Bulk defects
(microscopic defects, measurement methods)

"Physics at the Terascale"

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Movie: Life of Brian

How do I cope with having
10 quadrillion particles thrown at me?*

*10^{16} fluence/cm^2 at 4 *cm high luminosity* LHC

Outline

- Motivation
  - See lecture by M.Moll
- Radiation damage
  - Microscopic defects (changes in bulk material)
  - Macroscopic effects (changes in detector properties)
- Microscopic measurement techniques
  - TSC
  - DLTS
- Irradiation induced defects
  - With impact on the effective doping concentration
  - With impact on the leakage current
- Summary & outlook

Radiation exposure

LHC expected fluence:

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

➔ 10 years Φ (r=4 cm)

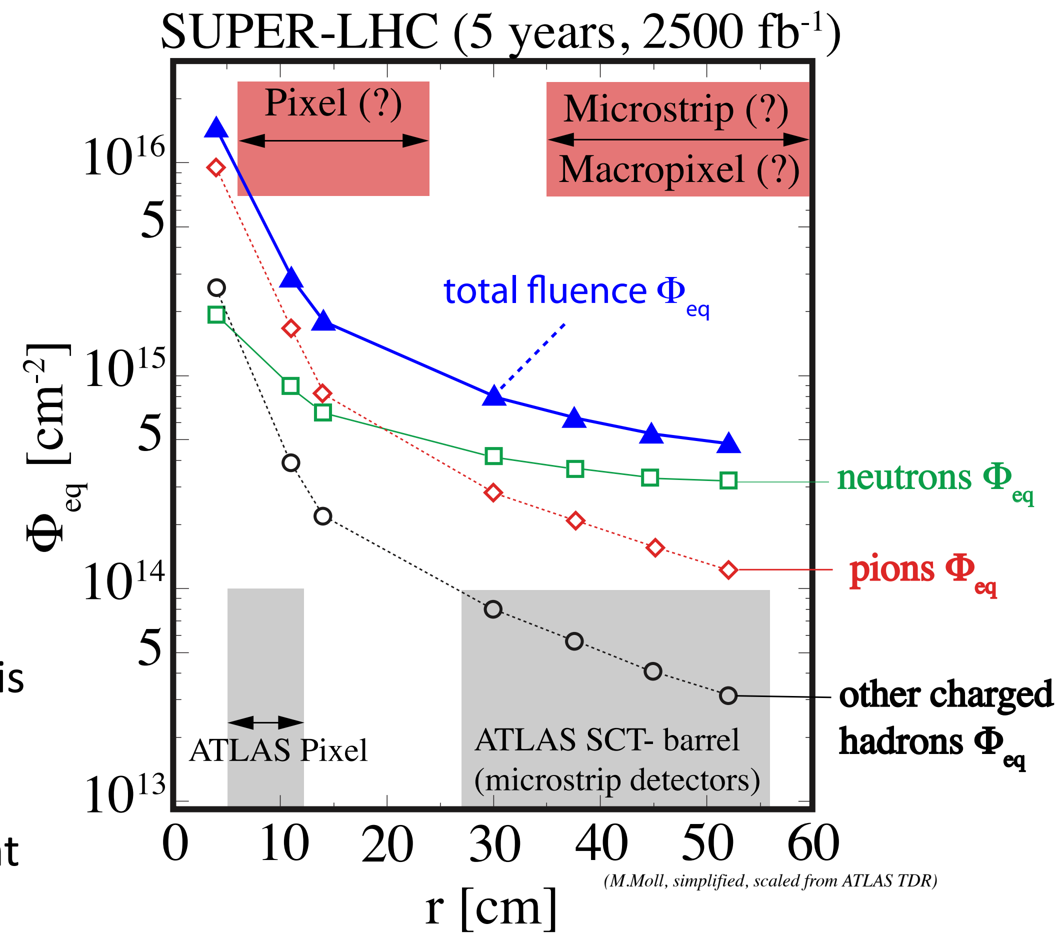
~3 x 10^{15} cm^{-2}

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 environment

➔ Increase of signal loss

➔ Distance to interaction point important for particle type and fluence

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

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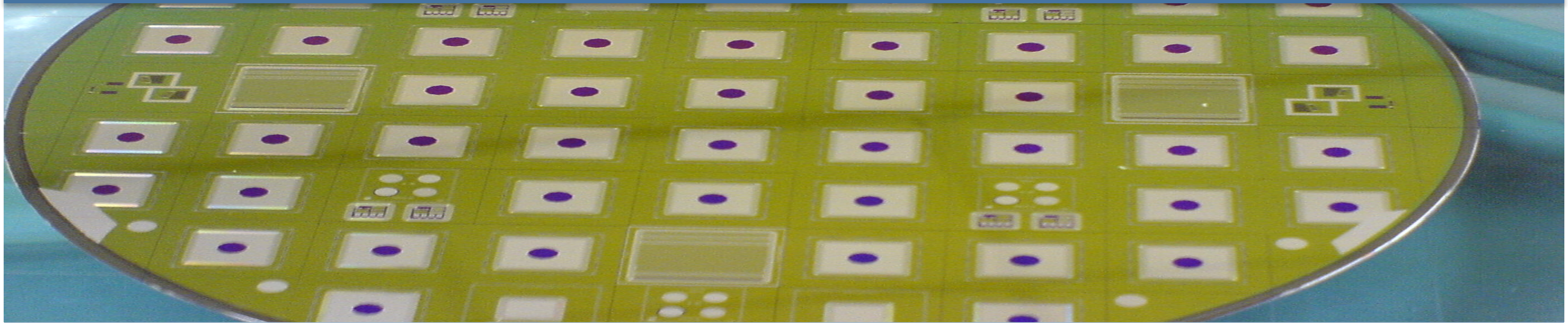
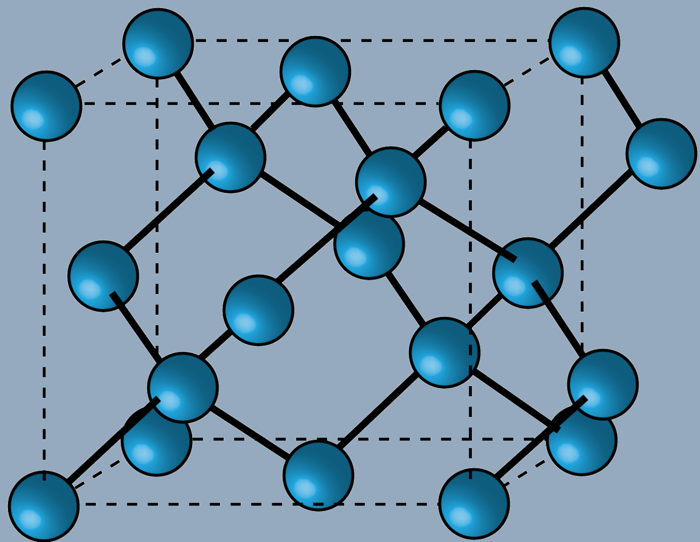
Silicon





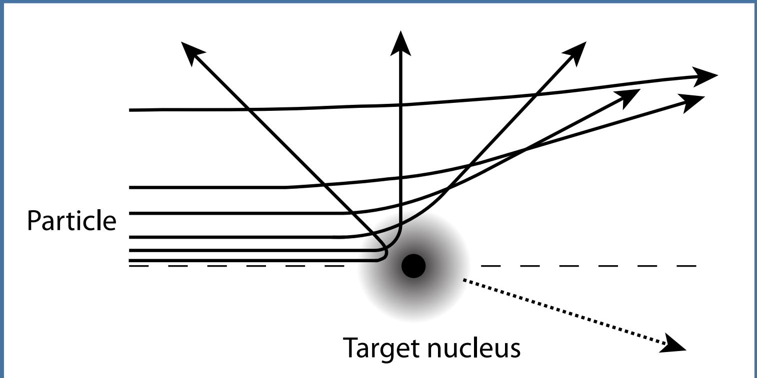
Diamond structure

Applications:

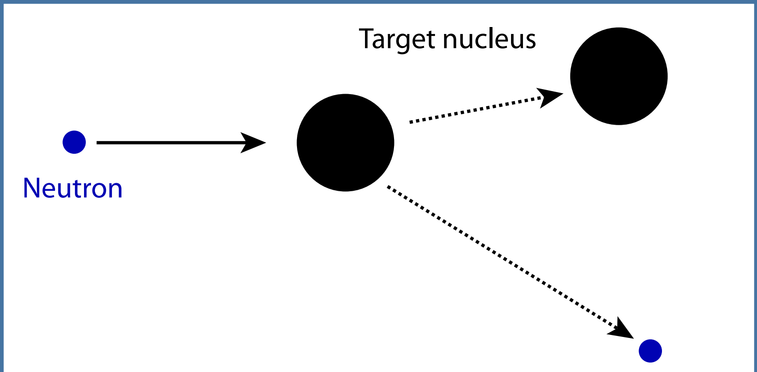
- Transistors (computer chips)
- Photovoltaic
- LCD' s
- Alloys
- Medical imaging
- X-ray diffraction
- Particle detectors...

Non Ionising Energy Loss → bulk damage

Coulomb scattering



Elastic nuclear scattering



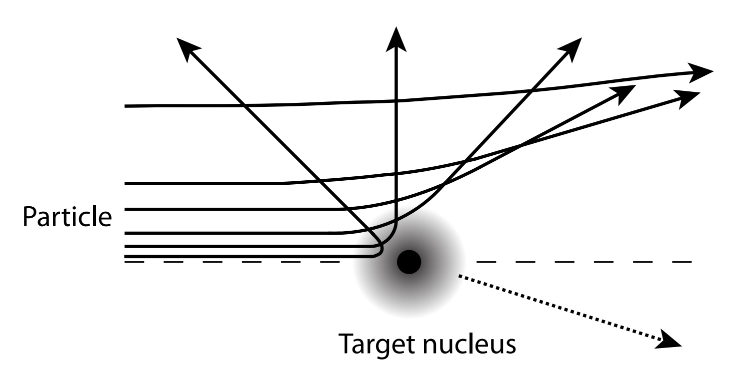
^{60}Co-γ	Electrons	Protons	Neutrons
compton electrons	coulomb scattering	coulomb & elastic nuclear scattering	elastic nuclear scattering

PKA **Primary Knock on Atom (PKA)**

Surface damage (Ionising Energy Loss) - oxide and oxide-si-interface damage (→lecture by E. Fretwurst)

Non Ionising Energy Loss → bulk damage

Coulomb scattering



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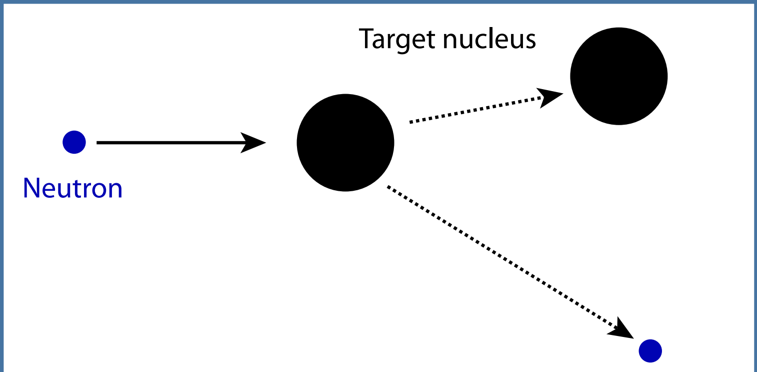

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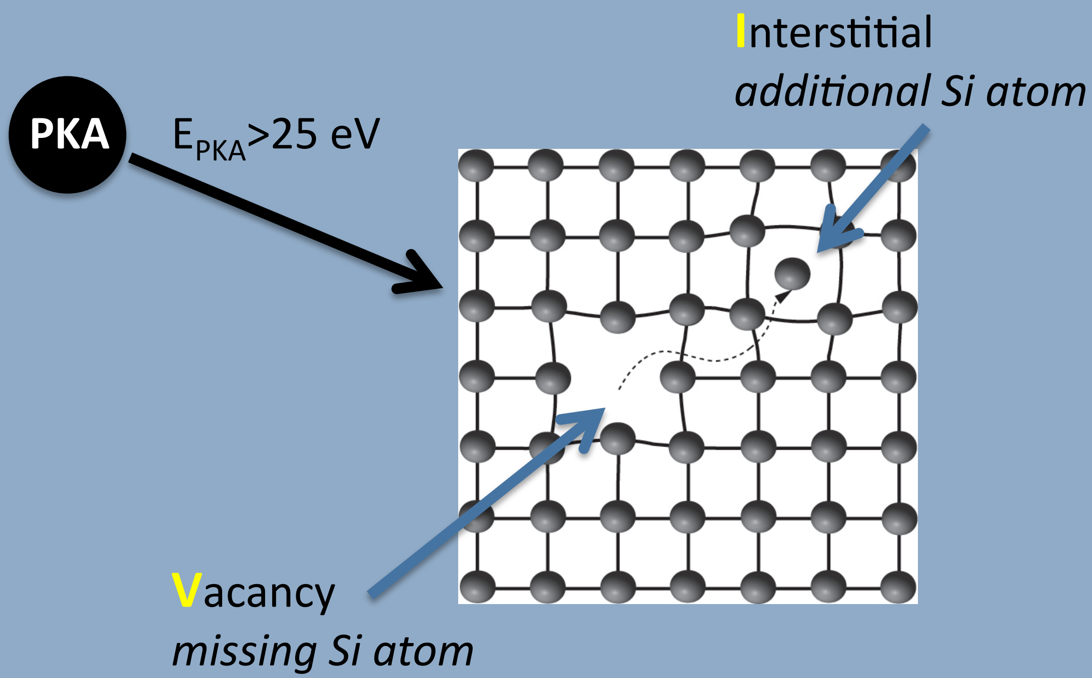
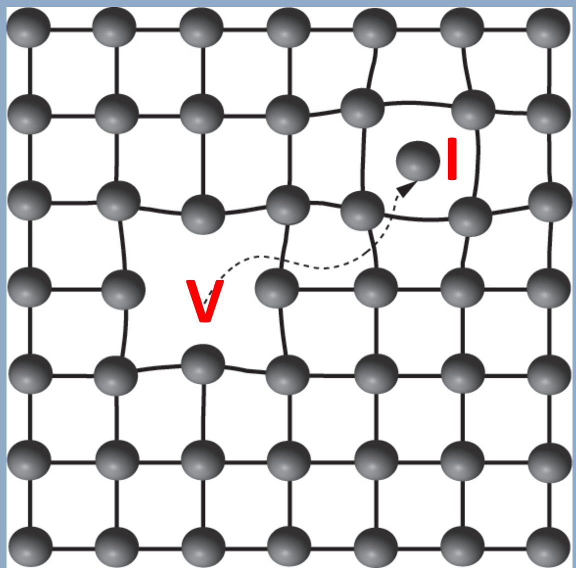


Bulk damage

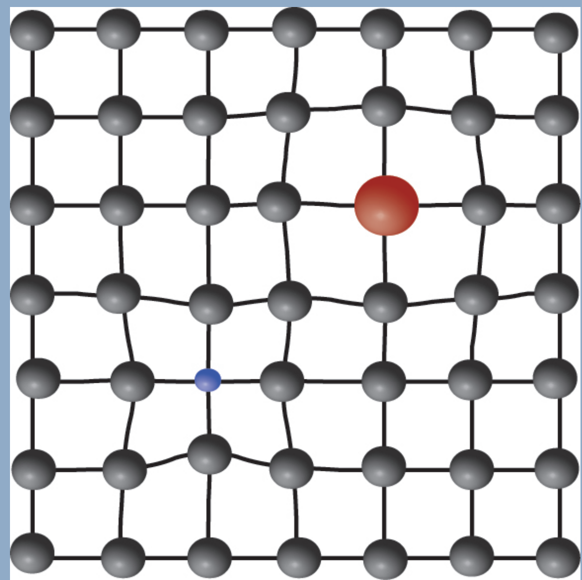
Radiation induced

Vacancies and Interstitials



Material impurities

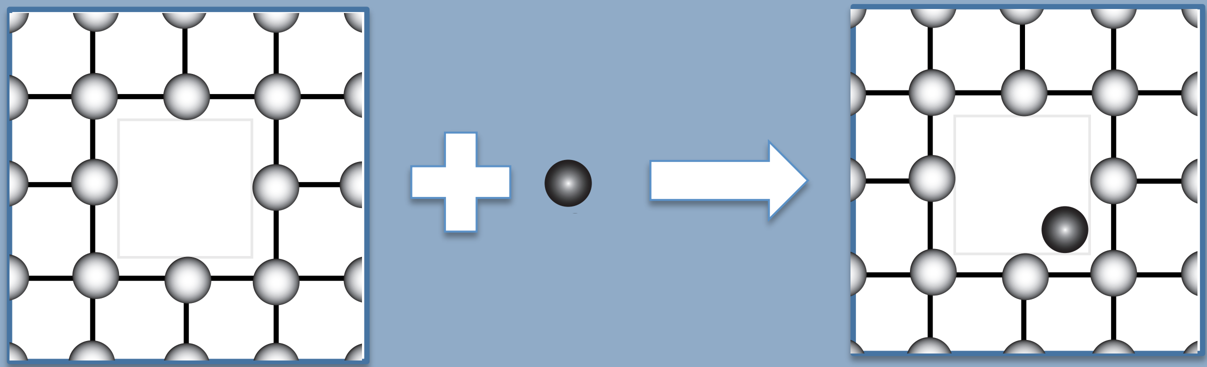
Oxygen, Carbon, Phosphorus, Boron…



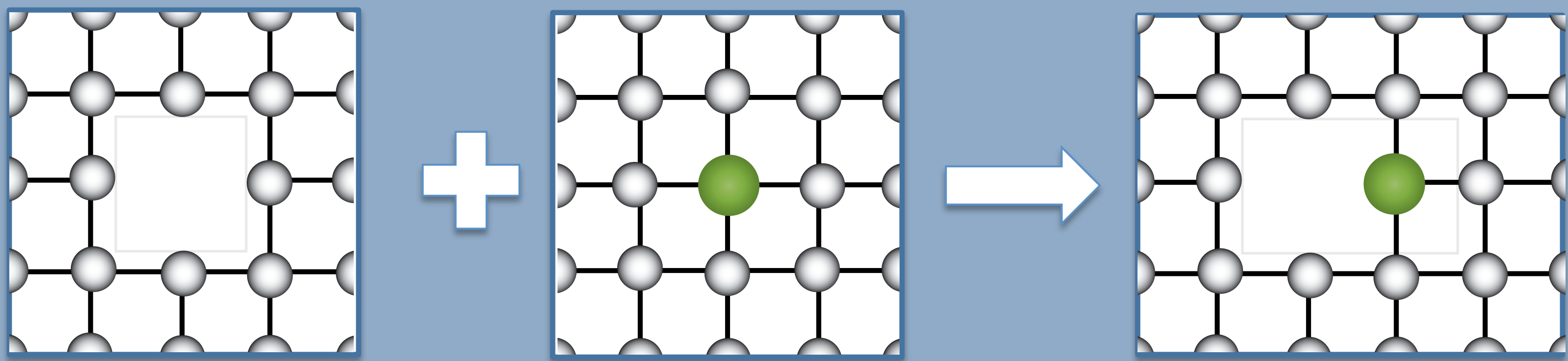
Some defects are mobile at room temperature…

Formation of defect complexes

$V + O_i \rightarrow VO_i$



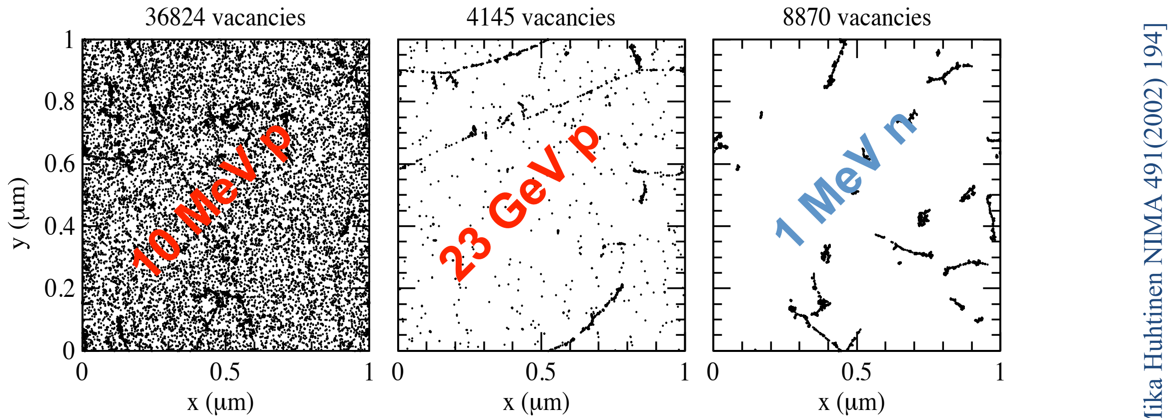
$V + P \rightarrow VP$



Single vacancies + impurities form point-like defects

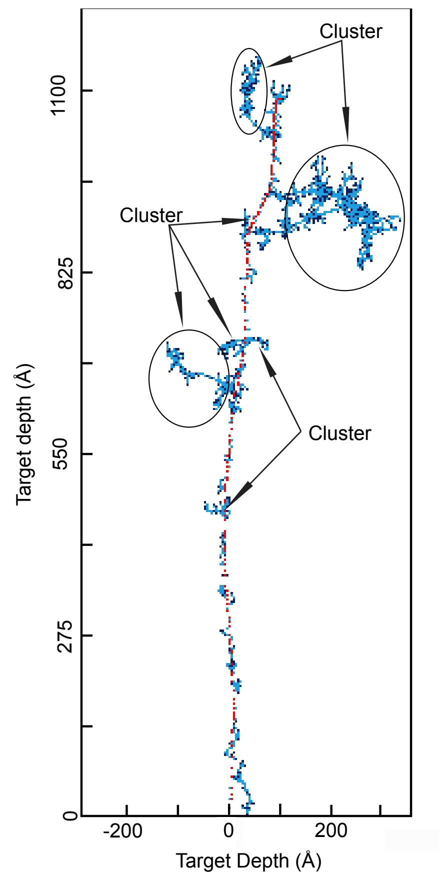
Creation of defect cluster (E_{PKA}>5 keV)

Depending on particle charge and mass



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

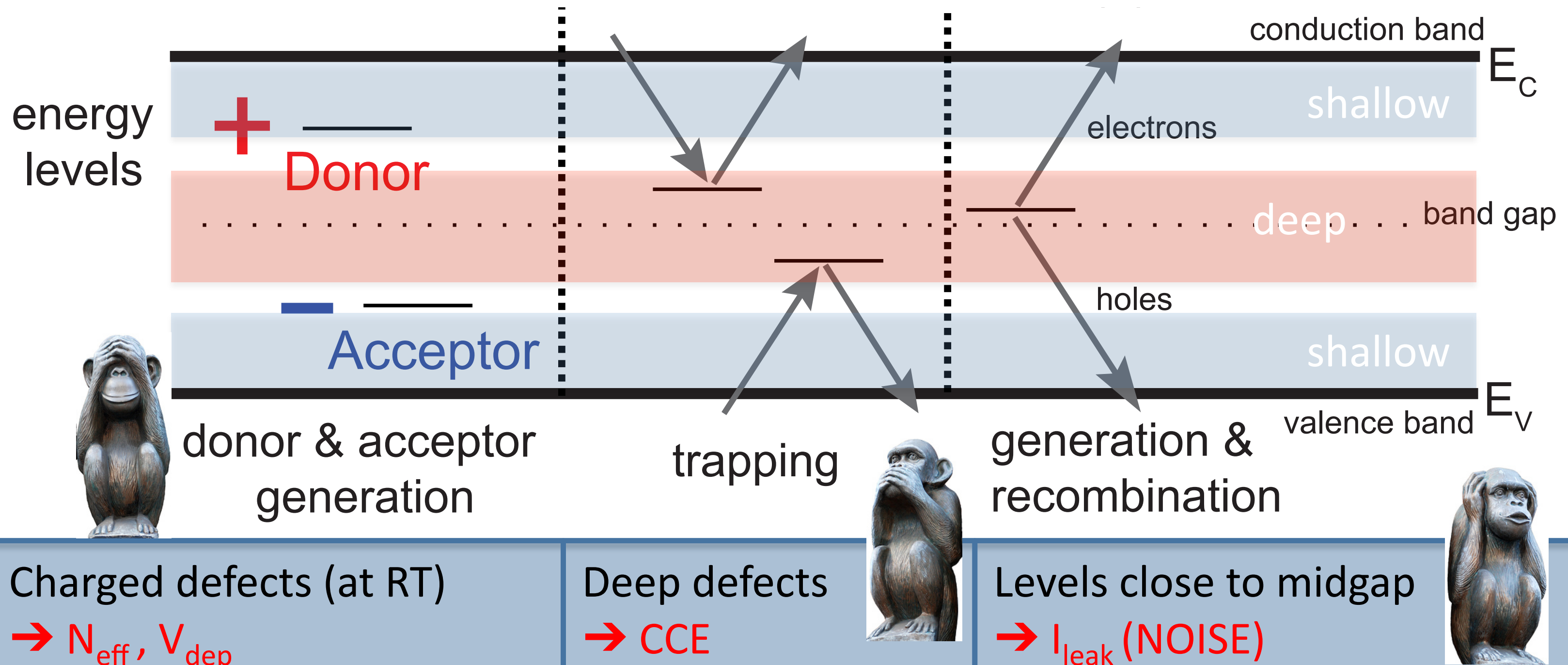
(1MeV) **Particle**	**^{60}Co-γ**	**Electrons**	**Protons**	**Neutrons**
Mean recoil energy	≈1 MeV	46 eV	210 eV	50 keV
E_{min} for point defects		255 keV	185 eV	185 eV
E_{min} cluster		8 MeV	35 keV	35 keV



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

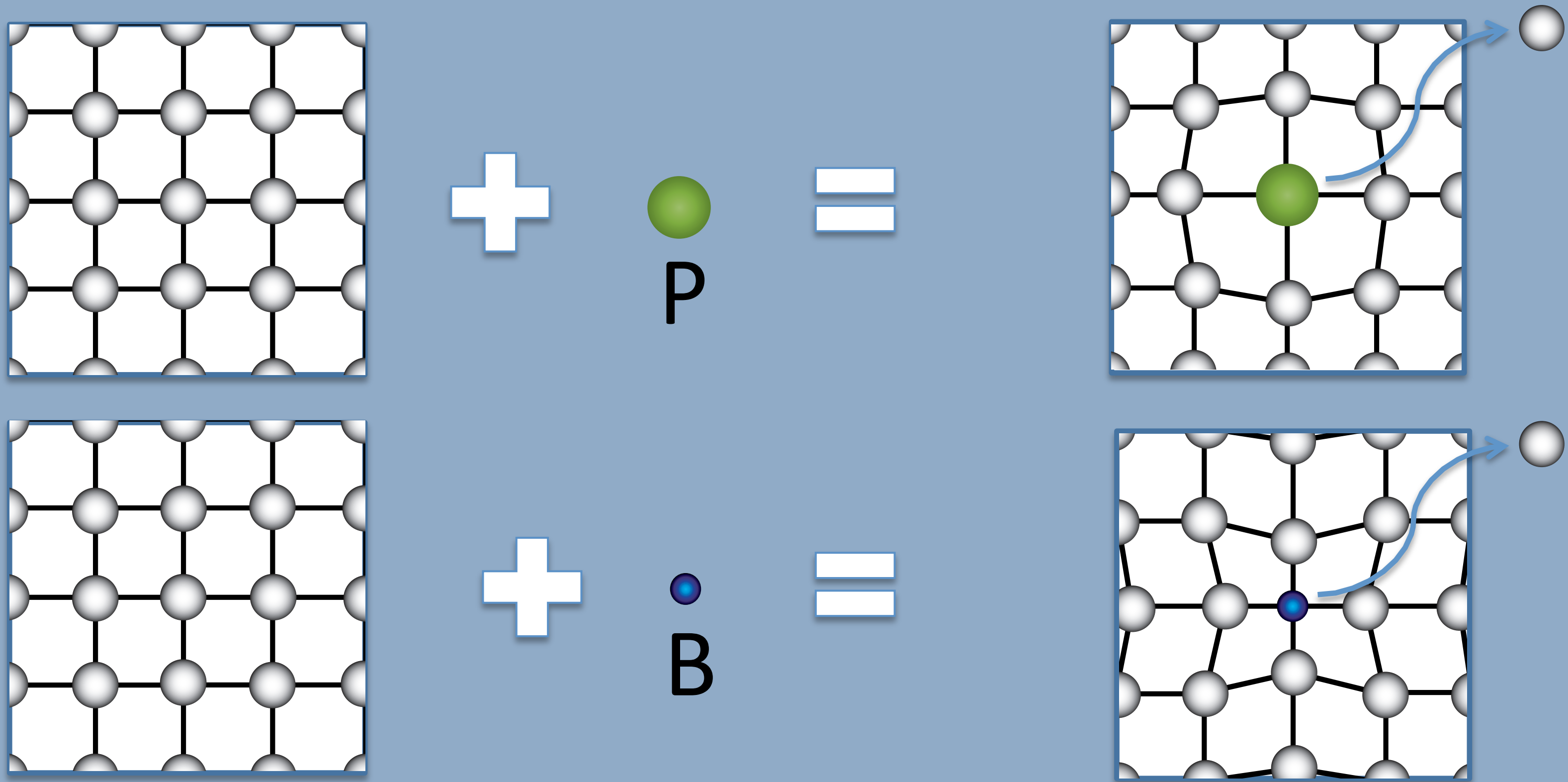
Impact of defects on detector properties

Determined by Shockley-Read-Hall statistics



Charged defects (at RT)	Deep defects	Levels close to midgap
➔ N_{eff} , V_{dep} (Acceptors in the lower half and donors in the upper half of the band gap)	➔ CCE (Shallow defects do not contribute due to detrapping)	➔ I_{leak} (NOISE) (Defect levels close to midgap most effective) ➔ Cooling during operation helps!

Doping atoms are “defects”…



…with desired impact on the detector properties.

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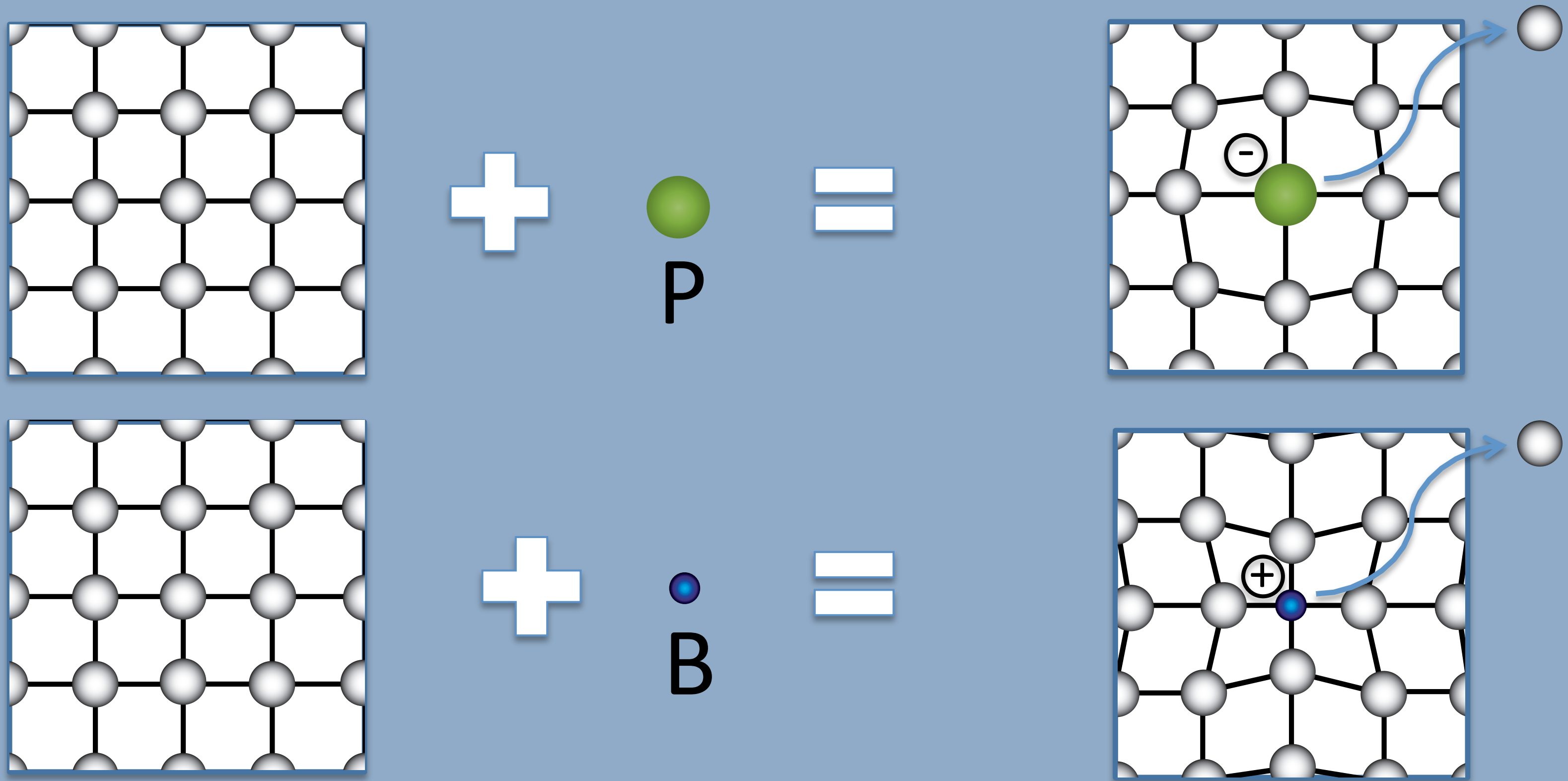

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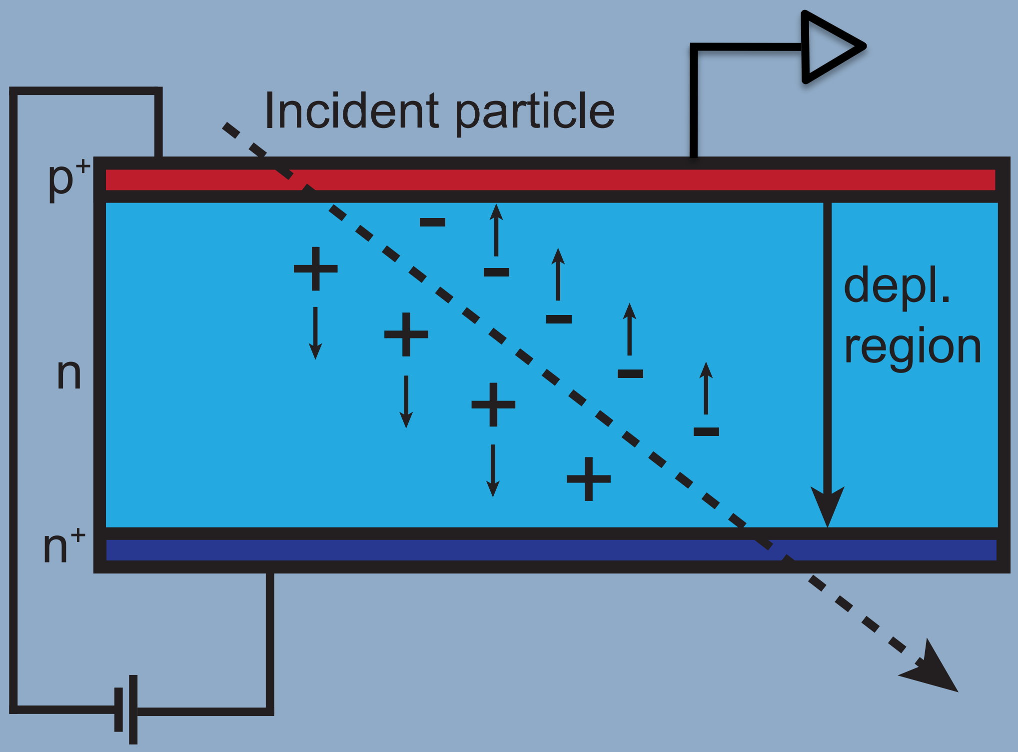
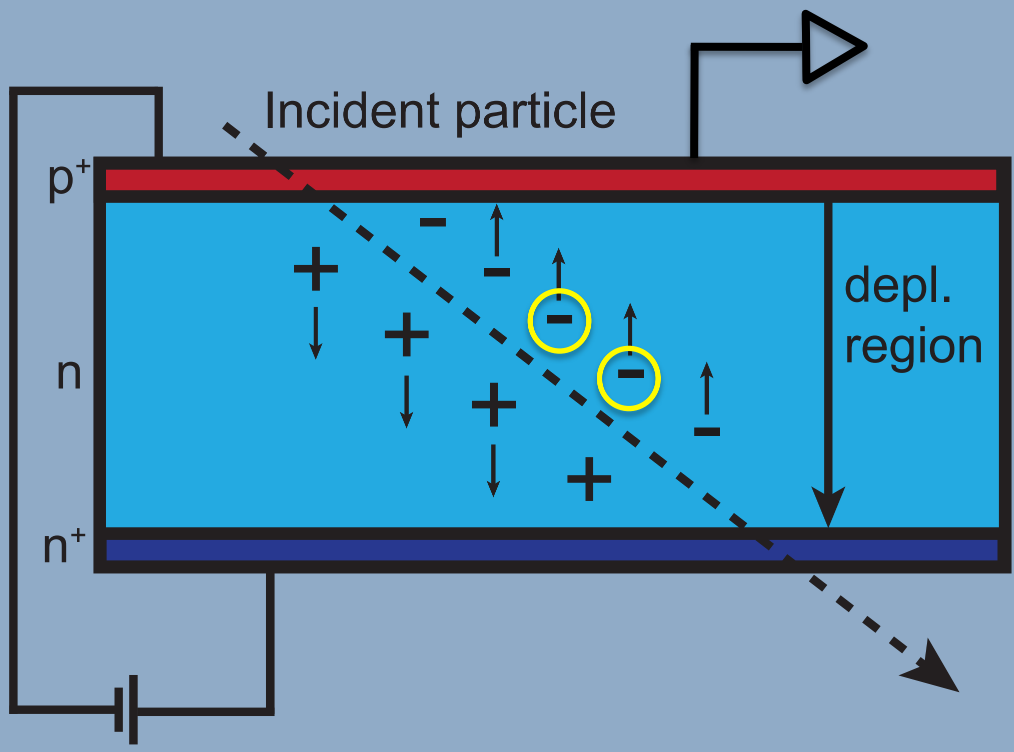
Sensor operation



Singnal generation

- Ionisation of depleted Si-bulk
- Generation of e^-/h^+-pairs
- Charge drift due to E-field
- Signal creation due to drift

Sensor operation



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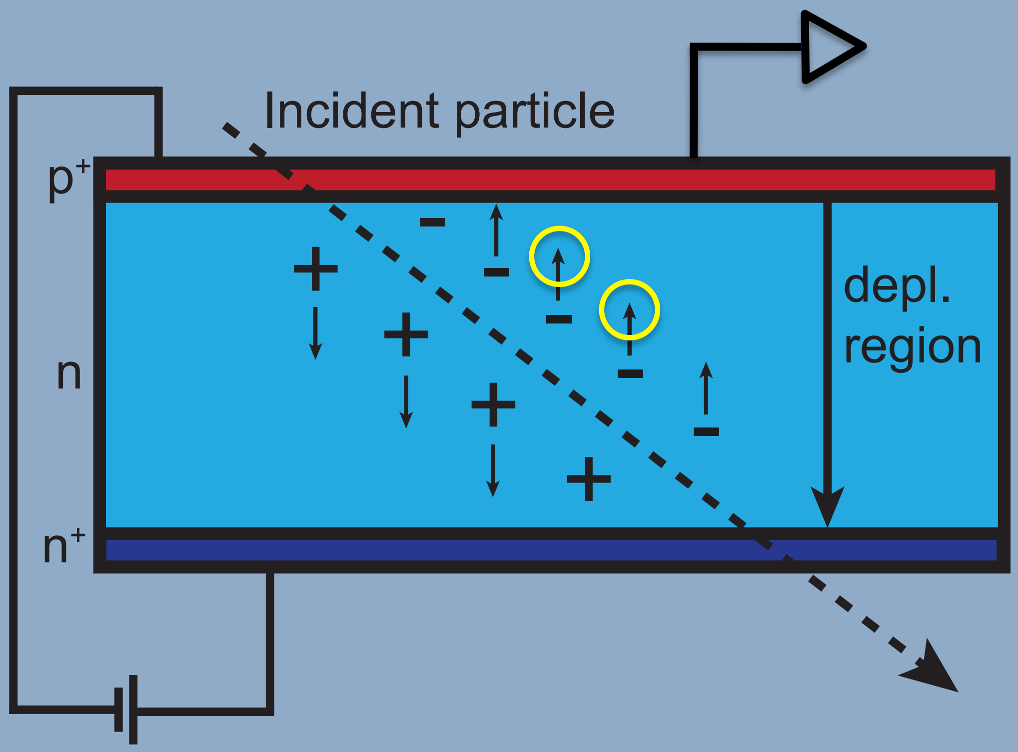
Singnal degradation

Loss of charge carriers due to

- decrease of free charges
- trapping of charge carriers
- noise increase due to current

Defects with impact on charge carriers are electrically active defects

Sensor operation



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Marble Maze

Detection of bulk defects

Technique	Based on/ measures	Results	Limits/ drawback
Deep Level Transient Spectroscopy (DLTS)	Charge capture-emission/ capacitance transients	Defects properties and concentration	- Low density of defects - Chemical nature (indirect)
Thermally Stimulated Current (TSC)	Charge capture-emission/ current	Defects properties and concentration	- Medium density of defects - Chemical nature (indirect)
Photoluminescence (PL)	Photon absorption-emission / luminescence	PL bands, defects ionisation energy	- Only for photo-active centers - Chemical nature (only indirect)
Infrared Absorption (IR)	Excitation of vibrational modes of molecules by IR absorption / Absorption of IR energy	Defects chemical structure and concentration	- Large density of defects - Electrical properties
Paramagnetic Resonance (EPR)	Zeeman effect and Spin resonance / microwave- photon absorption	Defects chemical structure and concentration	- Large density of defects - Only paramagnetic centers - Electrical properties
X-ray diffraction	Coherent interference/ Scattered intensity of X-ray beam	Atomic structure	- Only thin film/ nano structures - Only for Low defect variety
Scanning probe microscopy (STM)	Quantum tunneling/ tunneling current	Atomic structure	- Sample preparation - Large density of defects

No experimental technique provides all defects characteristics

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Electrical methods

No information about electrical properties

Not tried yet

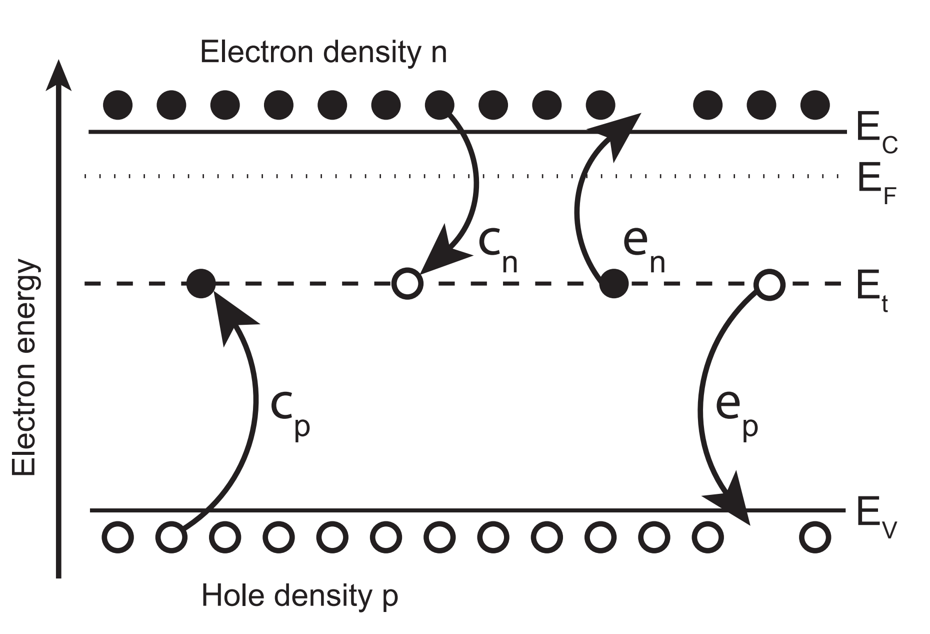
No experimental technique provides all defects characteristics

Defect properties

Scockley-Read-Hall statistik

Occupancy of defect states with electrons or holes is determined by

capture $c_{n,p} \propto \sigma_{n,p} \cdot n,p$ and emission $e_{n,p} \propto \sigma_{n,p} \cdot \exp\left(\pm \frac{E_t - E_{C,V}}{k_B T} \right)$



Defect properties

$\sigma_{n,p}$: e^-, h^+ capture cross section
E_a: activation energy for ionisation
N_t: trap concentration

Capture of electrons always combined with hole emission and vice versa

De- and recharging offers possibility to detect defects

Charging techniques

Play ***Chargeball***

- Balls represent charge carriers
- Semi circles are charge trapping positions

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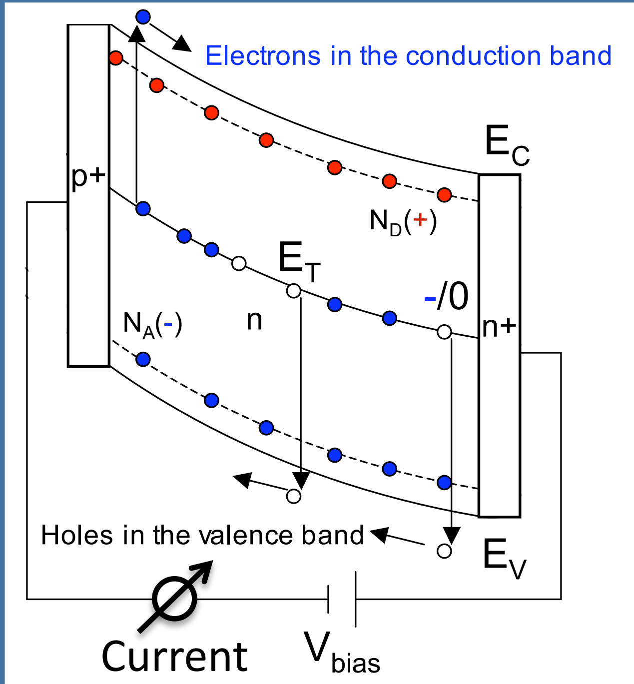
Thermally Stimulated Current technique

TSC principle

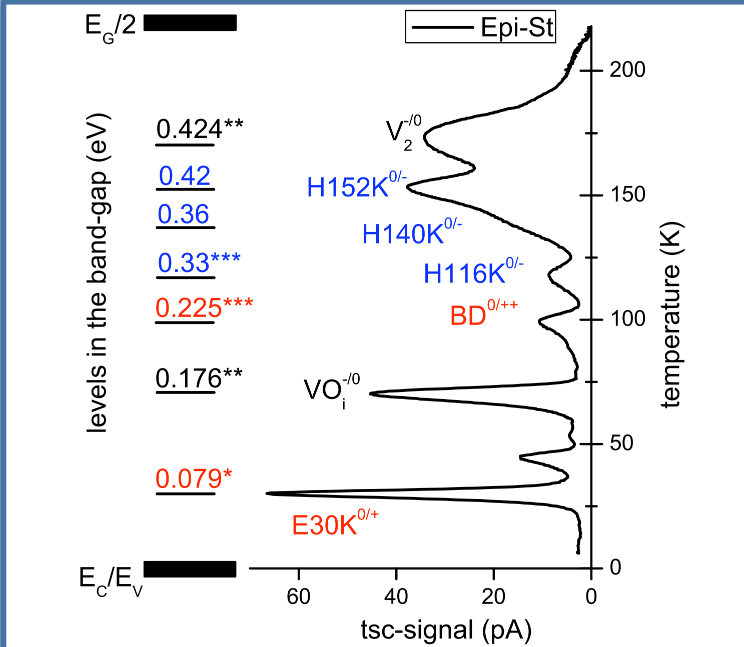


Single shot technique:

1. Filling of traps with charge carriers at low T (<30 K)

→Filling (majority carriers with zero bias, majority and minority carriers by forward bias, light)

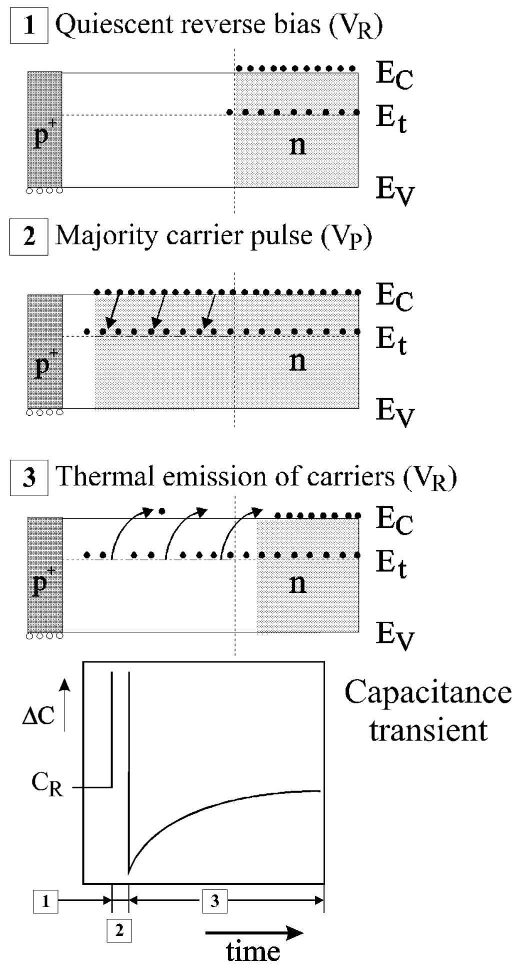
• Signal as function of temperature



2. Recording of charge emission ($e_{n,p}$) from filled traps during constant heating
3. N_t from integral of TSC-current

Deep Level Transient Spectroscopy

DLTS principle (electron traps)

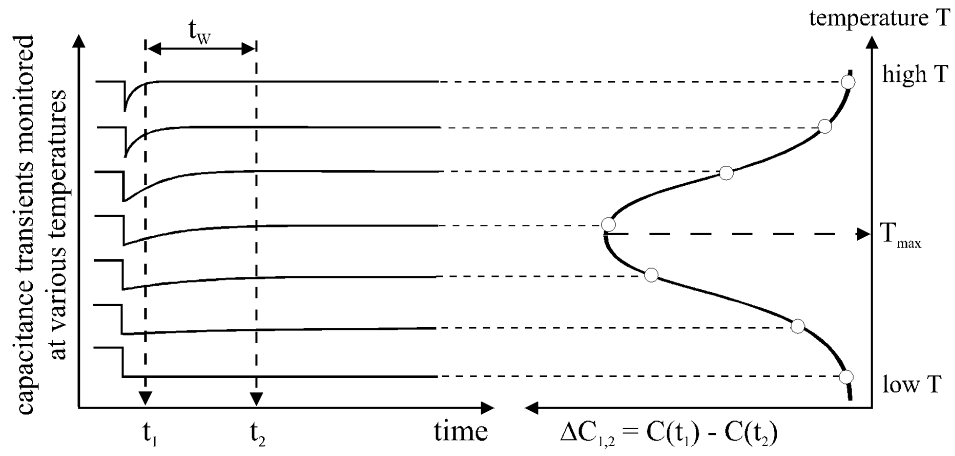


M. Moll, PhD thesis 1999, Uni Hamburg

Multi shot technique during T-scan:

1. Diode under reverse bias
2. Filling of traps with charge carriers at various T
3. Emission from filled traps → change of capacitance

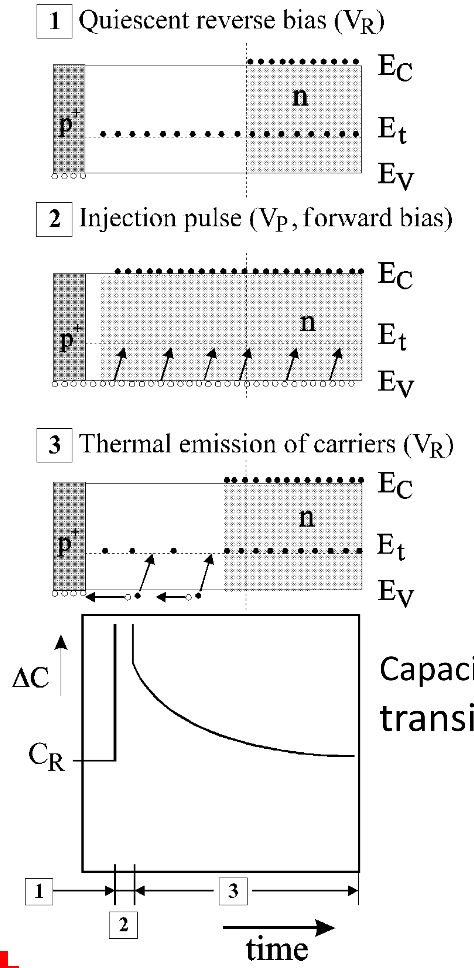
- Capacitance transients recorded as function of T
- Transient follows: $\Delta C = \Delta C_0 \exp(-e_n t)$
- Analysis from transient shape
- Concentration: $N_t \approx 2 N_D \frac{\Delta C}{C_0}$



M. Moll, PhD thesis 1999, Uni HH

Filling of minority carriers (DLTS)

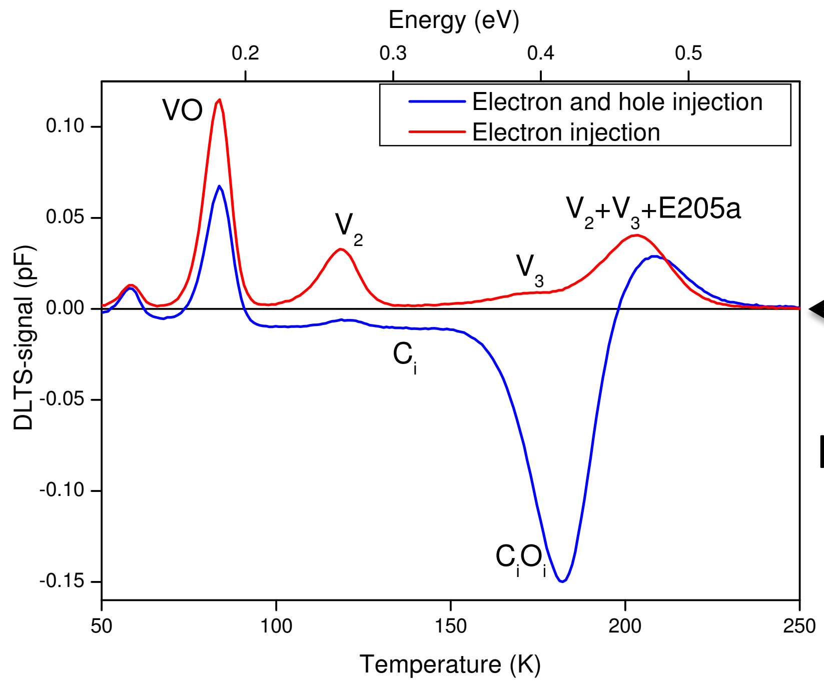
DLTS principle (hole traps)



Capacitance transient

M. Moll, PhD thesis 1999, Uni Hamburg

1. Diode under reverse bias
2. Filling of traps with forward bias (high current)
3. Emission from filled traps → change of capacitance



e⁻ traps

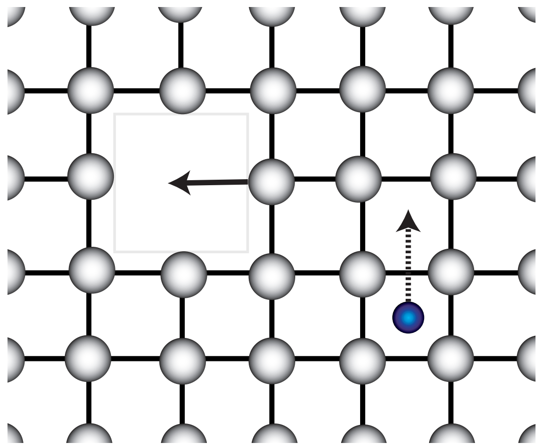
no traps

h⁺ traps

How connect bulk defects with sensor properties?

Annealing studies

Defect migration



- Defect migration at room temperature
- Acceleration of process by heating

1. Annealing studies at low temperatures (T< 100 °C)
   - Measurement of defect concentration and diode properties
   - Correlation of microscopic and macroscopic results

→ Identification of defects with impact on sLHC conditions

→ Forcast changes of detector properties

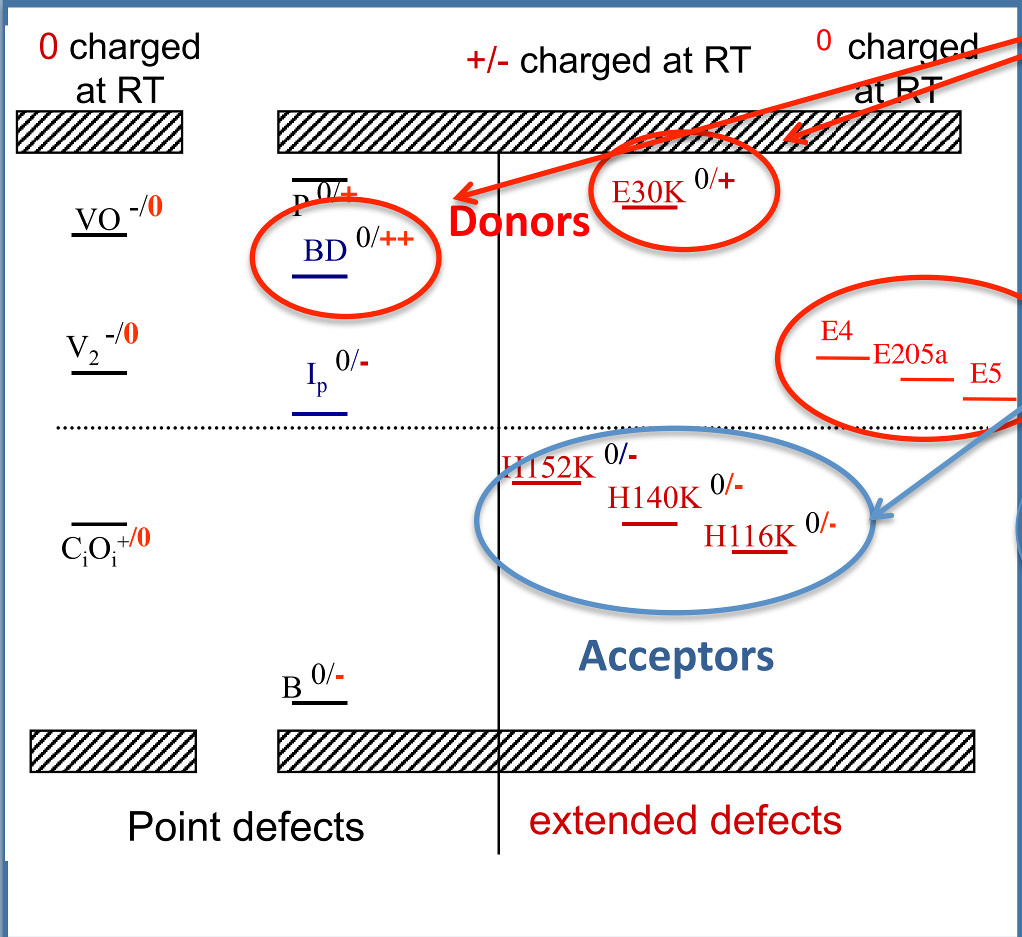
2. Annealing at temperatures above 100 °C
   - Measurement of different materials
   - Correlation of defects with material impurities

→ Identification of chemical structure of defects

→ Extraction of defect properties

Understand correlation between microscopic and macroscopic effects

Defects in the Band Gap



Positive space charge

Leakage current

Negative space charge

What am I doing here?

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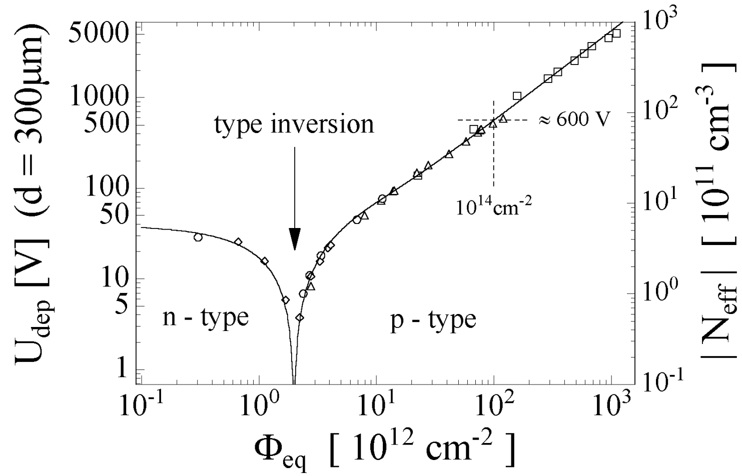
Depletion voltage

With particle fluence:



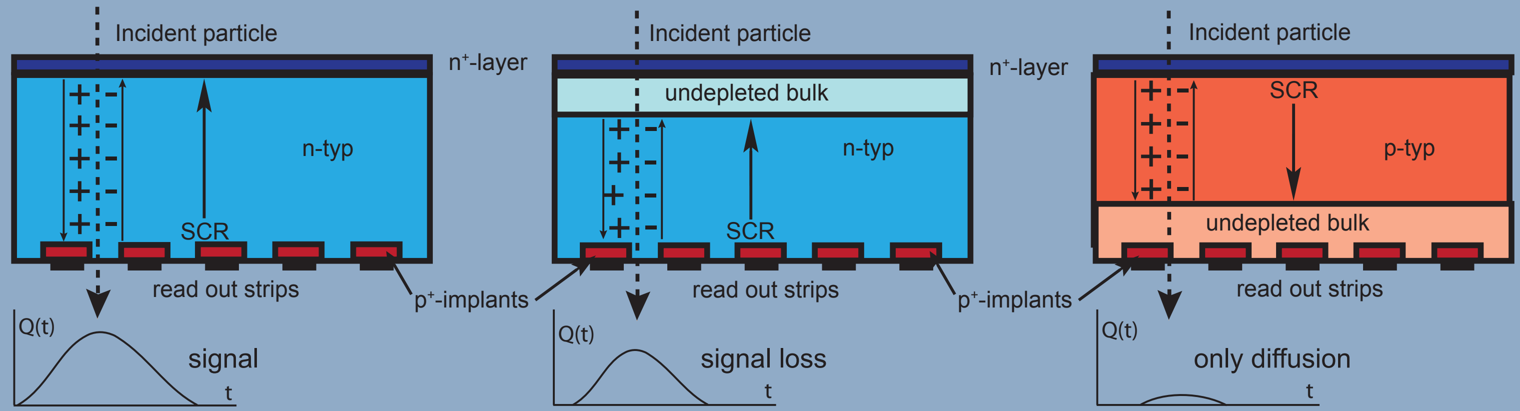
R. Wunsdorf, PhD thesis 1992, Uni Hamburg

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

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

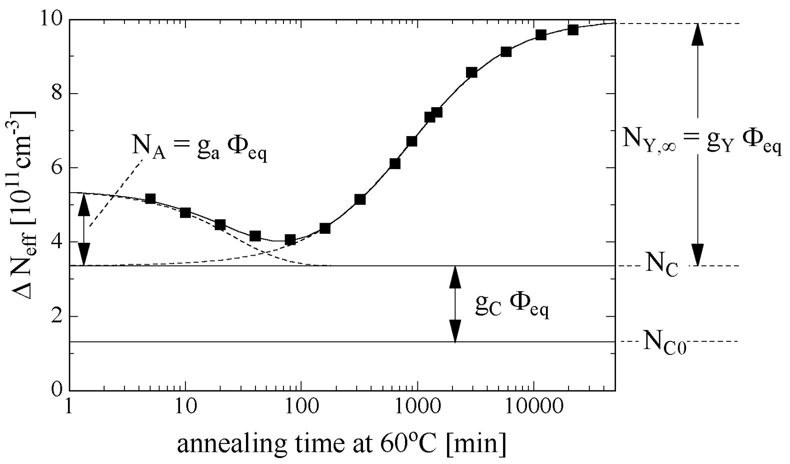
➔ Signal loss

- Annealing studies show impact of high T maintenance times



Depletion voltage

With annealing:



M. Moll, PhD thesis 1999, Uni Hamburg

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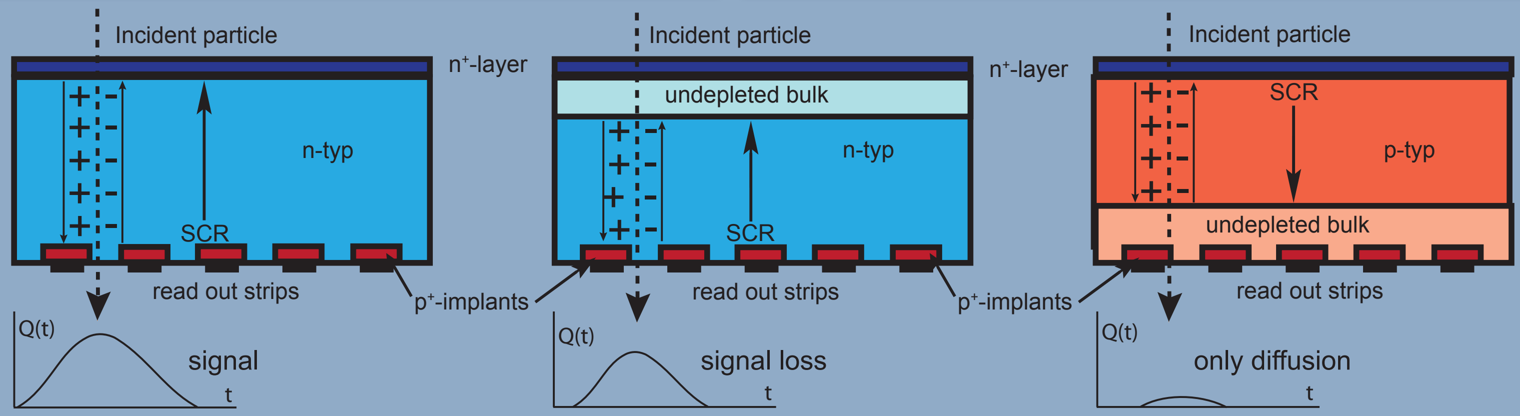
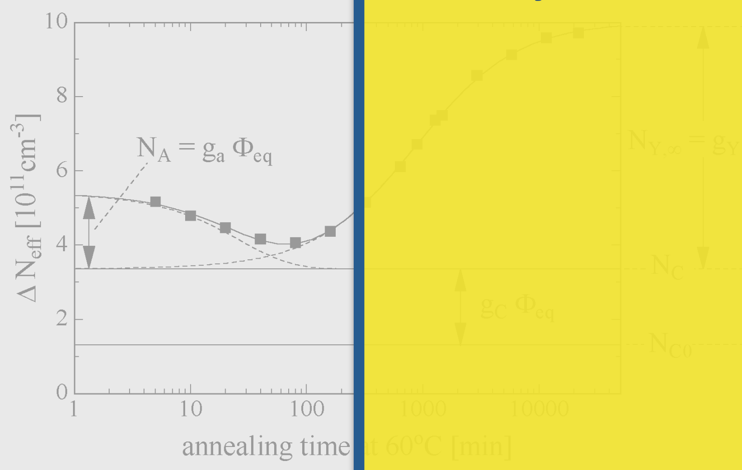


Depletion voltage

With annealing:

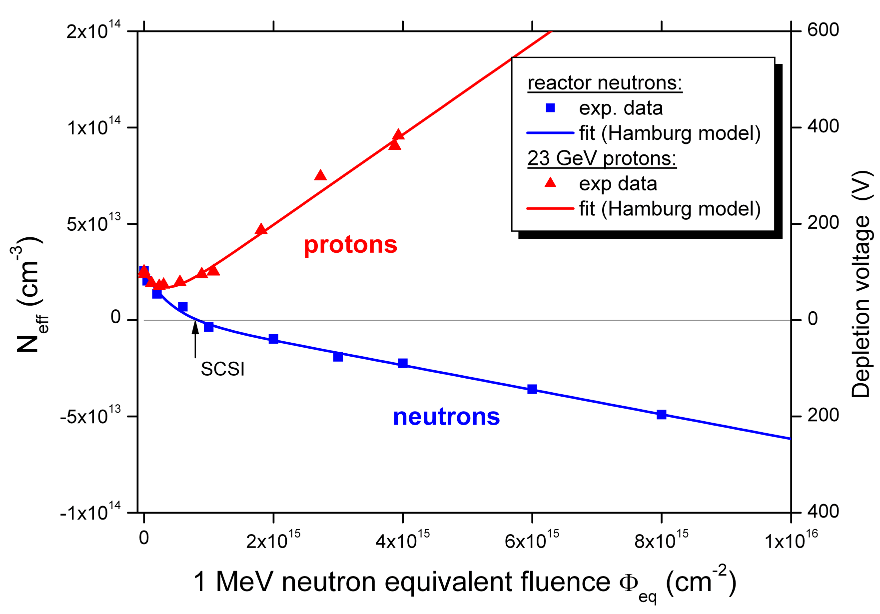


Monkey does not see particles

e original doping
to p-type
oltage after SCSI
impact of high T

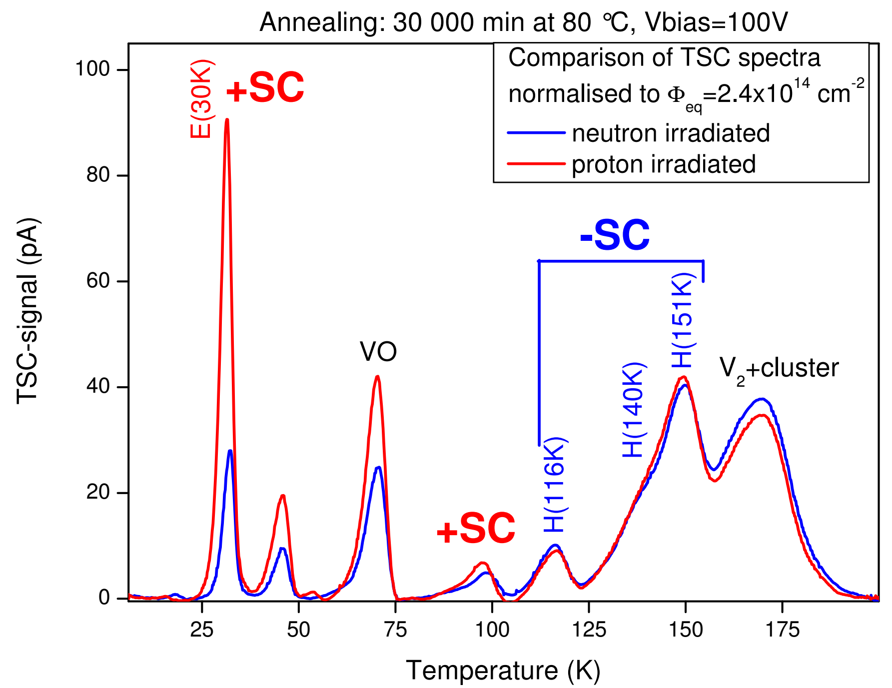
Defects with impact on N_{eff}

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



I. Pintilie et al. NIM A 611 (2009) 52

Corresponding defects (TSC)



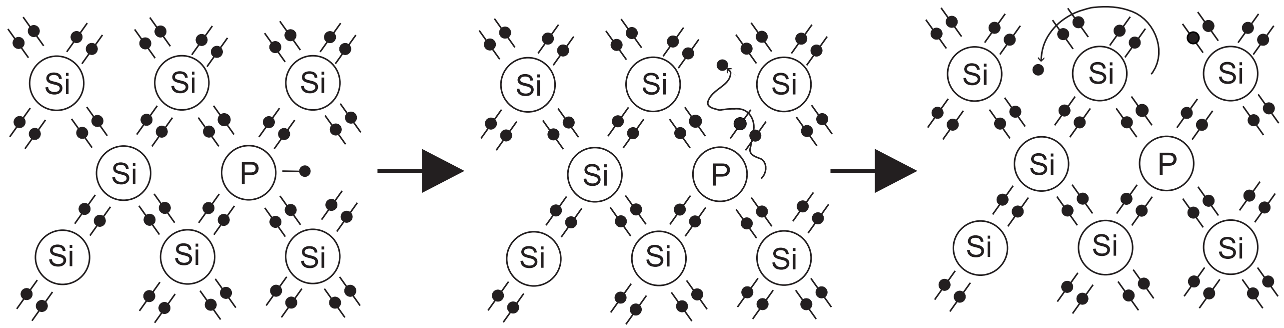
- Cluster defect E(30K) enhanced after protons
- Shallow donor E(30K) overcompensates deep acceptors

Phosphorus and boron doping

Donor

Electron conduction

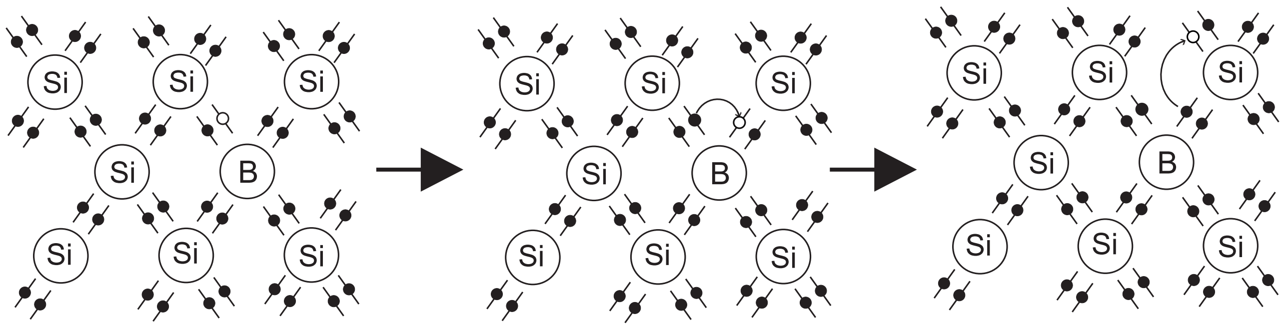
Phosphorus acts as donor
- Adds electrons
- Called n-type material



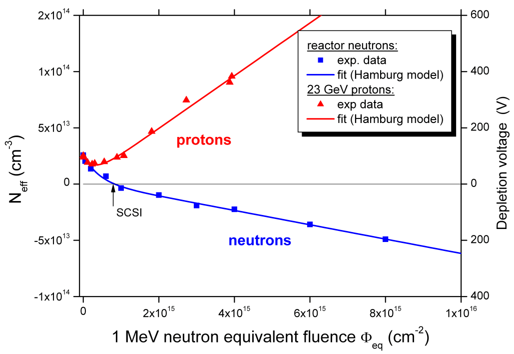
Acceptor

Hole conduction

Boron acts as donor
- Adds holes
- Called p-type material



Defect balance



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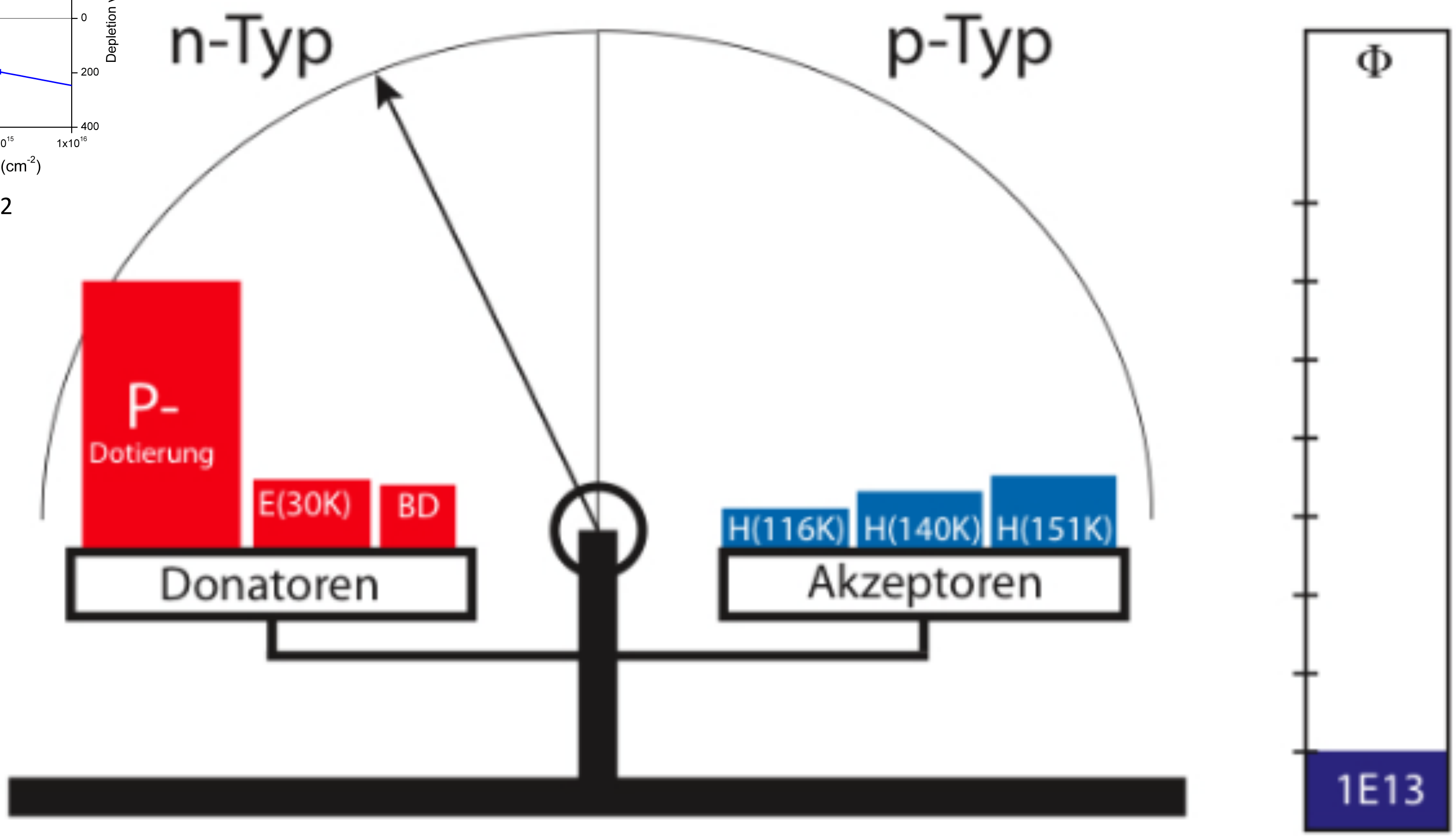
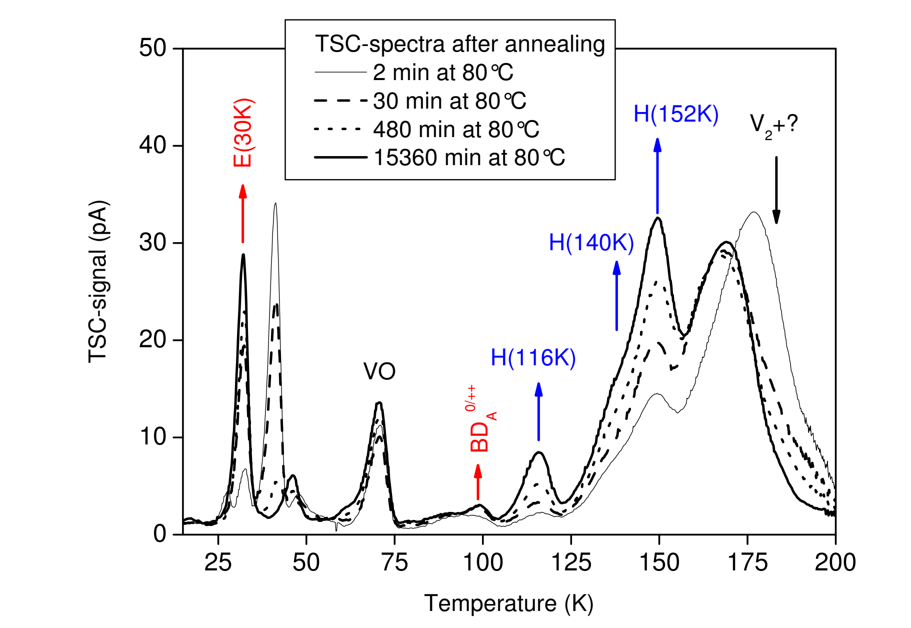
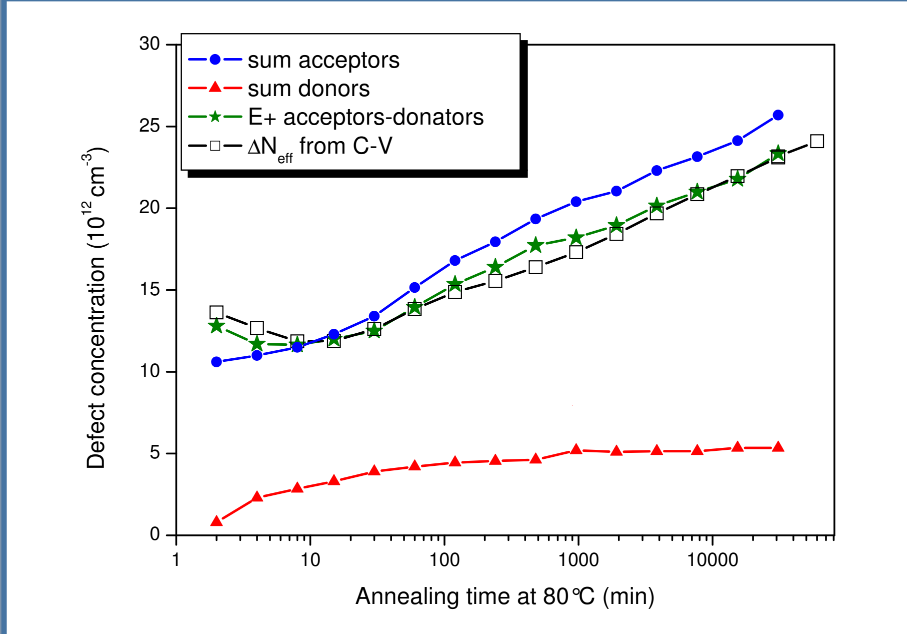


Annealing behaviour of N_{eff}

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



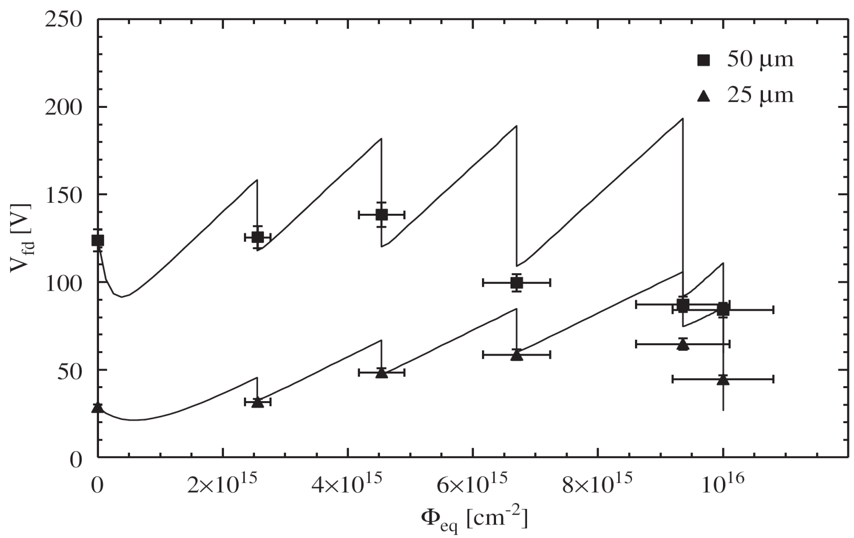
Defect concentrations vs N_{eff} (C-V)



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

Application of annealing results

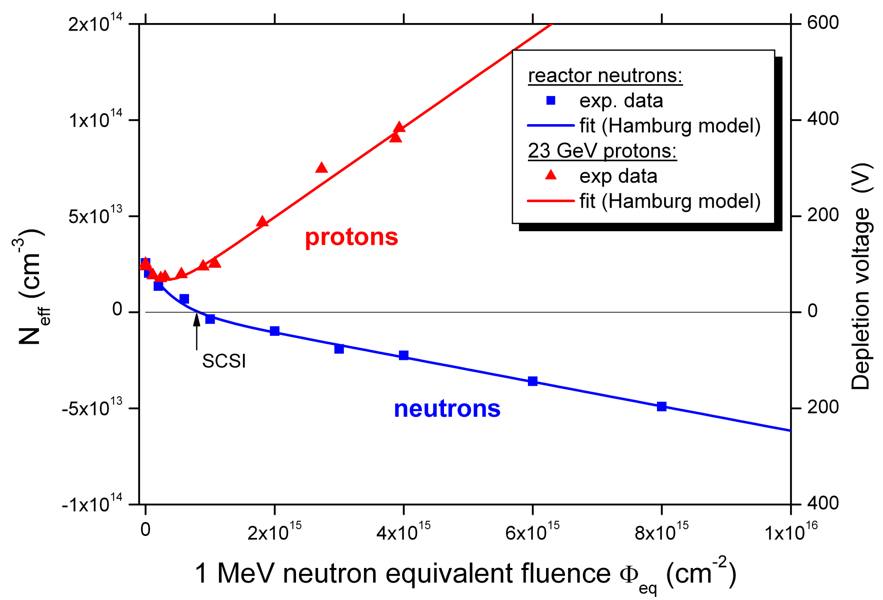
For an sLHC sczenario



F. Hönniger, PhD thesis 2008, Uni Hamburg

Irradiation in steps of Φ_p=2.2x10^{15} cm^{-2} with 23 GeV protons and additional annealing for 50 min at 60 °C

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



I. Pintilie et al. NIM A 611 (2009) 52

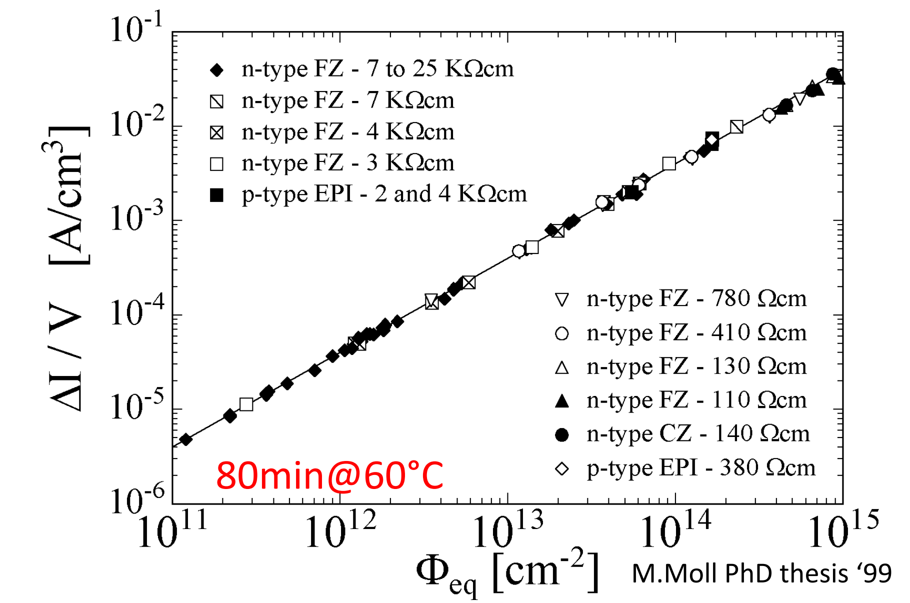
Improvement due to adaption of environmental conditions

Outline

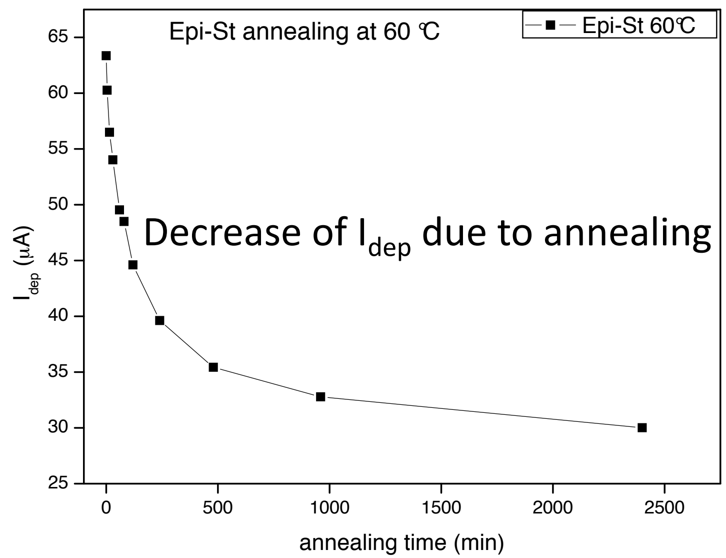
- Motivation
    - See lecture by M.Moll
- Radiation damage
    - Microscopic defects (changes in bulk material)
    - Macroscopic effects (changes in detector properties)
- Microscopic measurement techniques
    - TSC
    - DLTS
- Irradiation induced defects
    - With impact on the effective doping concentration
    - **With impact on the leakage current**
- Summary & outlook

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

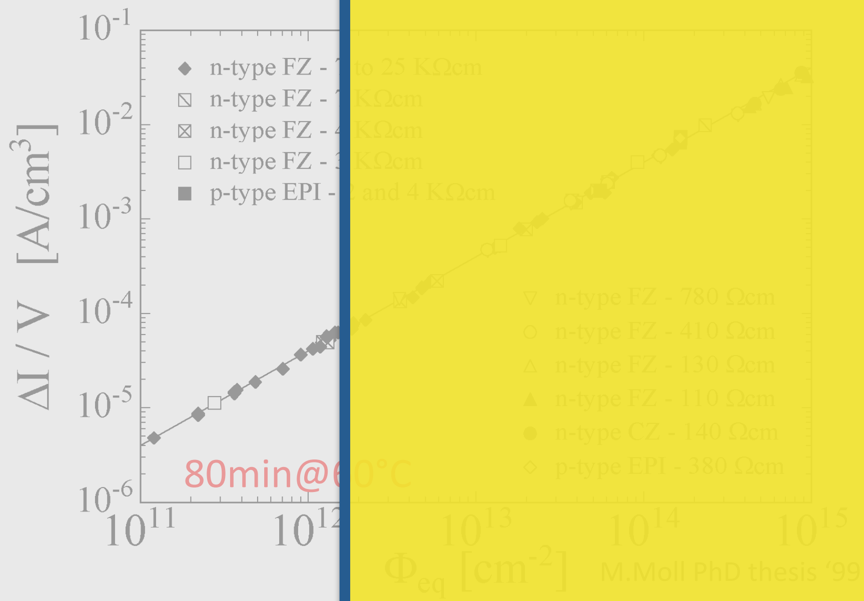
➔ Oxygen does not influence behaviour

- Constant over orders of magnitude

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

Change of leakage current…

… depending on the fluence… … and on …



Epi-St 60°C

… due to annealing

2000 2500

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

• Damage parameter α … for particle type

➔ Oxygen does not influence …

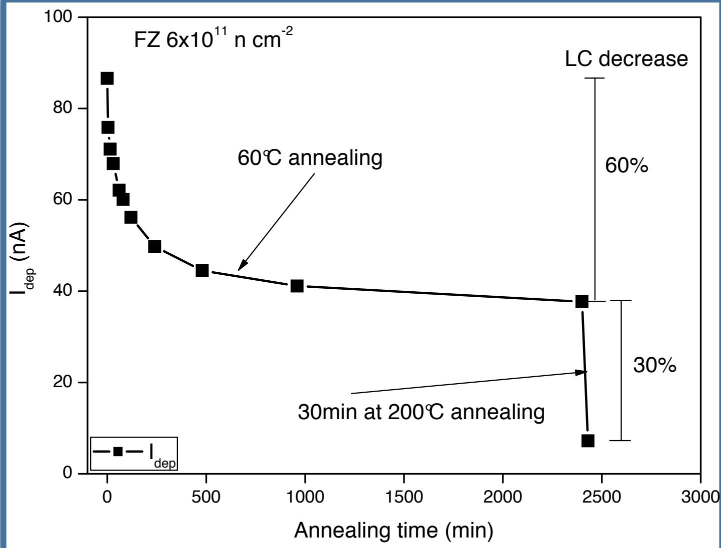
• Constant over orders of …

➔ Noise increase (cooling …)

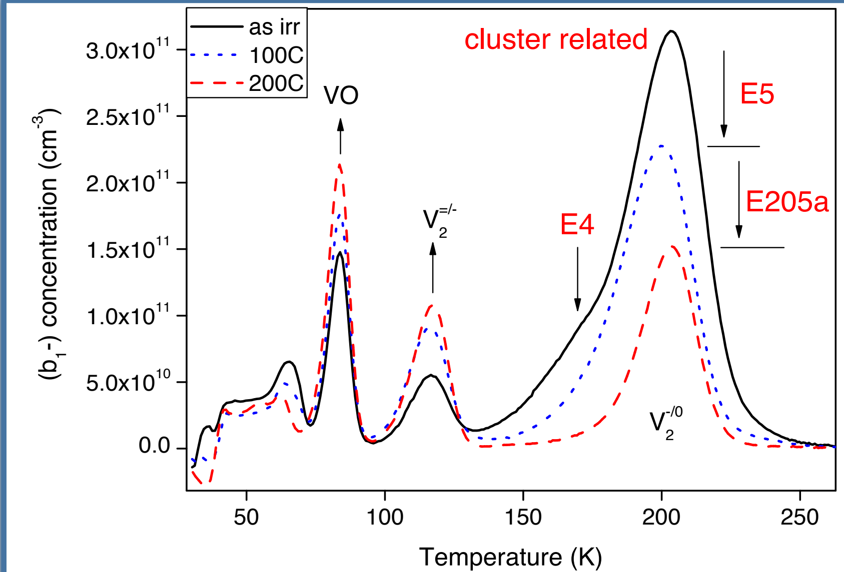
Monkey does not hear particles

Defects with impact on I_{leak}

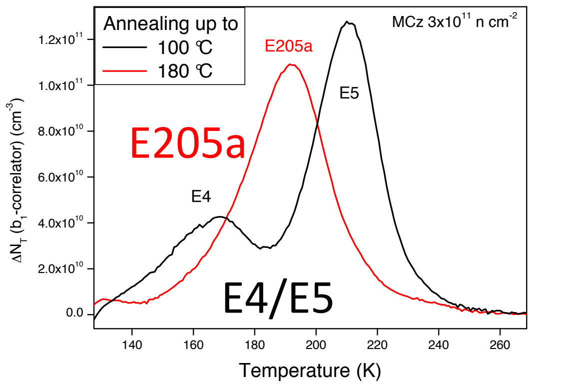
Decrease of I_{leak} during annealing



Corresponding defects from DLTS



Difference Spectra:



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

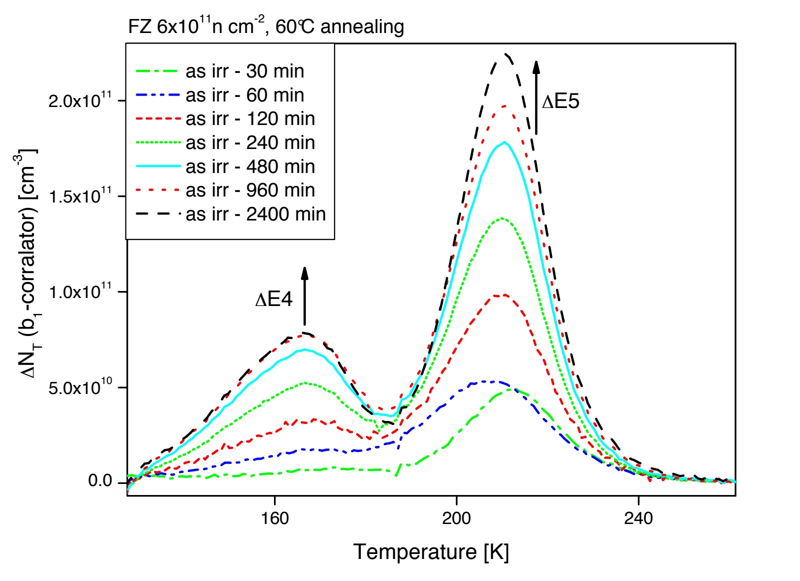
Corresponding defect annealing:

- E4 & E5 at 60 °C & E205a between 140 °C – 180 °C

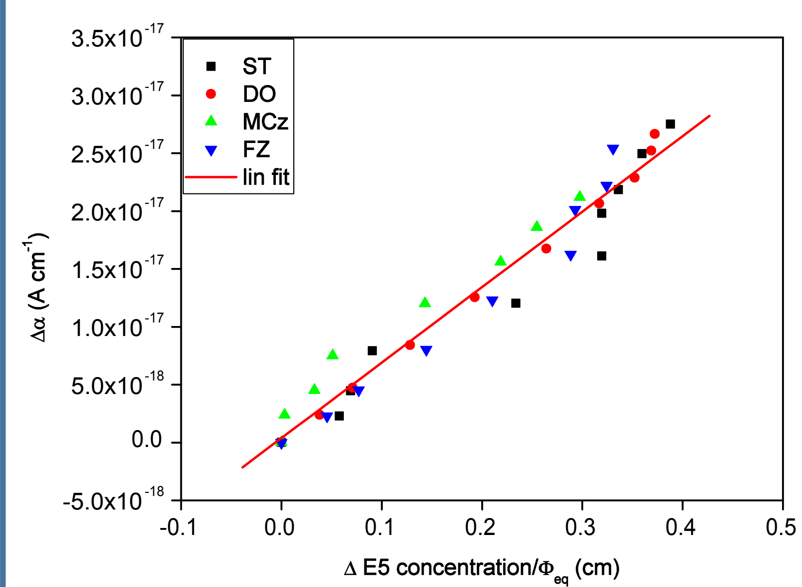
→ Responsible defects E4 & E5 & E205a

E4/E5 and E205a create I_{leak}

Difference Spectra



1 MeV **neutrons**



Correlation between E5-defect and current found!

How can I imagine clustering effects?

Play ***Chargeball***

- Balls represent charge carriers
- Semi circles are charge trapping positions
- Black dots represent potential barriers
- Multi Ball represents high current injection

- With high current injection also the shielded core can be reached

Summary

• sLHC environment create defects in the Si crystal
• Defects may influence detector properties
• Methods like DLTS and TSC provide information about electrically active defects
• Combination of microscopic & macroscopic methods reveals defects with impact on sensors

•Breakthrough in understanding the impacts of radiation induced defects on detector properties