PROTON-INDUCED BULK-DAMAGE IN SILICON PAD-DIODES

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12th TREDI Meeting – 20/02/2017

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Outline

1) Bulk damage in thin silicon pad-diodes
   Proton energies (23 MeV, 188 MeV, 23 GeV); $\Phi_{neq} < 3\cdot10^{14}$ cm^{-2}

2) Main challenge: clusters of defects

3) What we can learn from measurements:
   - IV + TSC: leakage current
   - CVf + TSC: space charge

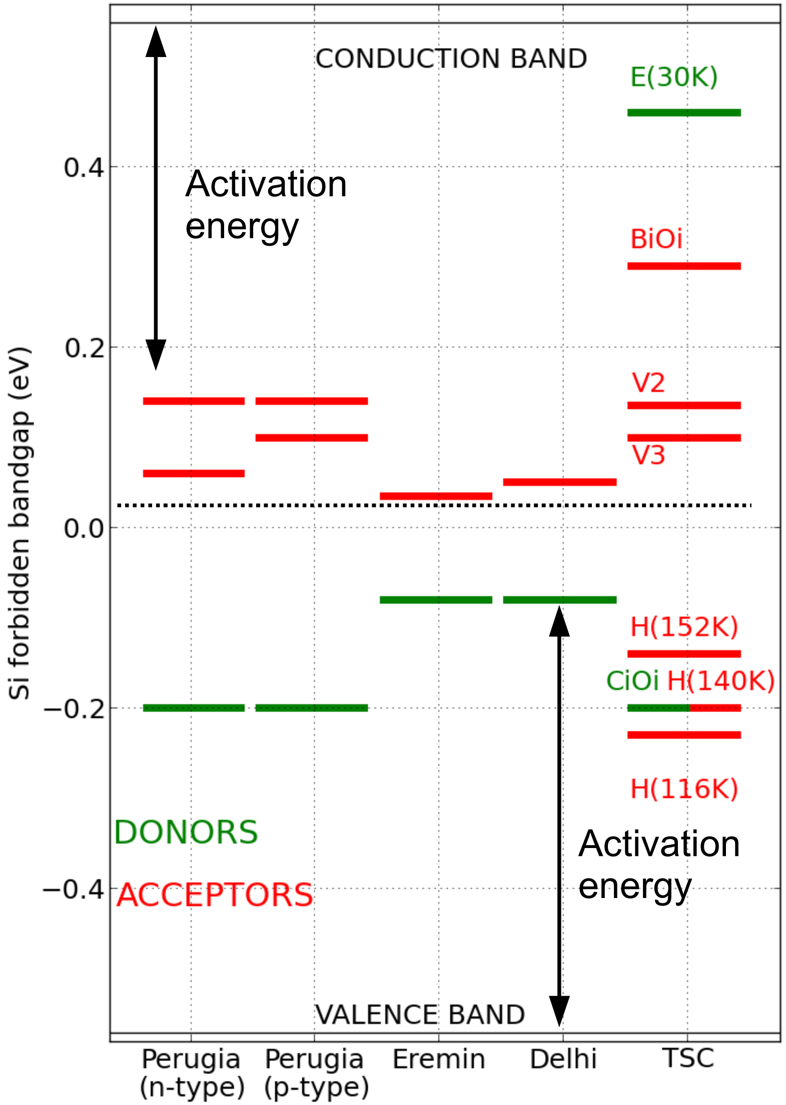
Motivations

1) Proton-energy dependent damage
Q1) NIEL scaling hypothesis?

2) Bulk defects in p-type Si-sensors

3) Models are based on few "effective" states, BUT fail to simultaneously describe IV/CV/CCE

Effective states in simulations vs. measured bulk defects



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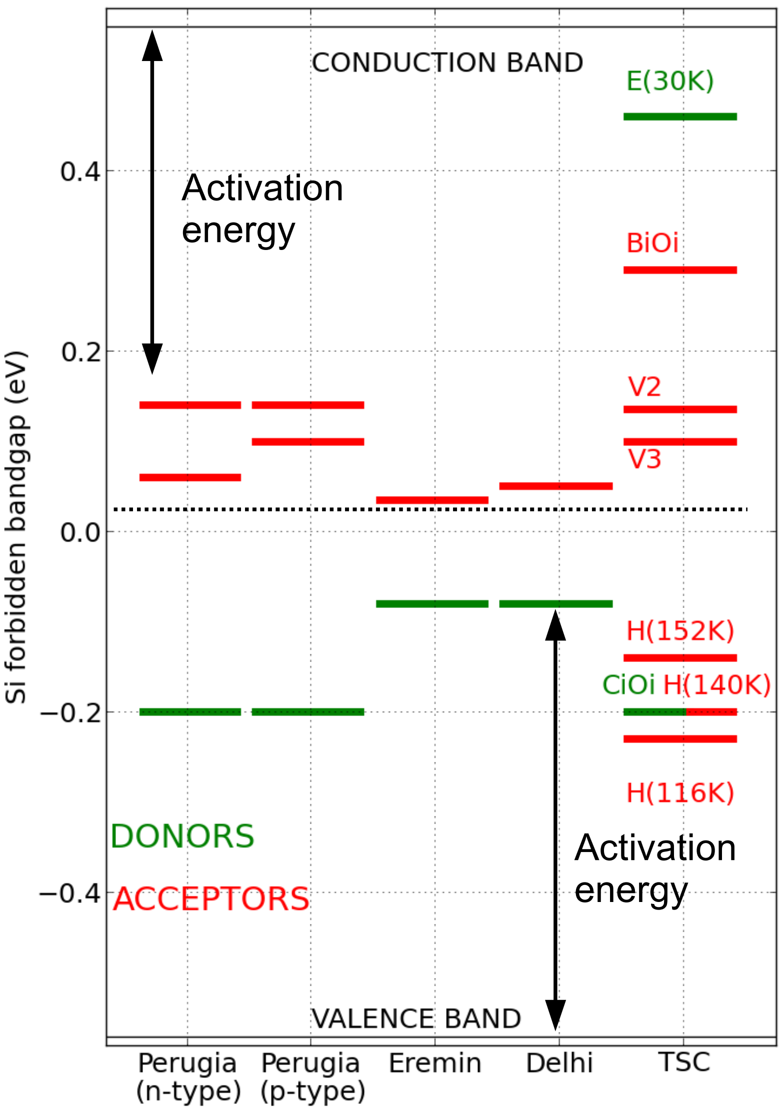
Motivations

1) Proton-energy dependent damage
Q1) NIEL scaling hypothesis?
- Proton energies (23 MeV, 188 MeV, 23 GeV)
- Hardness factors (2.0, 1.0, 0.62)
- Φ_{neq} fluence range: $[10^{13}, 3 \cdot 10^{14}]$ cm^{-2}

2) Bulk defects in p-type Si-sensors
- (200 μm thick, A = 0.25 cm^2) pad-diodes
- 3 bulk materials (MCz, FZ, dd-FZ)
- *n*- and *p*-type

3) Models are based on few "effective" states,
BUT fail to simultaneously describe IV/CV/CCE
- Annealing studies (at 80°C)
- TSC → microscopic properties of bulk defects
- IV/CVf → macroscopic effects on sensors

Effective states in simulations vs. measured bulk defects



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Main issue: clusters

- Account for clusters after proton irradiation
- Revisited Shockley – Read – Hall statistics

$$I_{TSC,n,p}(T) = \frac{Adq_0}{2} e_{n,p}(T) n_{t,n,p}(T)$$

1) Density of filled traps:

$$n_{t,n,p}(T) = n_{t,0,n,p} \times exp\left(-\frac{1}{\beta}\int_{T_0}^{T} e_{n,p}(T^{'})dT^{'}\right)$$

2) Emission probability:

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

3) Activation energy:

$$E_a^*(f_{n,p}) = \begin{cases} E_a^0 - f_n \cdot \delta E_0 & \text{for acceptors,} \\ E_a^0 + (1 - f_p) \cdot \delta E_0 & \text{for donors.} \end{cases}$$

- The fraction of filled traps $f_{n,p}(T)$ affects E^*_a
- Different topologies give a linear dependence in f

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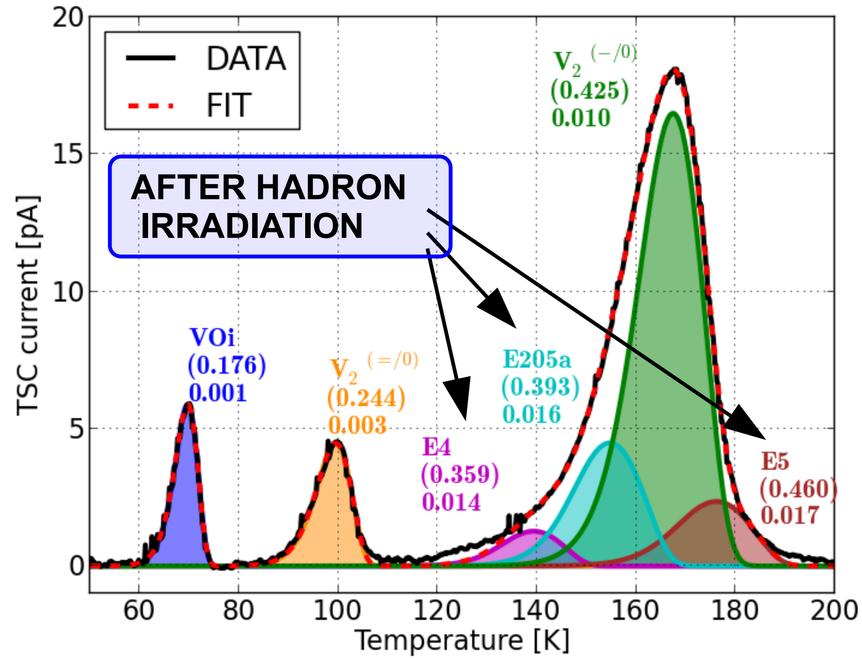


23 GeV protons; Φ_{neq} = 1E13cm^{-2}
120min@80°C; Epi 74µm
(Filling of e-traps only)
(E_a in eV), δE_0 in eV

- The fraction of filled traps $f_{n,p}(T)$ affects E^*_a
- Different topologies give a linear dependence in f
- To obtain all the defect parameters: N_t, σ, E_a
- Shift $\delta E_0 \approx$ 10-17 meV for cluster-related defects

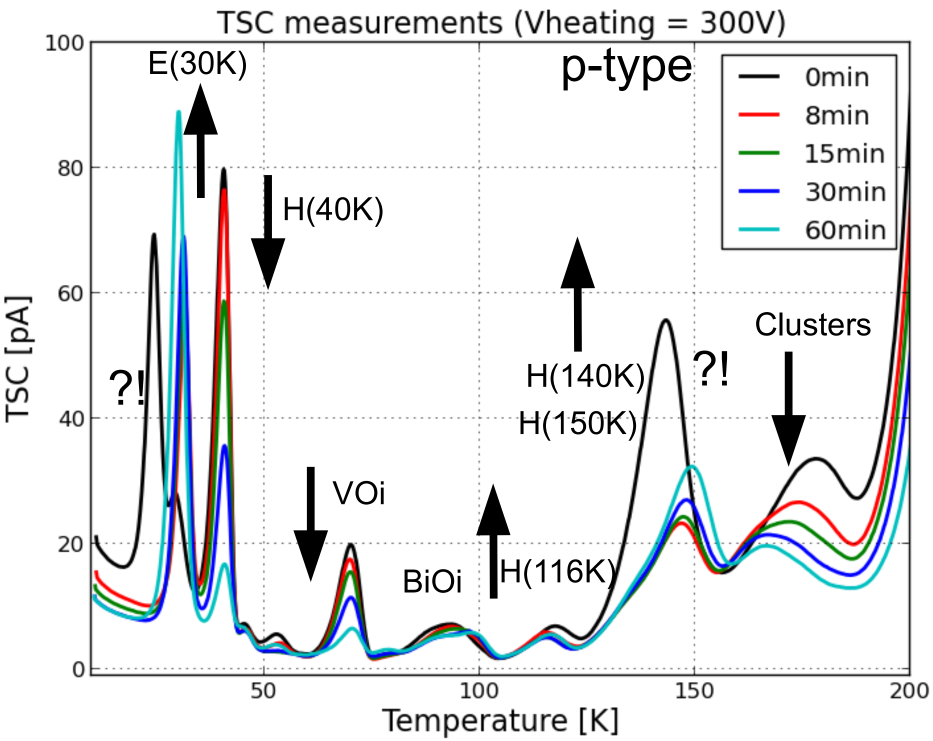
Defects & effects

Annealing studies at 80°C

FZ pad diodes
188 MeV protons
Φ_{neq} = 1.0E14cm^{-2}
Annealing at 80°C

H(40K) → unknown effect
X(10K) and X(140K) vanishing after 8min@80ºC

Donors → E(30K), *and also for p-type: BiOi*
Acceptors → H(116K), H(140K), H(152K)
Clusters → V_2, V_3, H(220K)



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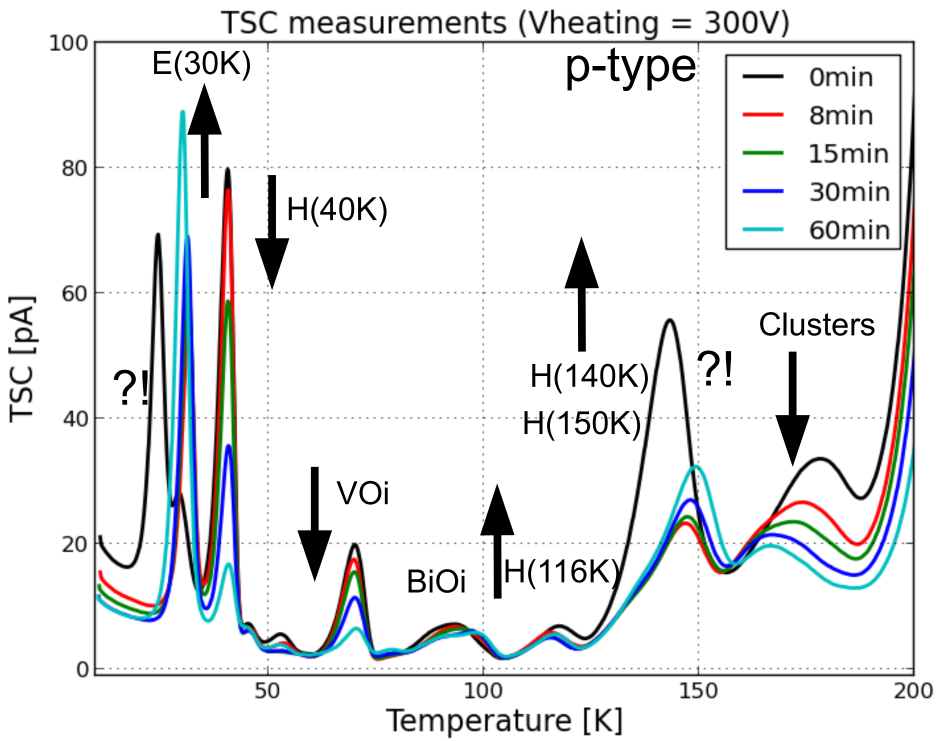
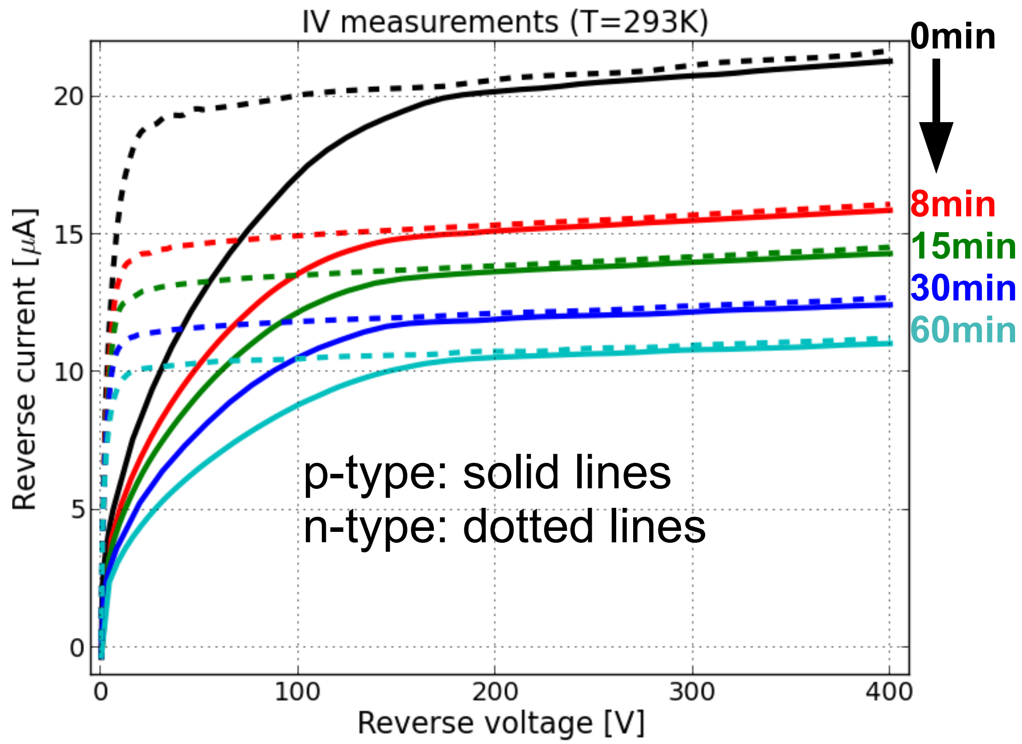




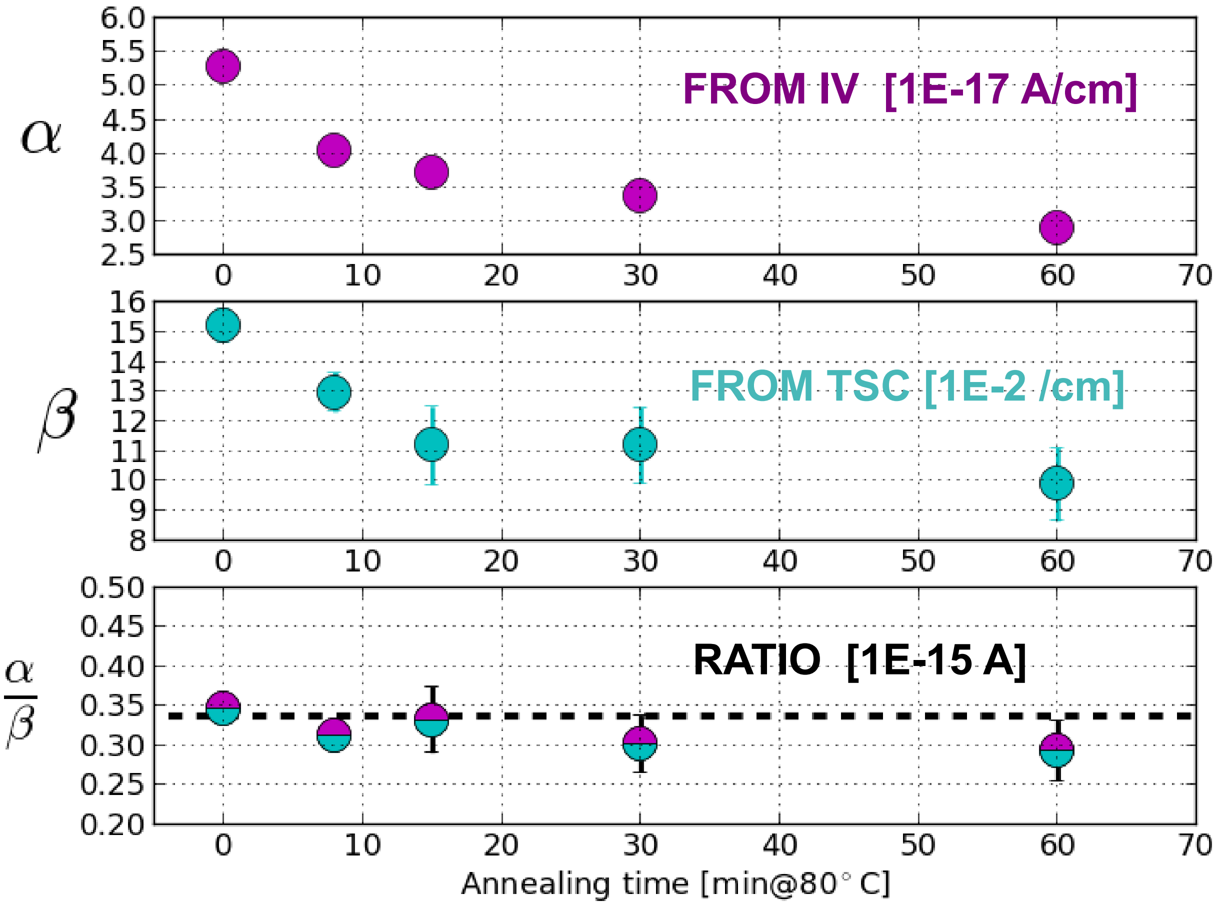
Leakage current

TSC + IV (Example at 300V)

From IV:
Damage rate α
Volume-current prop. to Φ_{neq}

From TSC:
Introduction rate β
Cluster concentrations prop. to Φ_{neq}

$$\frac{\alpha}{\beta} = (0.34 \pm 0.03)\, 10^{-15}\, A$$



- Leakage current & cluster concentrations decrease with annealing
- Deep defects (V_2, V_3, H(220K)) contributing to the leakage current
- Cluster introduction rate found for (1E13 < Φ_{neq} < 3E14)

Leakage current

TSC + IV (Example at 30min@80°C)

$$I_{leakage} \propto \left(w_1 \cdot N_{V_2} + w_2 \cdot N_{E5} + w_3 \cdot N_{H(220K)}\right)$$

$$w = \left(\frac{1}{e_n} + \frac{1}{e_p}\right)^{-1}$$

Weighted values:

$w_1 = 2.88 \cdot 10^{-2}$

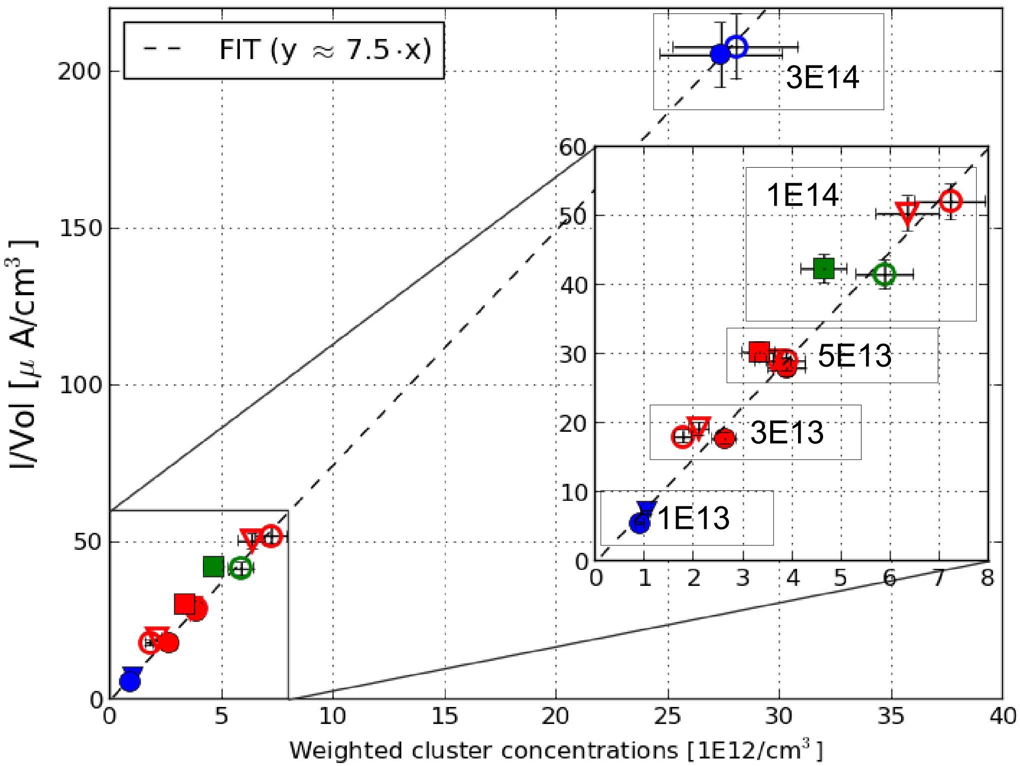
$w_2 = 8.85 \cdot 10^{-1}$

$w_3 = 8.60 \cdot 10^{-2}$

[Moll, Hallén, Radu]

	MCz		dd-FZ		FZ	
	N	P	N	P	N	P
23 MeV	●	○	▼	▽	■	□
188 MeV	●	○	▼	▽	■	□
23 GeV	●	○	▼	▽	■	□

Measured IV@ 253K, @ 300V



Calculated from TSC ($V_{heating}$ = 300V)

NIEL-scaling
leakage current for Φ_{neq}
(1E13 < Φ_{neq} < 3E14):
- No material dependence
- No proton-energy dependence

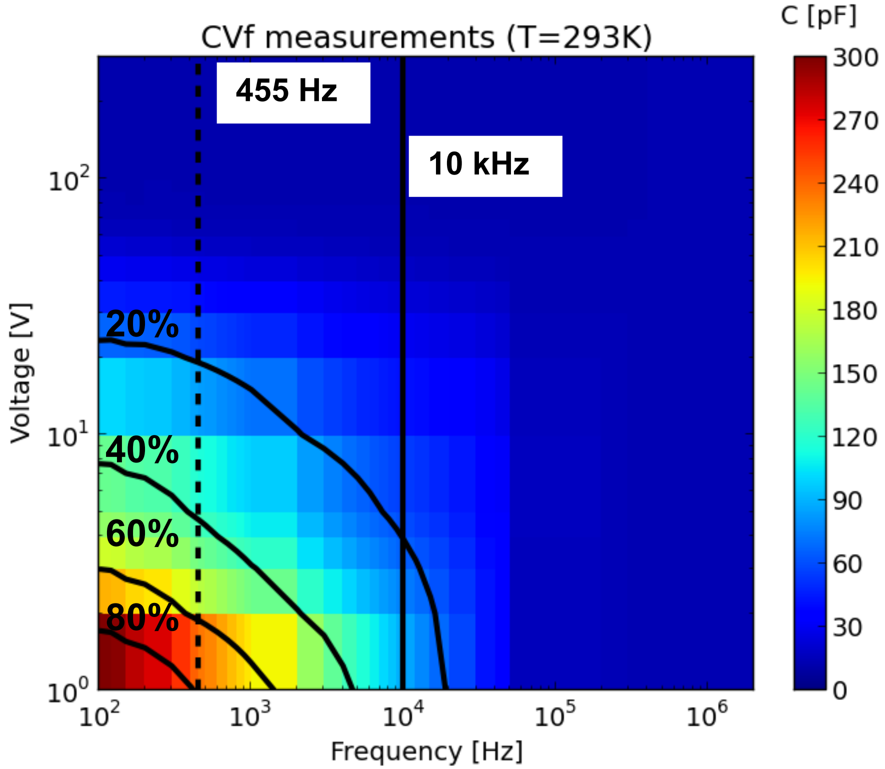
Defects & effects

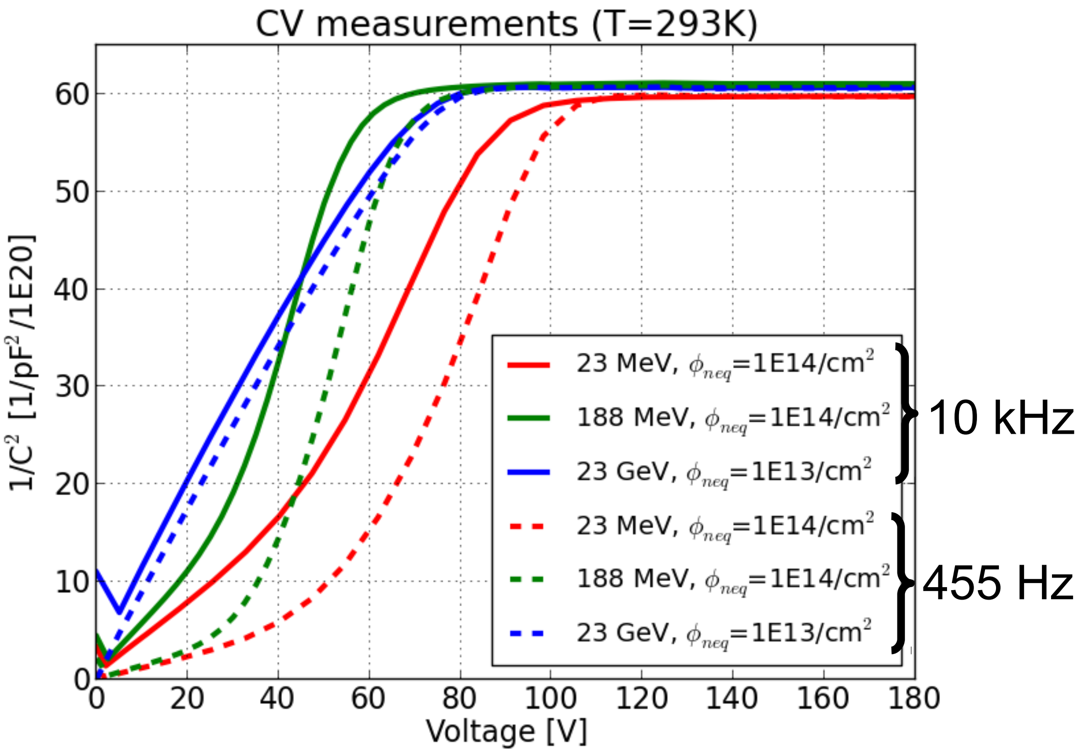
TSC + CVf

MCZ p-type
188 MeV protons
Φ_{neq} = 1.0E14cm^{-2}
Annealing 15min80°C

MCZ p-type
3 energies, 2 freq
Annealing 15min80°C

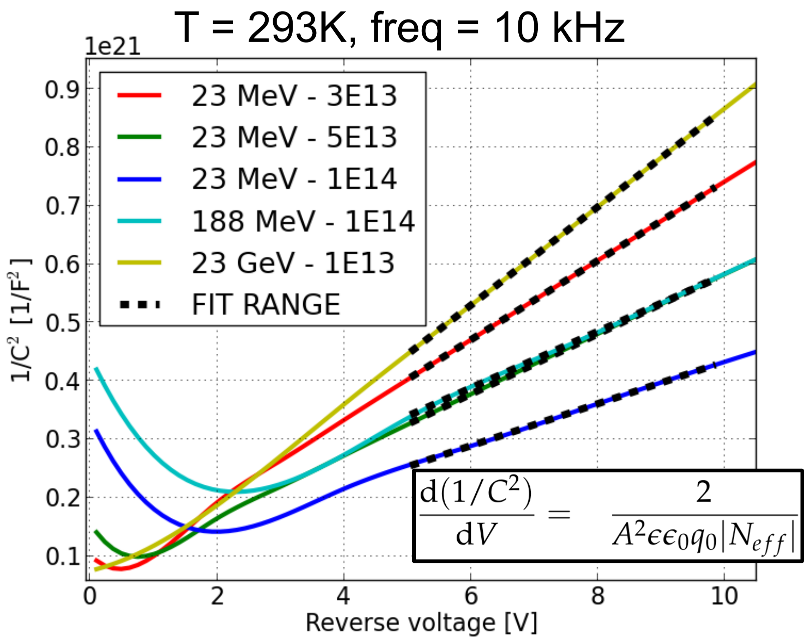
CVf → strongly dependent on E_p, Φ_{neq} and freq

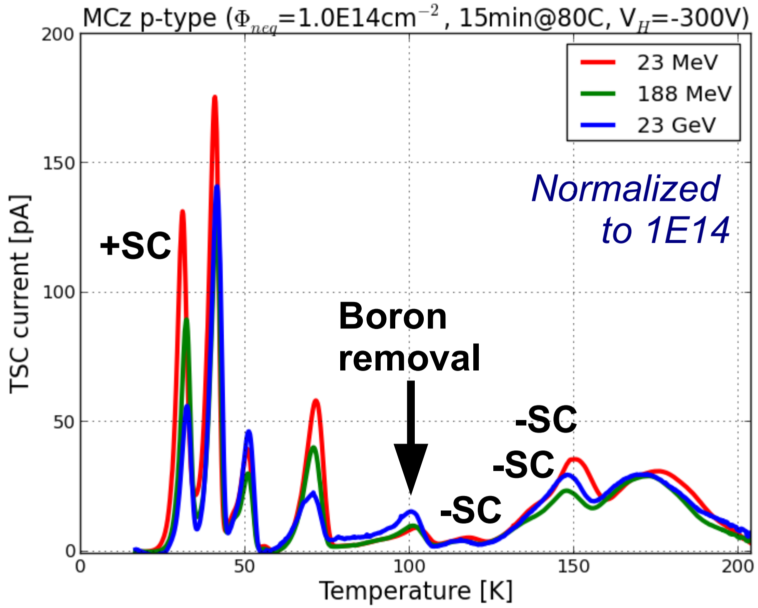


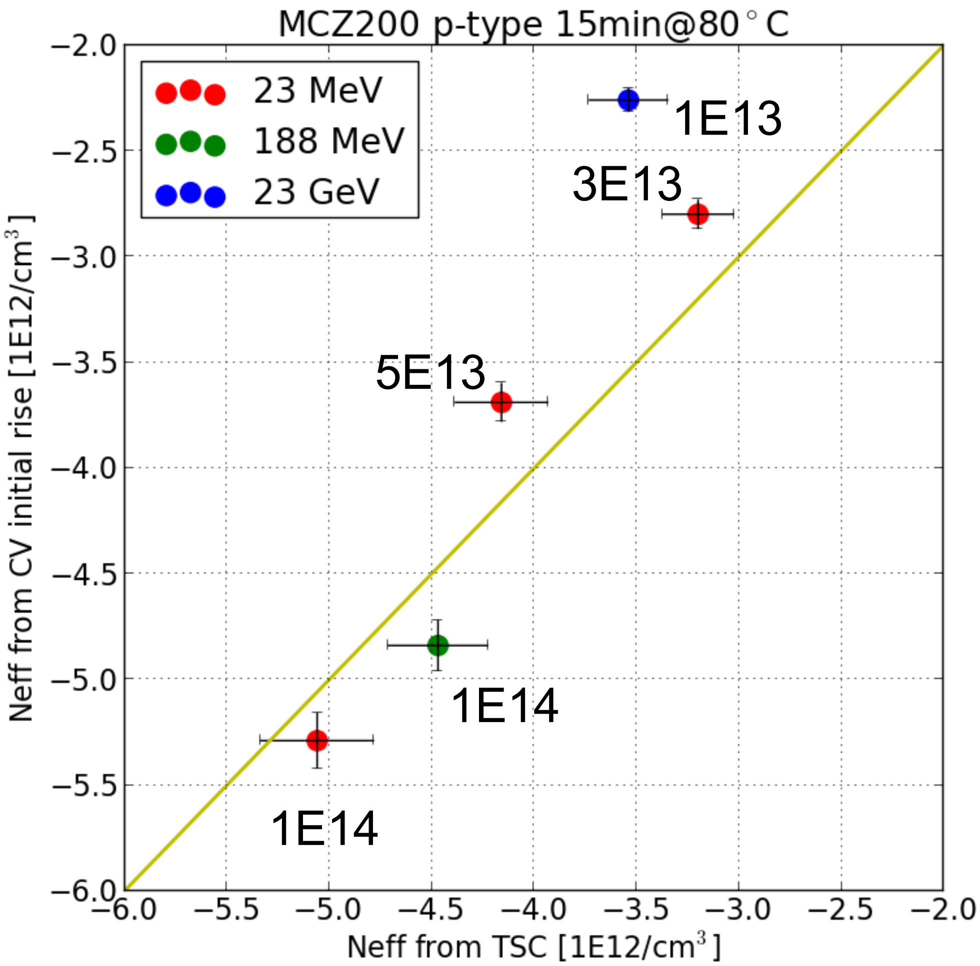


Defects & effects

TSC + CVf







$N_{eff,0}$ + E(30K) + BiOi
- H(116K) – H(140K) – H(152K)

N.B.: $N_{eff,0}$ is the same within 7%

Conclusions

- Bulk damage investigated in thin silicon n- and p- type pad diodes for proton energies (23 MeV, 188 MeV, 23 GeV), Φ_{neq} < 3E14 cm^{-2}

- Revisited SRH statistics to account for clusters in the analysis of TSC spectra
  - Activation energy change as a function of occupation $\delta E_0 \approx 10 – 17$ meV

- Annealing studies @ 80°C
- IV + TSC : leakage current
  - Correlation between deep traps and leakage current observed
  - Introduction of deep traps and leakage current scale with NIEL
- CVf + TSC: space charge
  - Initial rise method for CVf characteristics, defect concentrations from TSC
  - With increasing fluence, more -SC from CV as well from TSC for p-type

Thank you for your attention!

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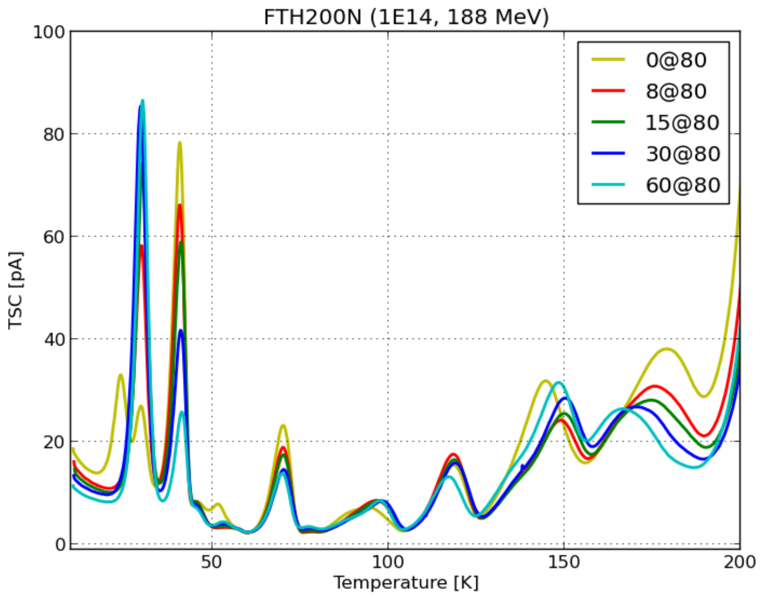
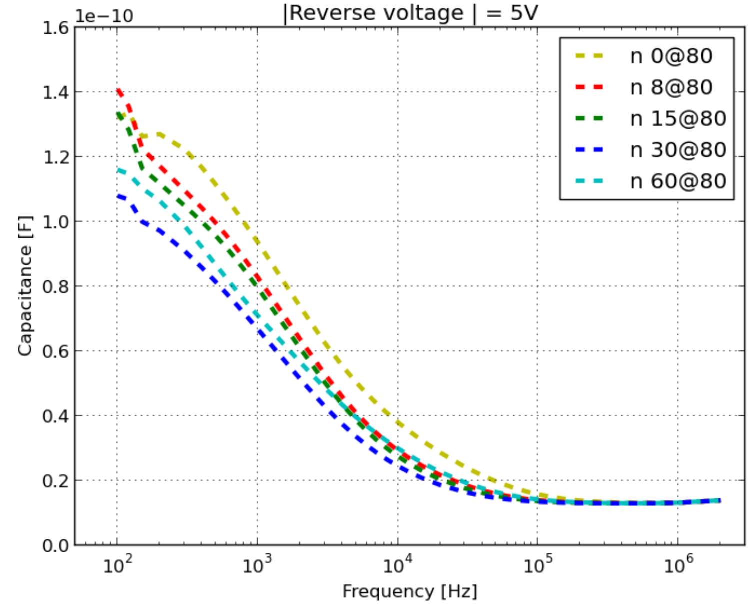
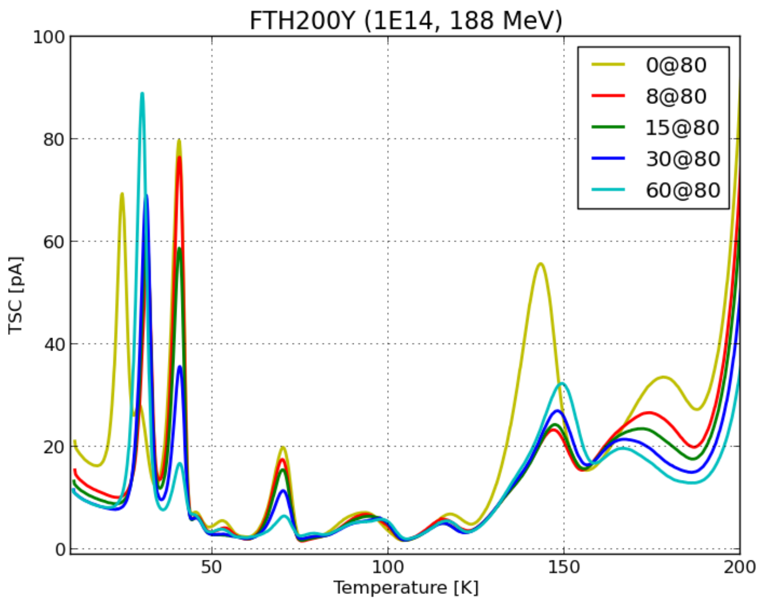
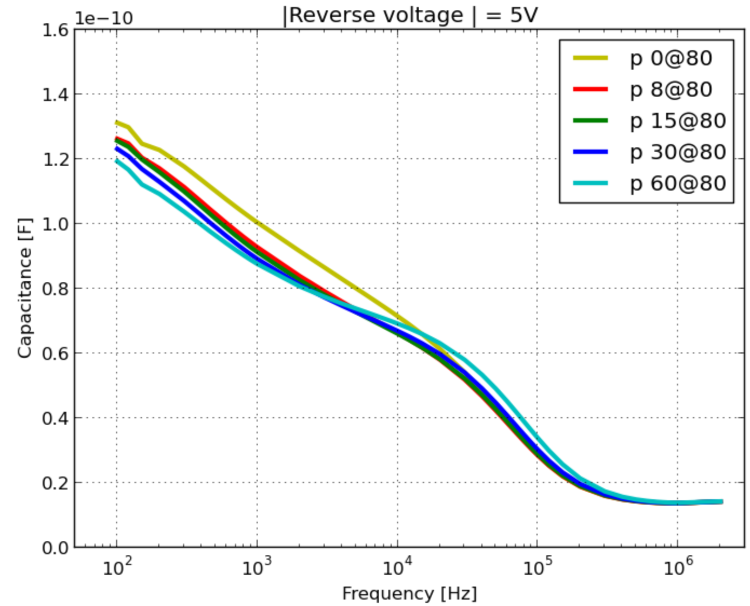
Space charge

TSC + CVf



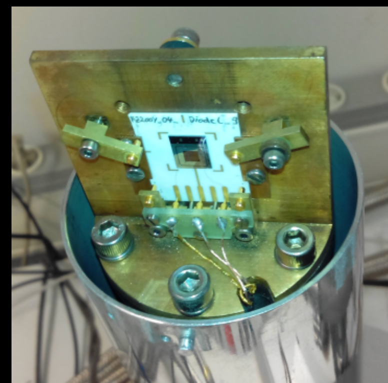




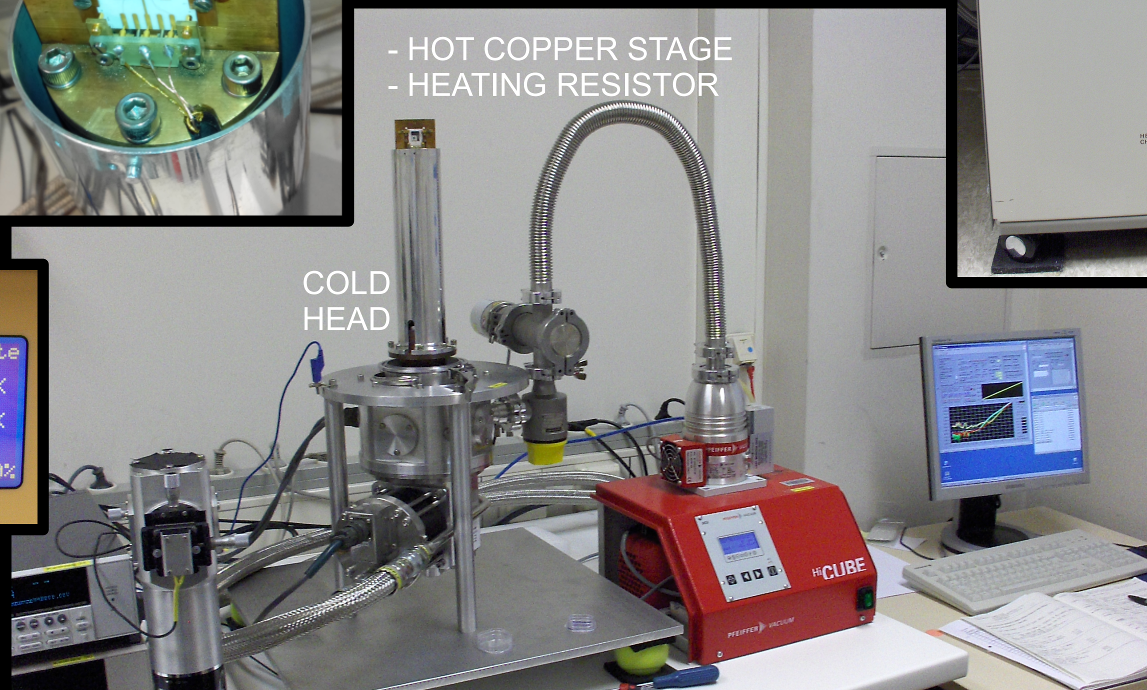


The TSC setup

Sample holder + T sensor



Helium compressor and cryogenerator



Temperature controller

front and back side illumination

Labview DAQ

Amperometer + Vsource

Light shield

Vacuum pump and meter