PROTON-ENERGY DEPENDENT DAMAGE TO THIN SILICON PAD-DIODES

Elena Donegani, Eckhart Fretwurst, Erika Garutti
Universität Hamburg

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GEFÖRDERT VOM
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für Bildung
und Forschung

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Outline

1) Proton-irradiated samples

2) IV/CVf/TSC measurements

3) Analysis of TSC spectra

4) Leakage current

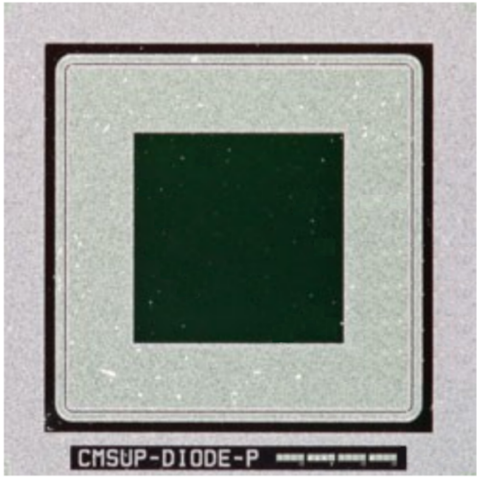
5) Effective doping concentration

Radiation damage

SAMPLES:

Si pad-diodes
(200 µm thick, A = 0.25 cm^2)

FTH, MCz, FZ
n- & p-types



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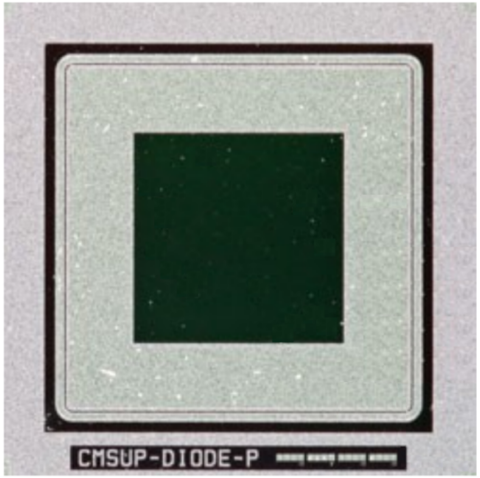

BULK DAMAGE:

Proton energies:
23 MeV, 188 MeV, 23 GeV
HF = 2.0, 1.0, 0.62
(KIT, KVI, CERN PS)

Proton fluences:
$1\cdot10^{13} - 3\cdot10^{14}$ neq/cm^2

Measurements:
IV, CVf, TSC

Annealing:
up to 60min@80°C

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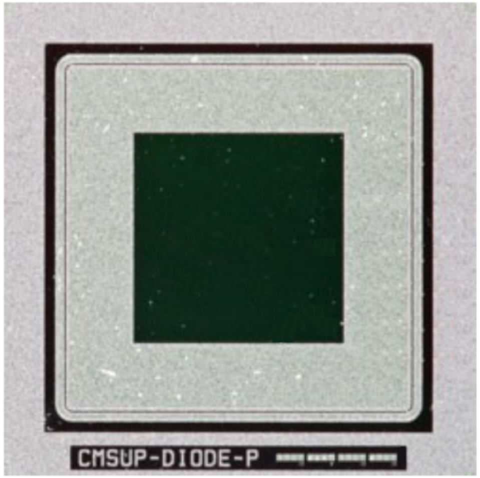

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BULK DEFECTS:

- Point-like & "clusters"
→ sensor properties
→ sensor performance

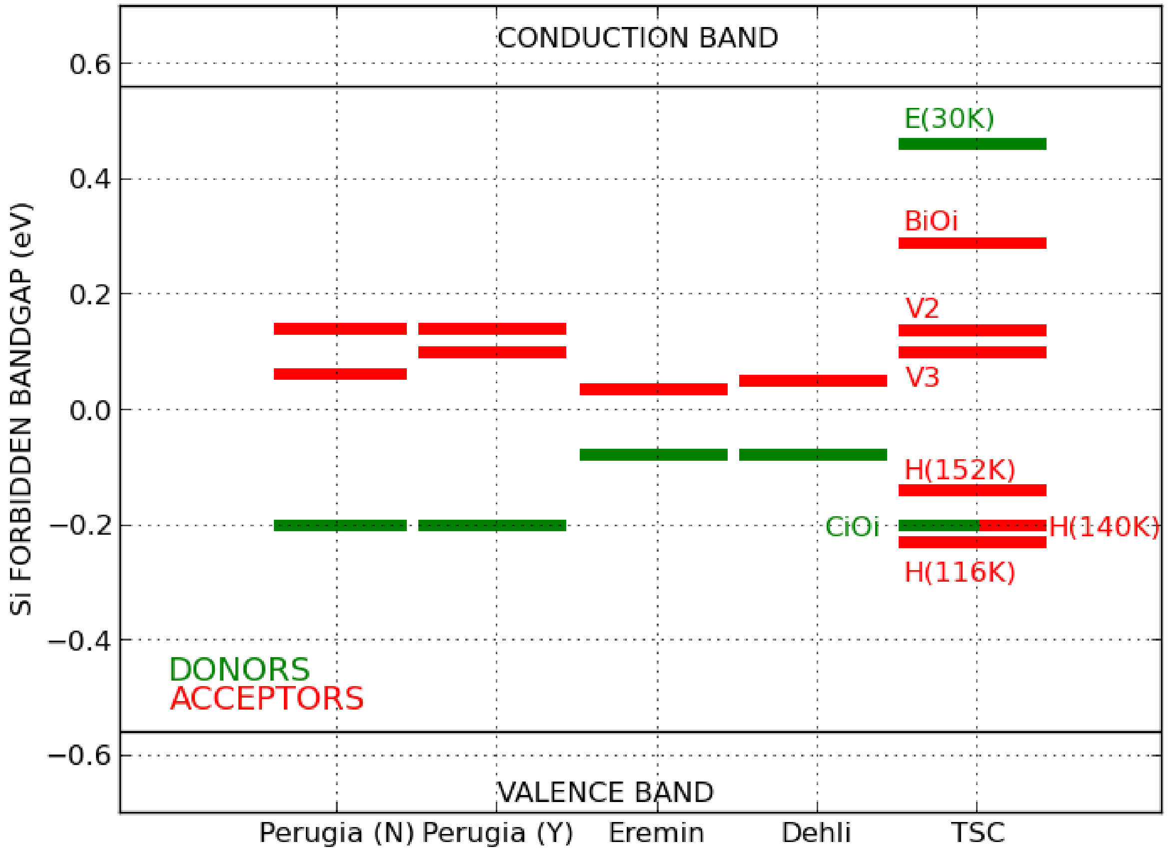
- Deep levels
→ leakage current

± Acceptors/Donors
→ space charge

To characterize:
1) defects
2) their effects

Defects & effects

- Knowledge of defects/effects especially in p-type Si sensors
- Models are based on "effective" states – unable to describe data



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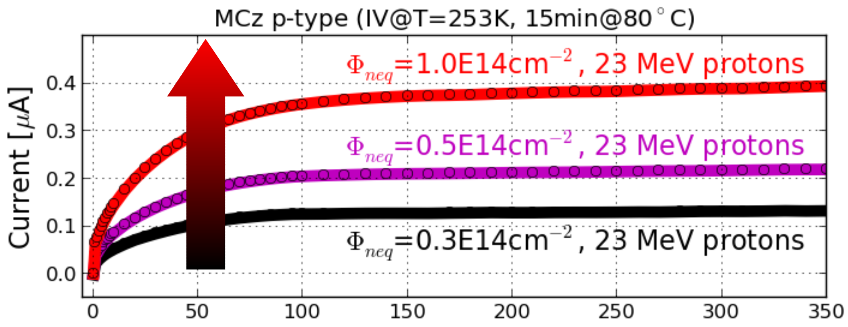

Φ_{neq}: NIEL scaling leakage current

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- Models are based on "effective" states – unable to describe data
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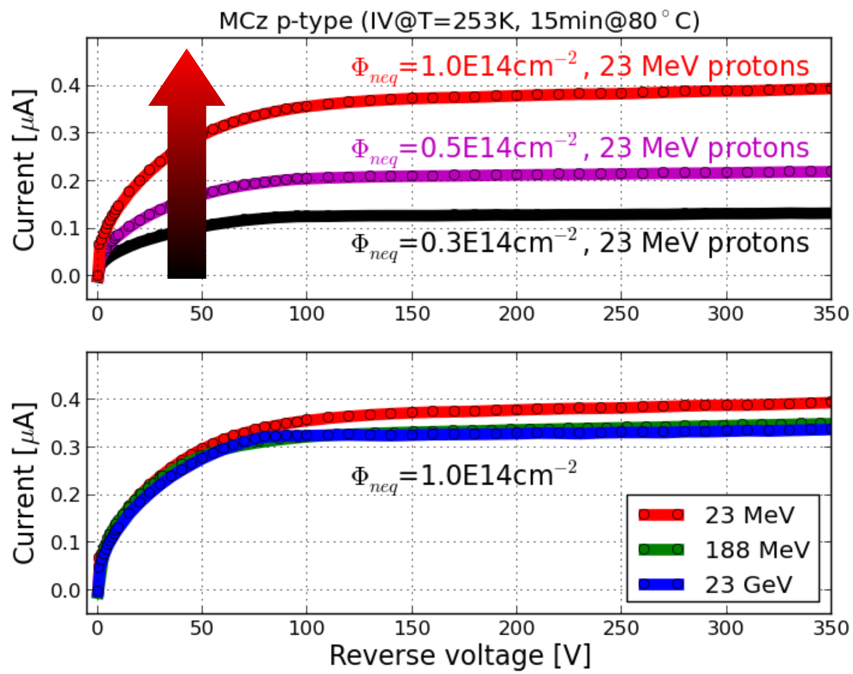
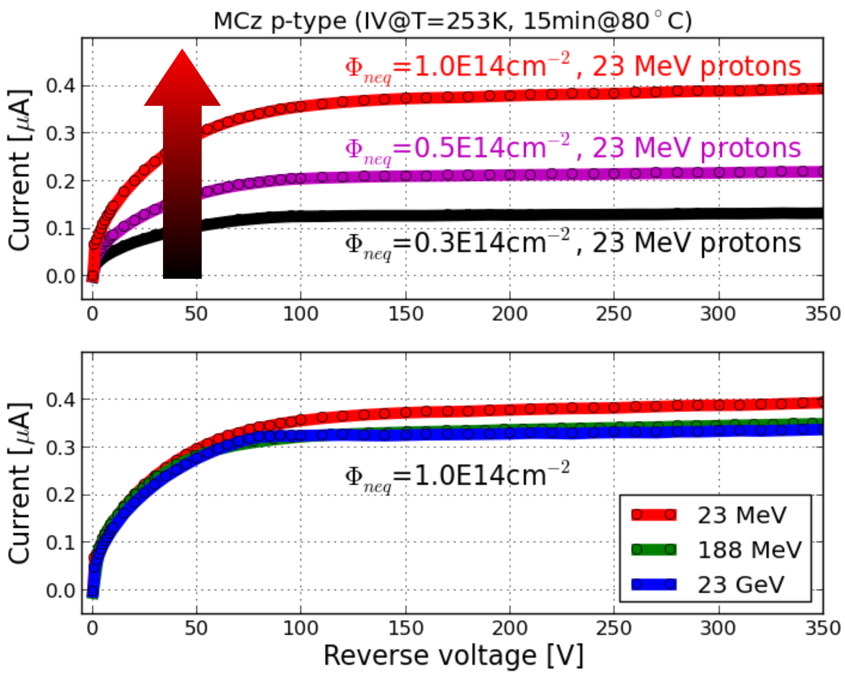
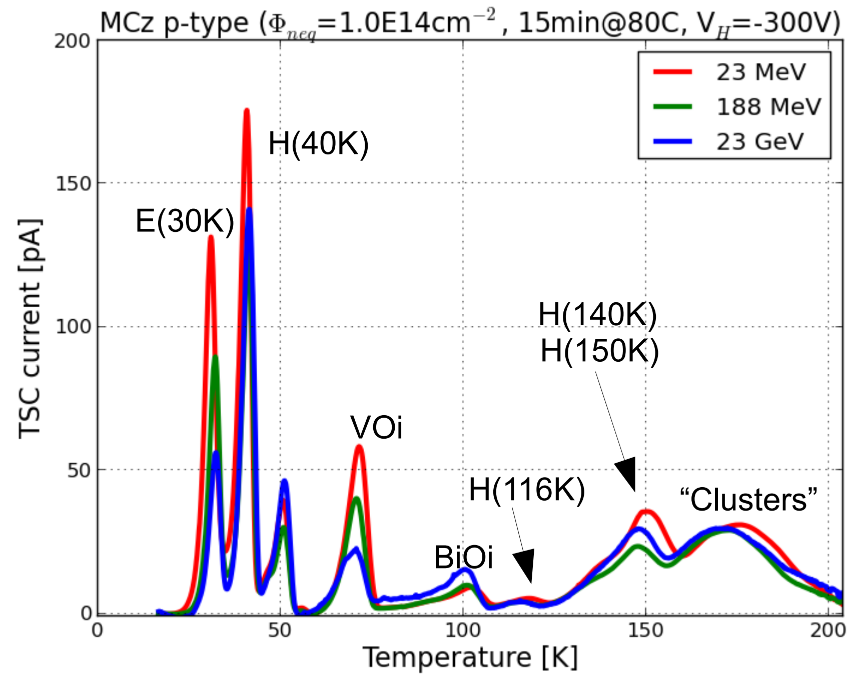


Φ_{neq}: NIEL scaling leakage current
Ep : no influence on LC within 18%
IV) no info regarding actual bulk defects

Defects & effects

- Knowledge of defects/effects in p-type Si sensors
- Models are based on "effective" states – limited predictive power
- e.g. Leakage current





Φ_{neq}: NIEL scaling leakage current
Ep : no influence on LC within 18%
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Φ_{neq} = 1E14 cm^{-2}, "limit for TSC"
Ep : no influence on "clusters"
TSC) info regarding N_t, $\sigma_{n,p}$, E_a

Analysis of TSC spectra

- Based on the Shockley – Read – Hall statistics
- Modified to account for charged clusters

1) Occupation of states:

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

2) Emission rate:

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

3) Activation energy:

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

- Uniformely spaced in the cluster region
- $f_{n,p}(T)$ fraction of filled traps
- δE_0 in the order of 10 meV for cluster-related defects

Analysis of TSC spectra

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

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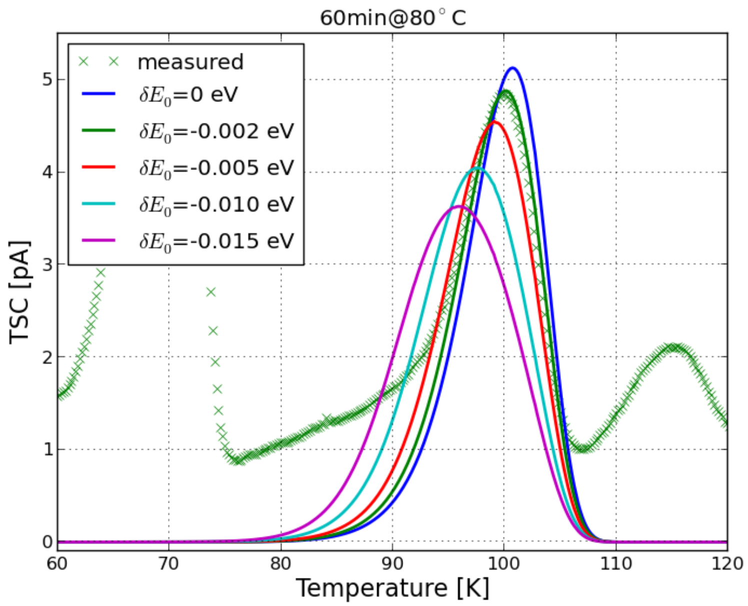


- Uniformely spaced in the cluster region
- $f_{n,p}$(T) fraction of filled traps
- δE_0 in the order of 10 meV for cluster-related defects

23 MeV protons
Φ_{neq} = 0.3E14cm^{-2}
60min@80°C

- N_t = 0.66E12cm^{-3}
- σ_n ~ 10E-16 cm^{-2}
- E_a = 0.23 eV
- δE_0 ~ 2 meV

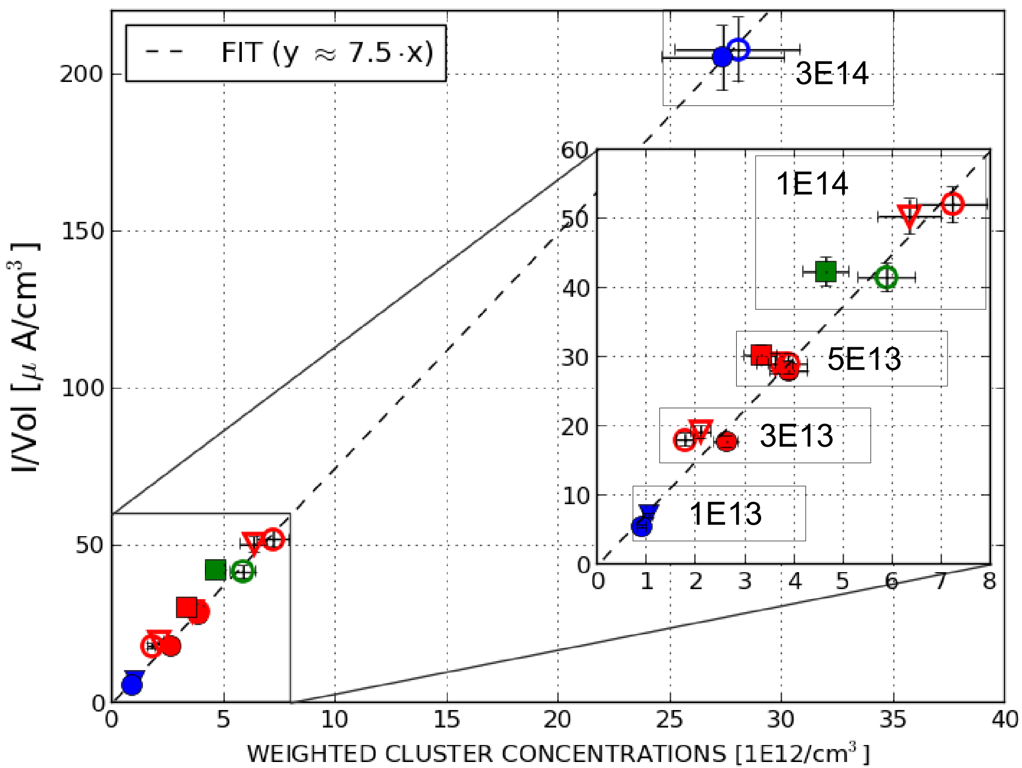
Leakage current

IV & TSC measurements

- IV vs. weighted TSC concentrations $$w = \left(\frac{1}{e_n} + \frac{1}{e_p}\right)^{-1}$$

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

Measured IV@ 253K, @ 300V



Calculated from TSC (Vheating = 300V)

	MCZ		FZ		FTH	
	N	Y	N	Y	N	Y
23 MeV	●	○	▼	▽	■	□
188 MeV	●	○	▼	▽	■	□
23 GeV	●	○	▼	▽	■	□

After annealing of 30min@80°C, (1E13<Φ_{neq}<3E14):

- Leakage current ↔ clusters
- No material dependence
- No proton-energy dependence

TBD) Check remaining samples
TBD) "Annealing" evolution

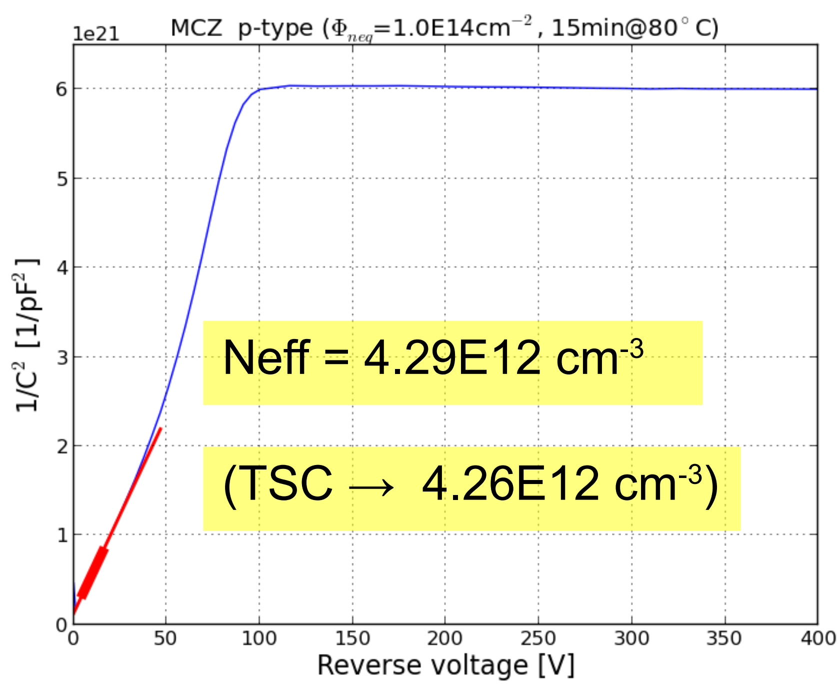
Effective doping

CV & TSC measurements

After 23 MeV protons

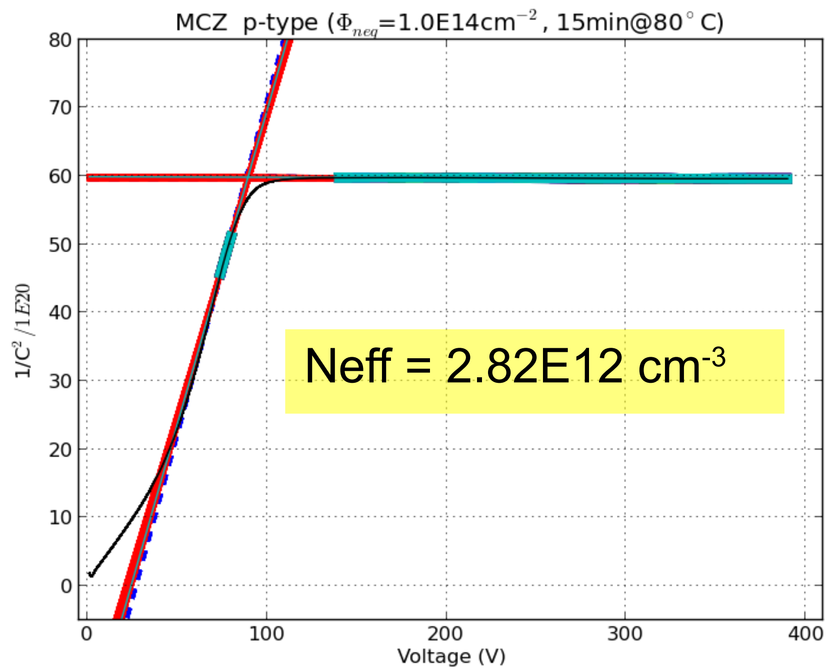
CV) Measured @253K, f=455 Hz
Neff from fit to initial 1/C² rise

$$N_{eff,CV} = -\frac{2}{A^2 \epsilon \epsilon_0 q_0 \frac{d(1/C^2)}{dV}}$$



CV) Measured @253K, f=455 Hz
Neff from depletion voltage

$$V_{dep} + V_{bi} = \frac{q_0}{2\epsilon\epsilon_0} |N_{eff}| d^2$$



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

Effective doping

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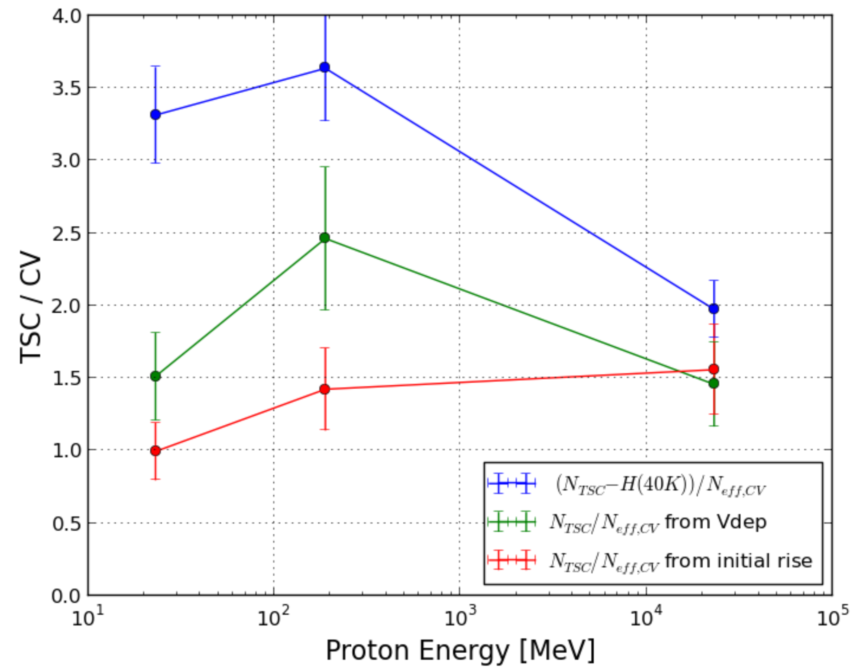

Φ_{neq} = 1E14 cm^{-2}, "limit for TSC"
Ep : influence on point-like defects
50% agreement

Effective doping

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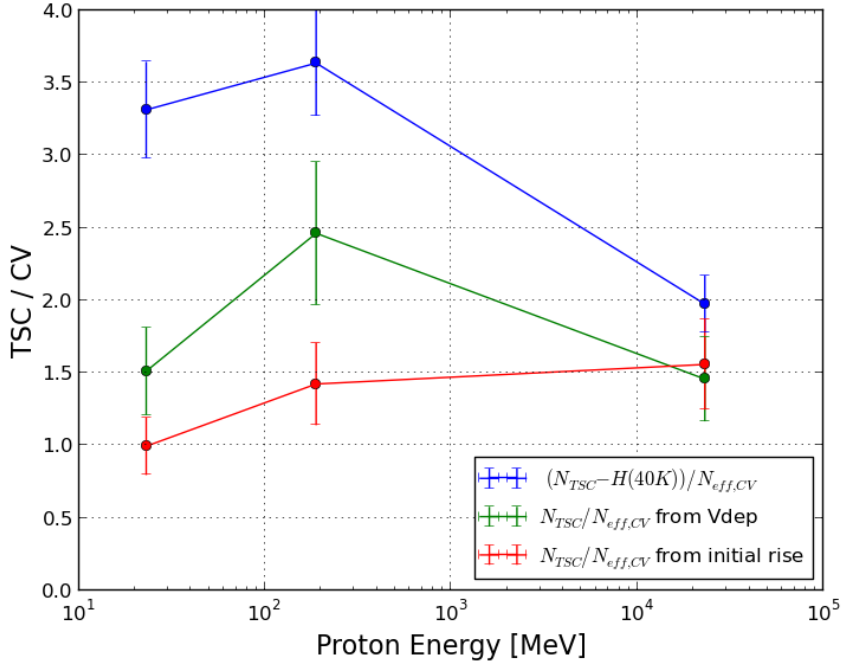


Open issues:
- H(40K) unknown nature & effects
- Effects of MANY defects
- Analysis of CVf (ongoing)

Φ_{neq} = 1E14 cm^{-2}, “limit for TSC”
Ep : influence on point-like defects
50% agreement

Outline / Conclusions

1) Proton-irradiated Si samples
   3 bulk material, n and p pad-diodes

2) IV/CVf/TSC measurements

3) Analysis of TSC spectra

4) Leakage current

5) Effective doping concentration

1) E_p (23 MeV – 188 MeV – 23 GeV)
   $1{\cdot}10^{13} < \Phi_{neq} < 3{\cdot}10^{14}$ neq/cm^2

2) Defects & their effects

3) Revisited SRH statistics

4) Cluster-related (V_2)

5) E(30K), BiOi, 3 deep acceptors

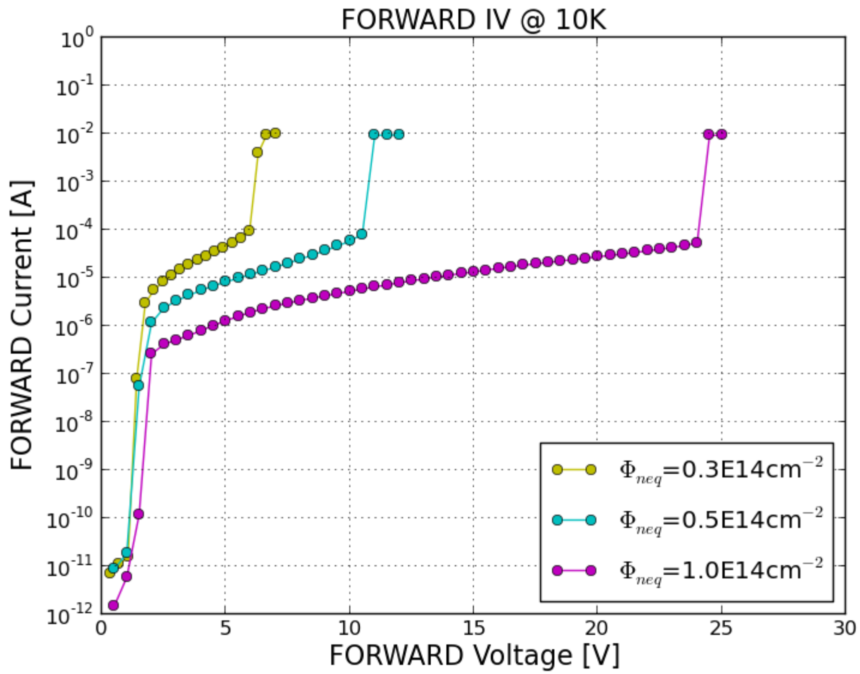
→ Input for TCAD simulations
→ Model RD at higher Φ_{neq} ?

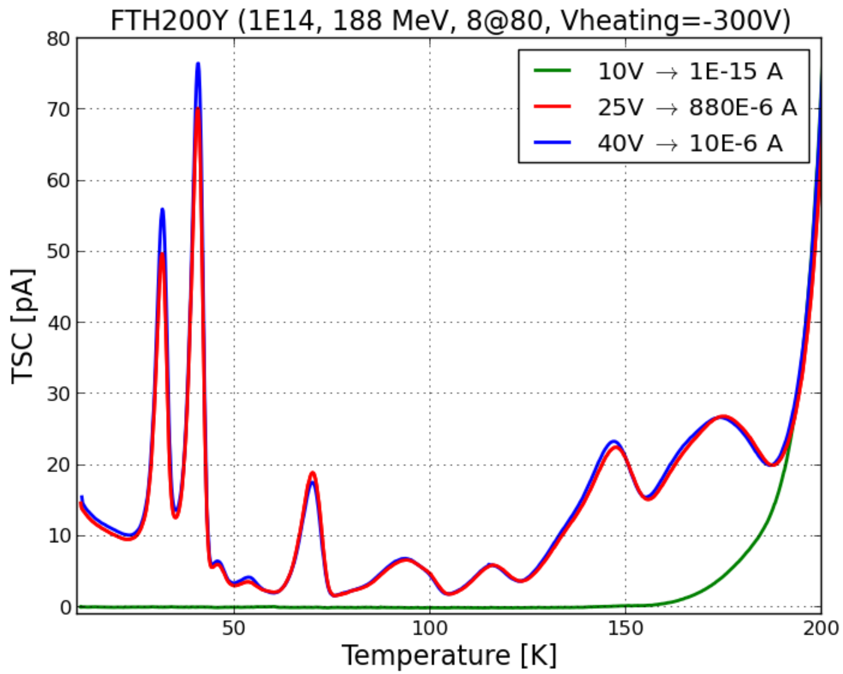
Two busillis

1) (Forward) Filling current @ 10 K

2) Filling temperatures > 10 K

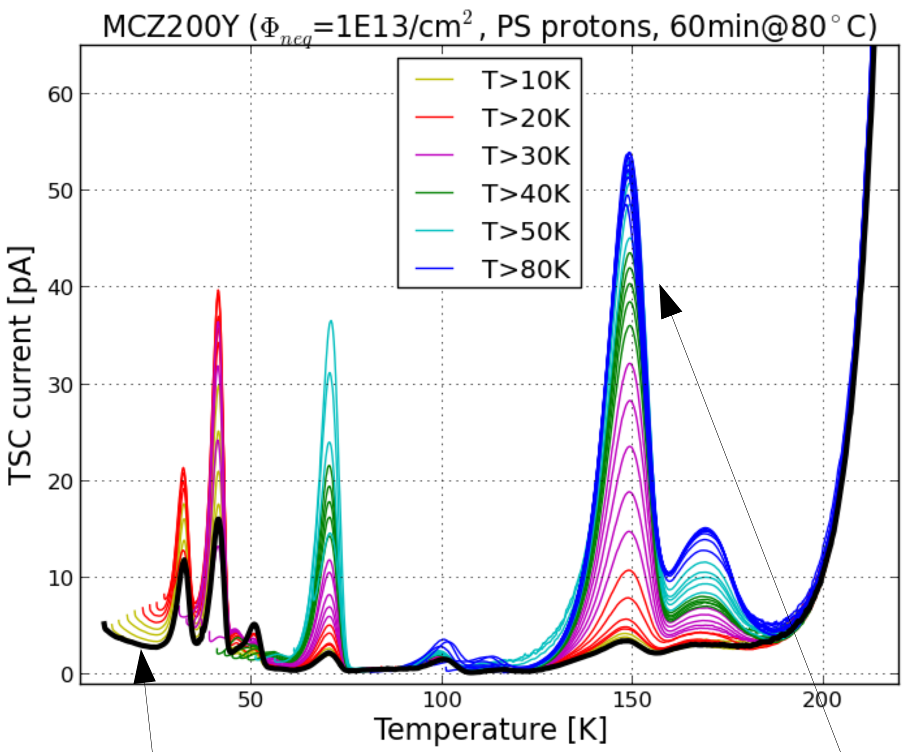
Issue#1: Filling current @ 10K

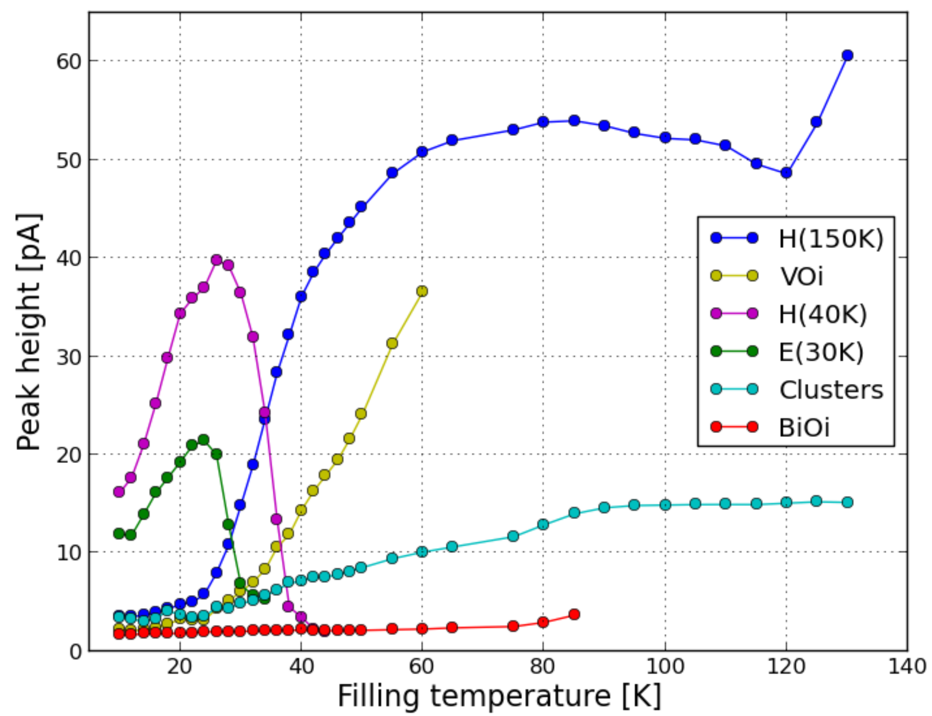




	Vfilling=25V	Vfilling=40V	Ratio
E(30K)	2.23E12 cm^{-3}	2.48E12 cm^{-3}	0.90
H(40K)	3.54E12 cm^{-3}	3.78E12 cm^{-3}	0.94

Issue#2: Filling temperature



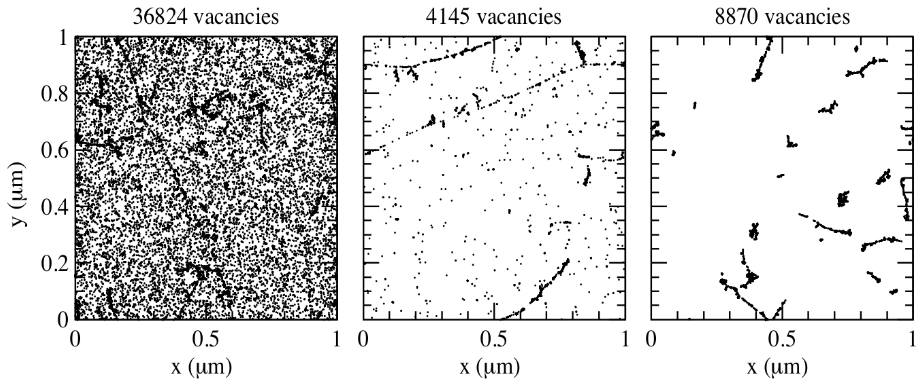


- Black line: “standard” TSC spectra, with Tfilling = 10K
- Dominant hole trap if Tfilling > 10K : CiOi (not seen if Tfilling = 10K)
- Enhanced peaks for E(30K), H(40K) and VOi, as well.
- TSC @ low temperatures ← ? → room temperature simulations

Thank you for your attention!

Defect(s) classification(s)

POINT-LIKE
after 10 MeV protons



CLUSTER
after 23 GeV protons

- **Single vacancies or single interstitials**
- **Di-vacancies or di-interstitials**
- **Combined with impurities**

Agglomeration of defects, Vol ~ (15 – 20 nm)^3
10^5 – 10^6 atoms

- **E4, E5, E205a only after hadron irradiation**
- **Practically: higher leakage current**

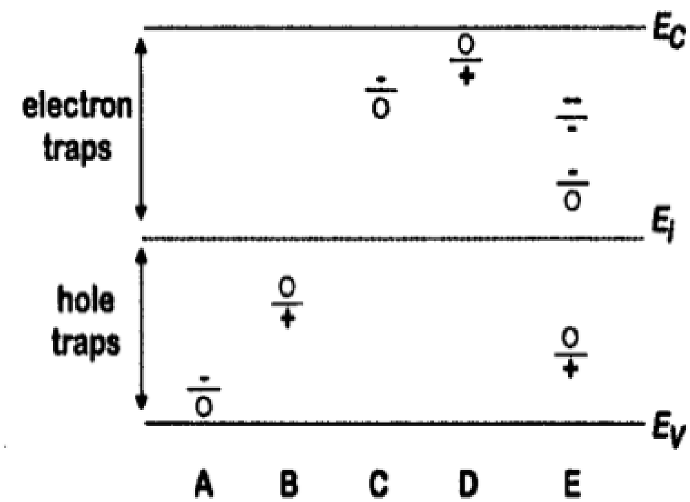
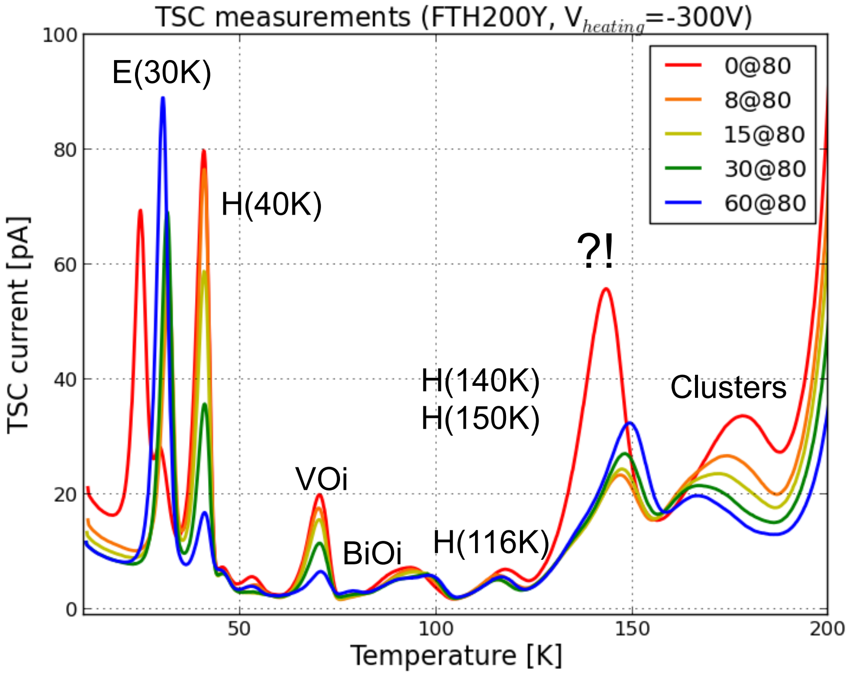


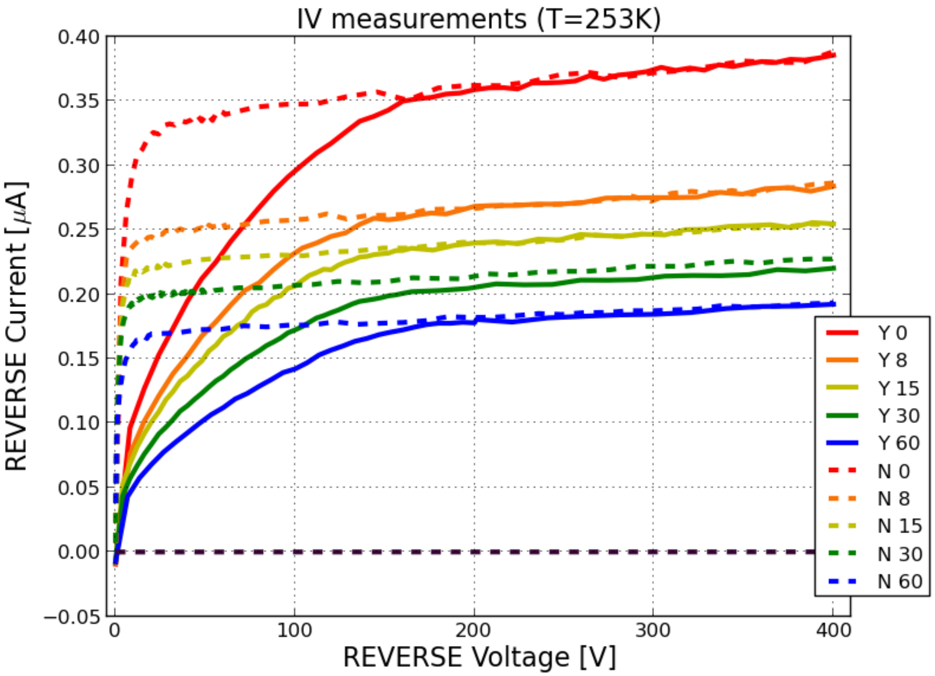
Fig. 3.24 Classification of levels in the forbidden gap.

A: shallow acceptor, e.g. B_s
B: deep donor, e.g. $C_i O_i$
C: deep acceptor, e.g. $V O_i$
D: shallow donor, e.g. P_s
E: amphoteric level, e.g. $V V$

Annealing studies

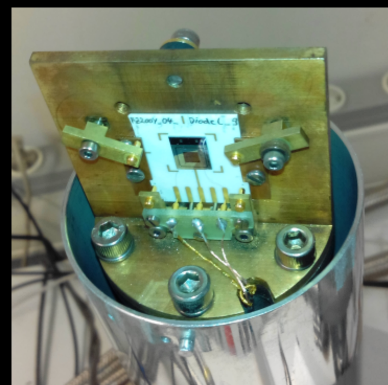
FTH200N/Y
188 MeV protons
Φ_{neq} = 1.0E14cm^{-2}



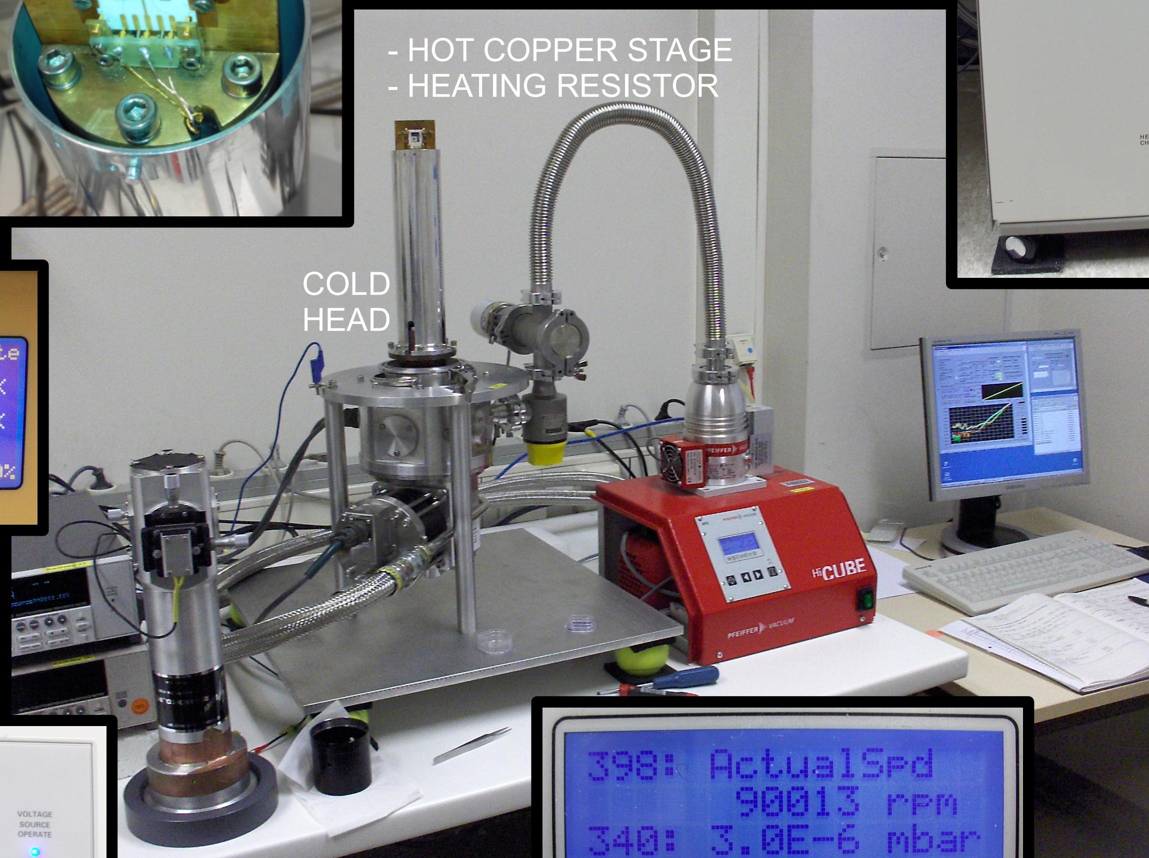


The TSC setup (goo.gl/Zd5Wmn)

Sample holder + T sensor



Helium compressor and cryogenerator



Temperature controller

front and back side illumination

Amperometer + Vsource

Light shield

Vacuum pump and meter

Labview DAQ