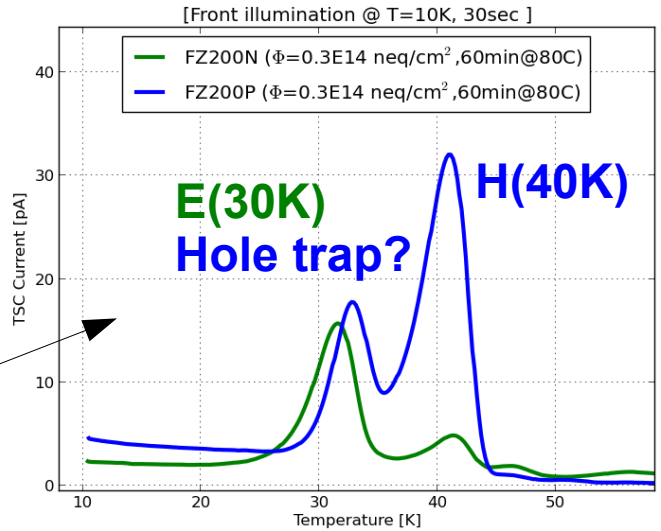

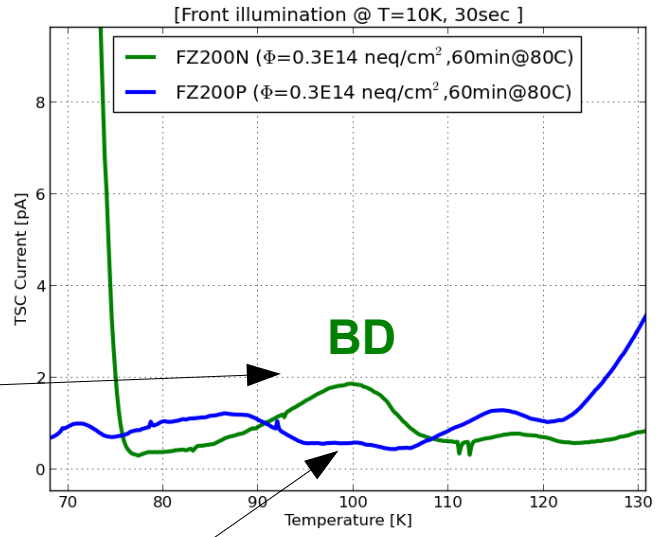

B_iO_i not detected as e-trap

Conclusions and Outlook

Conclusions:

- new analysis tool for calculating defect concentration from TSC spectra
- defect introduction from TSC in n- and p-type FZ diodes: quite similar
- *… except for boron-removal (BiOi) and E(30K) overestimation in p-type diodes*

- leakage current ← → "cluster defects" (V2, E5, H(220K)) proven
- Neff ← → defect concentrations of E(30K), BiOi, H(116K), H(140K, H(152K)
  … at low fluences ($\Phi_{eq} < 5 \cdot 10^{13}$ /cm^2)
- H(40K) seems not to have contributions to the space charge.

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Outlook:

1) IV/CV and TSC measurements:

- for materials with different [O]-concentration
  (physically thinned FTH200N/P and Magnetic Czochralski MCz200N/P)
- front and rear side illumination for FTH and MCz
- for different proton energies (23 MeV, 800 MeV, 24 GeV/c)

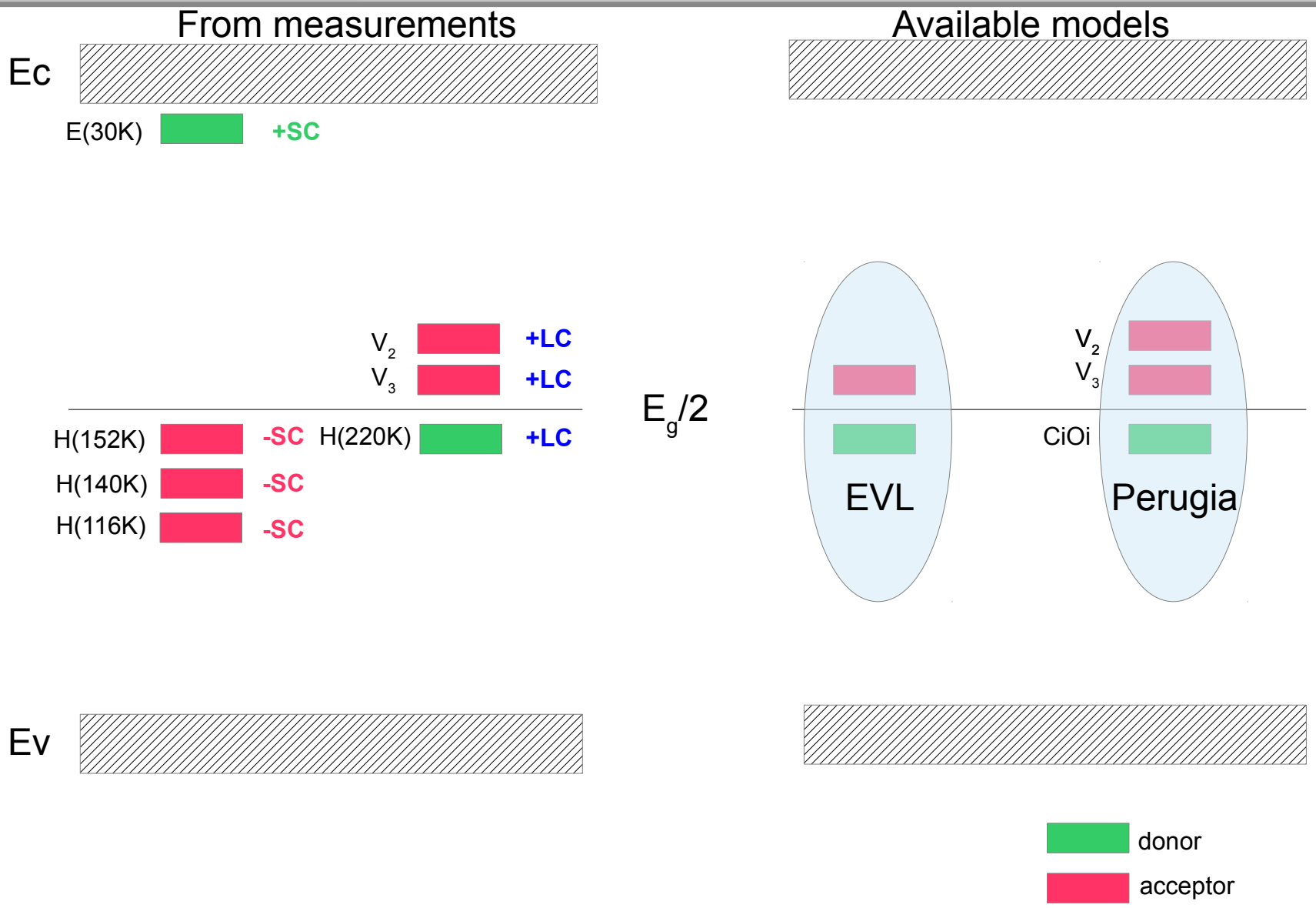
2) Damage model

- the relevant defects (for SC, leakage current, …) from TSC studies will be used as input for TCAD simulations

Thank you for your attention!

Back-up

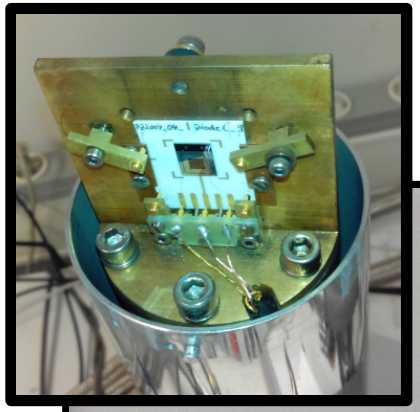
Back-up


From measurements
Available models
Ec
E(30K)
+SC
V2
V3
+LC
+LC
H(152K)
-SC
H(220K)
+LC
H(140K)
-SC
H(116K)
-SC
Eg/2
V2
V3
CiOi
EVL
Perugia
Ev
donor
acceptor

(back-up?)

Back-up

Sample holder:
+ 3 contact pins
+ T sensor
+ fixing screws

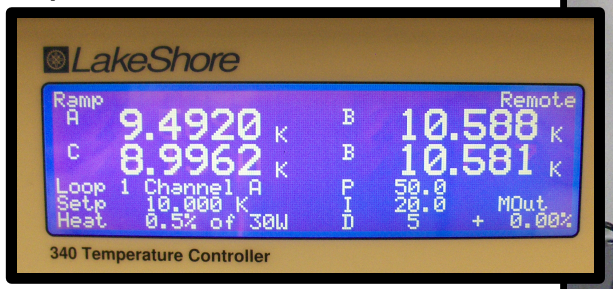


Helium compressor and cryogenerator

- HOT COPPER STAGE
- HEATING RESISTOR

COLD HEAD

Temperature controller

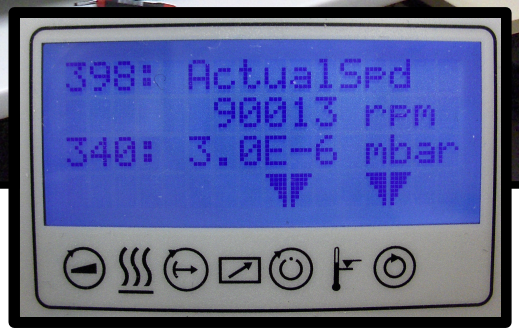


front and back side illumination

Labview DAQ

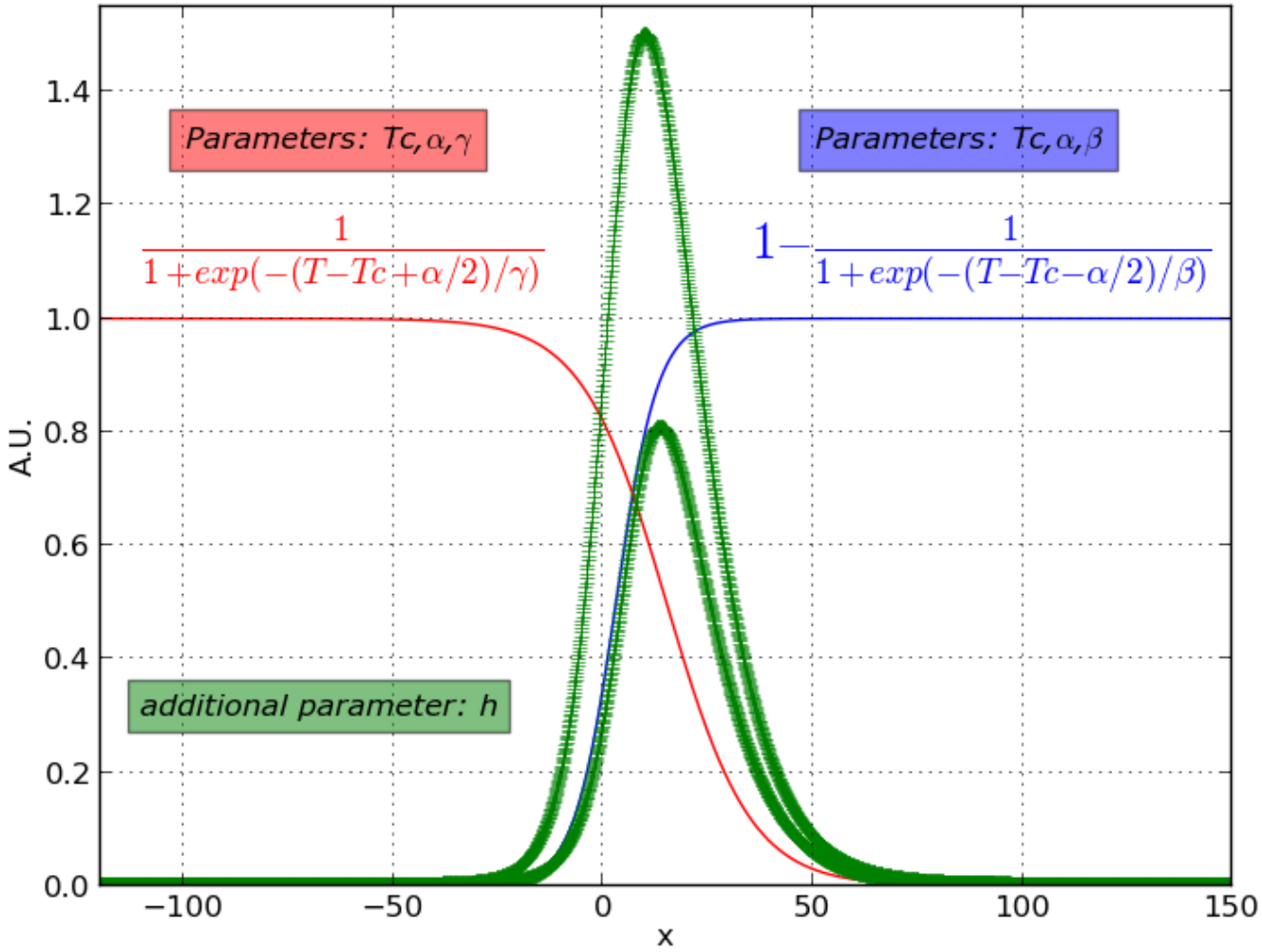
Electrometer + Vsource

Light shield

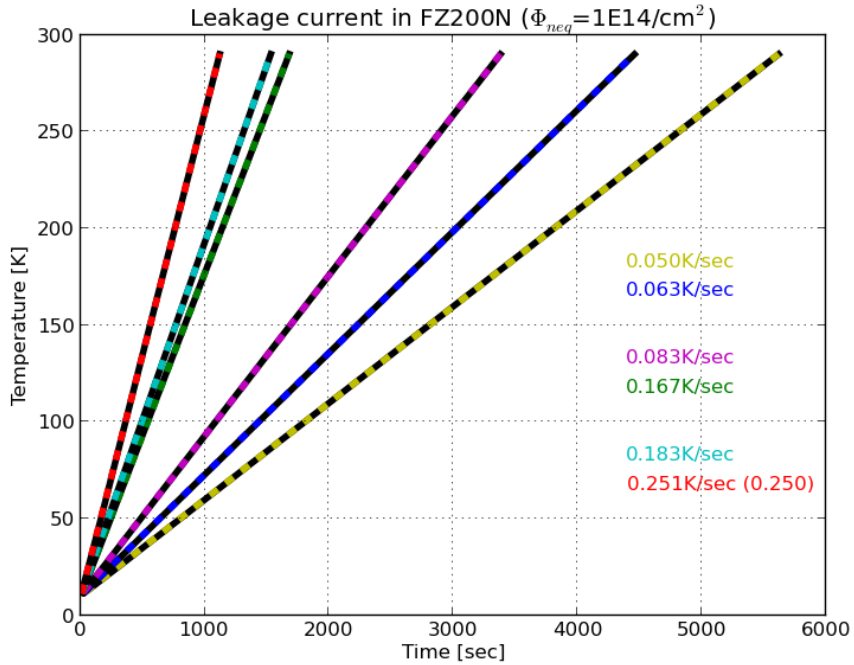


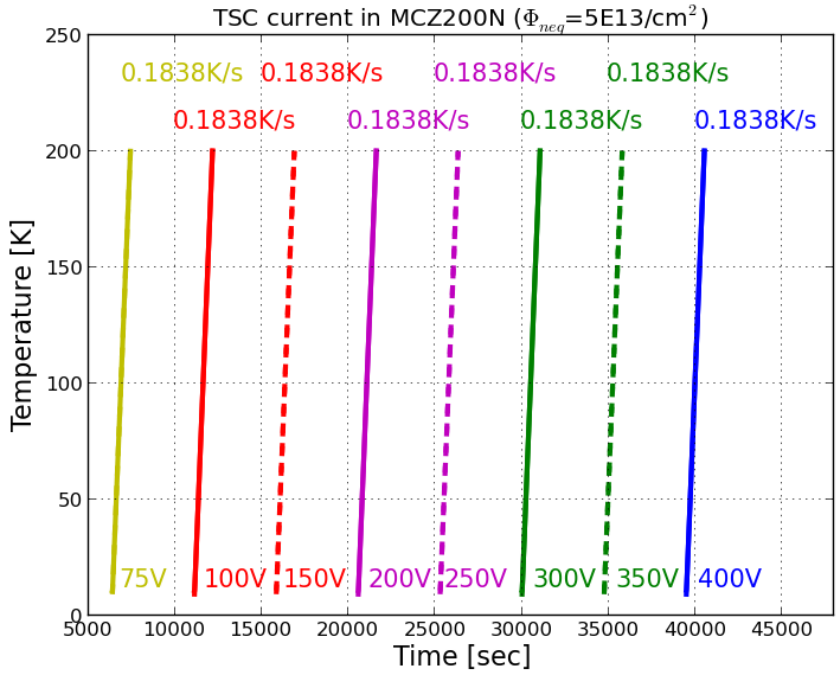
Vacuum pump and meter

Back-up


Parameters: Tc, α, γ
$\frac{1}{1+exp(-(T-Tc+\alpha/2)/\gamma)}$
Parameters: Tc, α, β
$1-\frac{1}{1+exp(-(T-Tc-\alpha/2)/\beta)}$
additional parameter: h
A.U.
x
0.0
0.2
0.4
0.6
0.8
1.0
1.2
1.4
−100
−50
0
50
100
150

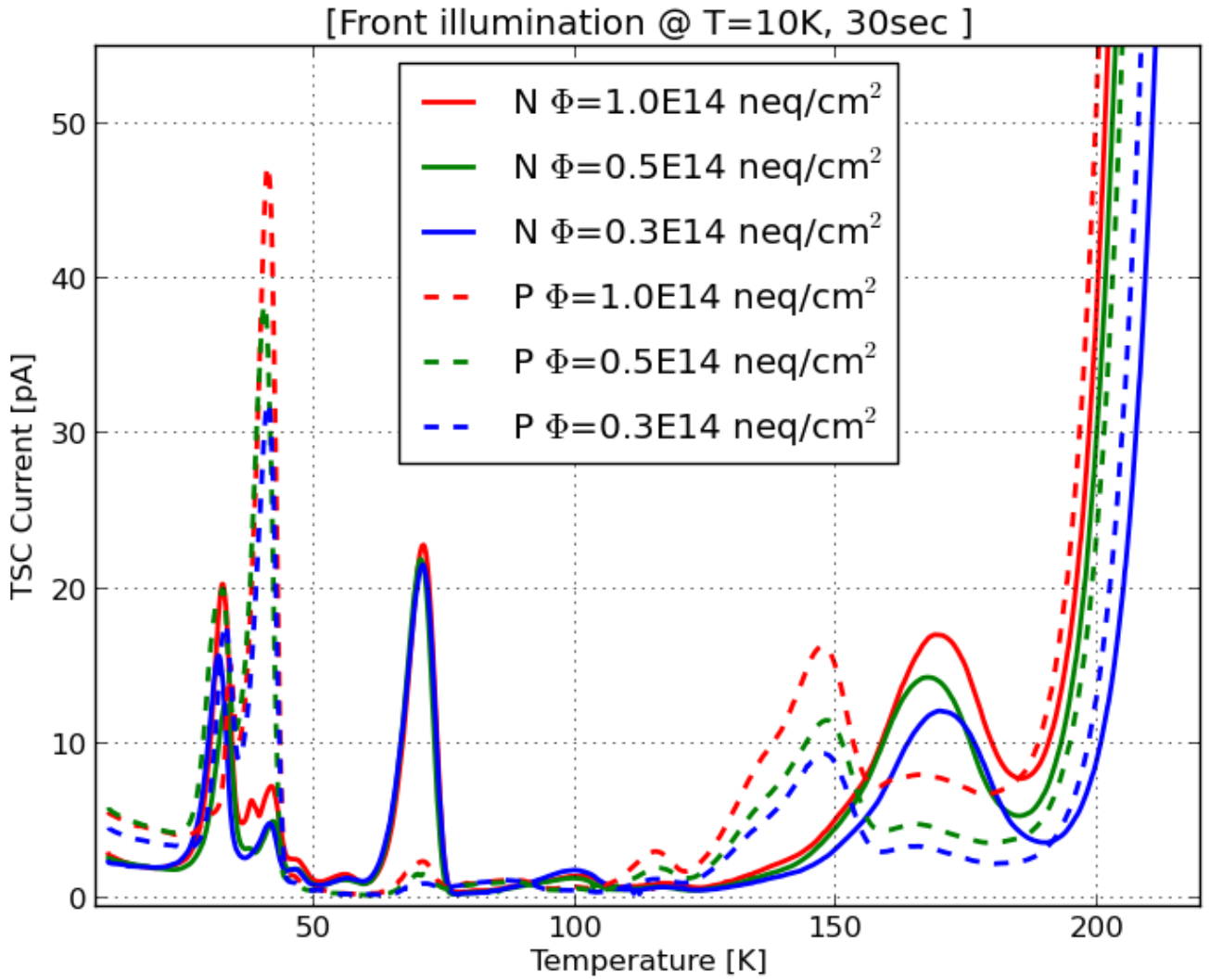
TSC setup stability



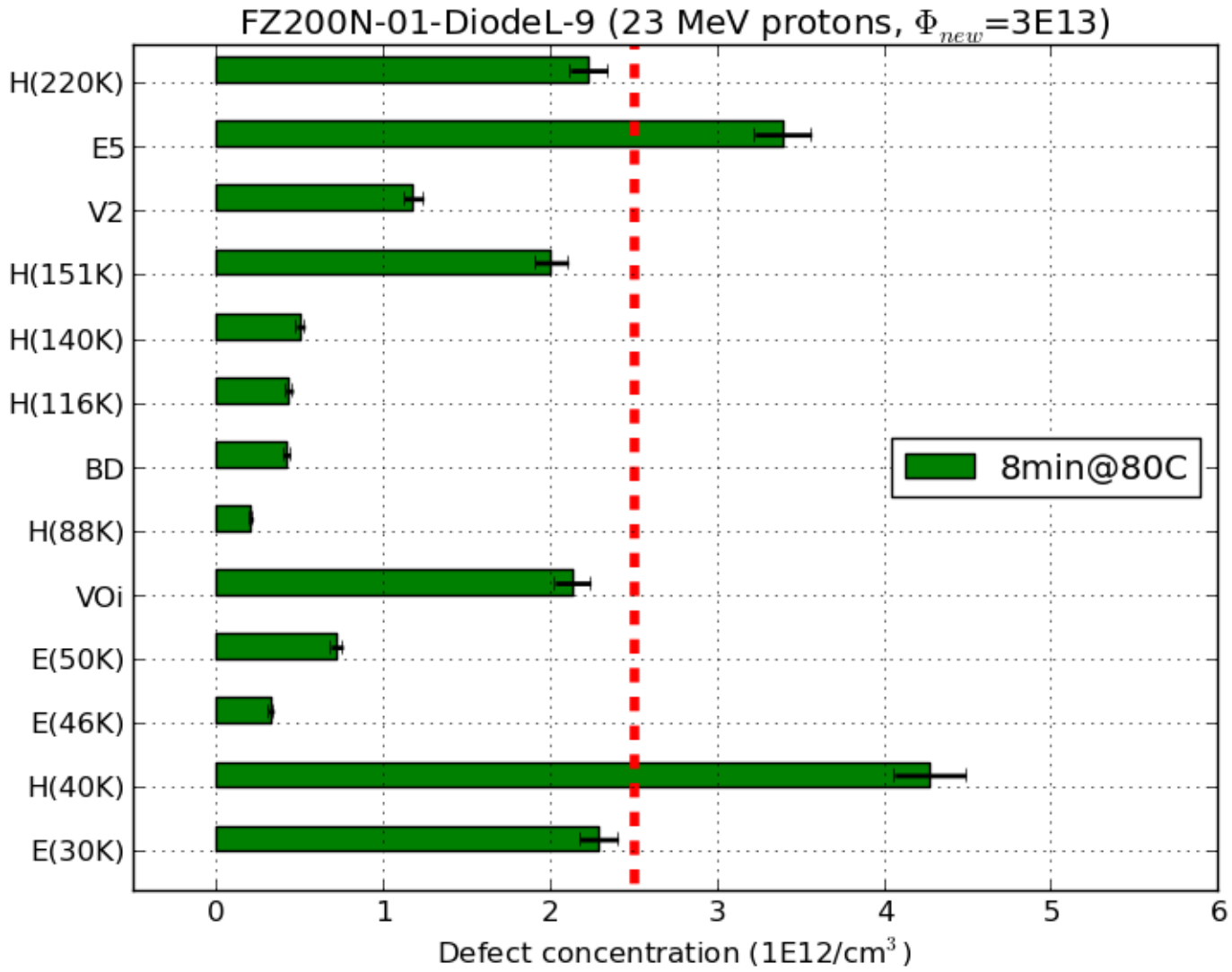


1) lekage current measured at different heating rates → β=0.183 K/sec
2) TSC current measured at different bias voltage during the heating phase
→ stability of the setup

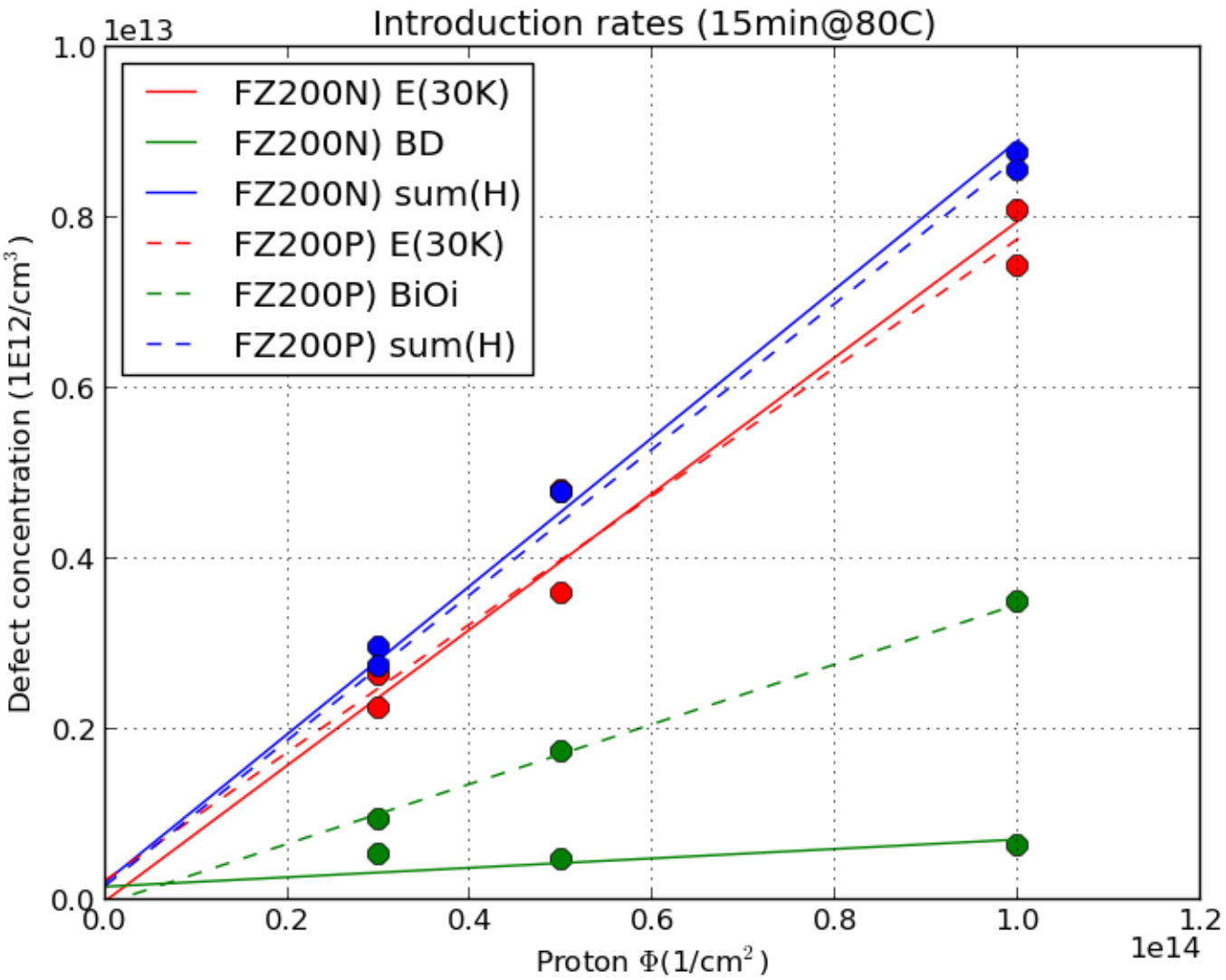
Back-up


[Front illumination @ T=10K, 30sec]
N Φ=1.0E14 neq/cm²
N Φ=0.5E14 neq/cm²
N Φ=0.3E14 neq/cm²
P Φ=1.0E14 neq/cm²
P Φ=0.5E14 neq/cm²
P Φ=0.3E14 neq/cm²
TSC Current [pA]
Temperature [K]
0
10
20
30
40
50
50
100
150
200

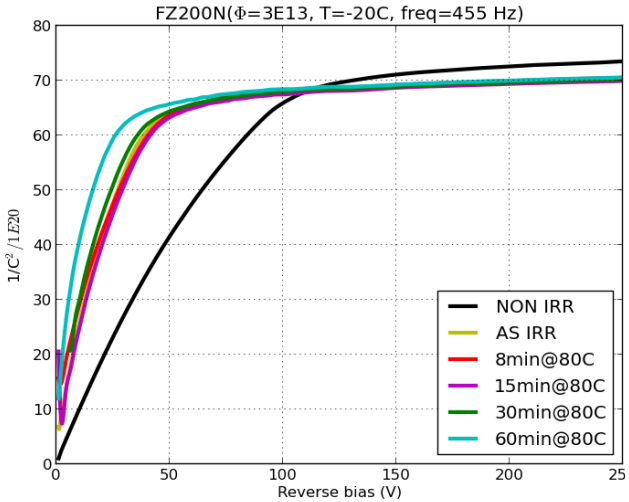
Back-up

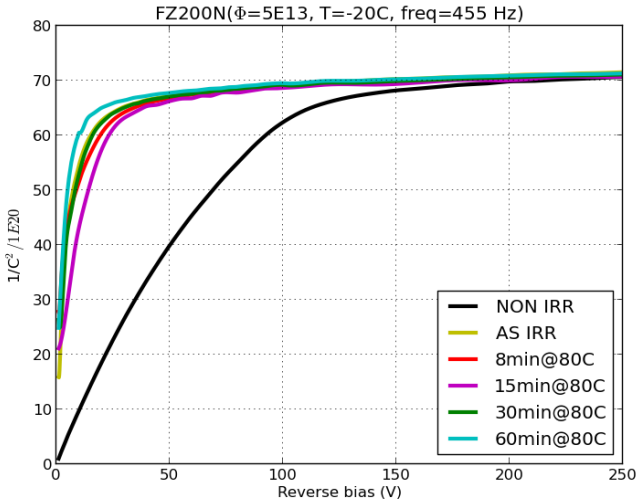

FZ200N-01-DiodeL-9 (23 MeV protons, Φ_{new}=3E13)
H(220K)
E5
V2
H(151K)
H(140K)
H(116K)
BD
H(88K)
VOi
E(50K)
E(46K)
H(40K)
E(30K)
8min@80C
0
1
2
3
4
5
6
Defect concentration (1E12/cm^3)

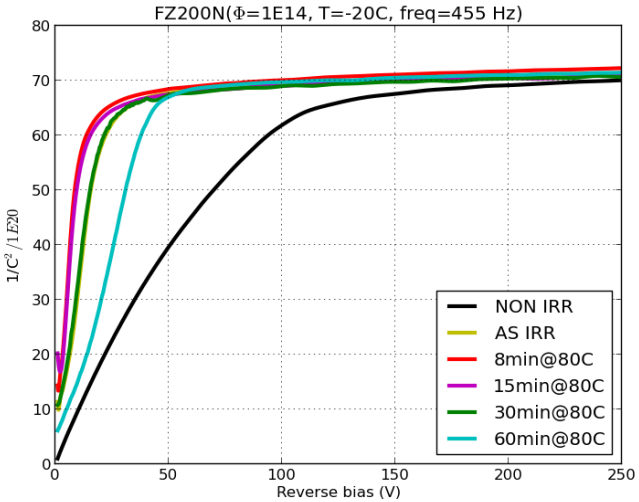
Introduction rates

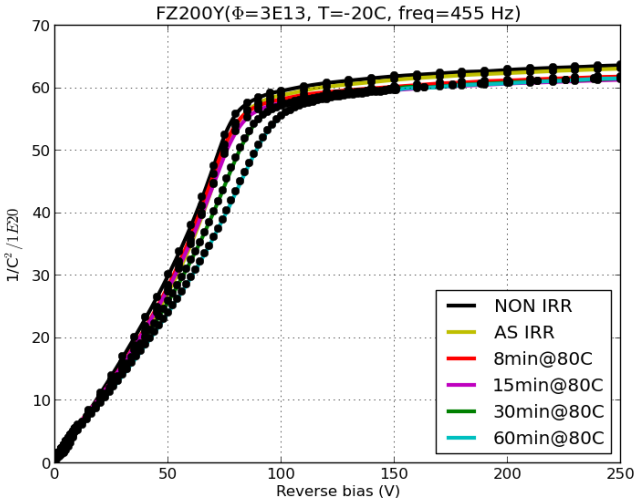


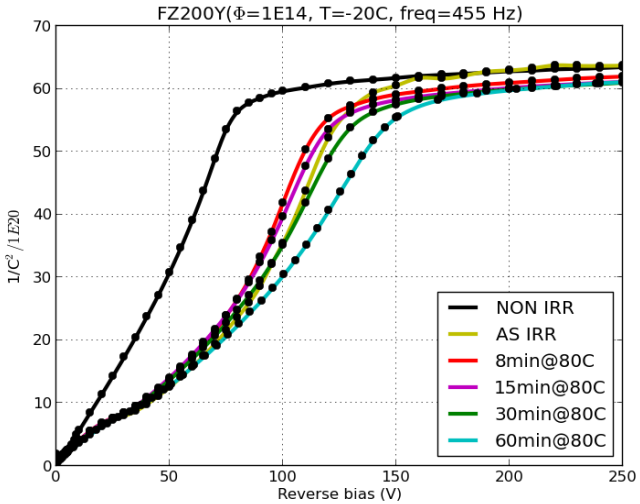
CV annealing (T=-20C)

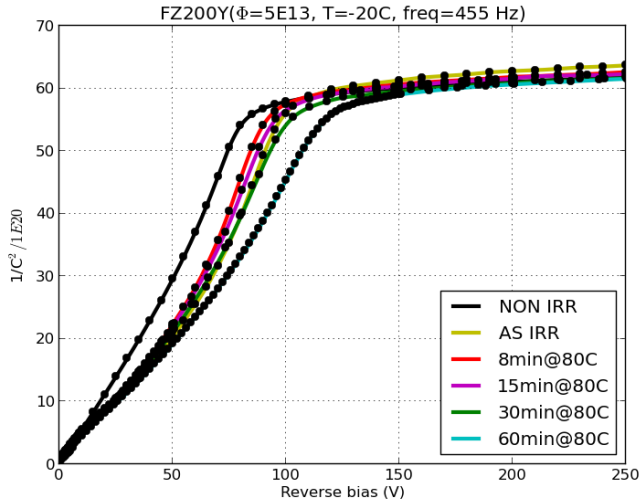




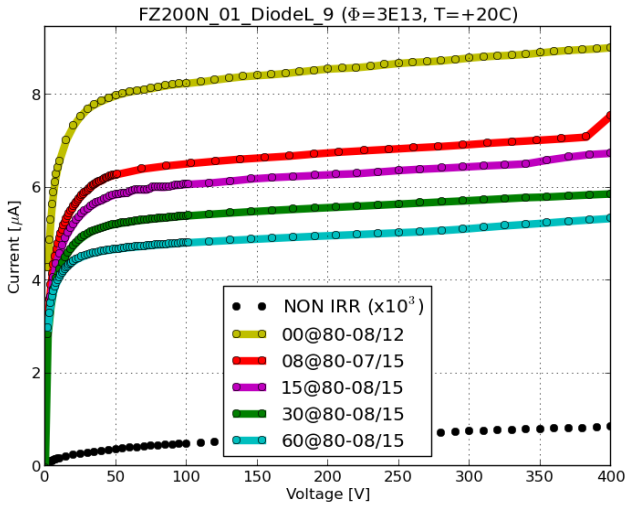


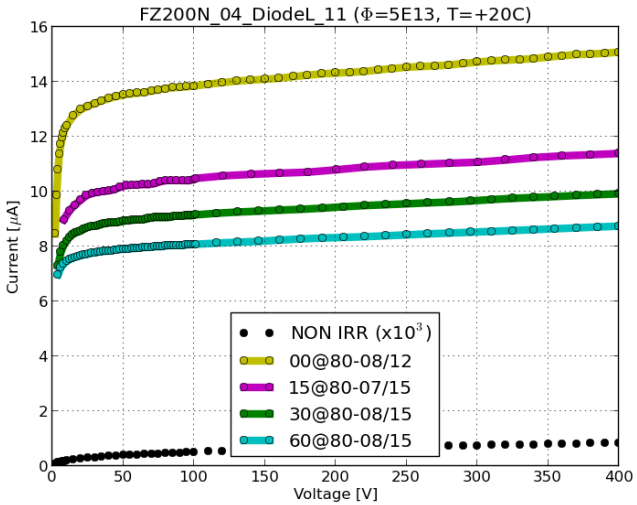


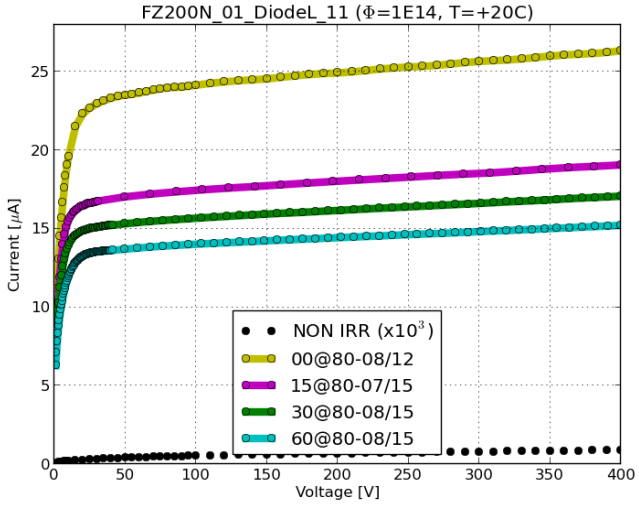


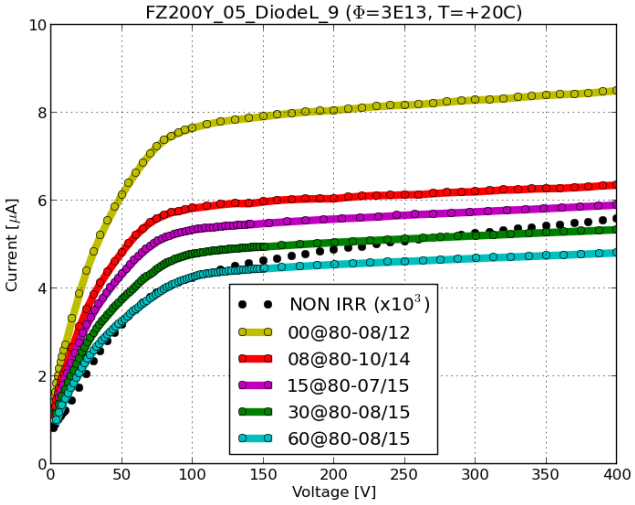


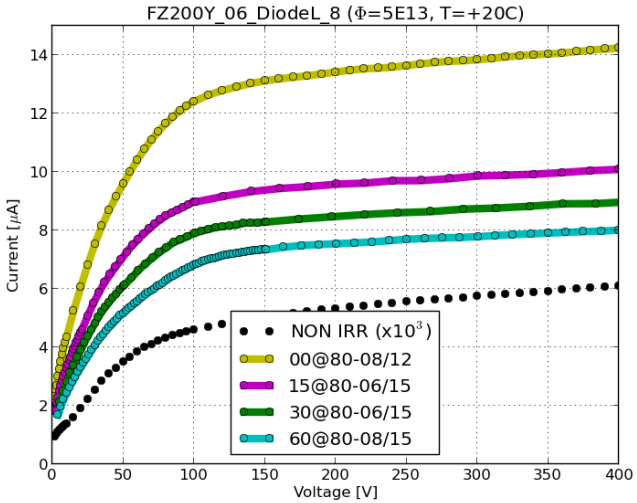
IV annealing (T=+20C)

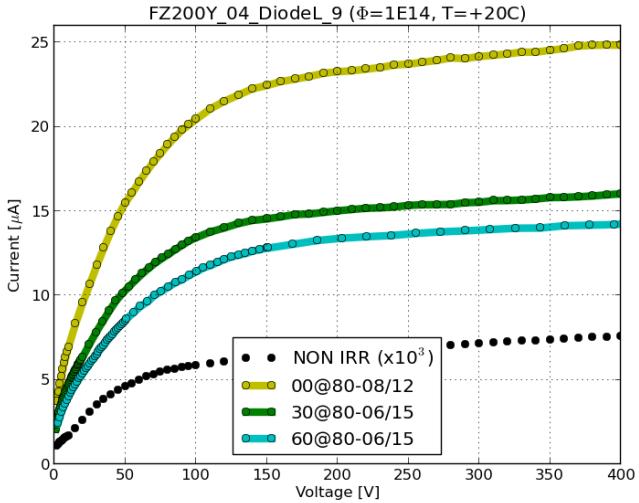












Deep diffusion