Status of defect investigations

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Universität Hamburg
DER FORSCHUNG | DER LEHRE | DER BILDUNG

PHYSICS AT THE TERA SCALE
Helmholtz Alliance

CMS Germany
BMBF FSP-CMS

Outline

- Introduction
- Defects with impact on
  - effective doping concentraion
  - leakage current
  - trapping
- Summary

Radiation exposure

LHC expected fluence:

L=10^{34} cm^{-2} s^{-1}, 500 fb^{-1}

➔ 10 years Φ (r=4 cm)

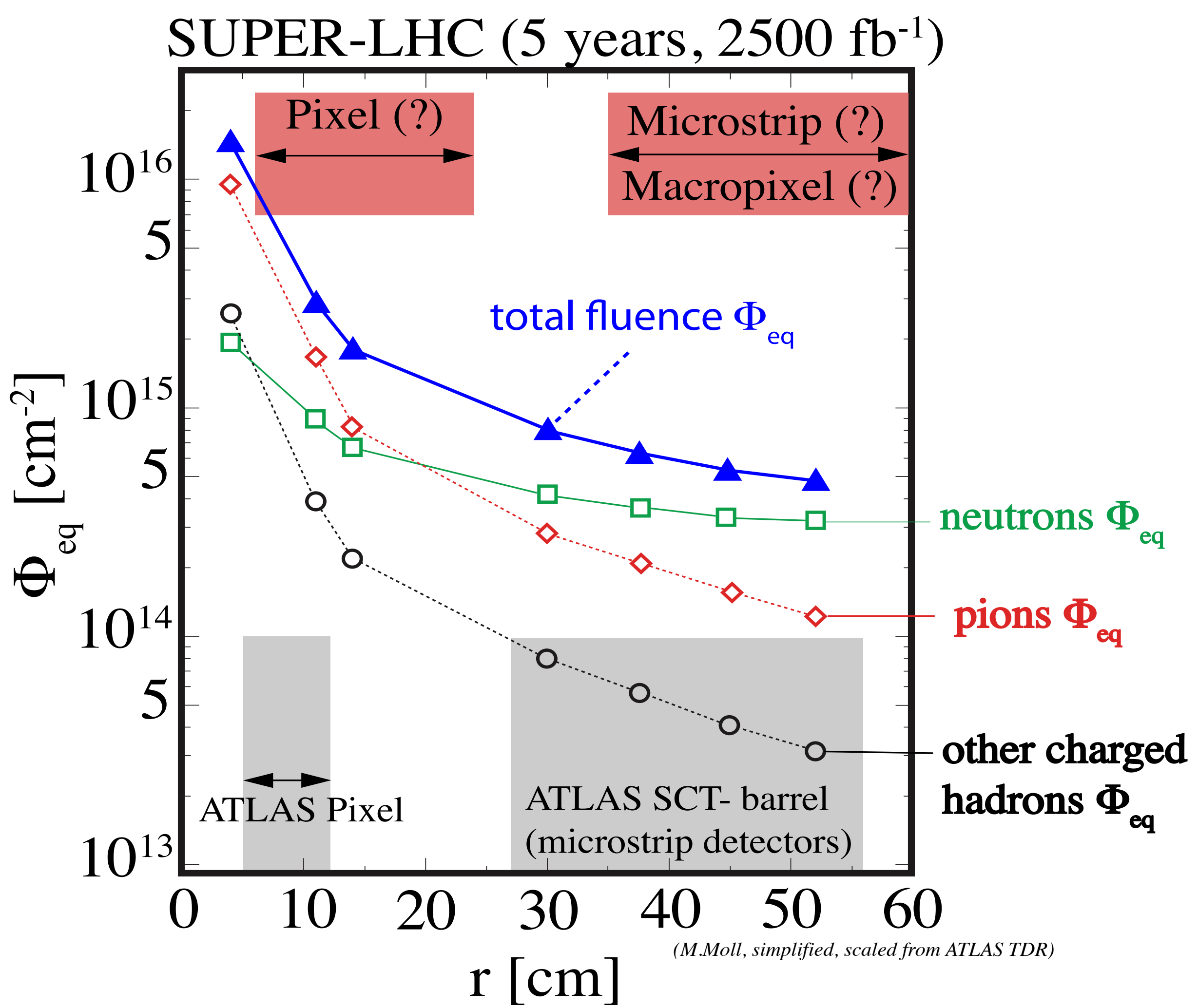
~3 x 10^{15} cm^{-2}

high luminosity LHC expected fluence:

L=10^{35} cm^{-2} s^{-1}, 2500 fb^{-1}

➔ 5 years Φ (r=4 cm)

~1.6 x 10^{16} cm^{-2}



No currently used material withstands this radiation exposure

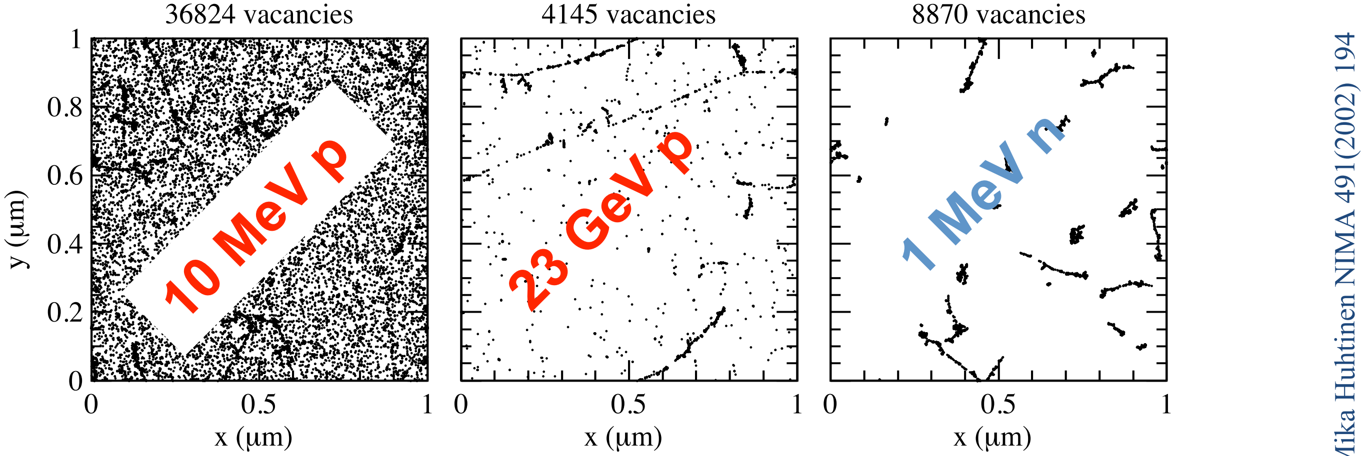
➔ Increase of signal loss

➔ Particle type and fluence depend on radius

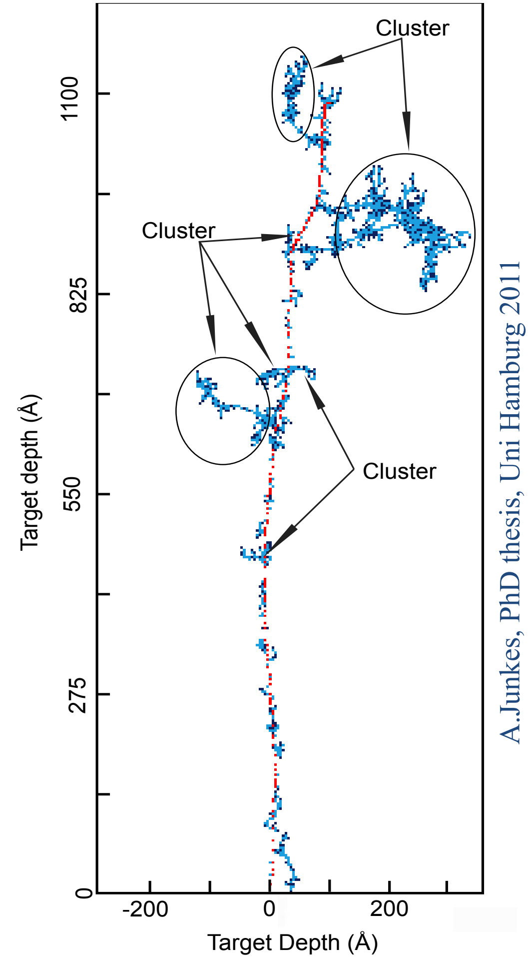
Aim: find best material for *high luminosity* LHC applications

Creation of bulk defects

Depends on particle charge, mass, energy



Simulation: Distribution of vacancies after $\Phi_{eq}=10^{14}$ cm^{-2}



Simulation of 50 keV PKA damage cascade (1 MeV n)

The *hl* LHC case

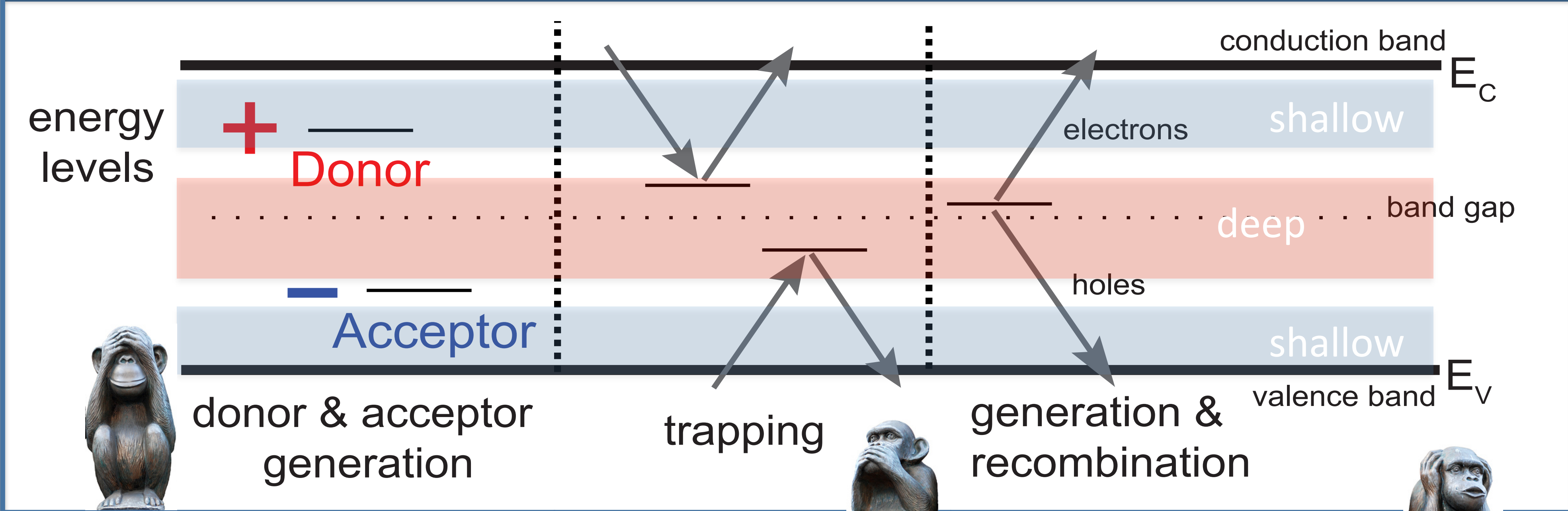
Pions (and protons) ➔ Point defects and cluster

Neutrons ➔ Large damaged regions

Good, bad or ugly... Influence of defects on detector performance?

Impact of defects on detector properties

Determined by Shockley-Read-Hall statistics

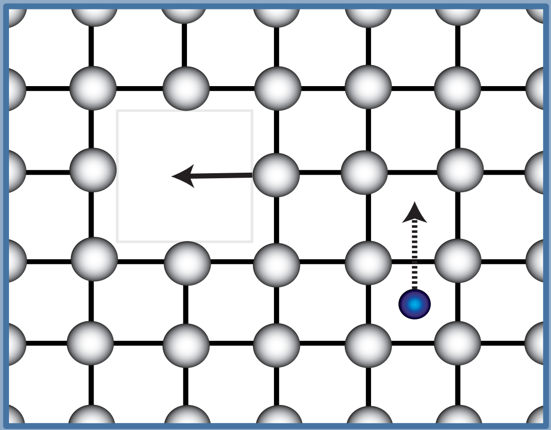


Charged defects (at RT)
→ N_{eff} , V_{dep}
(Acceptors in the lower half and donors in the upper half of the band gap)

Deep defects
→ CCE
(Shallow defects do not contribute due to detrapping)

Levels close to midgap
→ I_{dep} (NOISE)
(Defect levels close to midgap most effective)
→ Cooling during operation helps!

Defect engineering



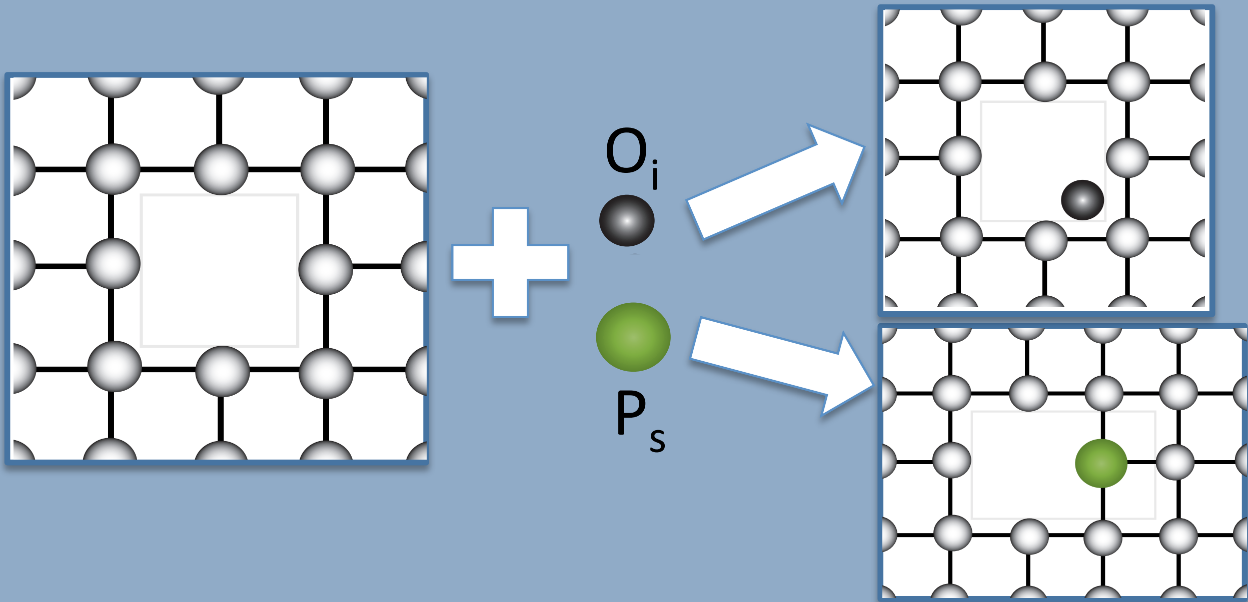
- Frenckel pairs are created due to irradiation
- Defect complexes form due to migration
  - → Migration depends on thermal energy
  - → Kinetics like in chemical reactions

Benefit of oxygen rich silicon: VO_i generation high – VP (donor removal) suppressed

$V+O_i \rightarrow VO_i$

or

$V+P_s \rightarrow VP$



No influence!

Donor remouval

Know thy enemy

Identification of defects with impact on detector performance

Detector properties

Capacitance-Voltage- (CV)
Current-Voltage-characteristics (IV)
Transient-Current-Technique (TCT)

Depletion voltage
Leakage current
Trapping

Defect properties

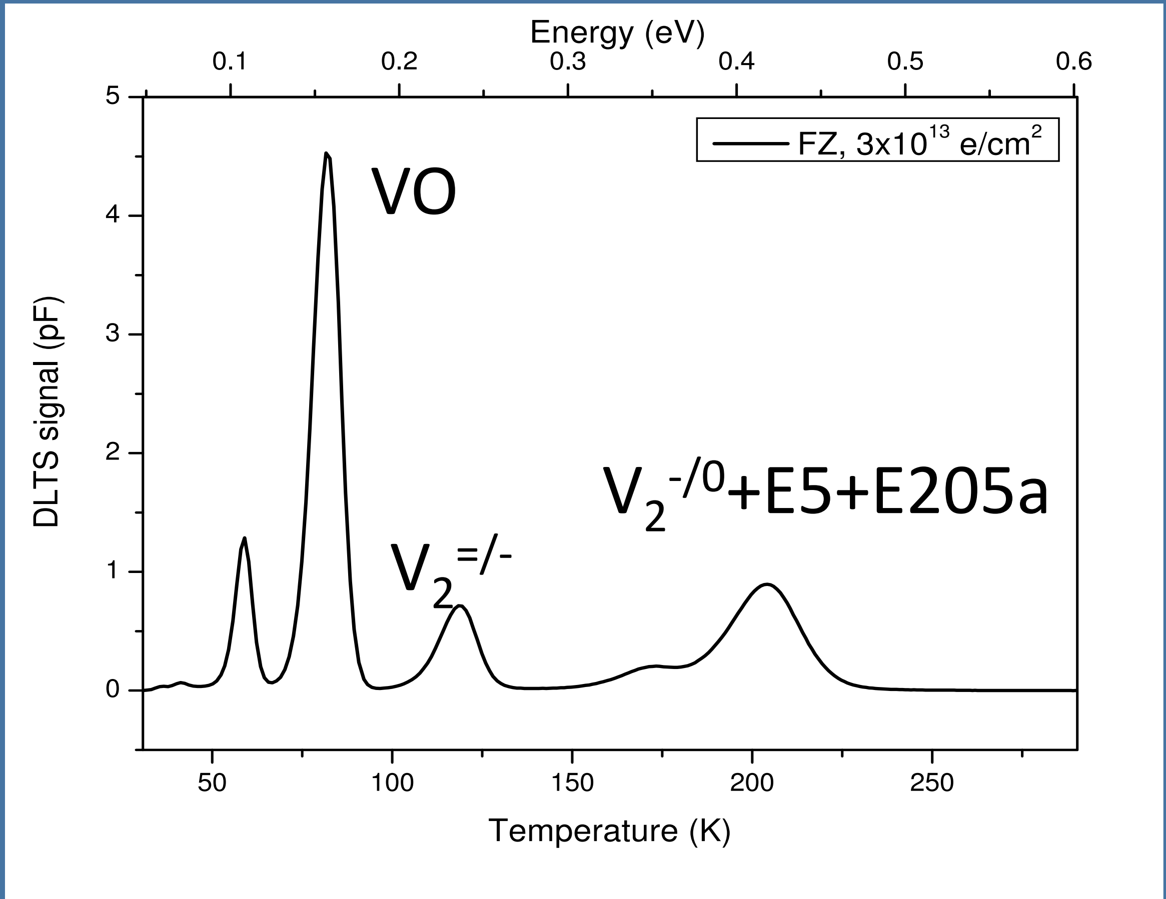
Deep Level Transient Spectroscopy (DLTS)
Thermally Stimulated Current (TSC)

Defect concentration
Ionisation energy
Capture cross section

Find correlation between them during annealing studies

Measurement techniques

• Signal as function of temperature (DLTS)



1. Filling of traps with charge carriers
2. Recording of charge emission from filled traps
   - DLTS: capacitance transients
   - TSC: current from emission
3. Defect concentration from peaks

DLTS: Filling and emission during Temperature-scan

TSC: Filling at low T, emission during constant heating rate

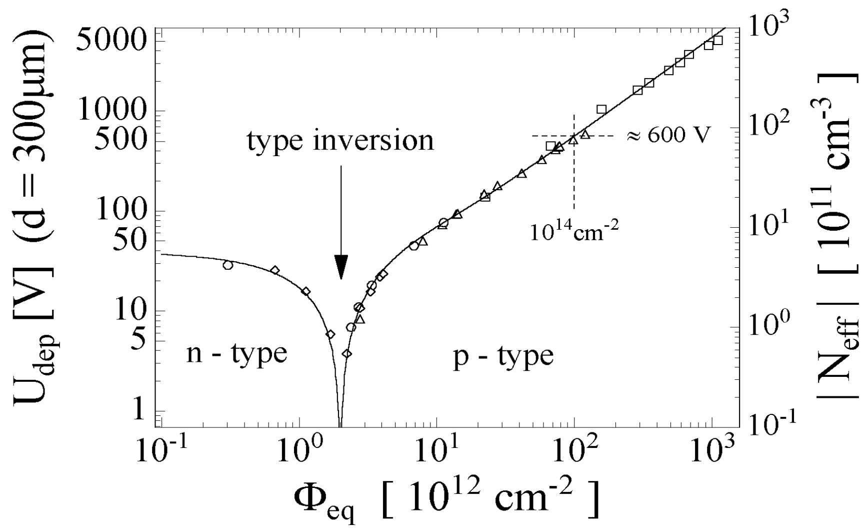
T-scan = Energy scan of the band gap

Depletion voltage

Monkey does not see particles

Depletion voltage

With particle fluence (FZ Si, neutrons):



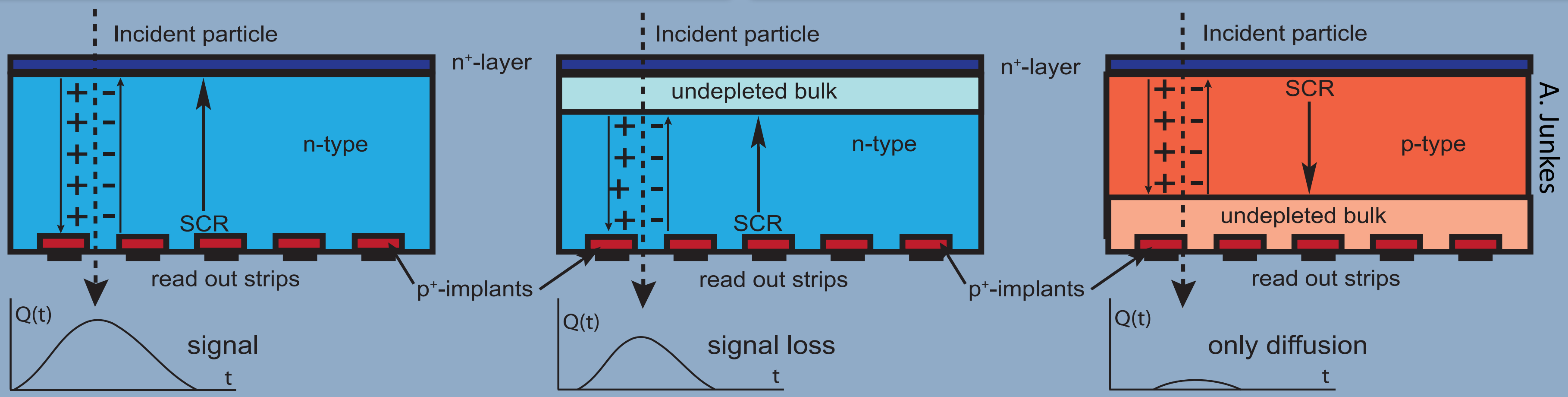
R. Wunstorf, PhD thesis 1992, Uni Hamburg

$$V_{dep} = \frac{q_0}{\varepsilon\varepsilon_0} \cdot \left|N_{eff}\right| \cdot d^2$$

- Acceptors compensate original doping
- Type inversion from n- to p-type
- Increase of depletion voltage after SCSI

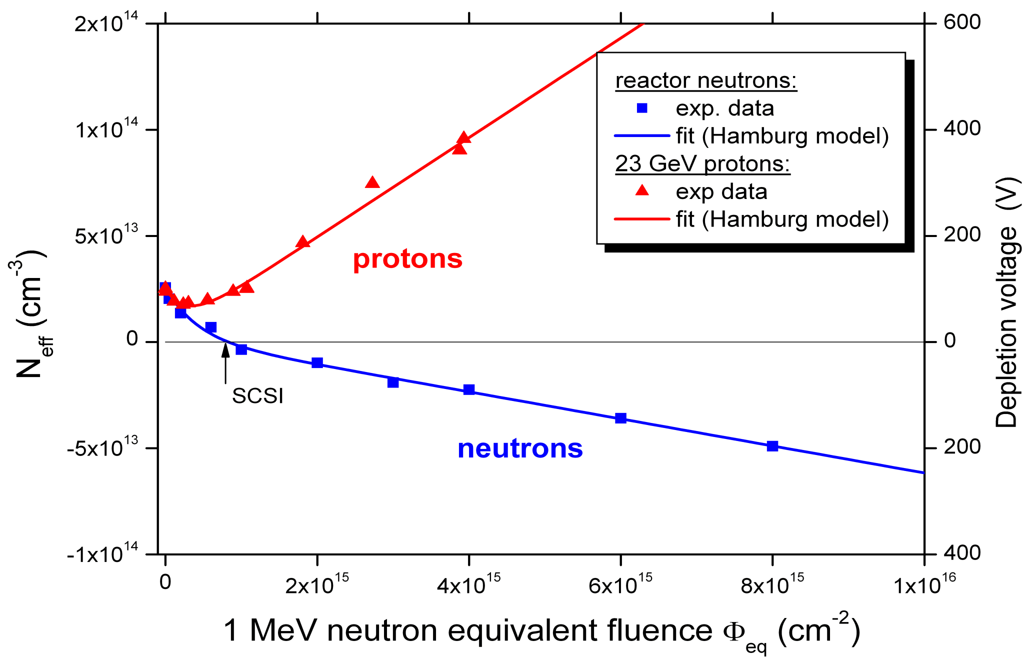
➔ Signal loss

- Annealing studies show impact of high T during maintenance times



Defects with impact on N_{eff}

N_{eff} for n and p irradiation (CV) for Epi-Do



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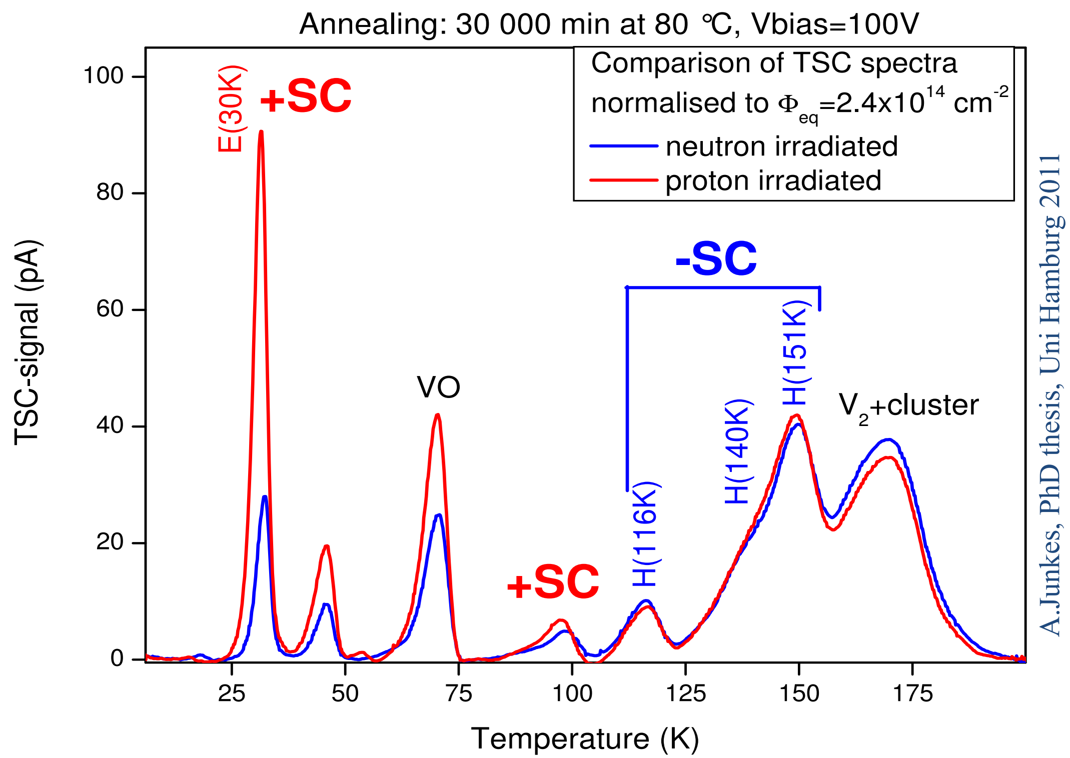
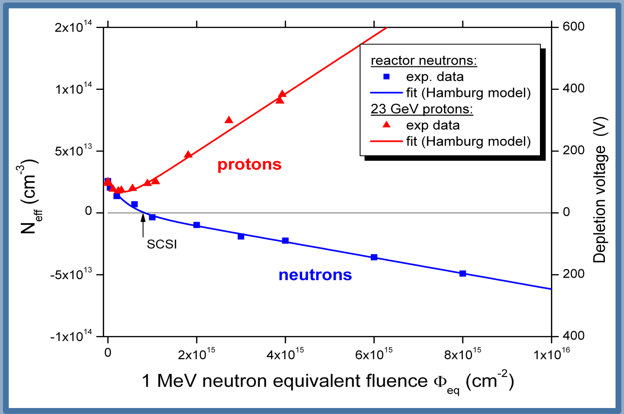
Corresponding defects (TSC)



- Deep acceptors (H-defects) generate negative space charge
- Shallow donor E(30K) generation high for proton irradiation
- E(30K) compensates deep acceptors ➔ no type inversion for protons

Defect balance



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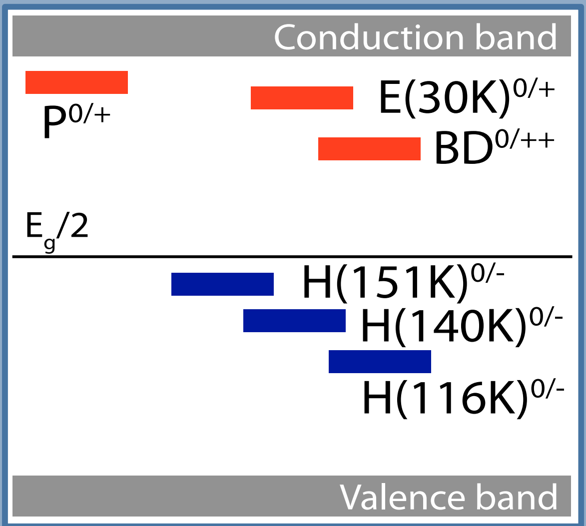
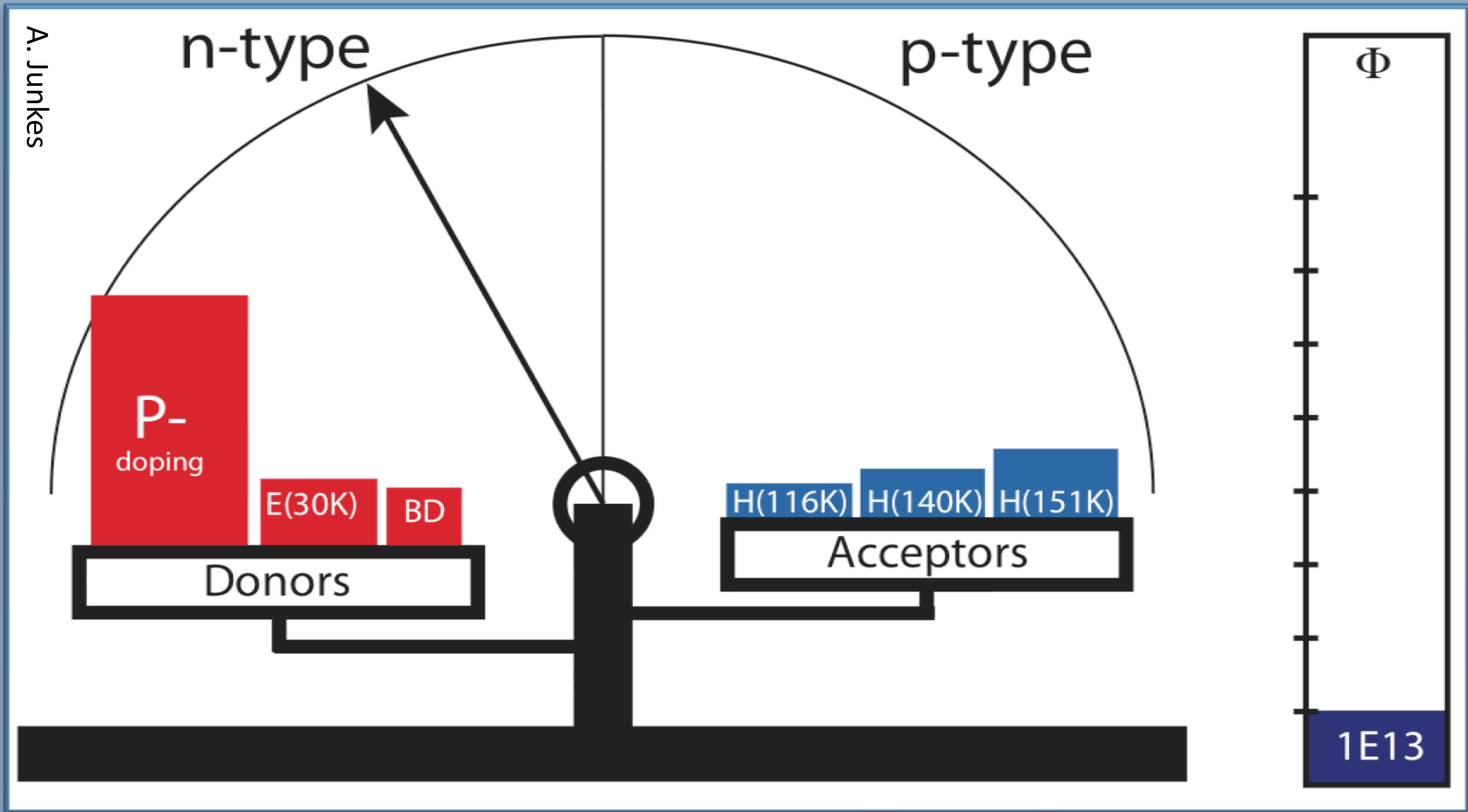
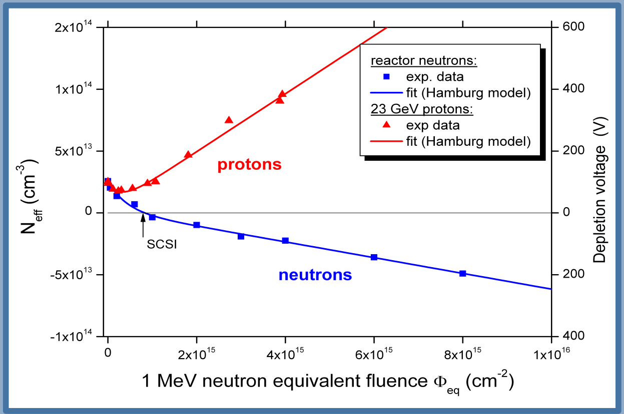


Neutron irradiation



Defect balance



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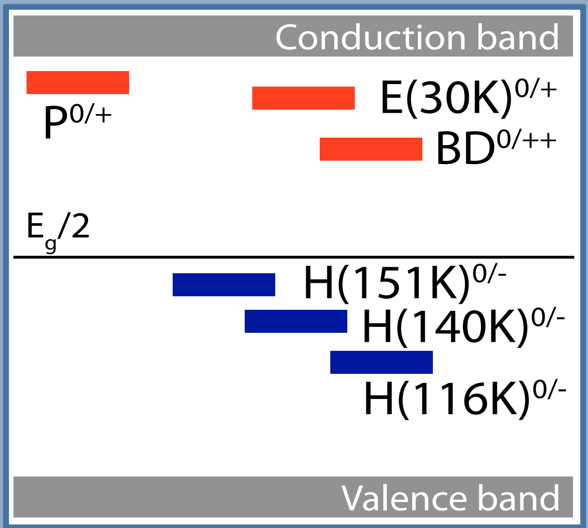
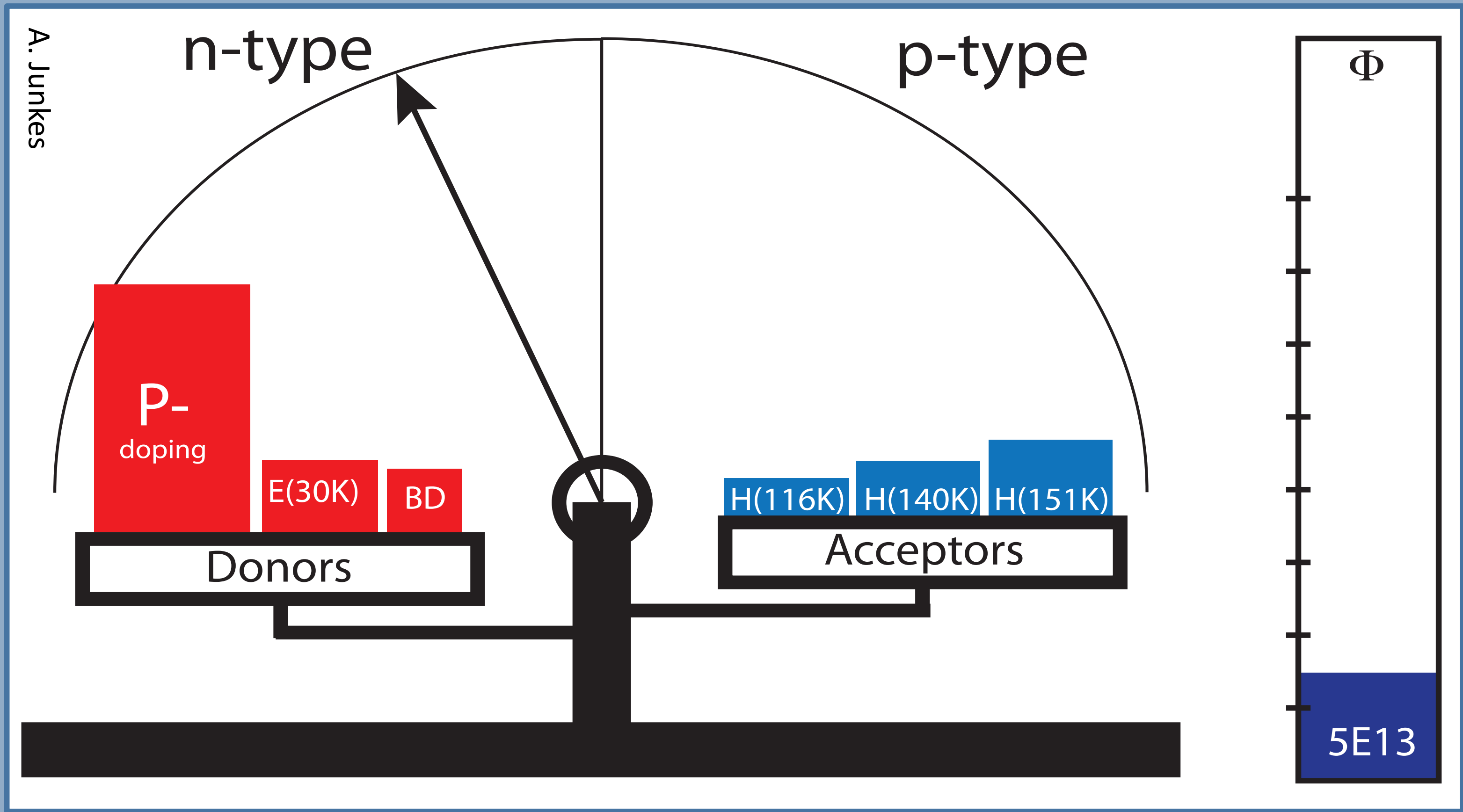
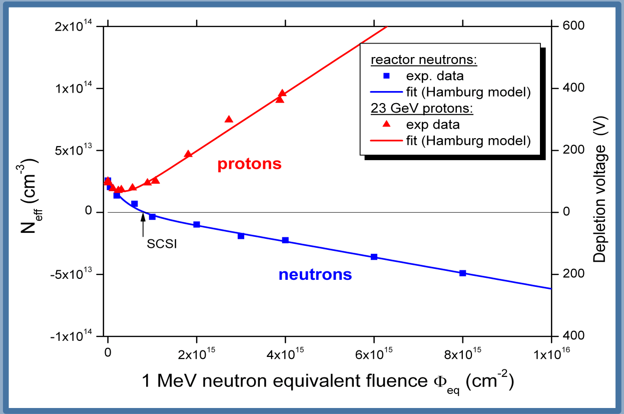


Neutron irradiation



Defect balance



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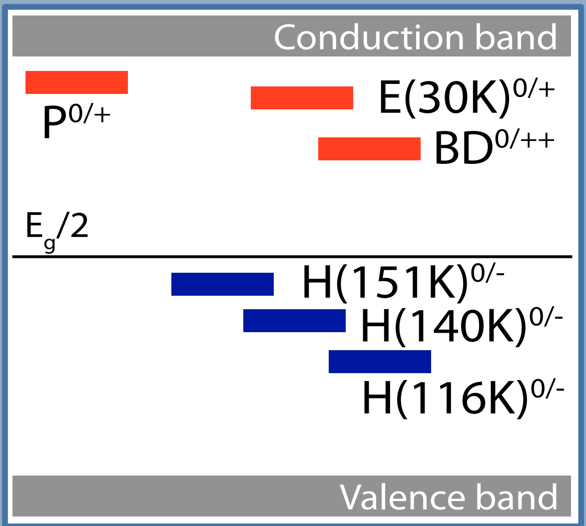

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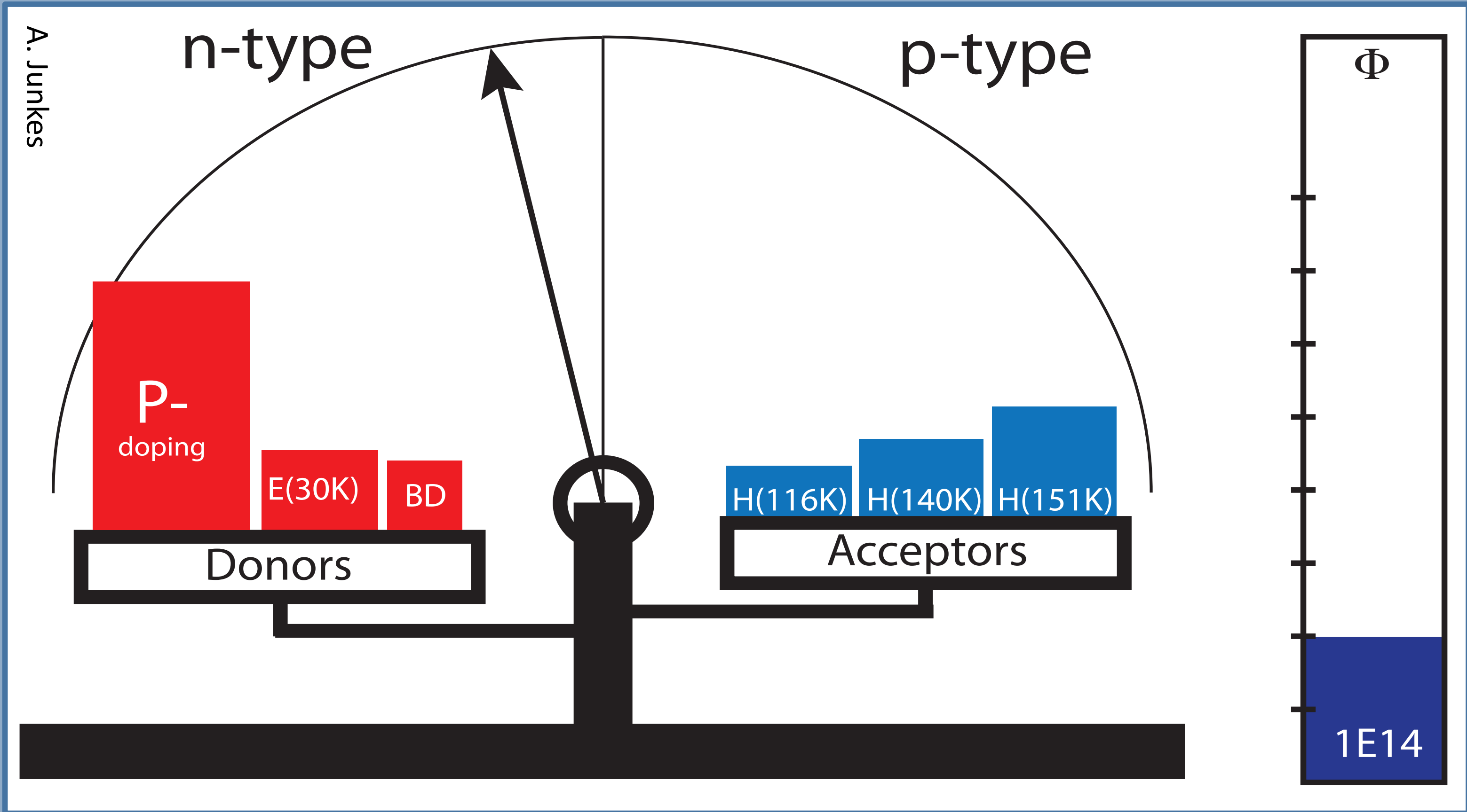

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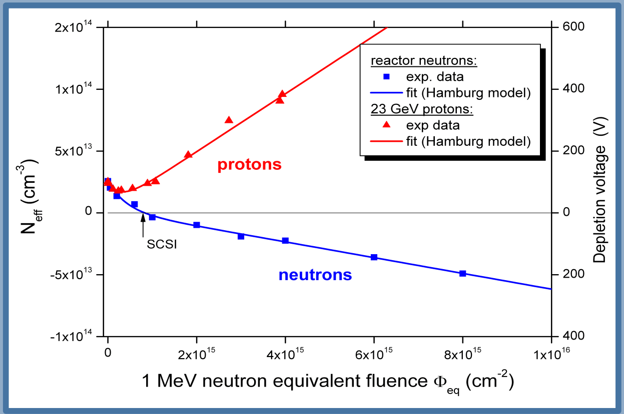

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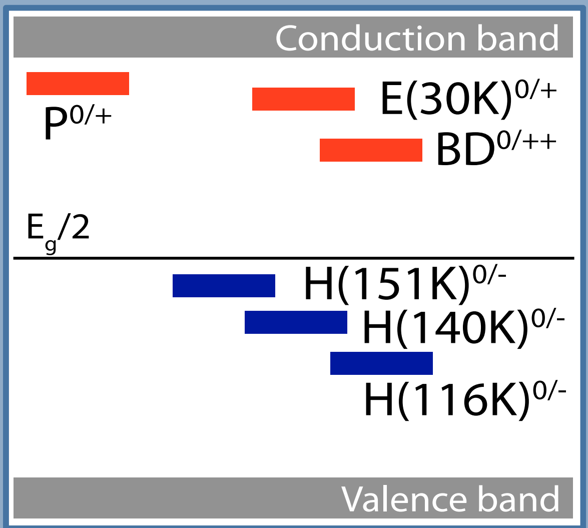
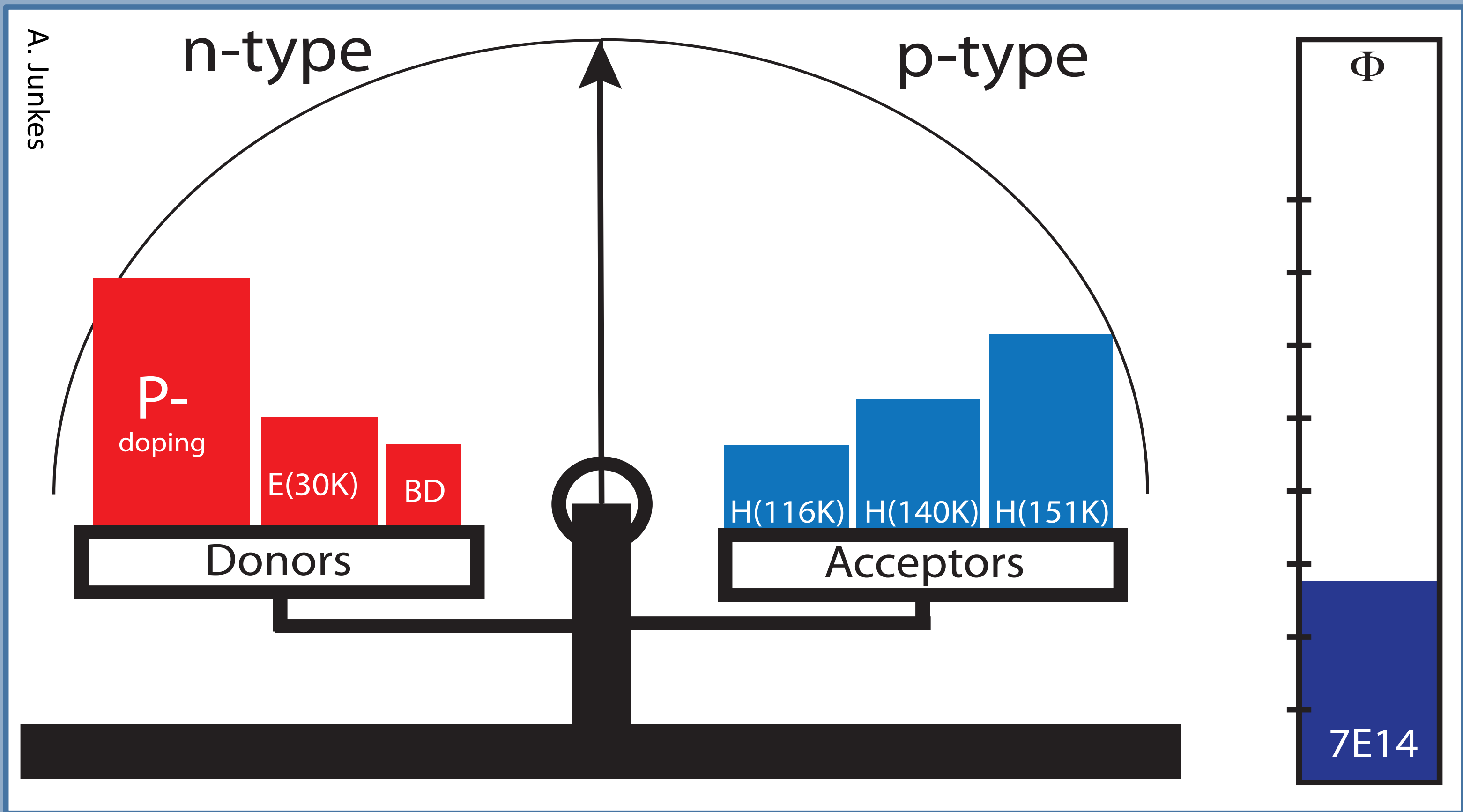
Neutron irradiation





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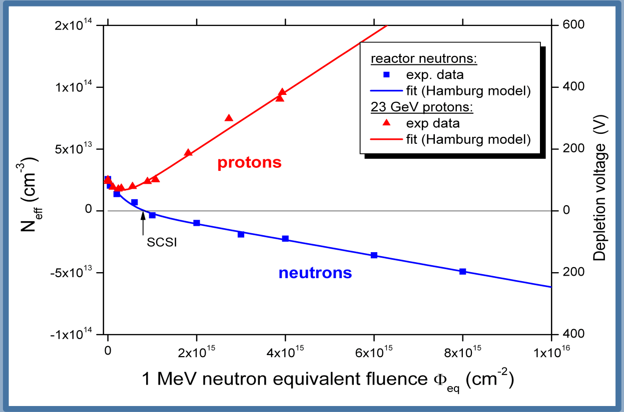

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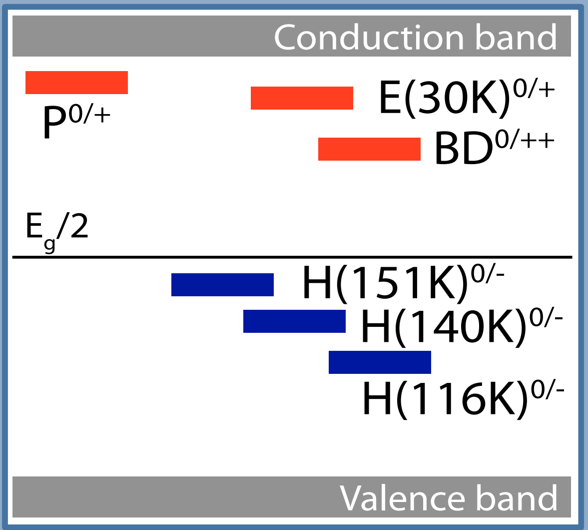

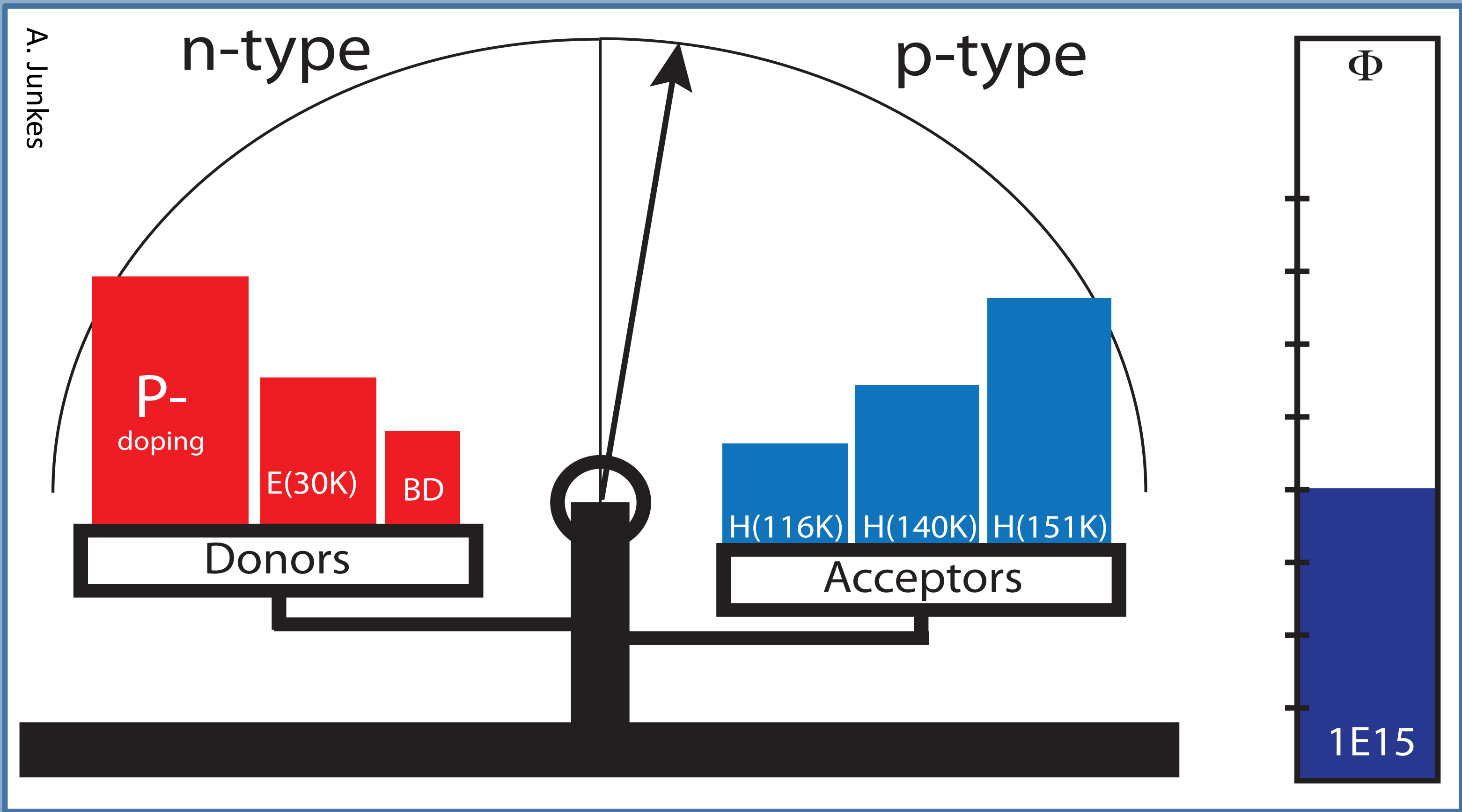

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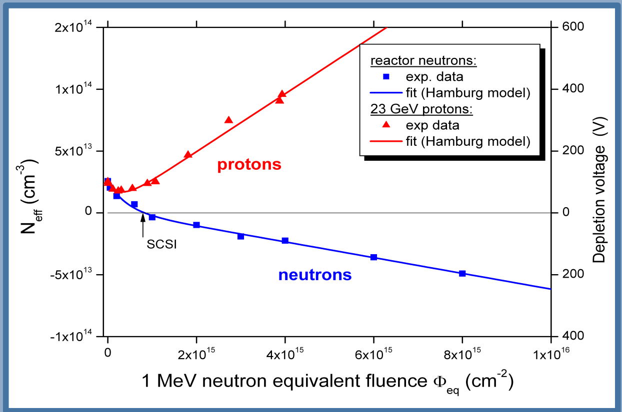

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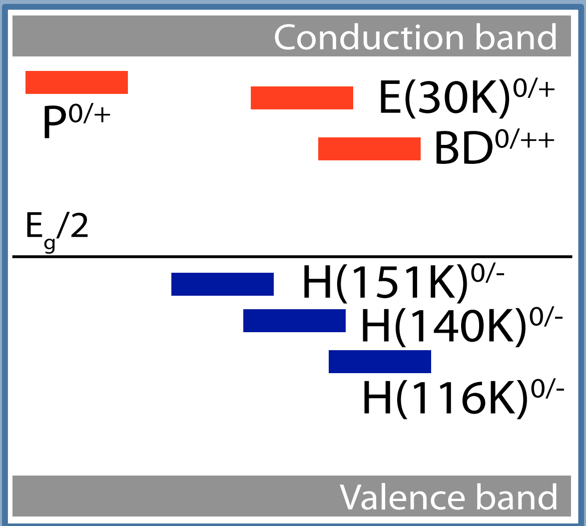

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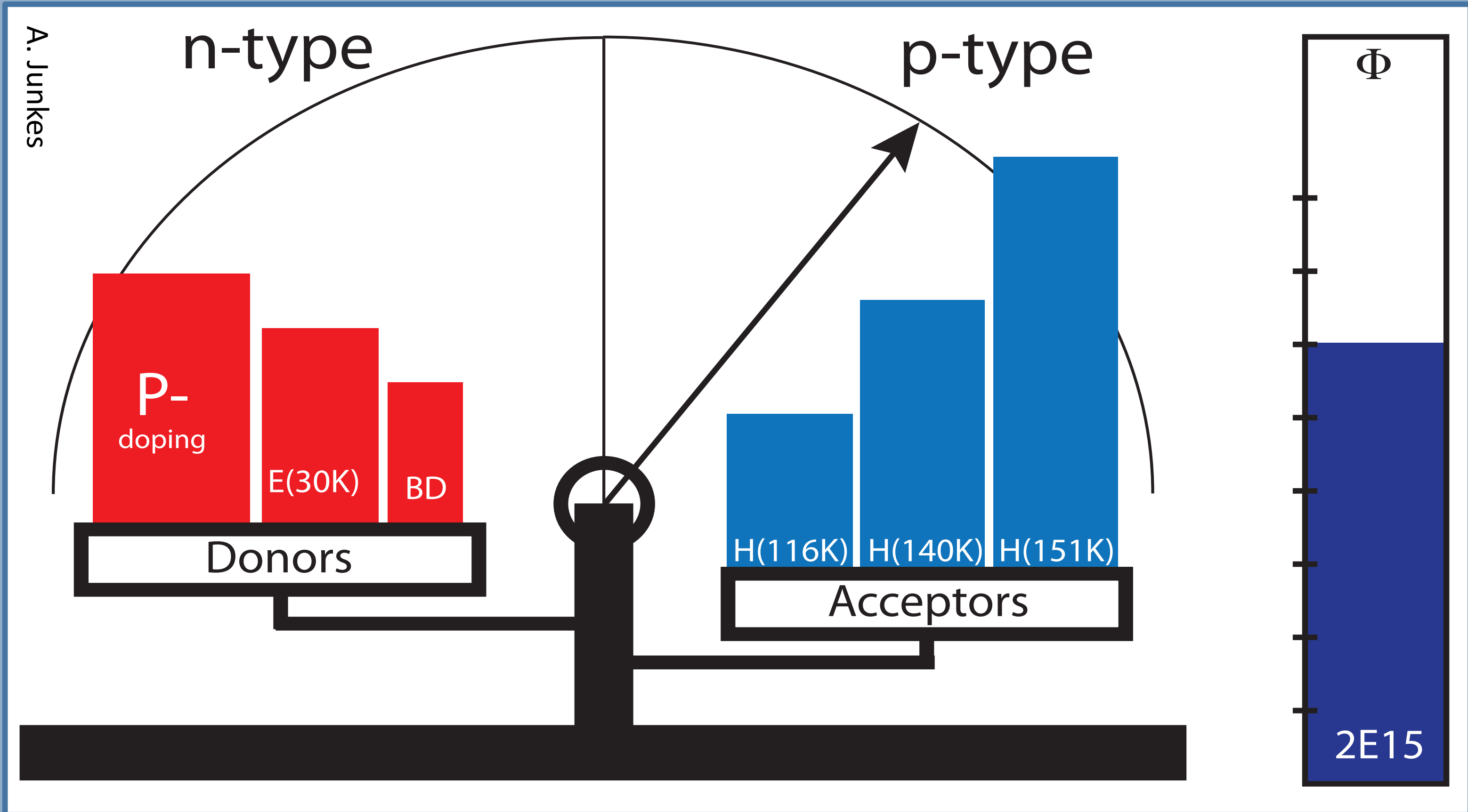

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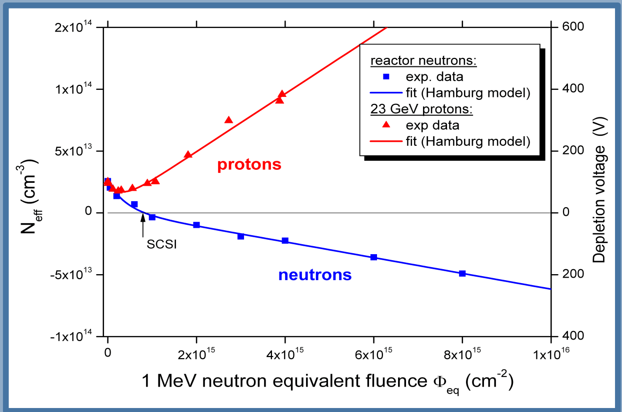

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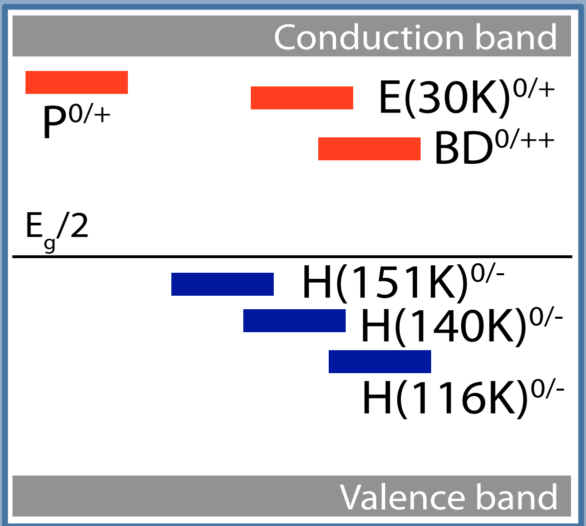
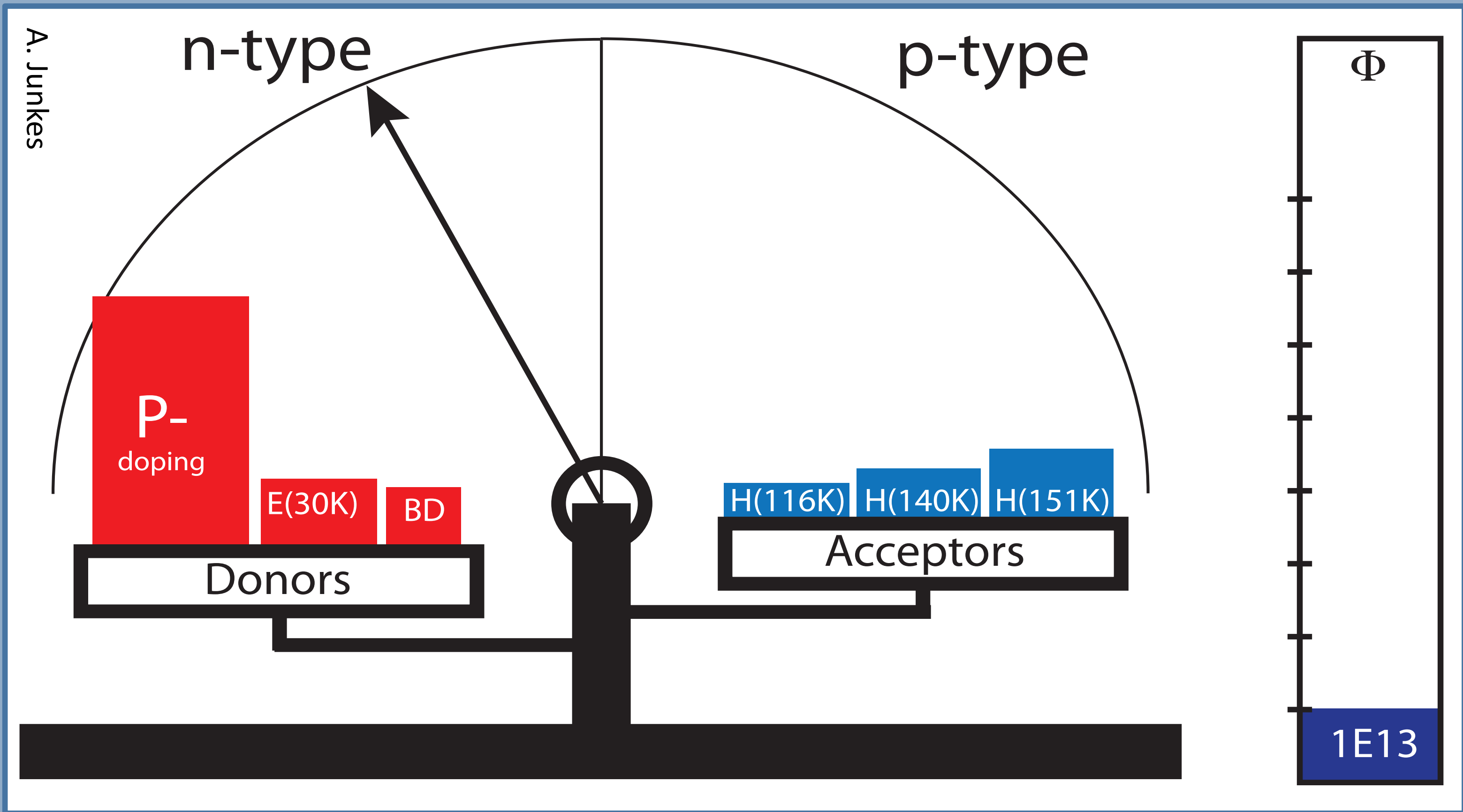
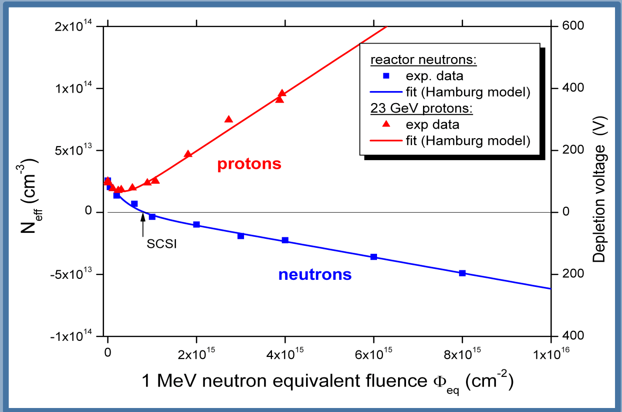


Proton irradiation



Defect balance



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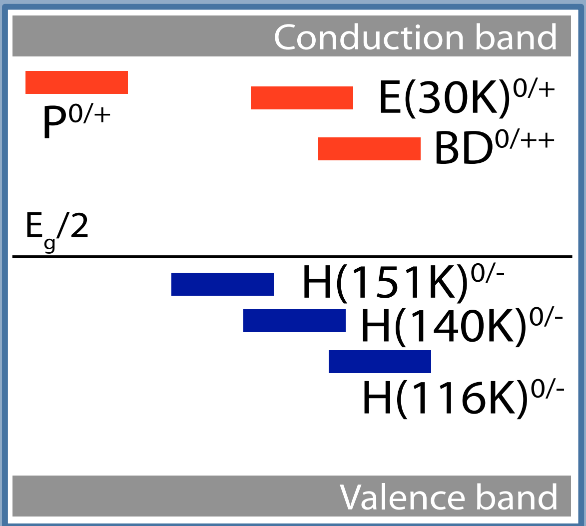

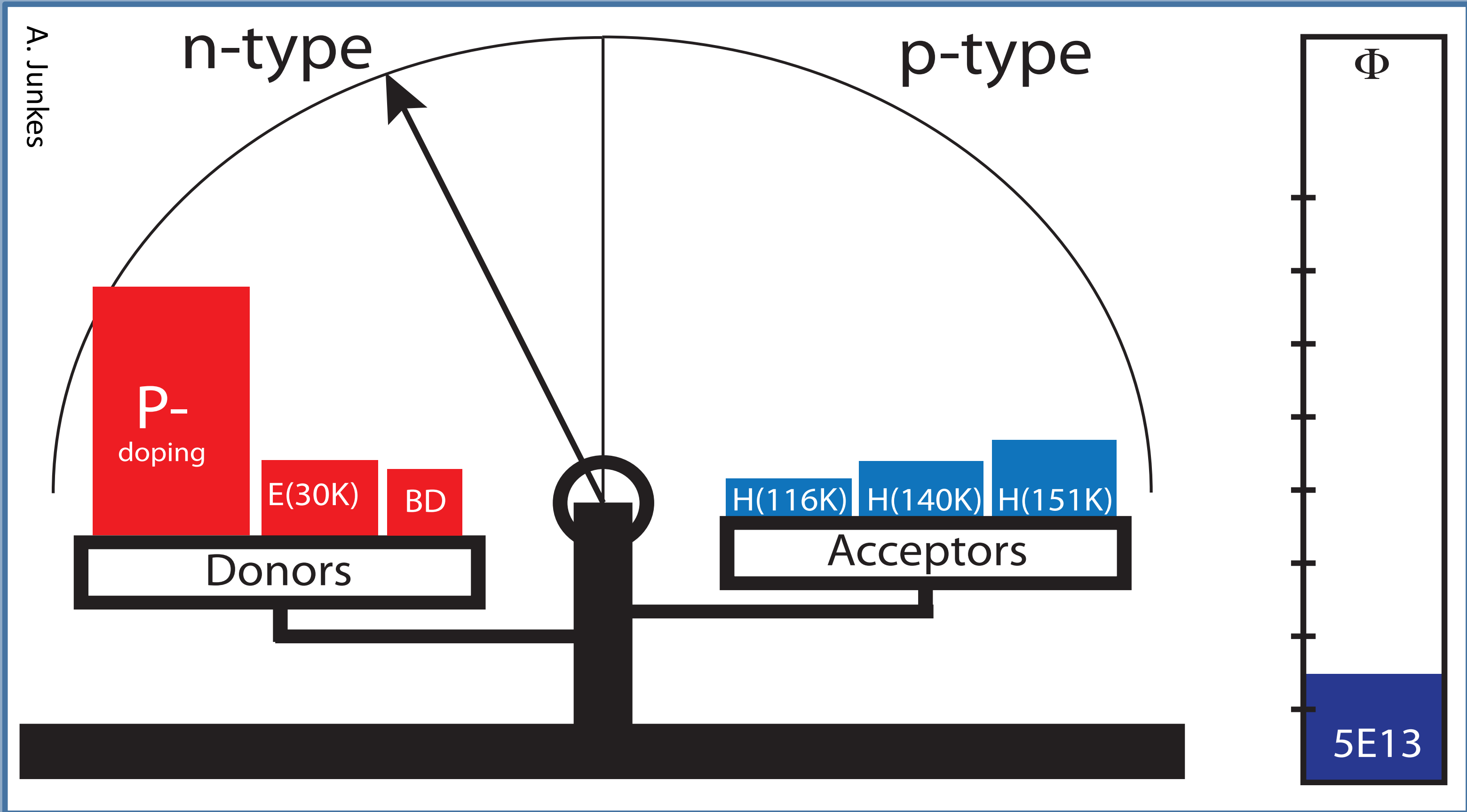

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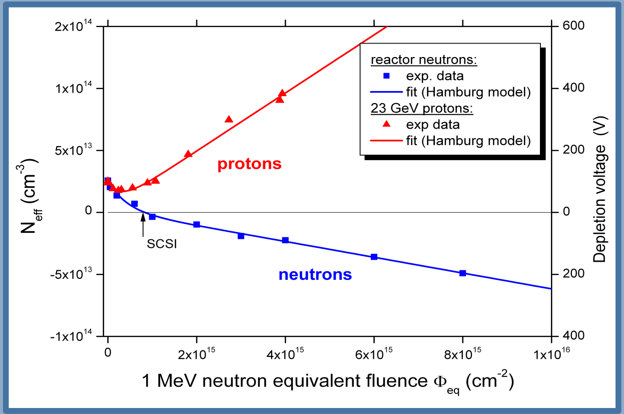

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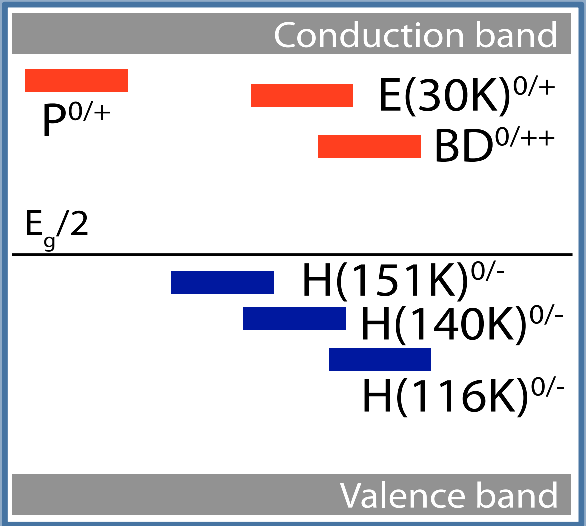

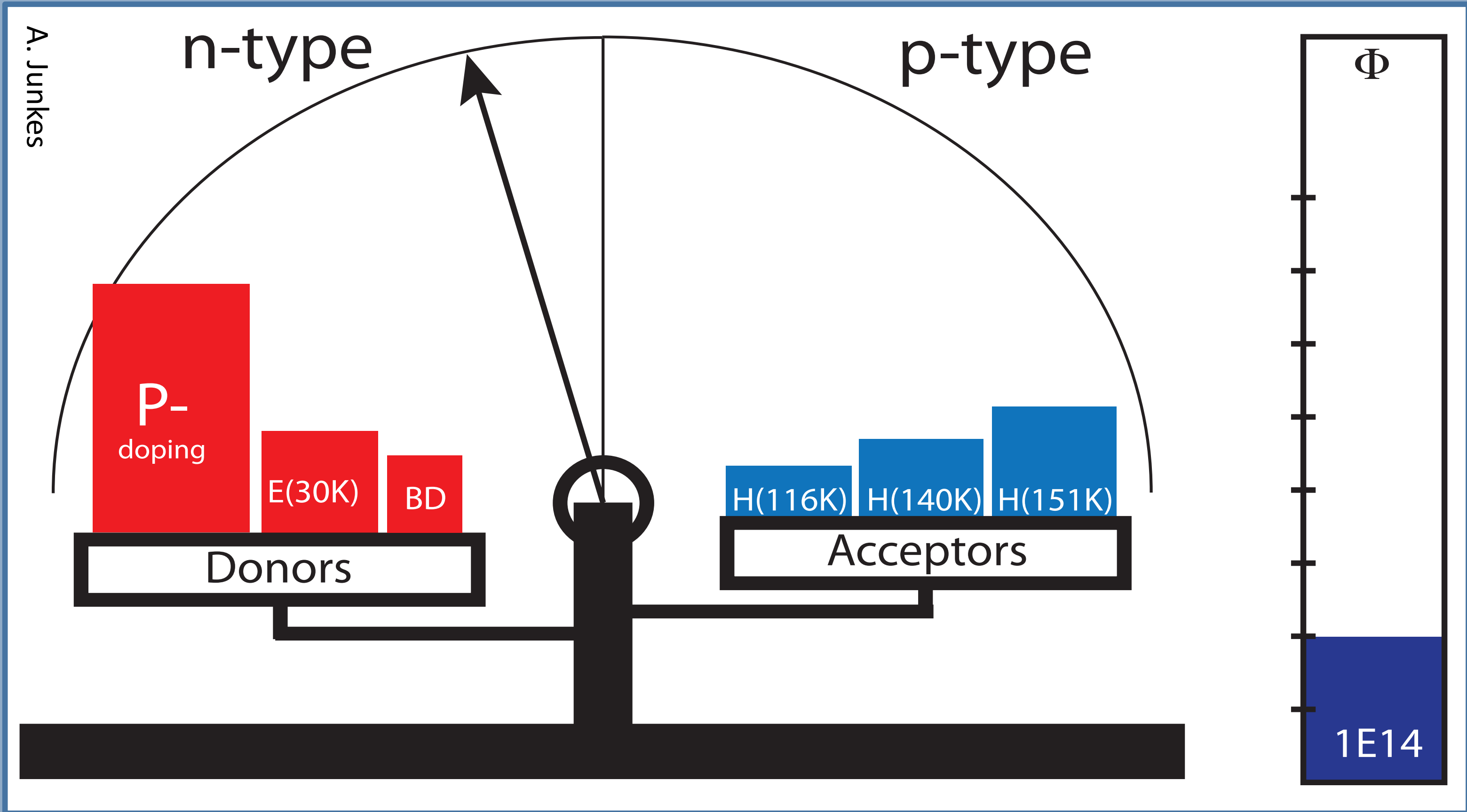

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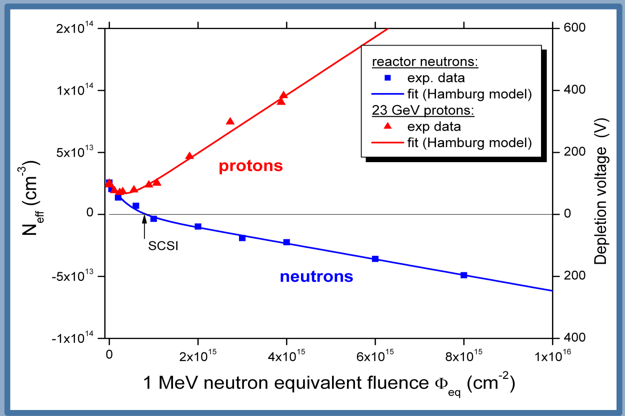

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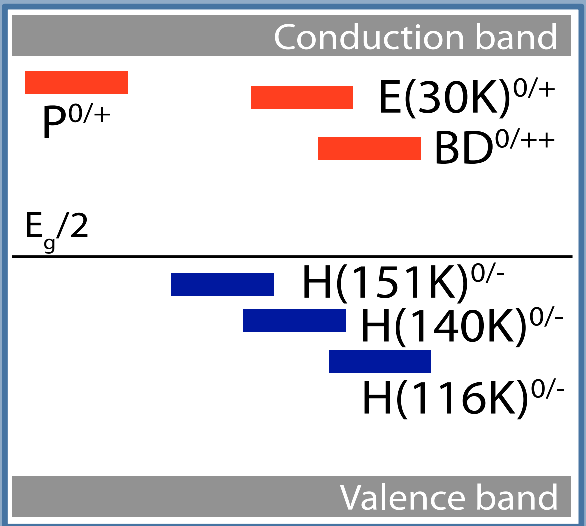
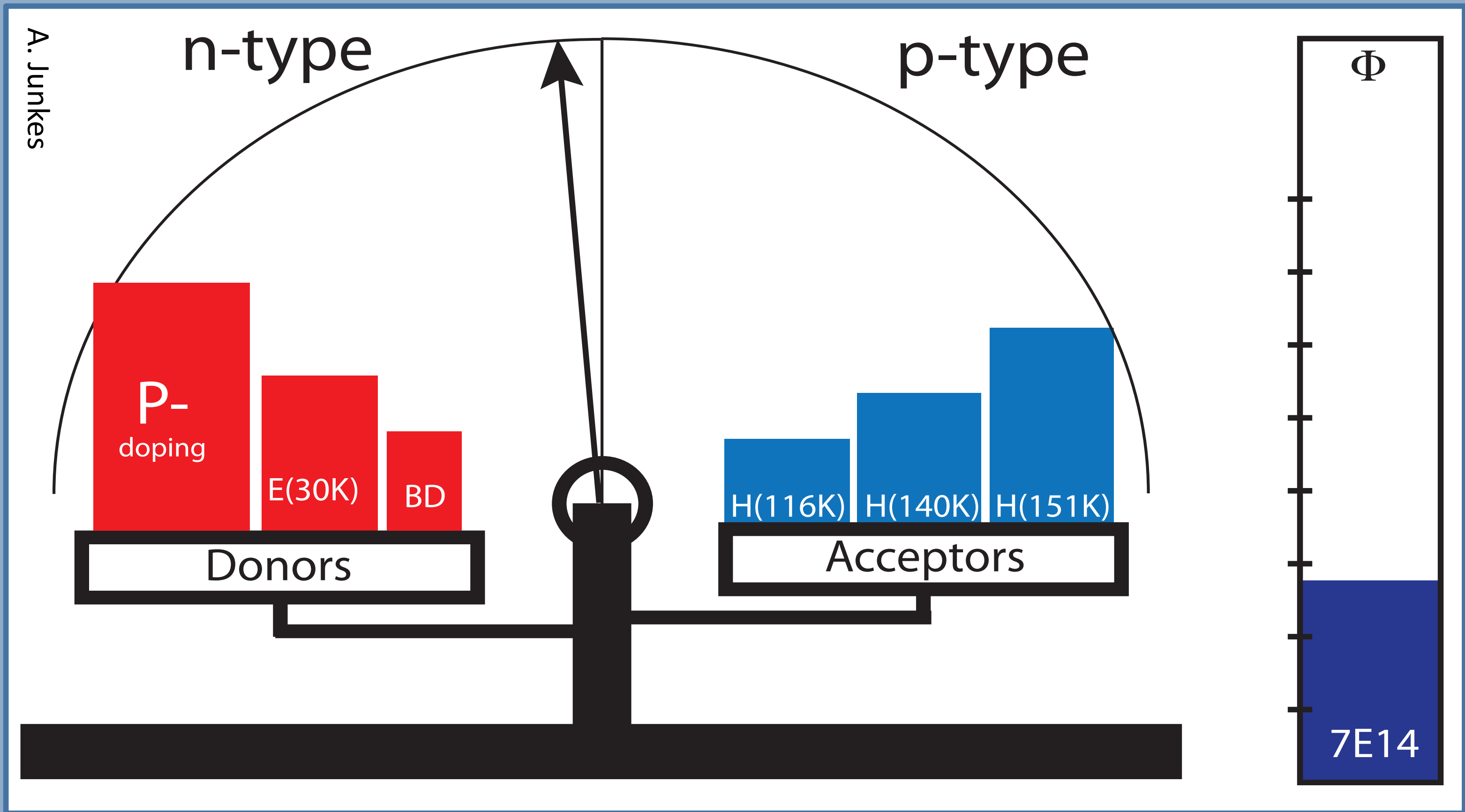
Proton irradiation





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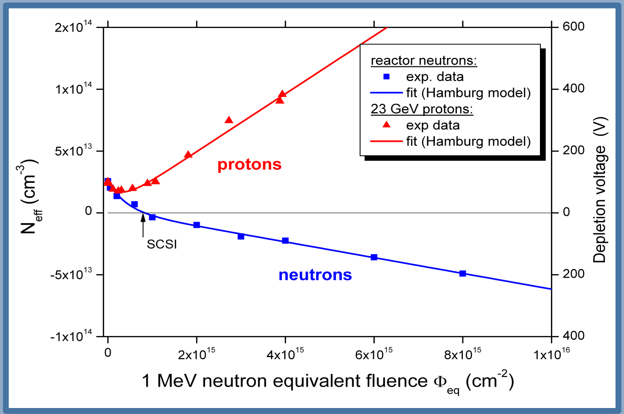

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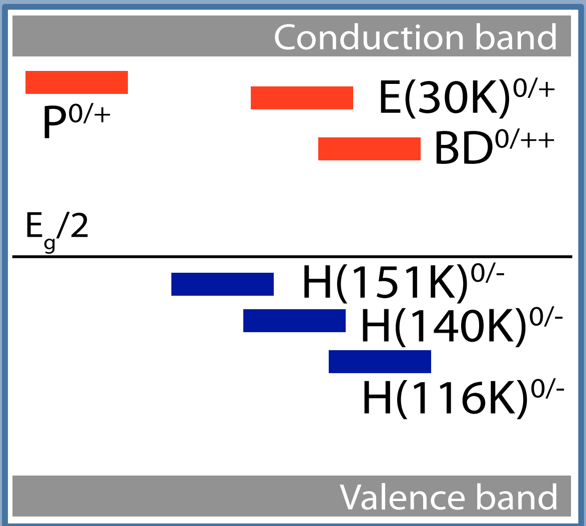
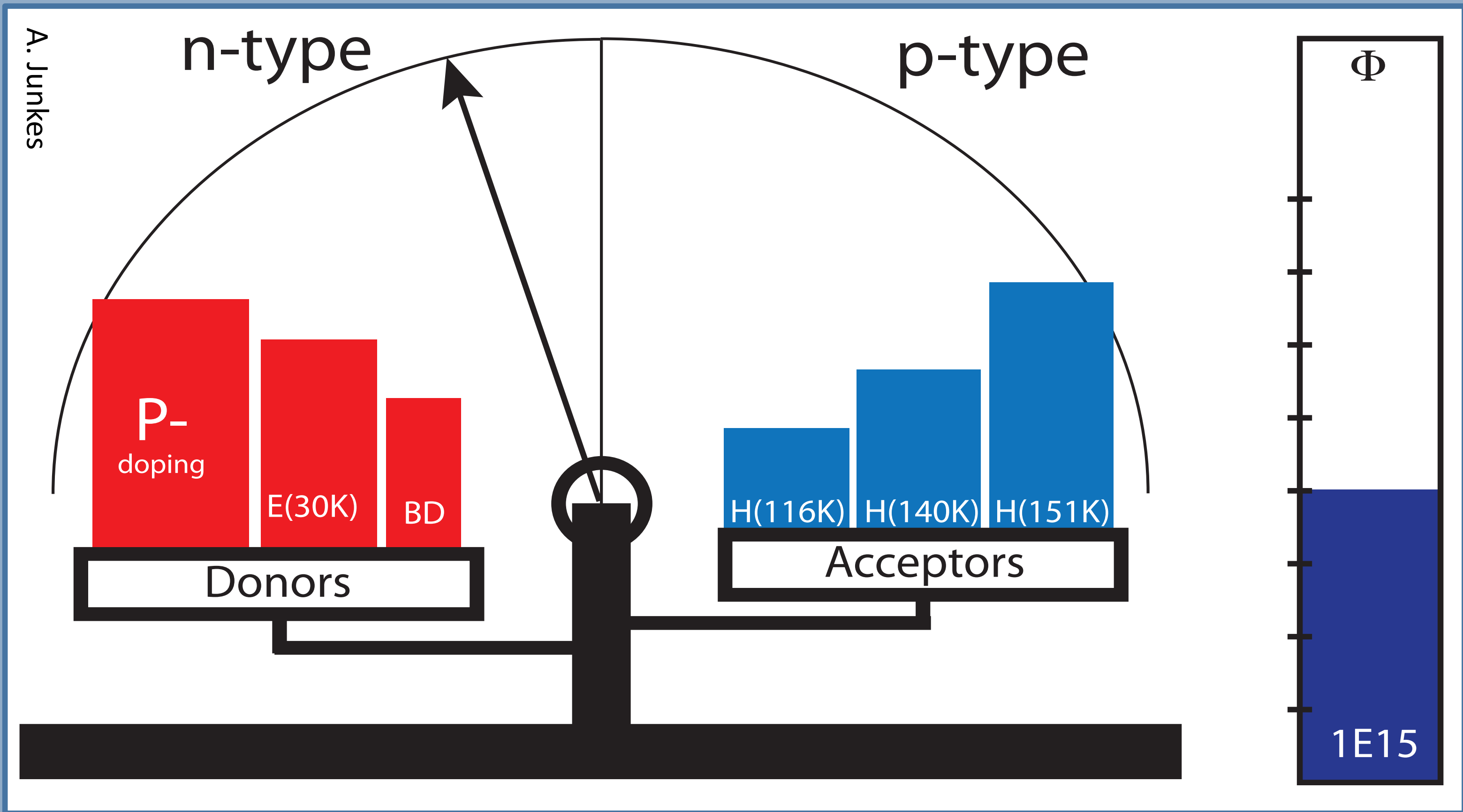
Proton irradiation





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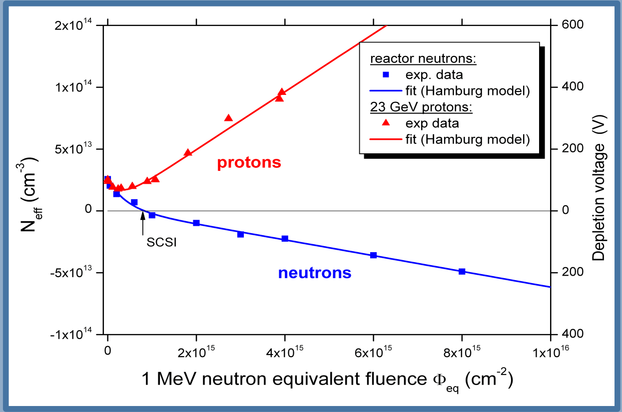

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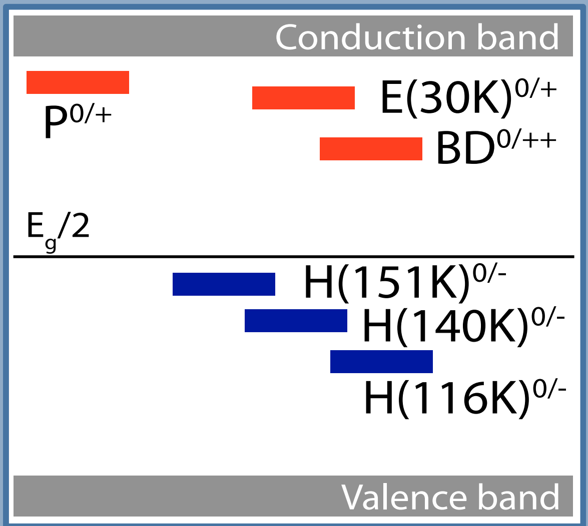
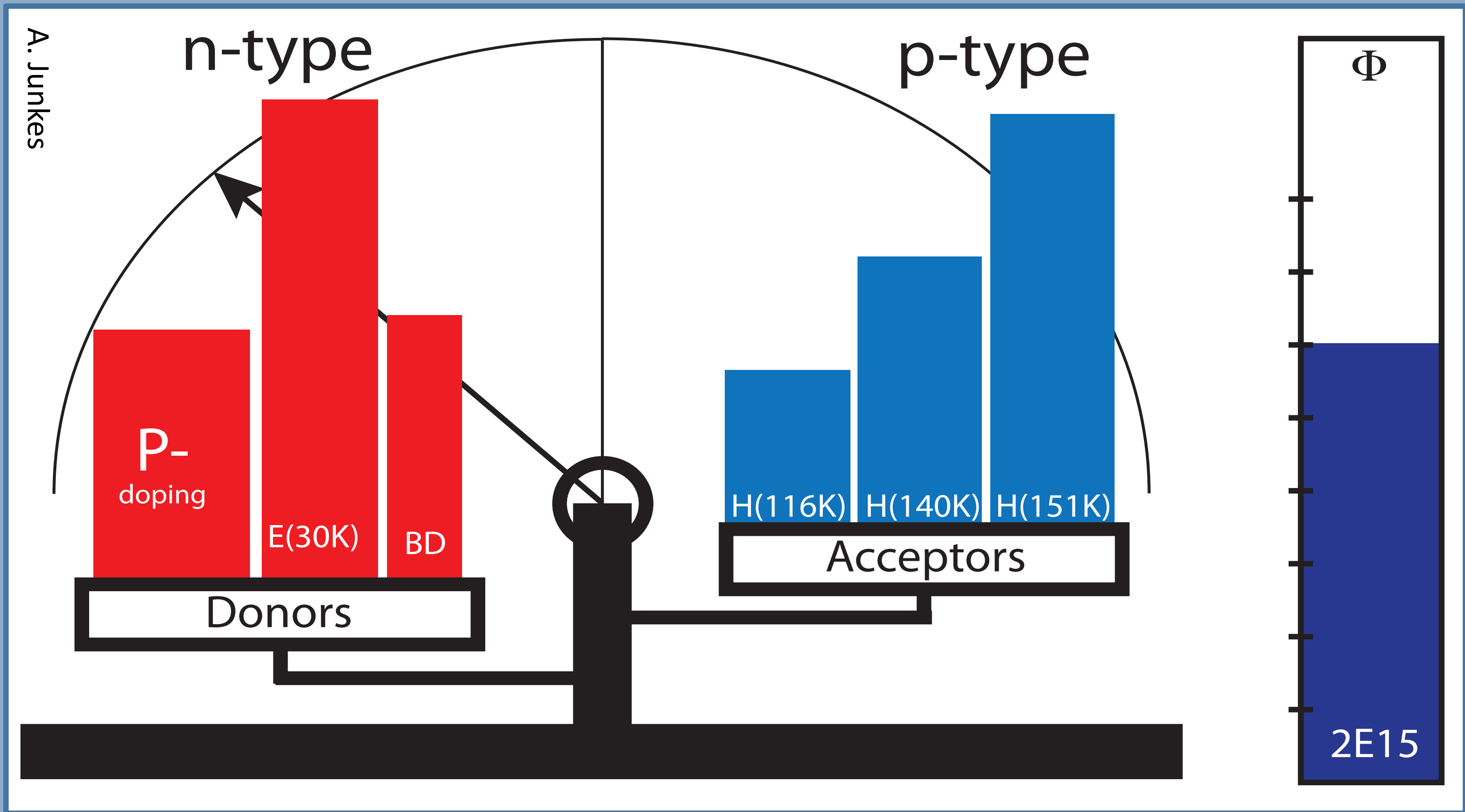
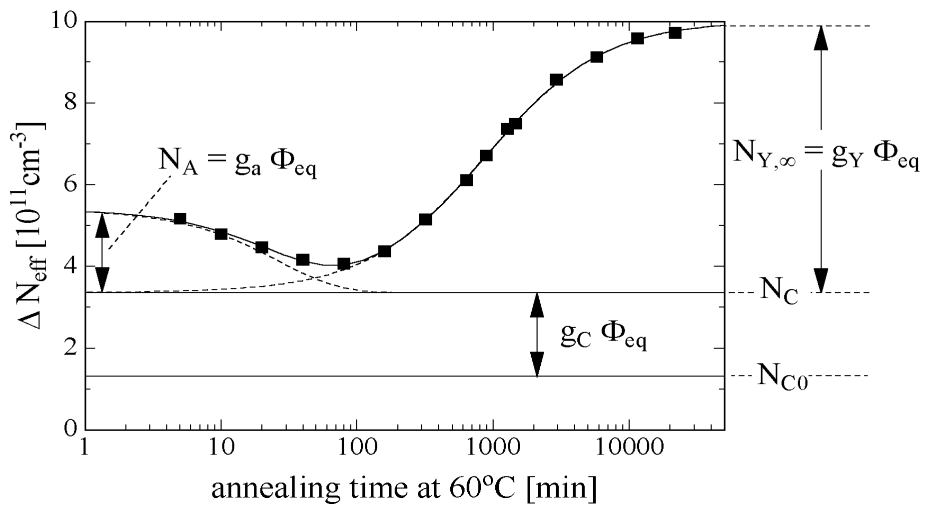




Annealing of depletion voltage

With annealing:



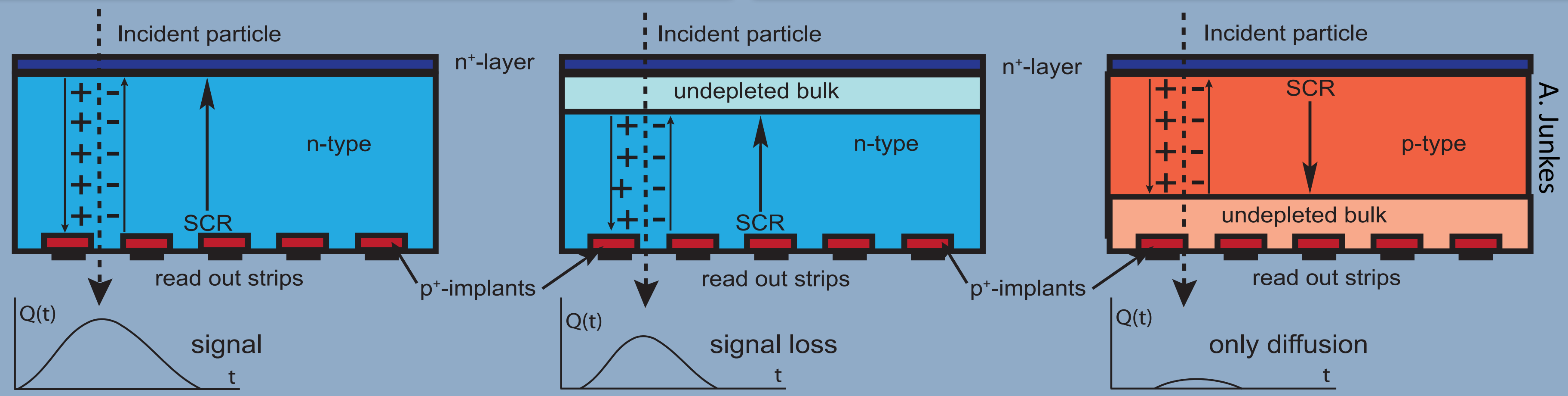
M. Moll, PhD thesis 1999, Uni Hamburg

$$V_{dep} = \frac{q_0}{\varepsilon\varepsilon_0} \cdot |N_{eff}| \cdot d^2$$

- Acceptors compensate original doping
- Type inversion from n- to p-type
- Increase of depletion voltage after SCSI

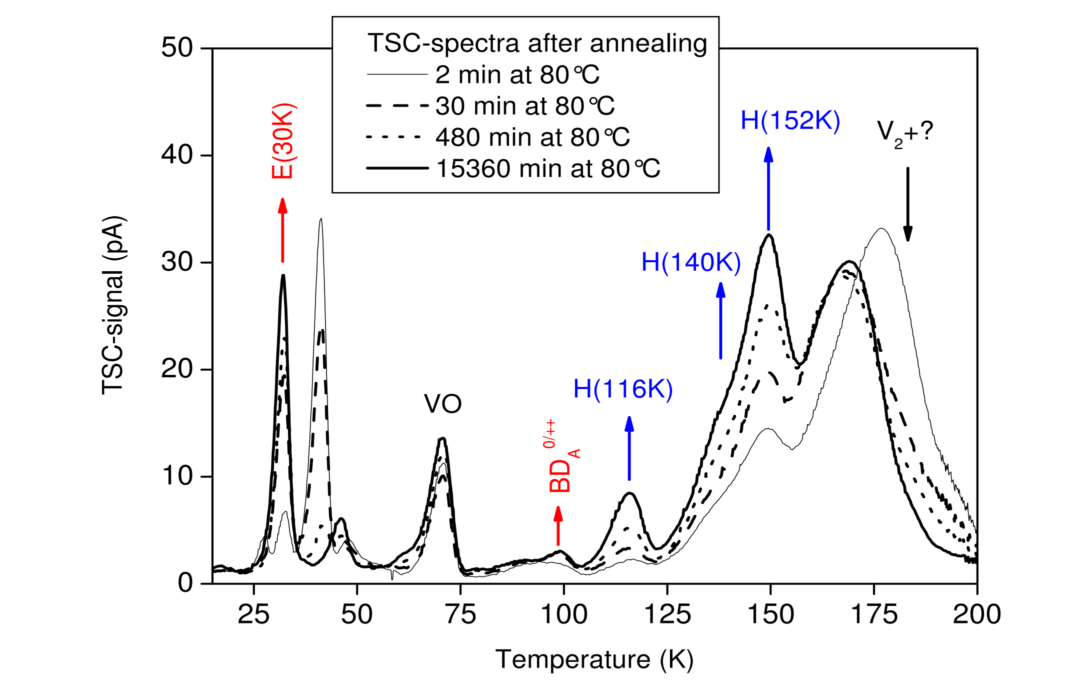
➔ Signal loss

- Annealing studies show impact of high T maintenance times

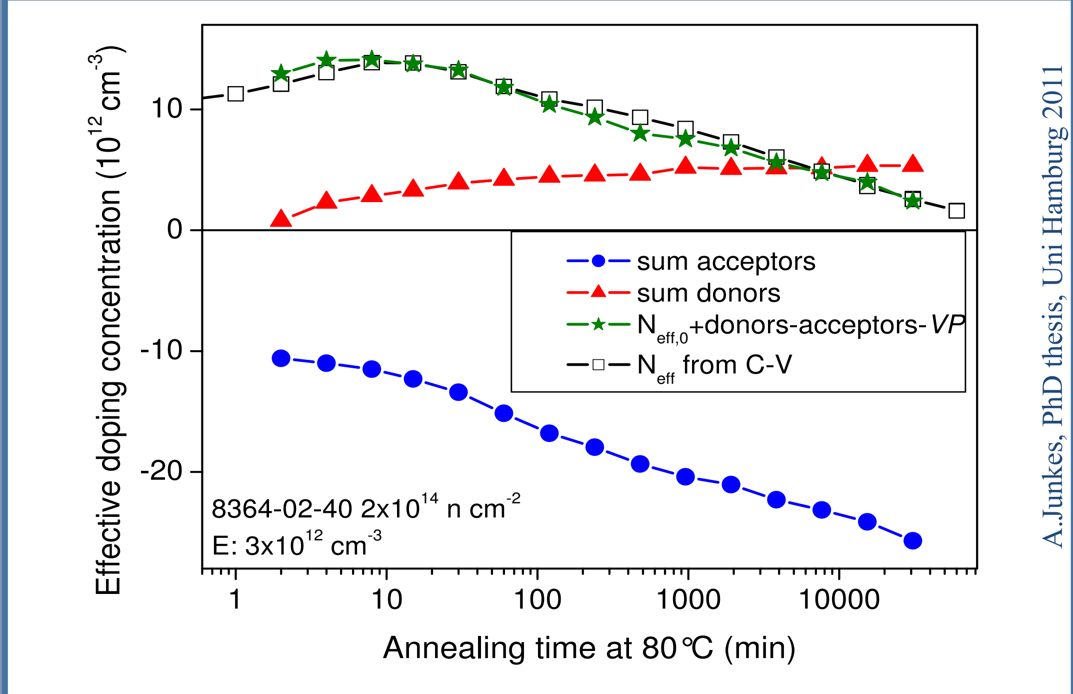


Annealing behavior understood

$2x10^{14}$ n cm^{-2}, Epi-St 75 μm (TSC)



Defect concentrations vs N_{eff} (C-V)



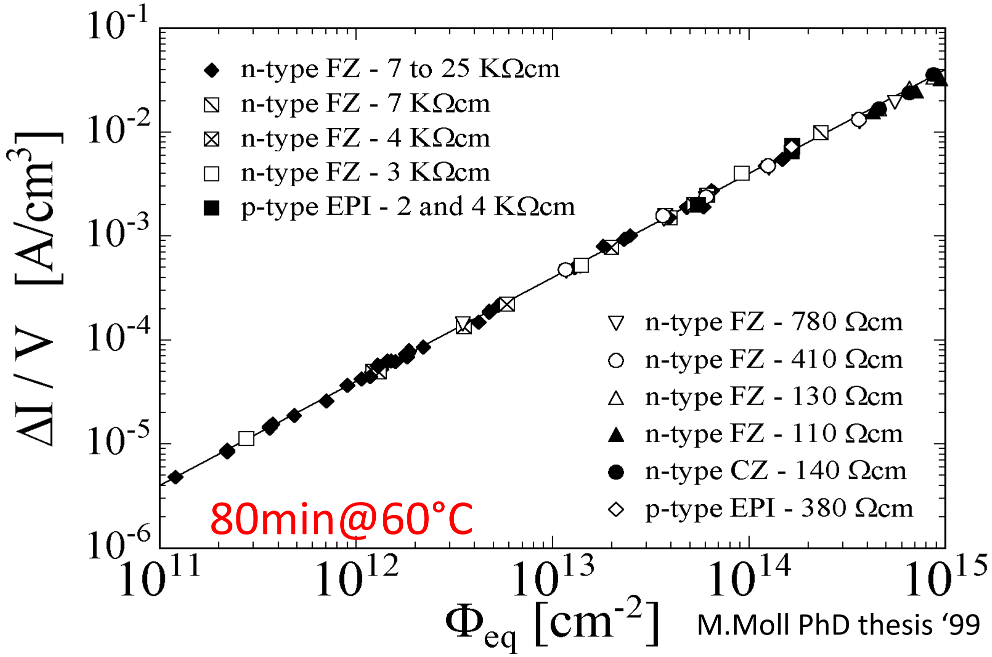
- Concentrations from microscopic measurements reproduce N_{eff} from C-V
- Prediction of V_{dep} possible also for neutron & proton irradiation!

Defects with impact on leakage current

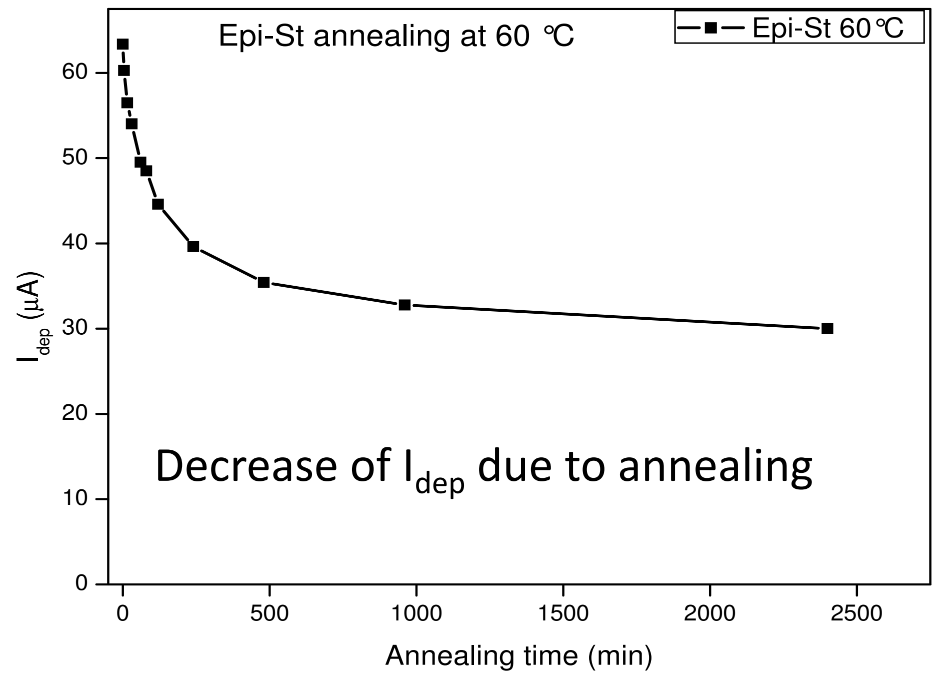
Monkey does not hear particles

Change of leakage current…

… depending on the fluence…



… and on annealing



$$\Delta I = \alpha \cdot V \cdot \Phi_{eq}$$

- Damage parameter α not depending on material or particle type

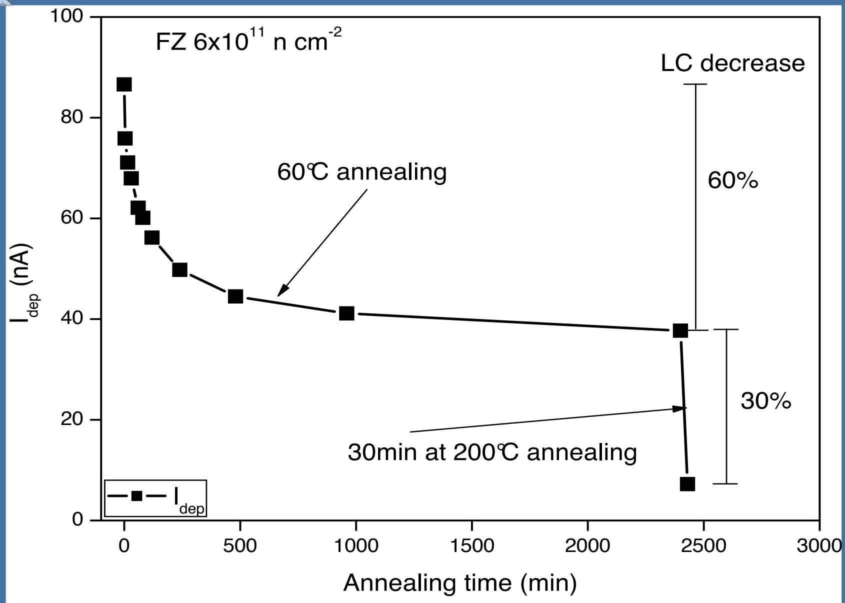
➔ Oxygen does not influence behavior

- Constant over orders of magnitude

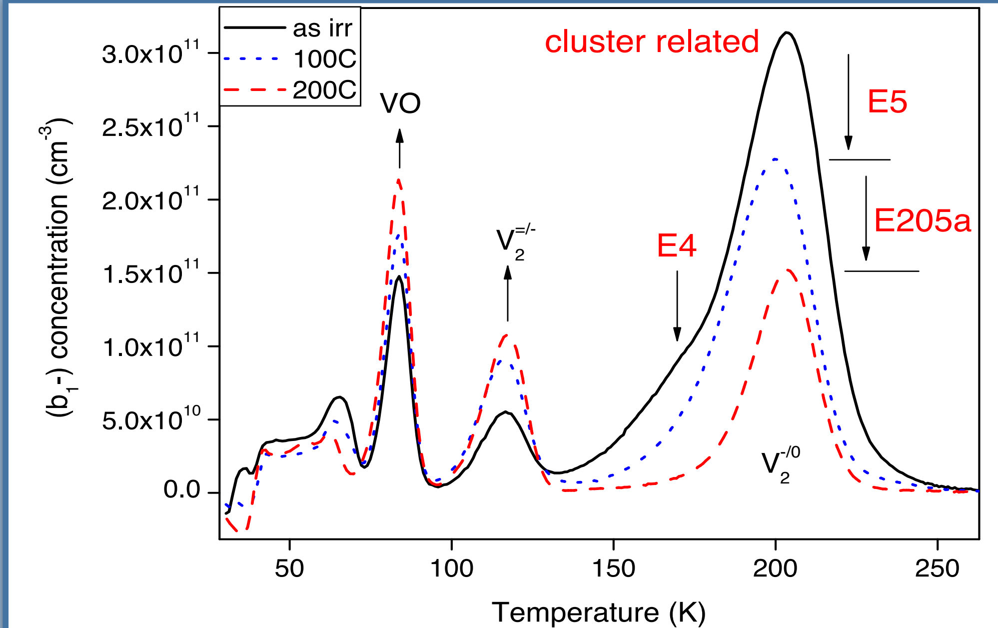
➔Noise increase (cooling helps due to T-dependence of I_{dep})

Defects with impact on I_{dep}

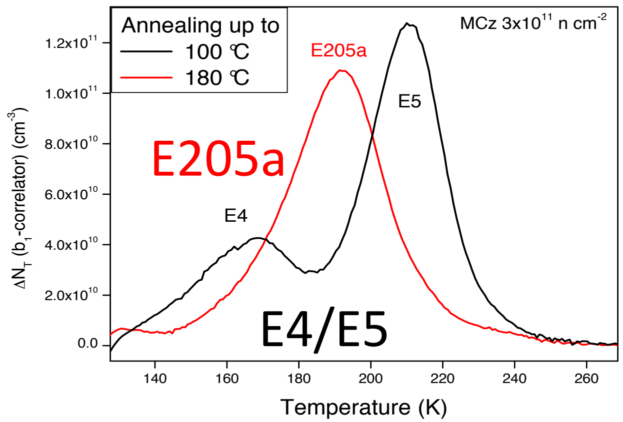
Decrease of I_{dep} during annealing



Corresponding defects from DLTS



Difference Spectra:



- 60 % decrease during 60 °C annealing
- 30 % decrease during 200 °C annealing

Corresponding defect annealing:

- E5 at 60 °C & E205a between 140 °C – 180 °C

➔ Responsible defects E5 & E205a

Tri-vacancy shows direct correlation

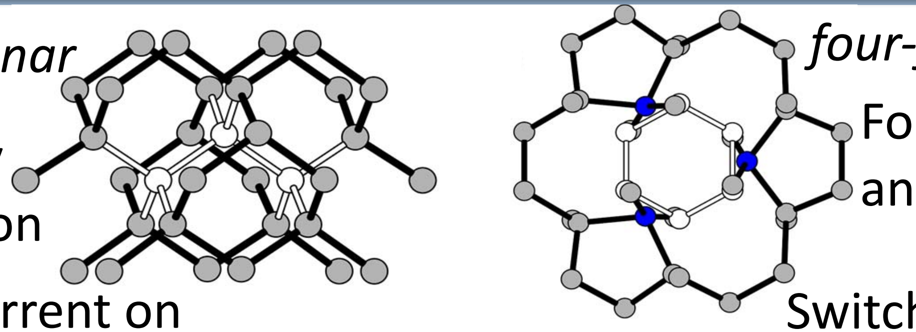
E4 & E5 can be related to V_3

2 configurations:

planar

Formed by 1 A injection

Switch current on



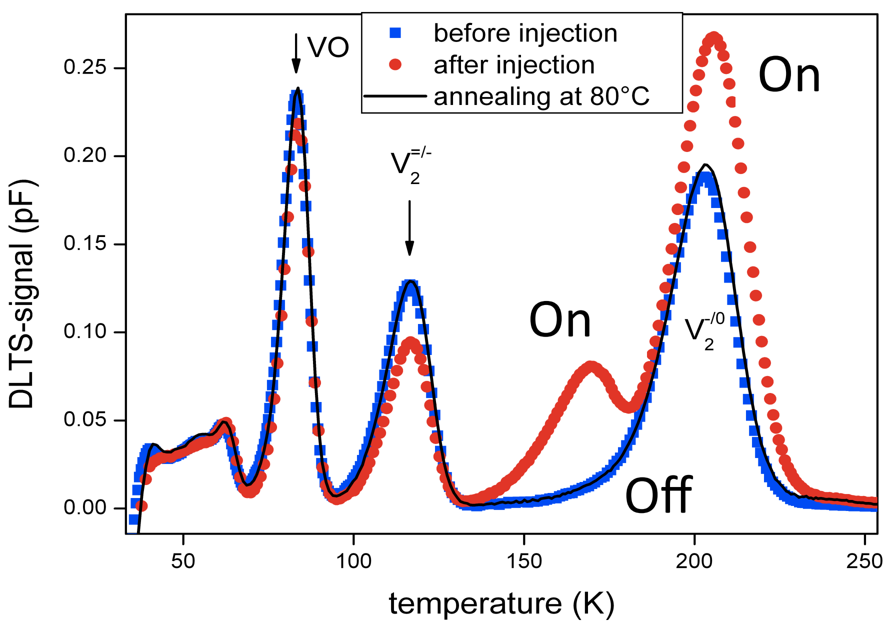
four-fold

Formed during annealing

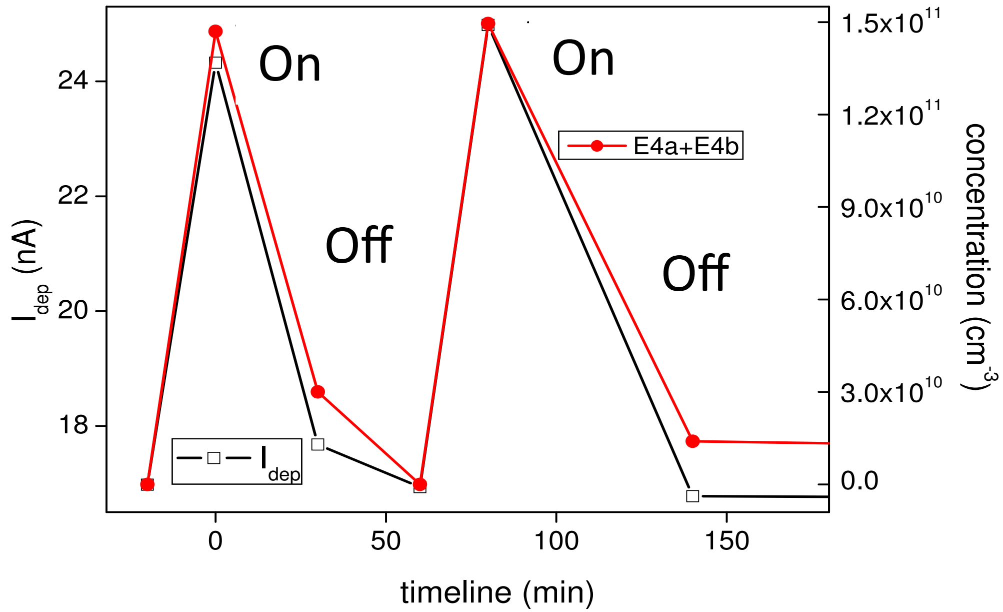
Switch current off

Markevich et al. Phys Rev B 80 (2009) 235207

Defect recovery seen by DLTS after 200 °C



Correlation I_{dep} and defect concentration



A.Junkes, PhD thesis, Uni Hamburg 2011

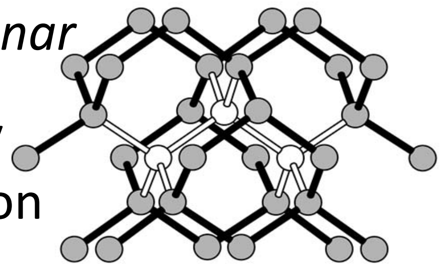
Tri-vacancy shows direct correlation

E4 & E5 can be related to V_3

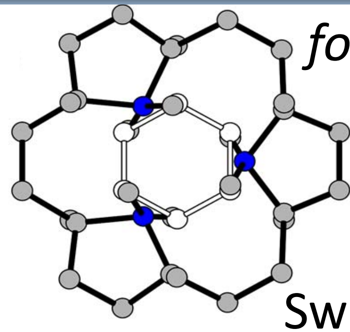
2 configurations:

planar

Formed by
1 A injection



Switch current on



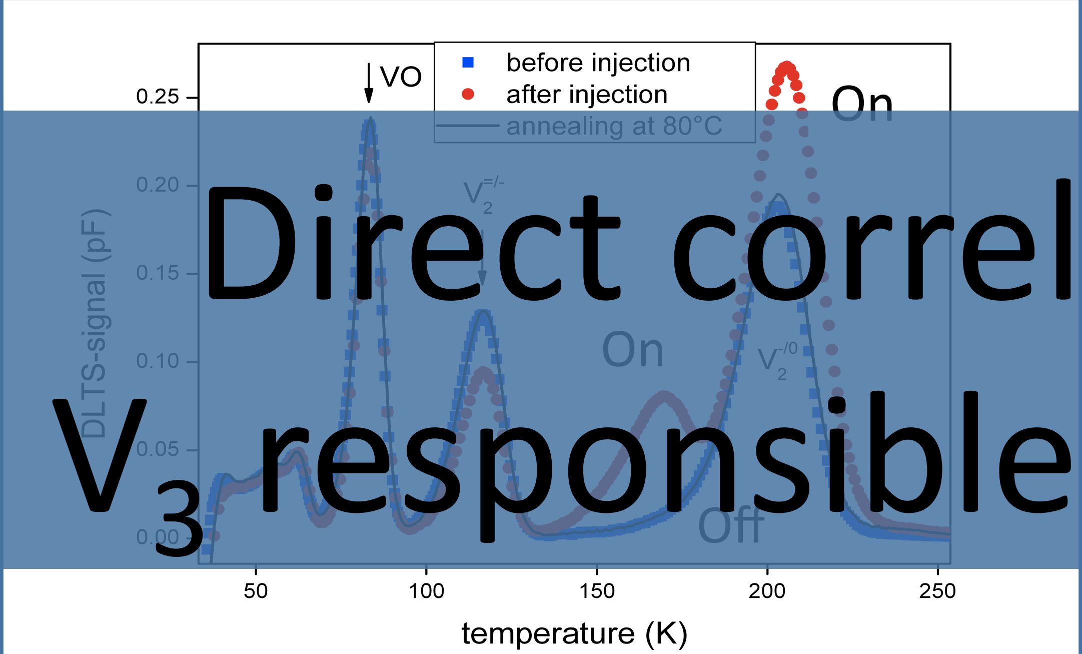
four-fold

Formed during annealing

Switch current off

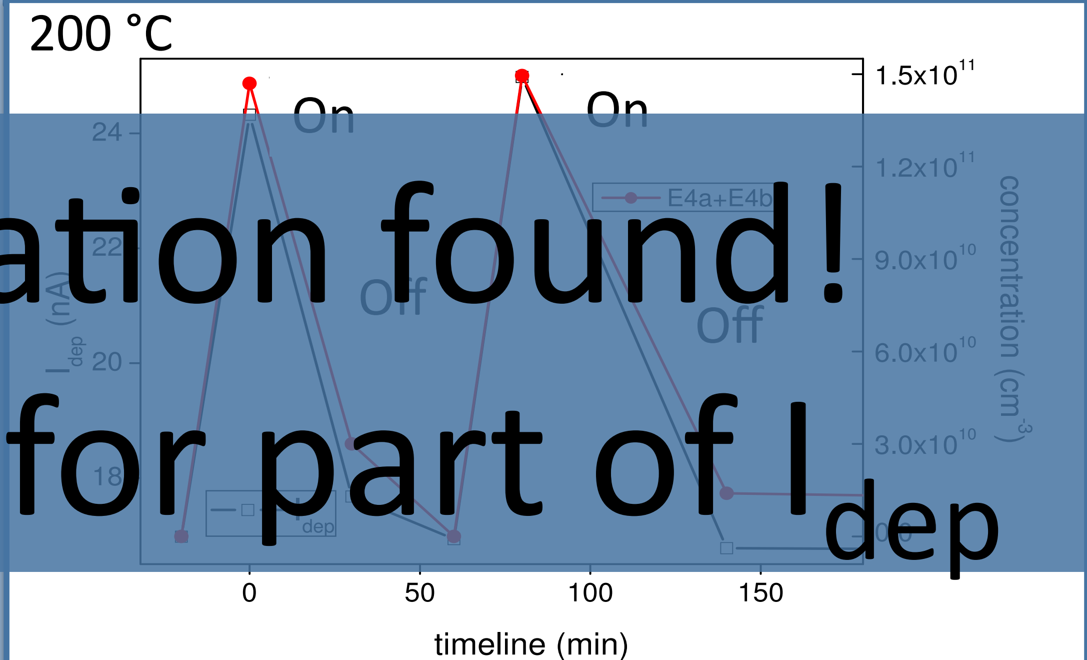
Markevich et al. Phys Rev B 80 (2009) 235207

Defect recovery seen by DLTS after 200 °C



Correlation I_{dep} and defect concentration

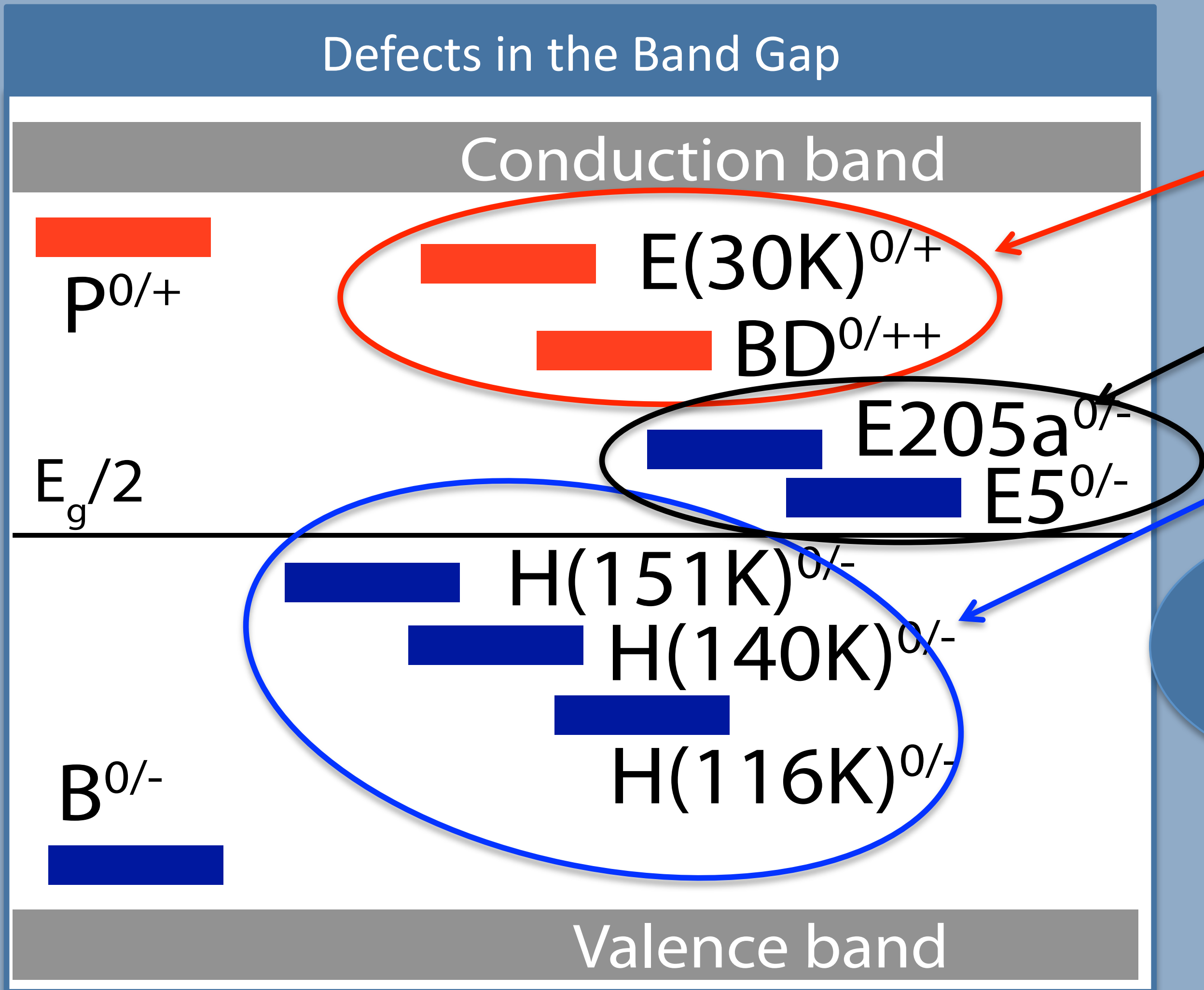
200 °C



Direct correlation found!
V_3 responsible for part of I_{dep}

A.Junkes, PhD thesis, Uni Hamburg 2011

Defect summary (1)



Donors:
positive space charge

Leakage current

Acceptors:
Negative space charge

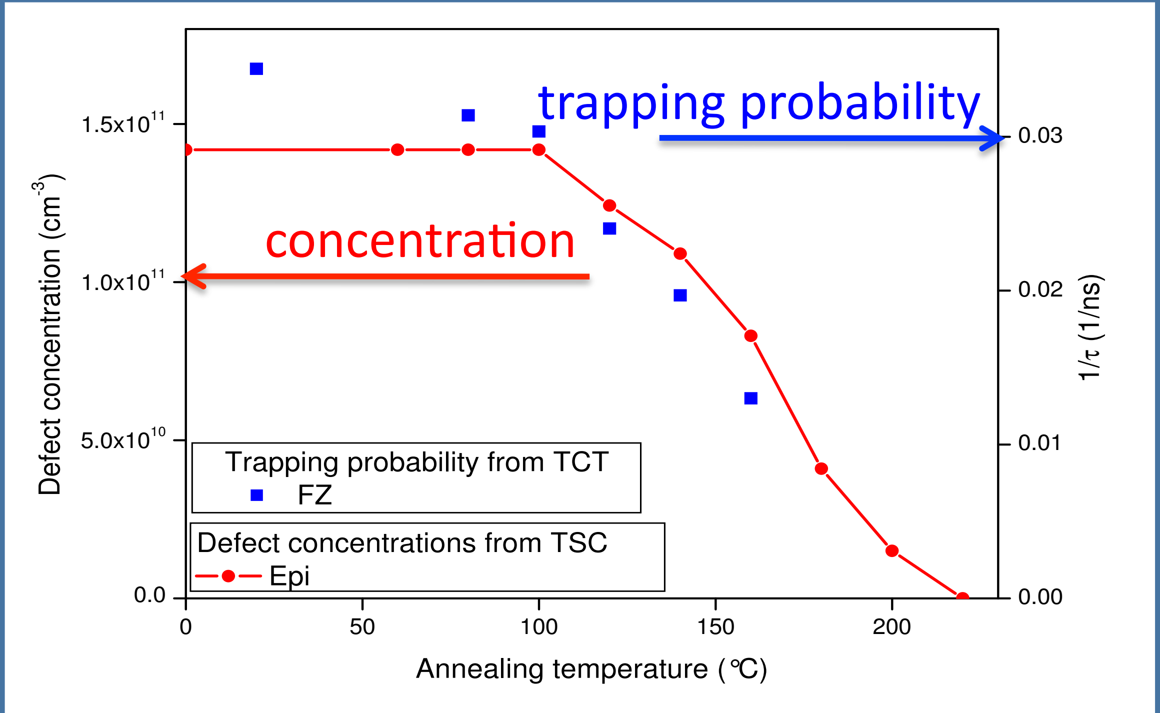
What am I doing here?

Trapping

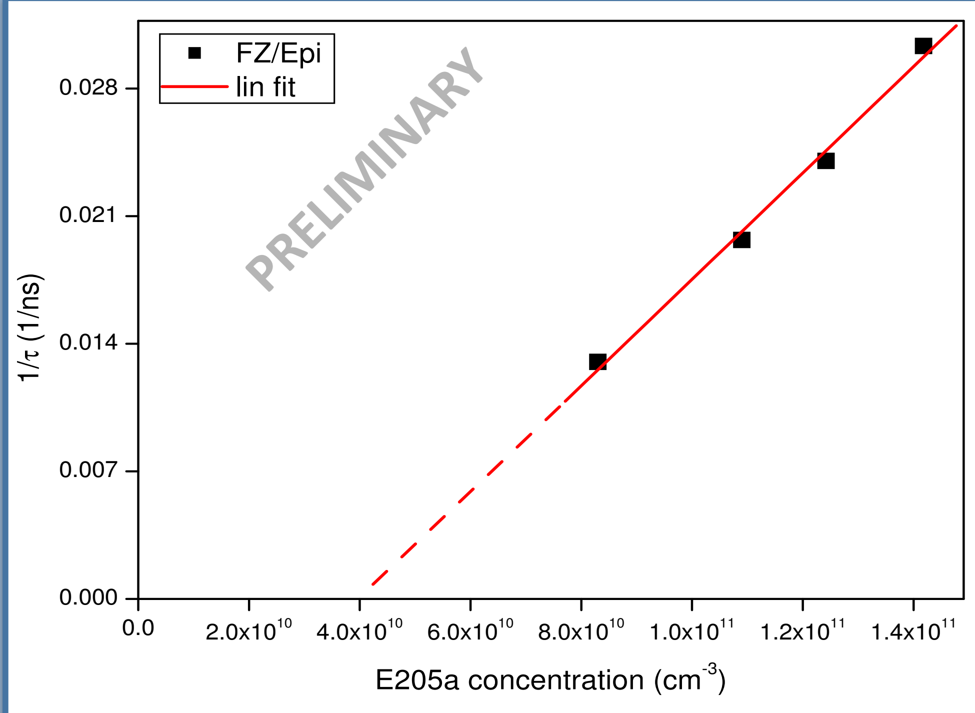
Monkey does not speak about particles

E205a cause of electron trapping

Trapping probability vs E205a concentration



Linear behaviour – only by chance ?

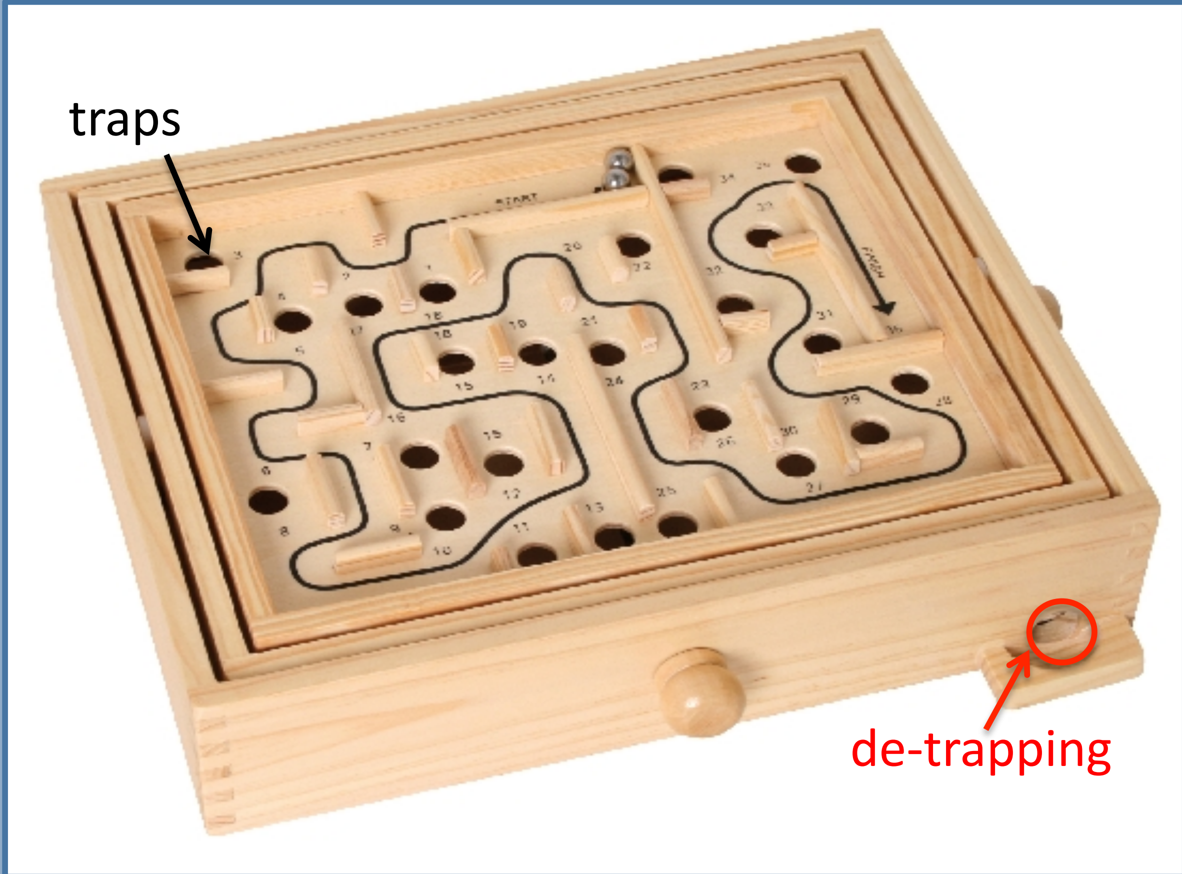


Assuming cluster defects and trapping linear with fluence, independent of material and neglecting many open questions...

Annealing behavior of E205a concentration similar to electron trapping annealing

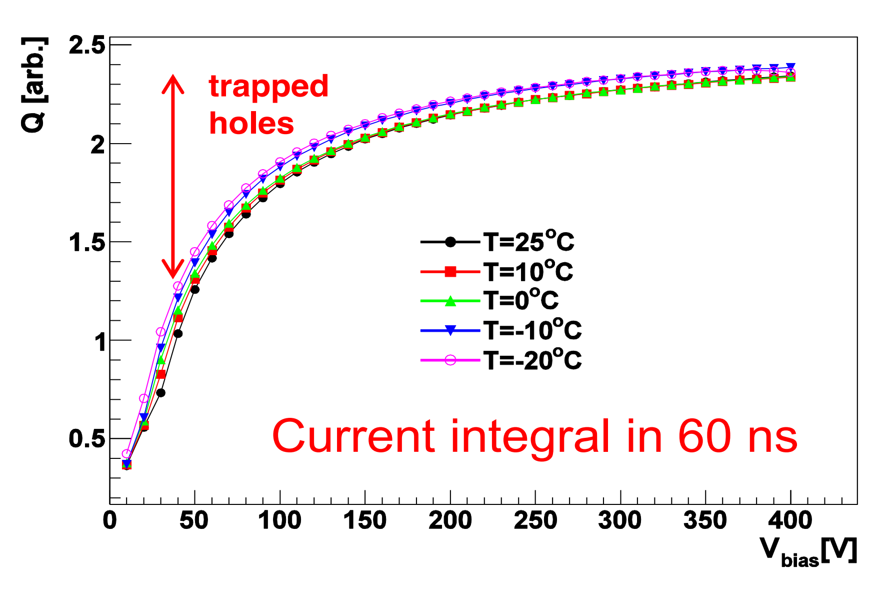
Hole trapping

New method by G. Kramberger using de-trapping:

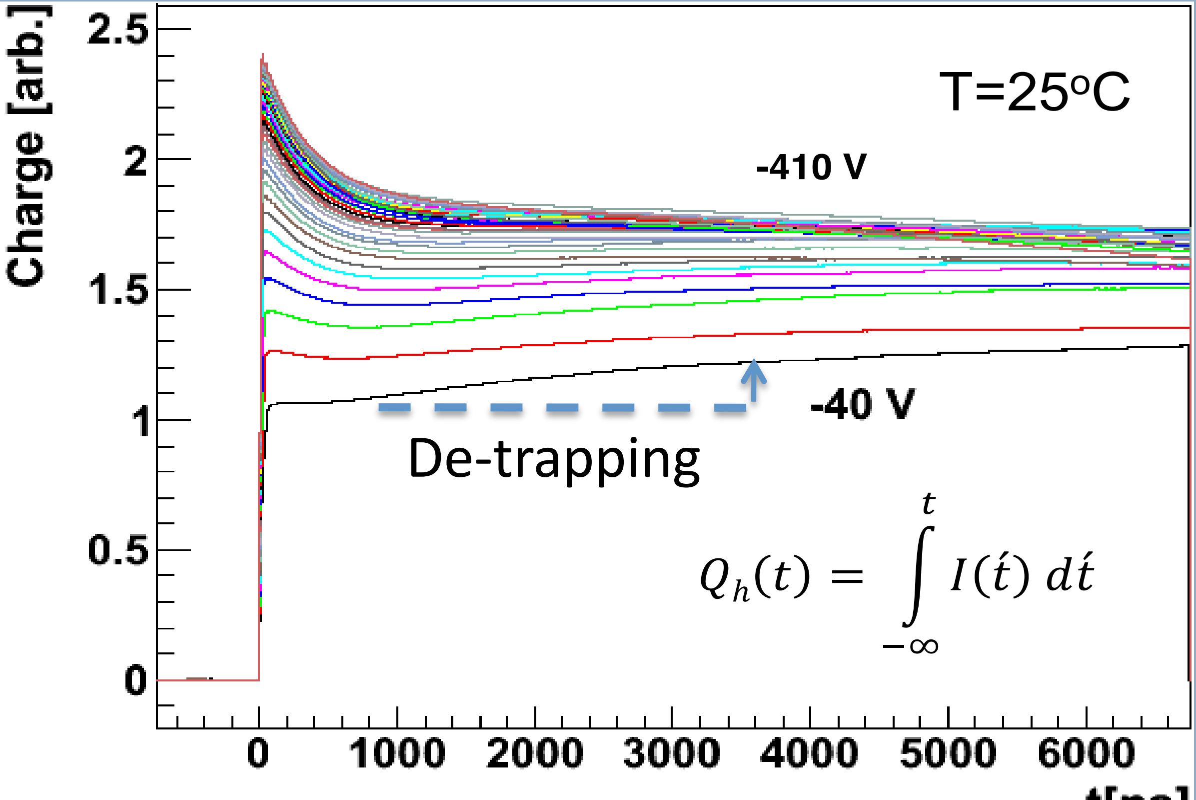


Investigation of hole trapping

Trapping observed by TCT predominantly at low voltages



G. Kramberger et al., 18th RD50 Workshop Liverpool, May 2011

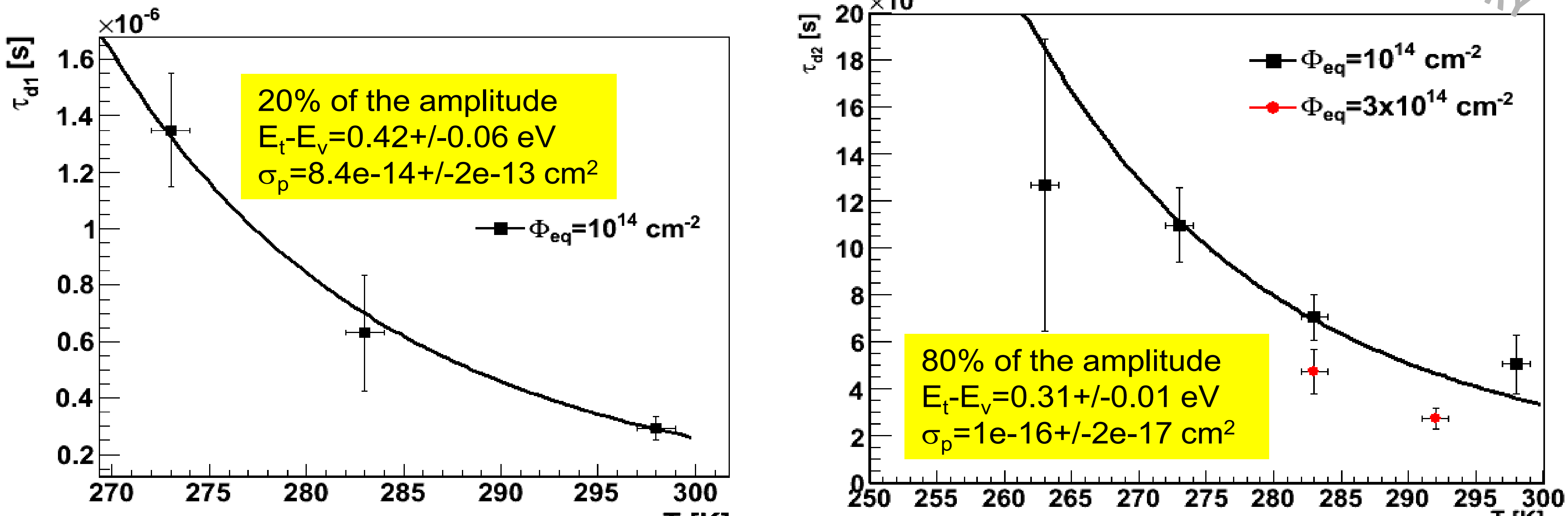


G. Kramberger et al., 18th RD50 Workshop Liverpool, May 2011

- De-trapping observed for integration times up to several microseconds
- For the extraction of de-trapping time constants the transfer-function of the electronics has to be taken into account
- Two components have been found in the de-trapping of holes

Trap level evaluation

$$\frac{1}{\tau_d} = n_i \cdot v_{th,h} \cdot \sigma_p \cdot \exp\left(\frac{E_t - E_i}{k_B T}\right)$$ ← fit to the data – free parameter σ_p and E_t

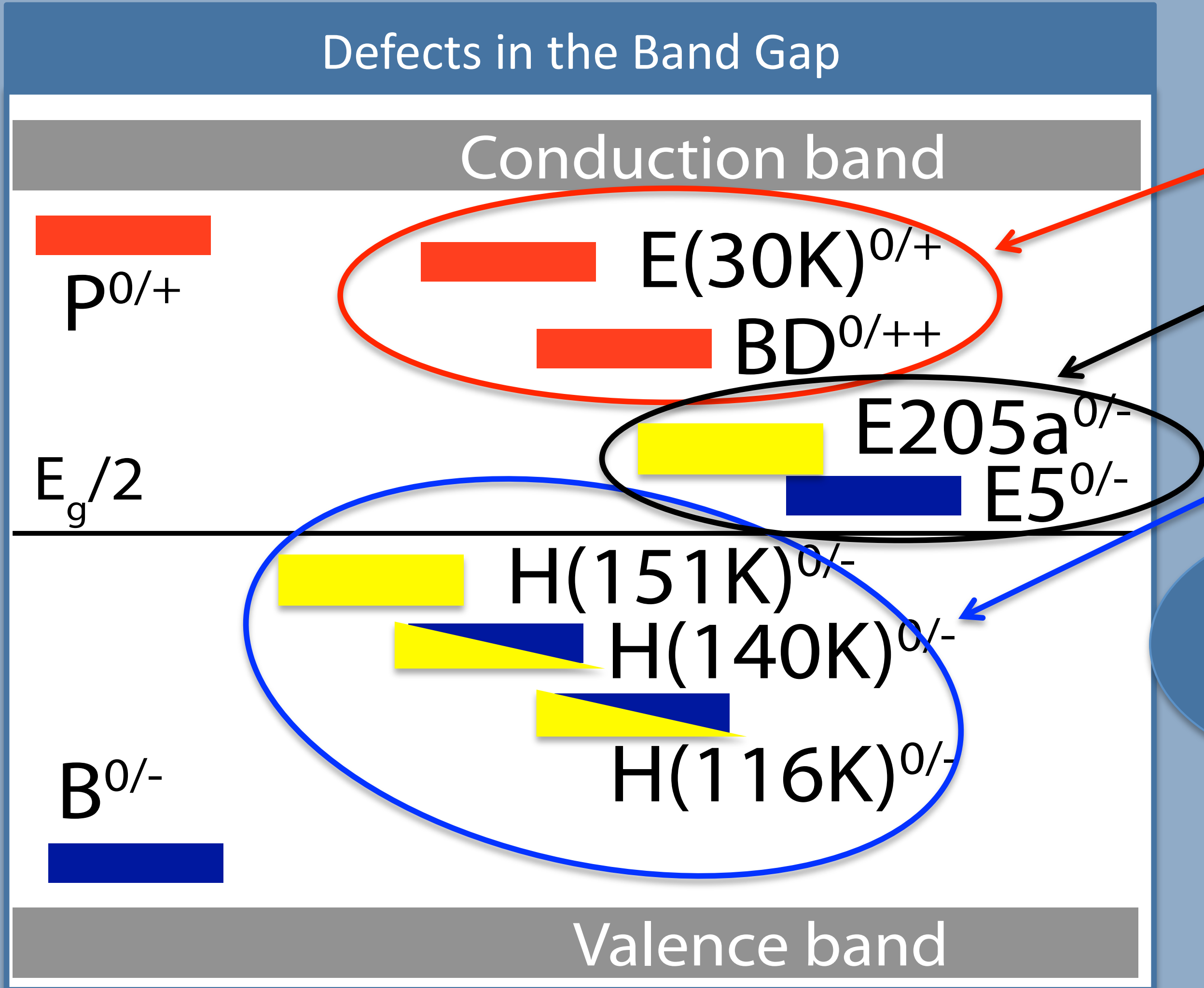


G. Kramberger et al., 18th RD50 Workshop Liverpool, May 2011

Fast component:
Level at 0.42 eV

Slow component:
Level at 0.31 eV

Defect summary (2)



Donors:
positive space charge

Leakage current

Trapping ?

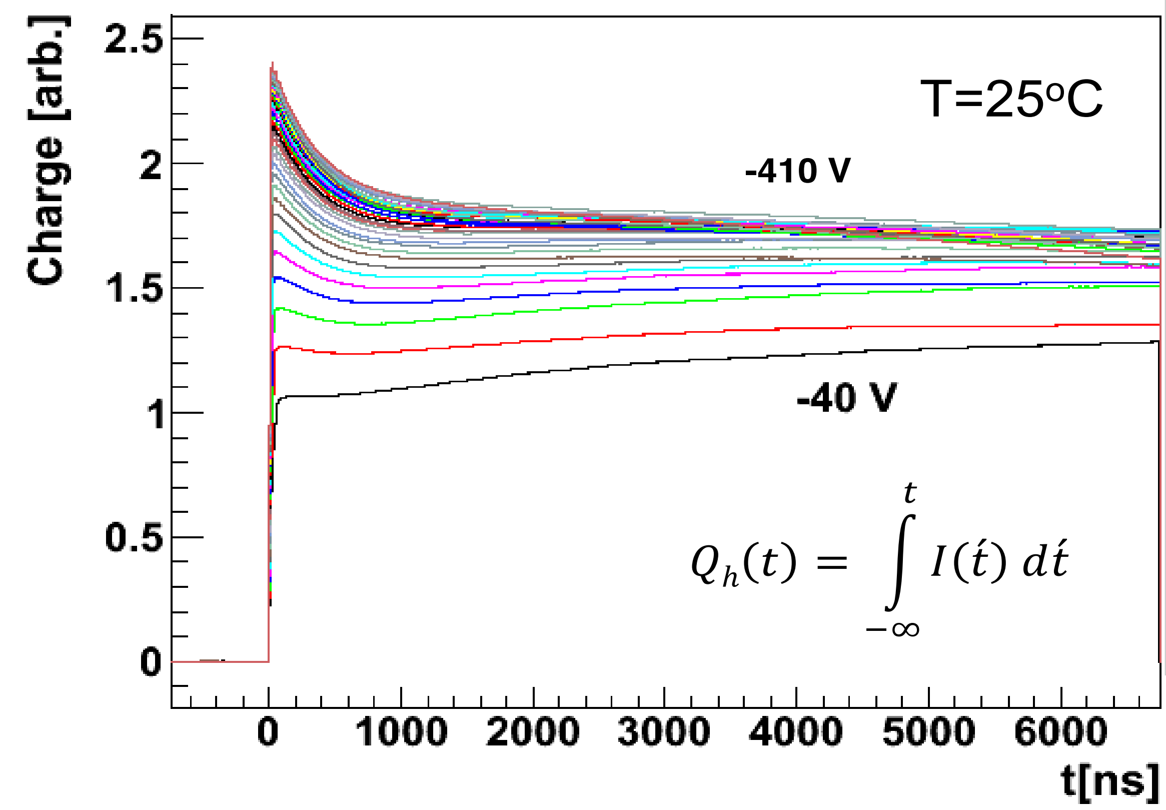
Acceptors:
Negative space charge

What am I doing here?

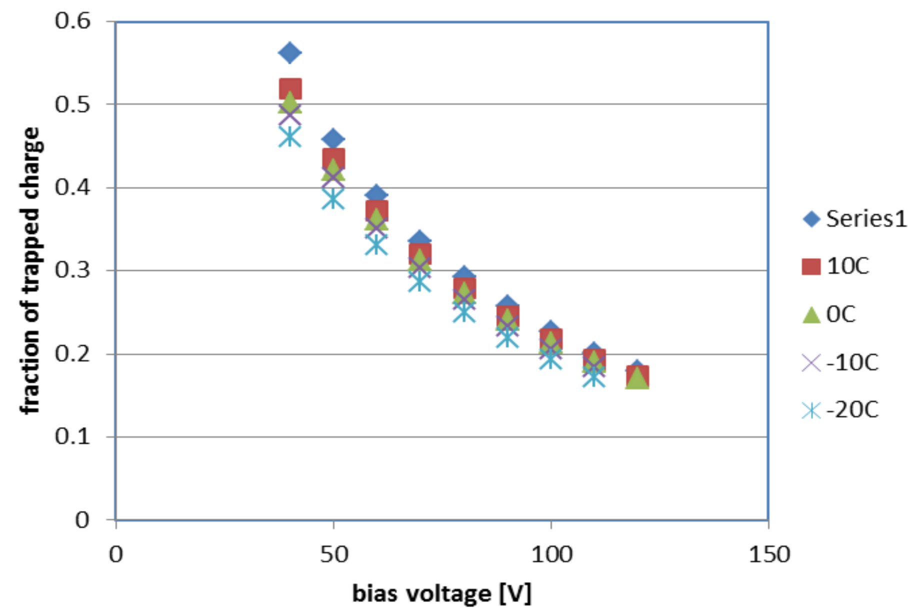
Summary

- Defects responsible for change of N_{eff} identified
  - Reverse annealing can be explained
- Defects responsible for increase of LC identified
  - Tri-vacancy responsible for main part of I_{dep}
- First results hint to the origin of trapping
  - Focus on H(150K) and E205a

Hole trapping



G. Kramberger et al., 18th RD50 Workshop Liverpool, May 2011



Charge trapped by many traps

$$Q_0(1 - CCE) = \sum_i Q_{t_i}$$

Measurement performed with charge sensitive amplifier
Electronics need to be taken into account