Radiation Tolerant Silicon Detectors

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Outline

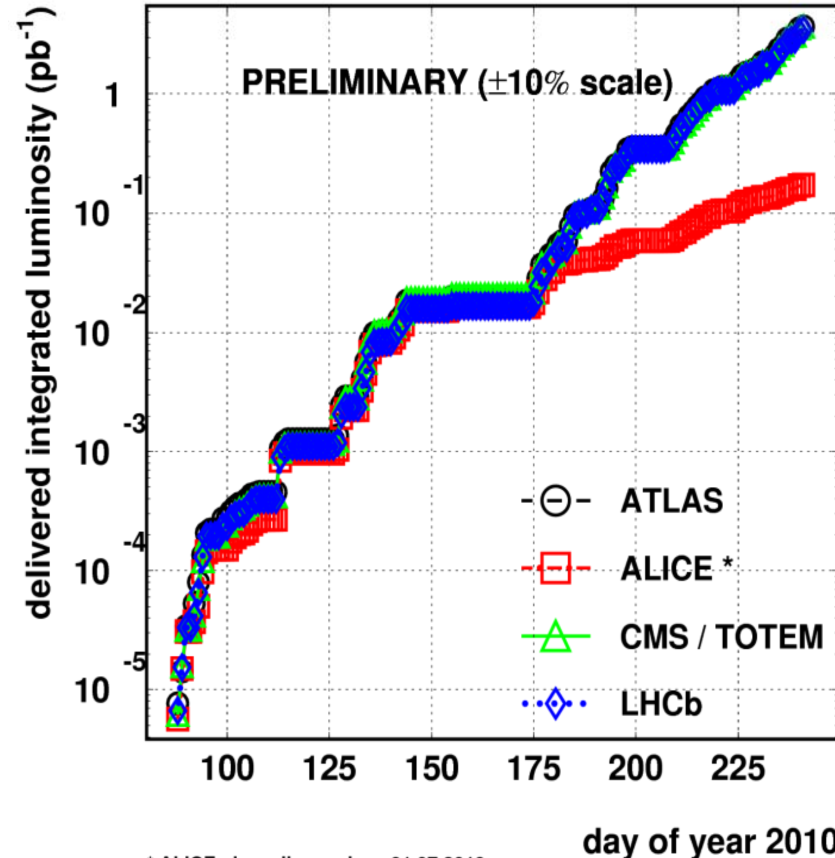
- **Motivation to develop radiation harder detectors**
  - expected radiation levels at the upgraded LHC (sLHC)
  - Radiation induced degradation of detector performance

- **Radiation Damage in Silicon Detectors**
  - Microscopic damage (crystal damage), NIEL
  - Macroscopic damage (changes in detector properties: N_{eff}, I_R, CC(V)
- **Changes with time after irradiation**
  - Annealing of the detector electrical properties: N_{eff}, I_R, CCE(V)
- **Radiation hardening of Silicon sensors**
  - Material Engineering
    - New silicon materials – FZ, MCZ, DOFZ, EPI
  - Device Engineering
    - p-in-n, n-in-n and n-in-p sensors, 3D sensors
- **Conclusions**

LHC Machine Performance in 2010

"Luminosity", measured in $b^{-1}s^{-1}$* or $cm^{-2}s^{-1}$ is an indication of how fast collisions are produced, it represents the flux as seen by all the protons in one beam of oncoming protons in the other.

Cross-section (σ): measure of the probability of a process per flux of incoming particles. $\mathcal{L}$ multiplied by the total cross-section, gives the total event rate.



*1 barn = $10^{-28}m^2$

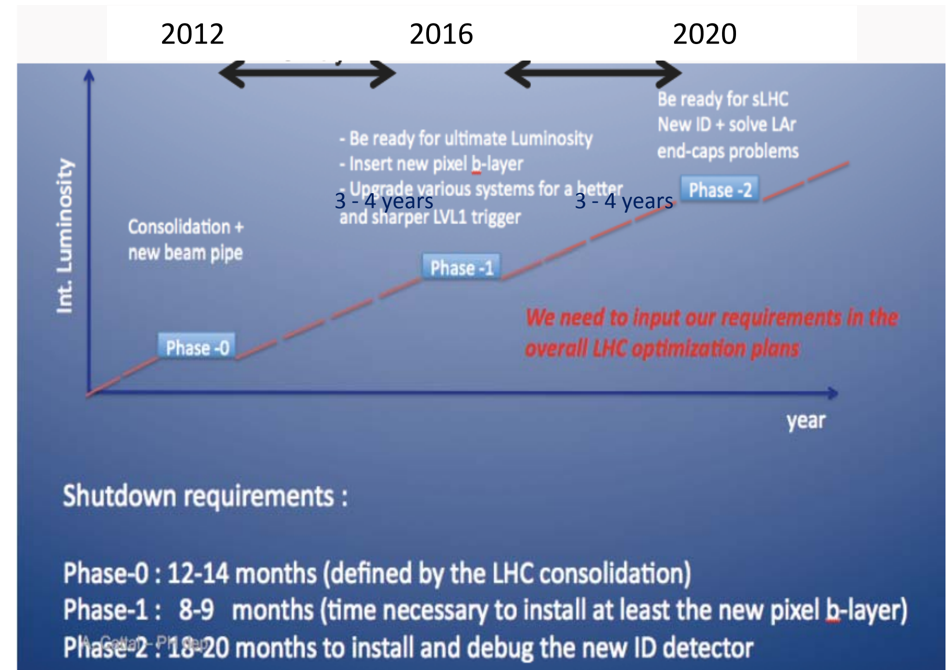
The design number of protons per bunch, 1.1 x 10^{11} , was first achieved 10th June 2010 and is now routine. Emphasis now is on increasing number of bunches circulating at any time in the LHC and then further improve the final focus. Record luminosity: ~ 4 x 10^{31} $cm^{-2}s^{-1}$ achieved 24th September.

Upgrading the LHC for High Luminosity

With modest investment, the <u>LHC can run at much higher collision rates</u>, greatly increasing the scope to search for new particles and study rare processes

Expected Development in Luminosity

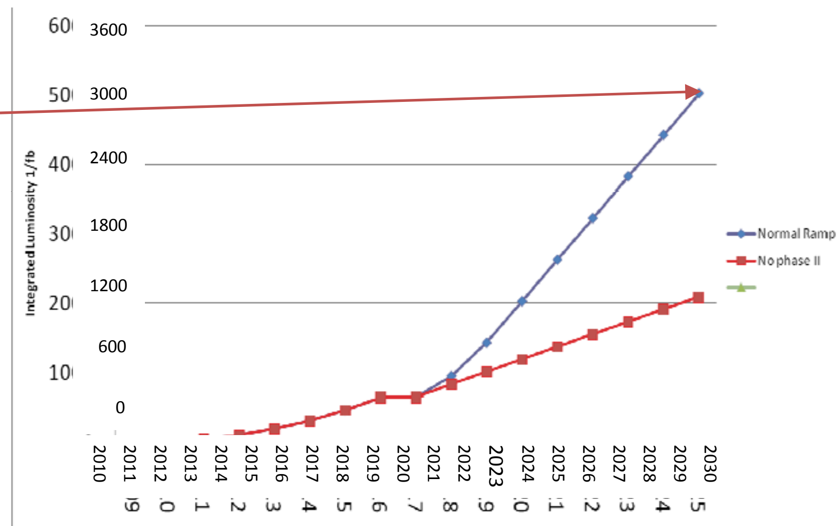
- Phase-I (after 5 years)
  - Up to ~ $60fb^{-1}$/year
  - Experiments need:
    - <u>New vertex detectors</u>
    - New off-line electronics
    - ...
- Phase-II (after 10 years)
  - Up to ~ $300fb^{-1}$/year
  - Experiments need:
    - <u>Complete tracker replacement</u>
    - Much improved on-line filtering
    - New read-out for many subsystems
    - ...



Upgrading the Experiments

To keep ATLAS and CMS running beyond ~10 years requires tracker replacement
Current trackers designed to survive up to 10Mrad in strip detectors (≤ 700 fb^{-1})
For the luminosity-upgrade the new trackers will have to cope with:

- **much higher integrated doses**
  (need to plan for ≥ 3000 fb^{-1})
- **much higher occupancy levels (up to 400 collisions per beam crossing)**
- **Installation inside an existing 4π coverage experiment**



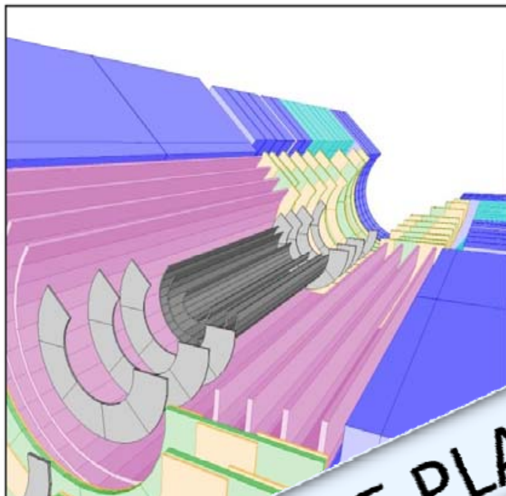
- **Budgets are likely to be such that replacement trackers, while needing higher performance to cope with the extreme environment, cannot cost more than the ones they replace**

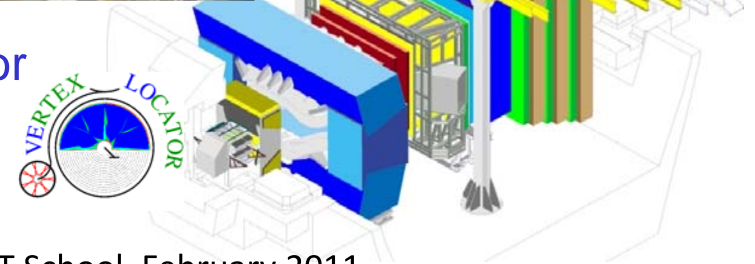
To install a new tracker in ~2020, require Technical Design Report 2014/15
(Note the ATLAS Tracker TDR: April 1997; CMS Tracker TDR: April 1998)

Technology in Current Highest Dose Regions

LHC vertex detectors closes to the interaction point:

- Required to be very radiation hard and to be very finely segmented because of the very high density of tracks close to primary collisions
- Doses $5 - 10 \times 10^{14}\ n_{eq}cm^{-2}$ (~100 Mrad)
- 0.05mm ×0.4mm pixels (40 million images per second)





ALL USE PLANAR N-IN-N SILICON DETECTORS

ATL...

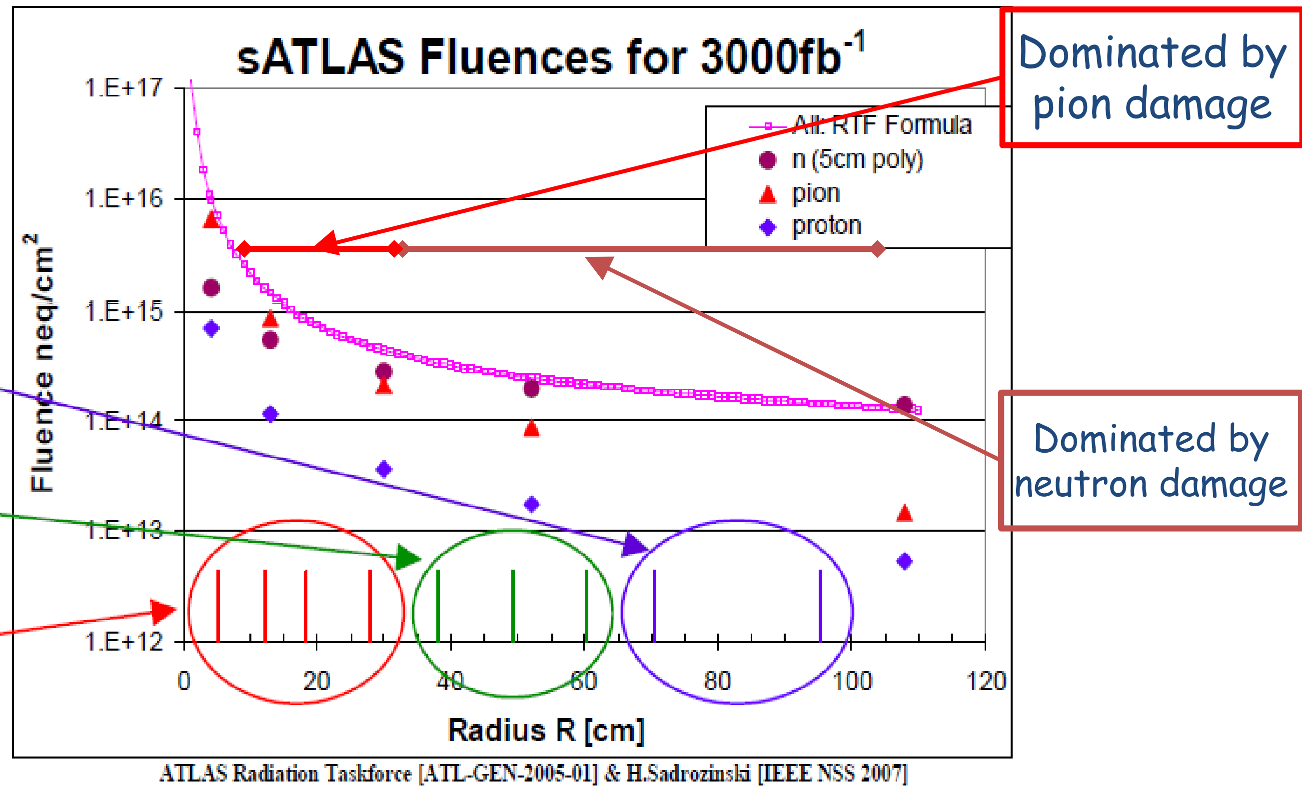
...xels

LHCb

Vertex Locator

Z(mm)=0-990

Radiation levels expected with sLHC

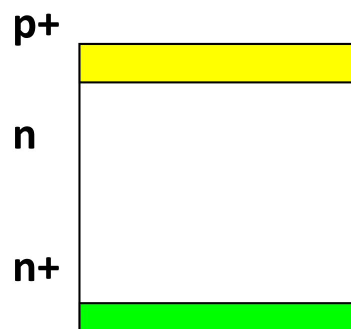


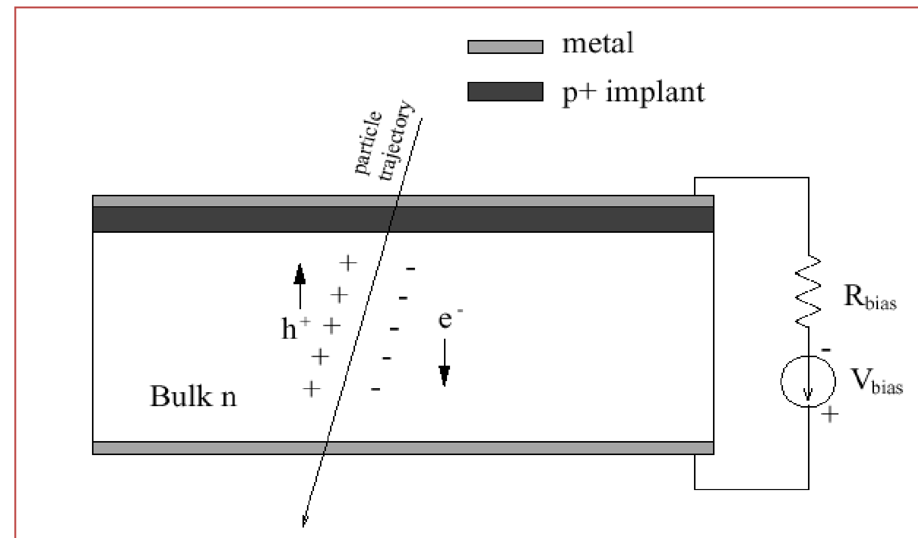
- **Radiation hardness requirements (including safety factor of 2)**
  - **2×10^{16} n_{eq}/cm^2 for the innermost pixel layers**
  - **1×10^{15} n_{eq}/cm^2 for the innermost strip layers**

[M.Moll]

Silicon Detector: Working Principles

- **Standard Si Detectors are p^+- n diodes made on high resistivity silicon:**
- **Float Zone silicon (FZ)**
- **n-type: 2…20 KΩcm**
- **[P] = 20…2×10^{11} cm^{-3} (very low concentration !! below 1ppba = $5\times10^{13}cm^{-3}$)**
- **[O] ≈ several $10^{15}cm^{-3}$**
- **[C] ≈ some $10^{15}cm^{-3}$, usually [C] < [O]**
- **crystal orientation: <111> or <100>**



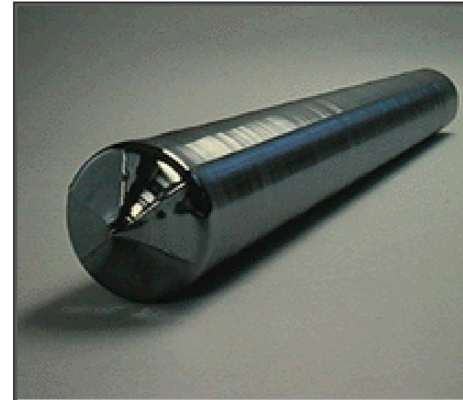


Material: Float Zone Silicon (FZ)

Float Zone process

- Using a single Si crystal seed, melt the vertically oriented rod onto the seed using RF power and "pull" the monocrystalline ingot

Mono-crystalline Ingot



Wafer production

- Slicing, lapping, etching, polishing

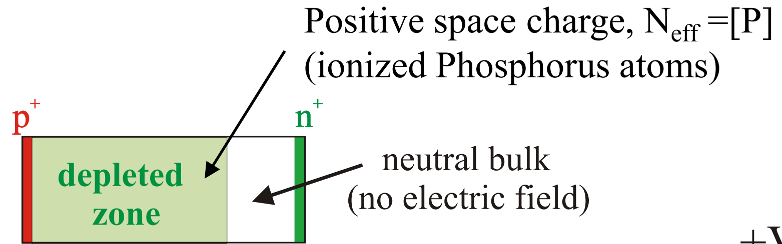
Highly pure crystal

- Low concentration of [O] and [C] $10^{15}cm^{-3}$

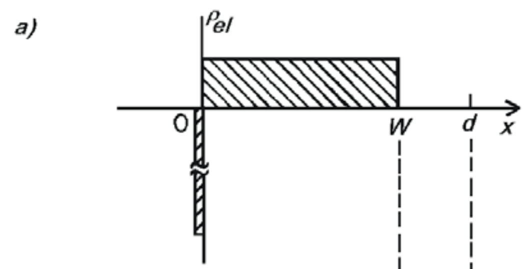
Reminder: Reverse biased abrupt p+-n junction

Poisson's equation

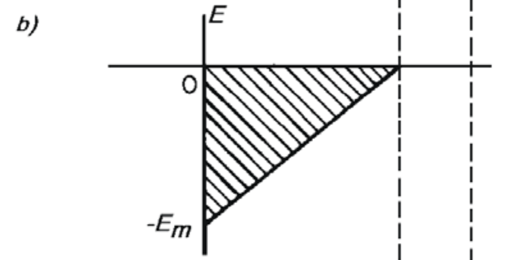
$$-\frac{d^2}{dx^2}\phi(x) = \frac{q_0}{\varepsilon\varepsilon_0}\cdot N_{eff}$$



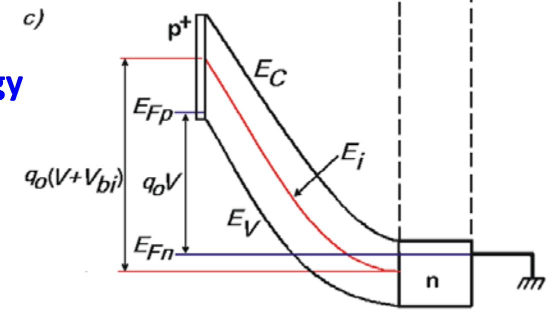
Electrical charge density

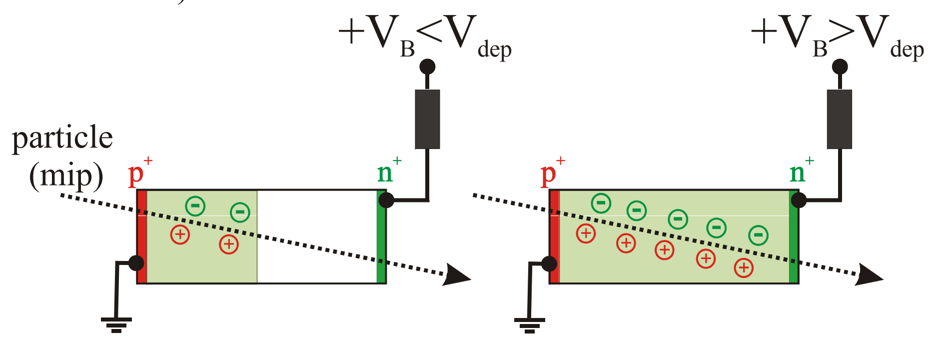


Electrical field strength



Electron potential energy





Full charge collection only for $V_B > V_{dep}$!

depletion voltage

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

effective space charge density

Relevant parameters of the detector based on a p-n junction

Leakage Current

$$J_{rev} = \frac{1}{2} q \frac{n_i}{\tau_0} W \alpha \sqrt{V_{rev}}$$

Capacitance

$$C = \frac{\varepsilon \cdot Area}{d}$$

Depletion thickness

$$d = \sqrt{\frac{2\varepsilon}{qN_{eff}}(V_{rev} + V_{built-in})}$$

Effective space charge concentration in depleted region

$$N_{eff} = \frac{2 \cdot \varepsilon \cdot V_{dep}}{q \cdot W^2}$$

Radiation Tolerant Silicon Detectors, Mara Bruzzi, Gianluigi Casse, EDIT School, February 2011

The charge signal

Collected Charge for a Minimum Ionizing Particle (MIP)

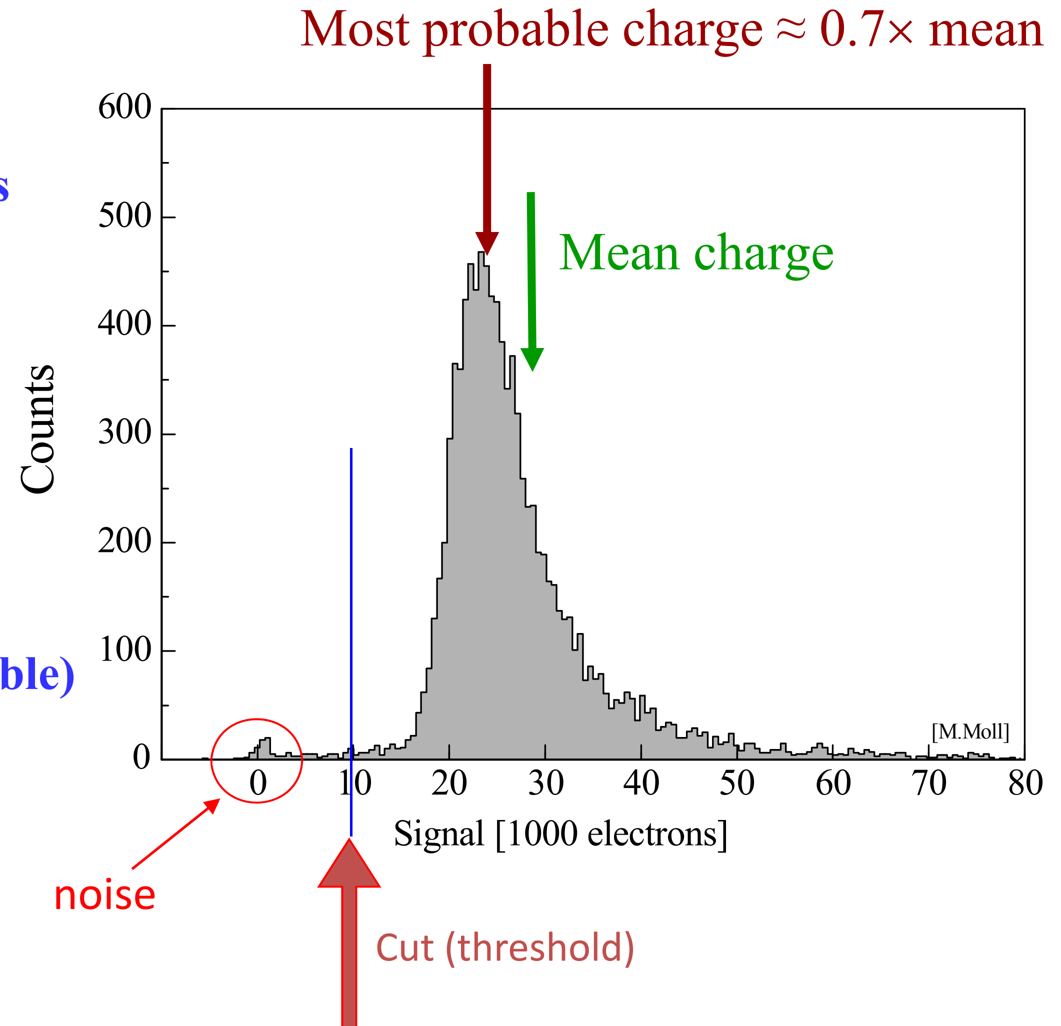
- **Mean energy loss**
  dE/dx (Si) = 3.88 MeV/cm
  ⇒ 116 keV for 300μm thickness

- **Most probable energy loss**
  ≈ 0.7 ×mean
  ⇒ 81 keV

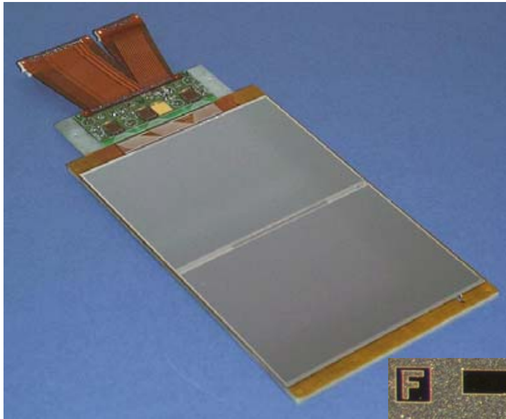
- **3.6 eV to create an e-h pair**
  ⇒ 72 e-h / μm (mean)
  ⇒ 108 e-h / μm (most probable)

- **Most probable charge (300 μm)**

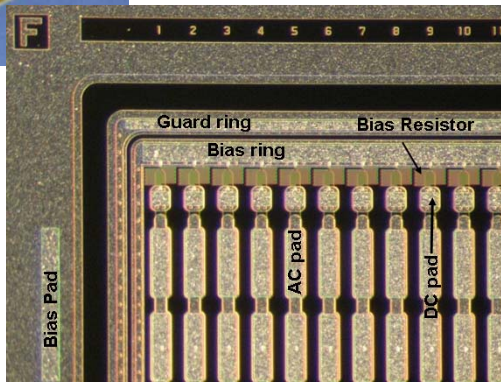
  ≈ 22500 e ≈ 3.6 fC

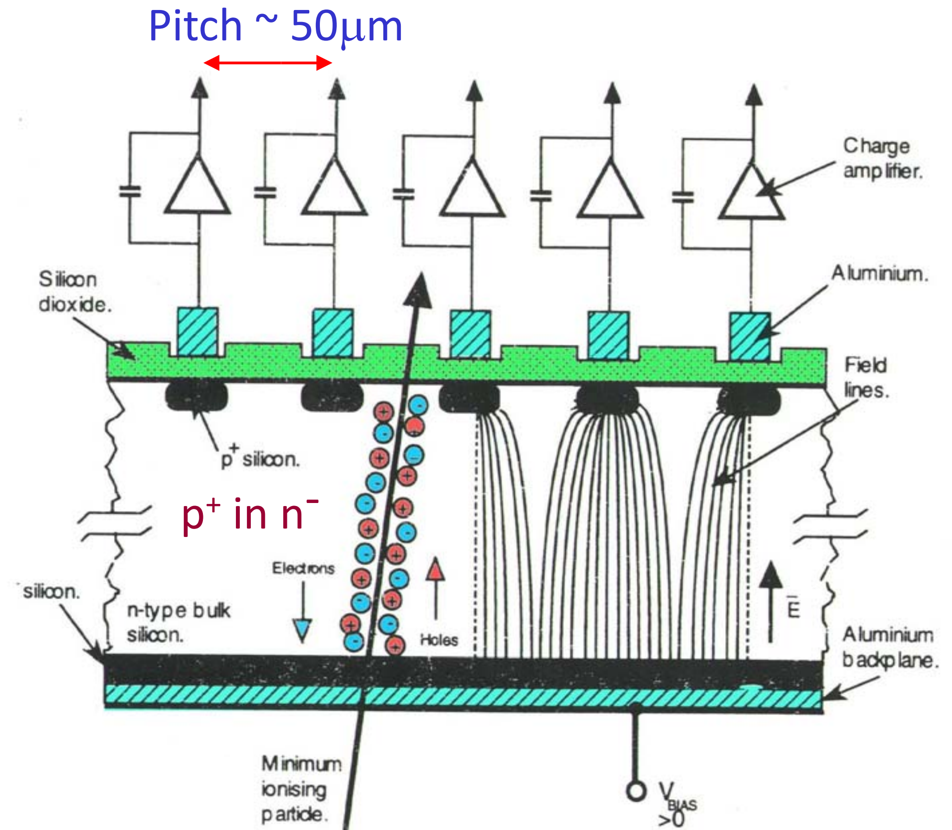


Micro-strip Silicon Detectors



Highly segmented silicon detectors have been used in Particle Physics experiments for nearly 30 years. They are favourite choice for Tracker and Vertex detectors (high resolution, speed, low mass, relatively low cost)

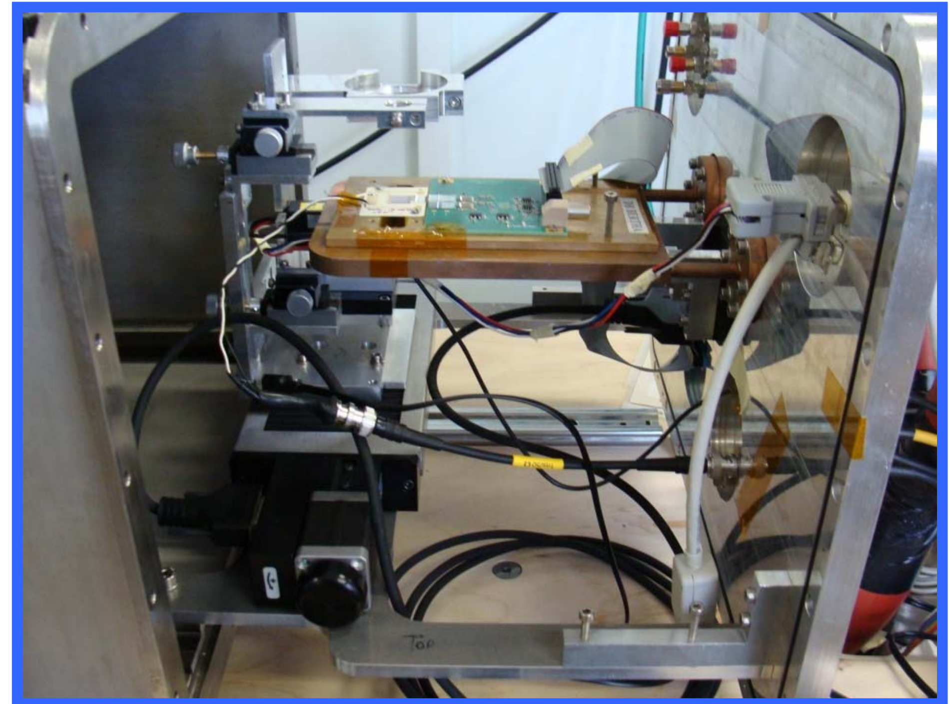




Main application: detect the passage of ionising radiation with high <u>spatial</u> resolution and good efficiency.
Segmentation → position

The CERN CCE experimental system (strips)

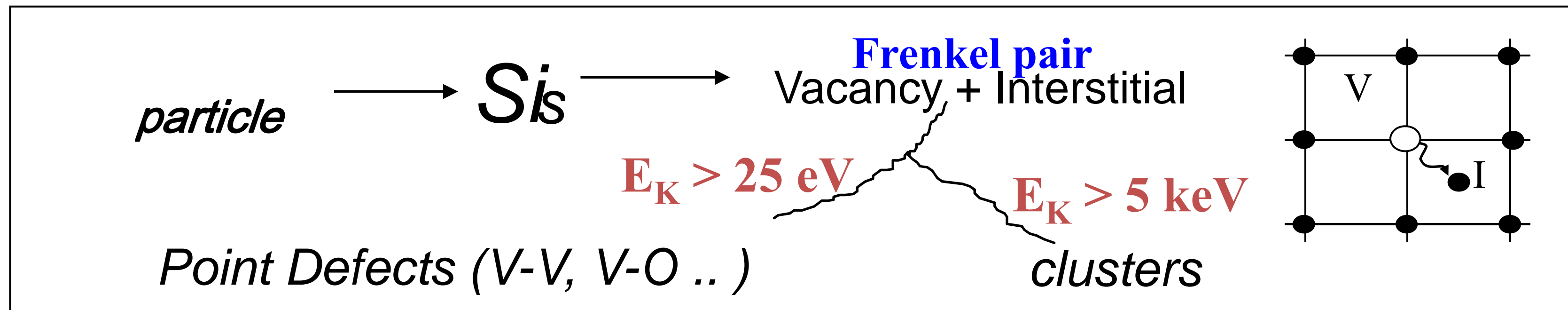
- Alibava based setup
- 3.6 MBq ^{90}Sr source
- - 30±0.5°C temperature (provided with closed circuit silicon-oil cooling) – Presented measurements performed at -20°C
- Single scintillator triggering (collimation provided by small cross section of the scintillator)
- Custom modified version of the Alibava DAQ software (0.1.5) with automatic voltage ramping implemented
- Custom version of the analysis root macros

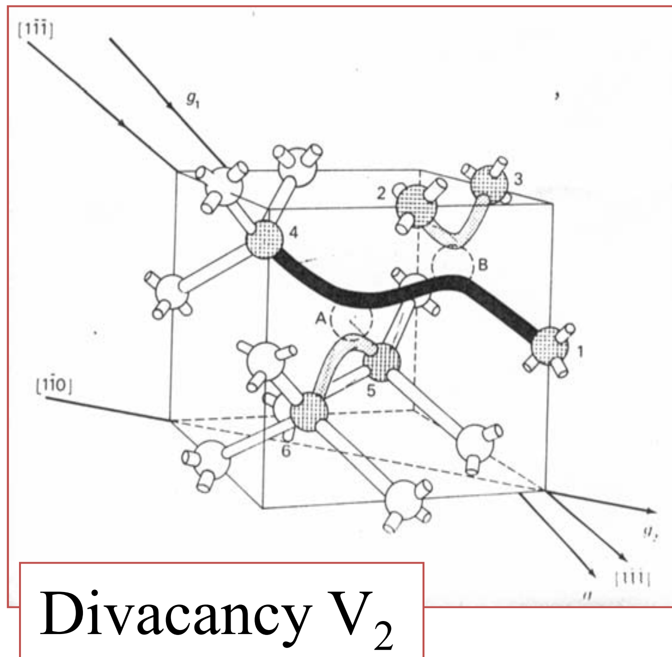


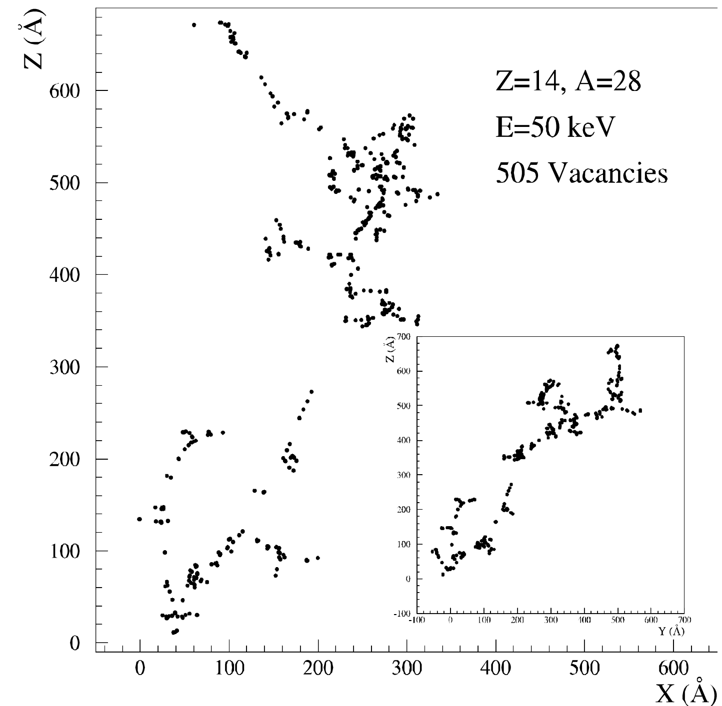
Nicola Pacifico & al. - RESMDD10 Conference – Florence, October 2010

More on Laboratory 3: Hands on Silicon Strip Detectors
by Richard Bates (Glasgow U.) , Irena Dolenc Kittelmann (CERN) , Marco Milanovic

Radiation damage: a microscopic view







Vacancy amount and distribution depends on particle kind and energy

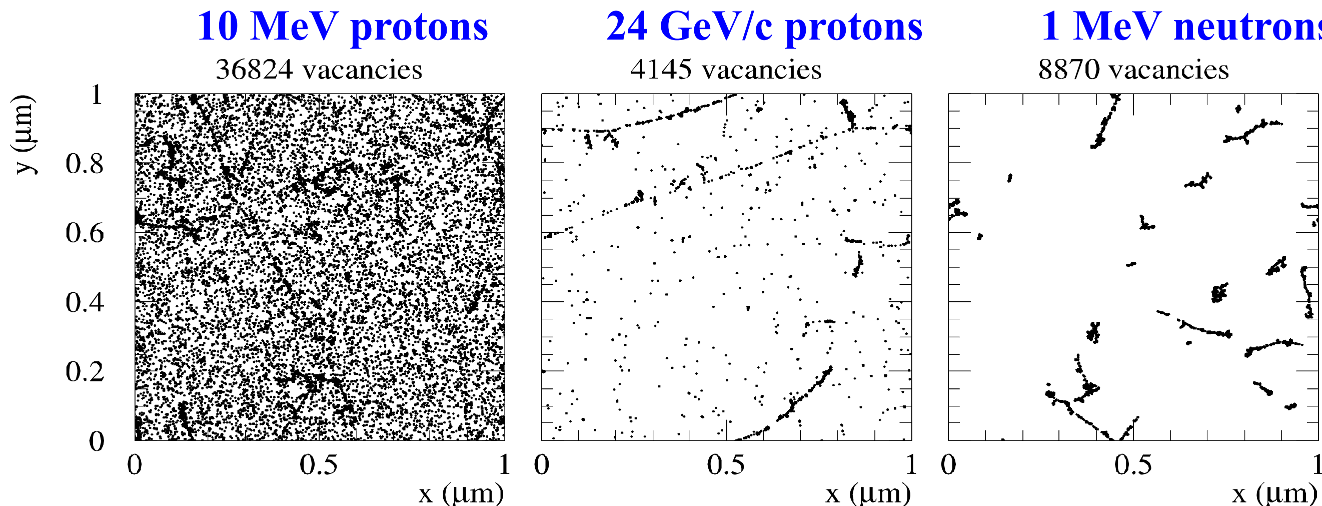
^{60}Co-gammas
- Compton Electrons with max. $E_\gamma \approx 1$ MeV (no cluster production)

Electrons
- E_e > 255 keV for displacement
- E_e > 8 MeV for cluster

Neutrons (elastic scattering)
- E_n > 185 eV for displacement
- E_n > 35 keV for cluster

Only point defects ⟷ point defects & clusters ⟷ Mainly clusters

Initial distribution of vacancies in $(1\mu m)^3$ after 10^{14} particles/cm^2



[Mika Huhtinen NIMA 491(2002) 194]

How to normalize radiation damage from different particles?

- **NIEL - Non Ionizing Energy Loss scaling using hardness factors**

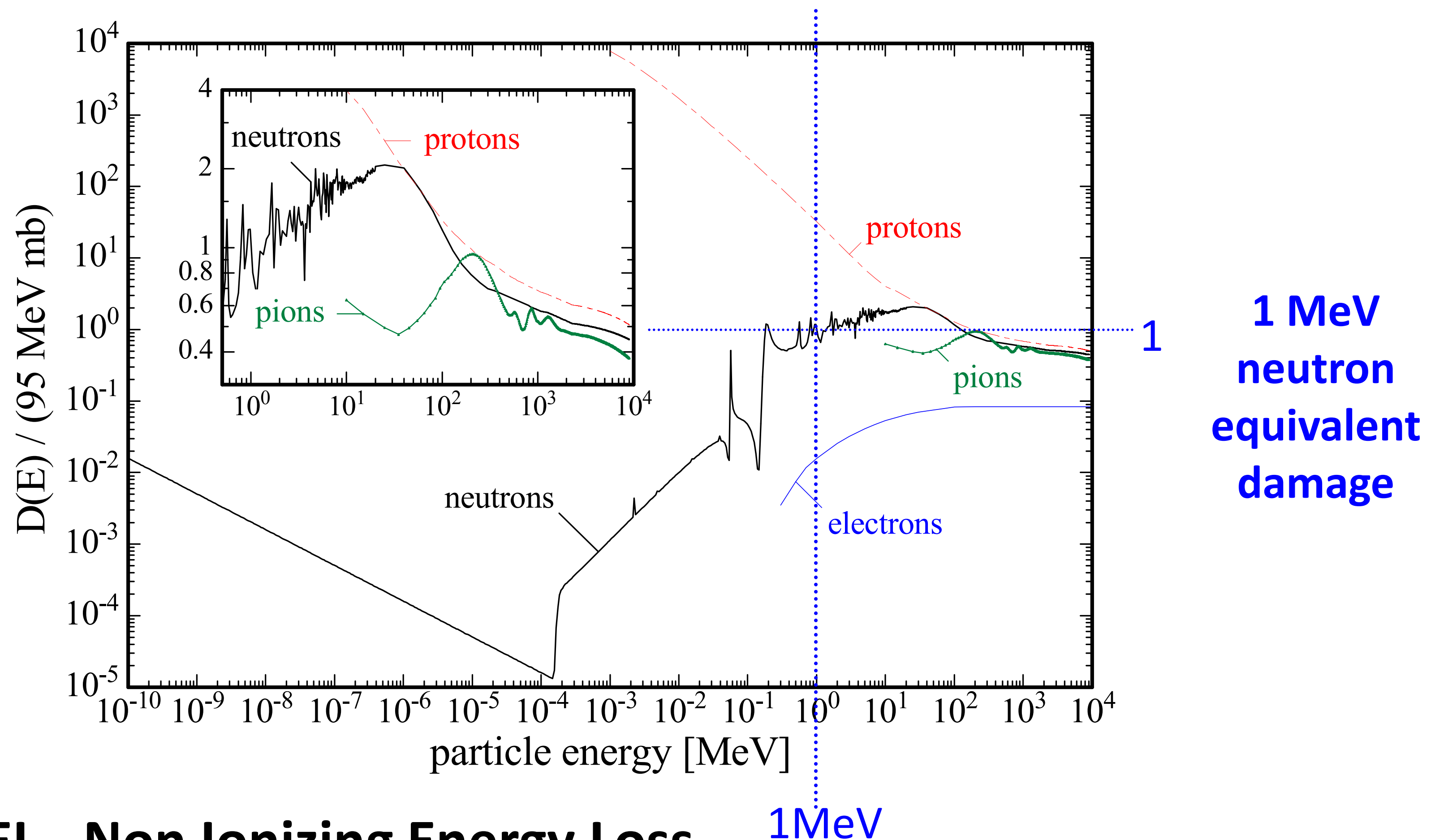
$$\kappa = \frac{1}{D(1MeV\ neutrons)} \bullet \frac{\int D(E)\,\phi(E)\,dE}{\int \phi(E)\,dE}$$

Hardness factor κ of a radiation field (or monoenergetic particle) with respect to 1 MeV neutrons.

- **E** energy of particle
- **D(E)** displacement damage cross section for a certain particle at energy E
  D(1MeV neutrons)=95 MeV·mb
- **ϕ(E)** energy spectrum of radiation field

The integrals are evaluated for the interval $[E_{MIN},E_{MAX}]$, being E_{MIN} and E_{MAX} the minimum and maximum cut-off energy values, respectively, and covering all particle types present in the radiation field

NIEL - Displacement damage functions



- **NIEL - Non Ionizing Energy Loss**
- **NIEL - Hypothesis: Damage parameters scale with the NIEL**
  - ***Be careful, does not hold for all particles & damage parameters (see later)***

Primary Damage and Secondary Defect Formation

- **Two basic defects**

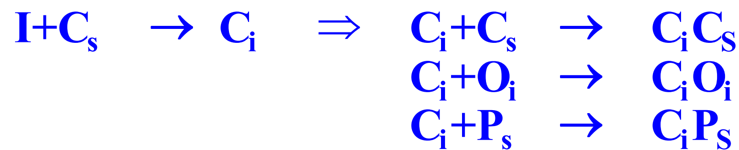
  I - Silicon Interstitial   V - Vacancy

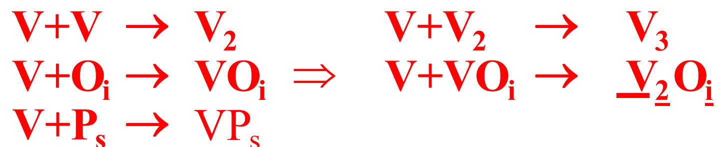
- **Primary defect generation**

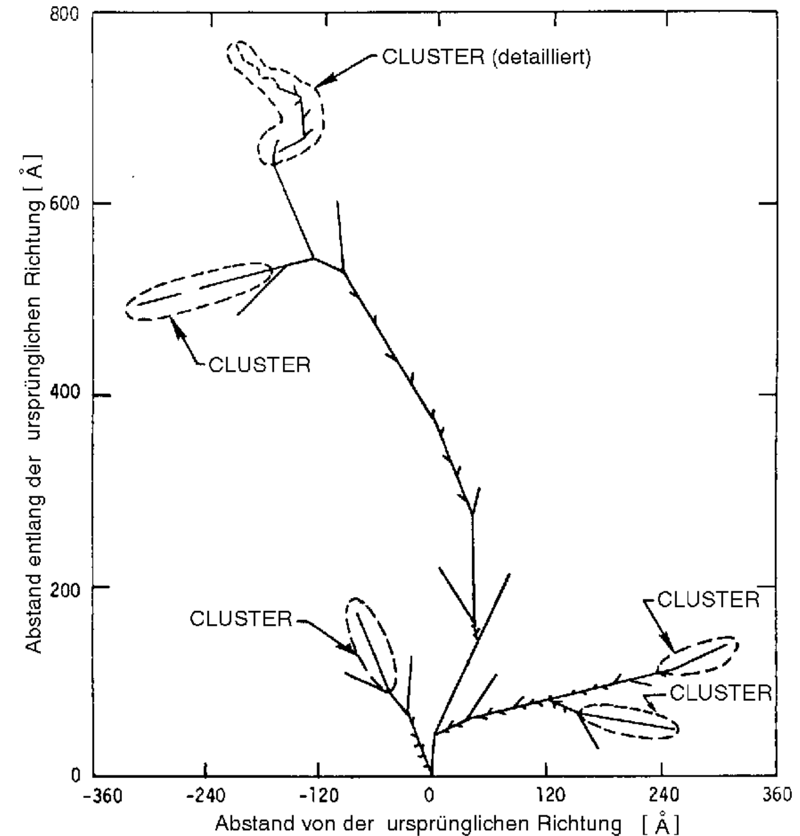
  I, I_2 higher order I (?)
  ⇒ **I** -CLUSTER (?) ⟸
  V, V_2, higher order V (?)
  ⇒ V -CLUSTER (?) ⟸

- **Secondary defect generation**

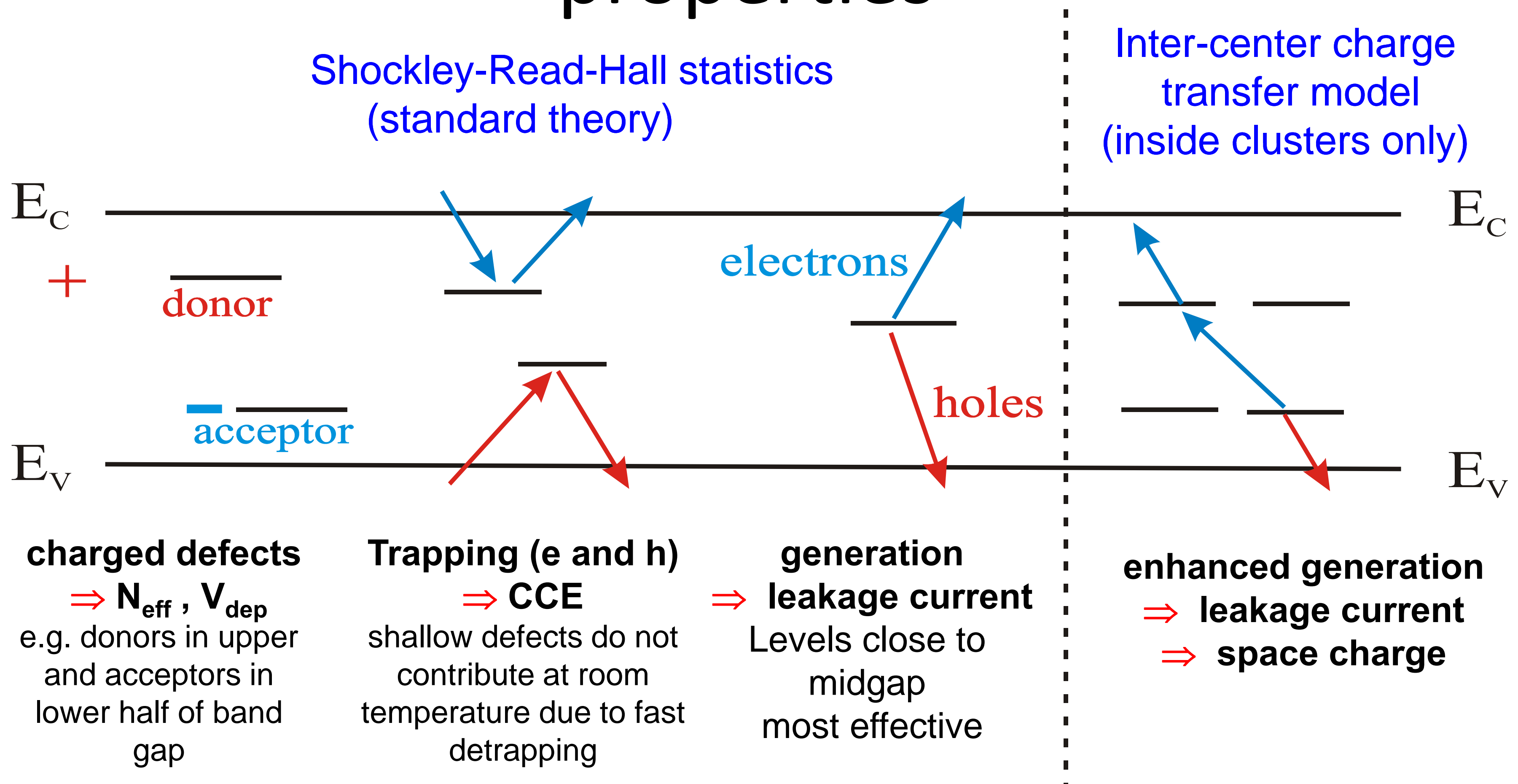
  Dopants : P, B
  Main impurities in silicon: Carbon C_s
  Oxygen O_i
  Oxygen dimer: O_{2i}







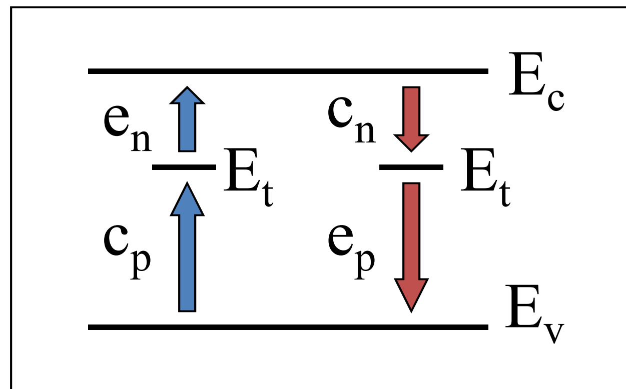
Impact of Defects on Detector properties

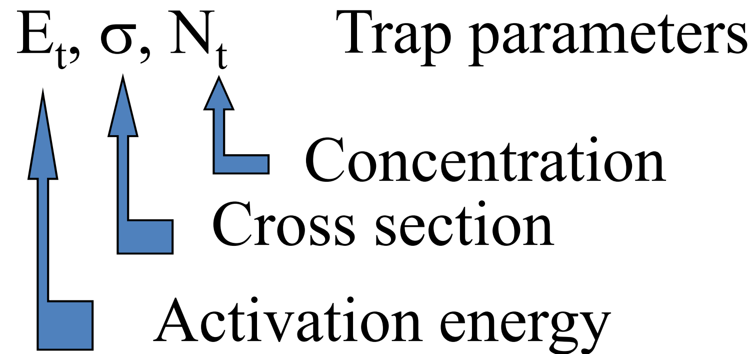


Impact on detector properties can be calculated if all defect parameters are known:

$\sigma_{n,p}$: cross sections **E_t : activation energy** **N_t : concentration**

Experimental techniques to analyise defects in semiconductor materials





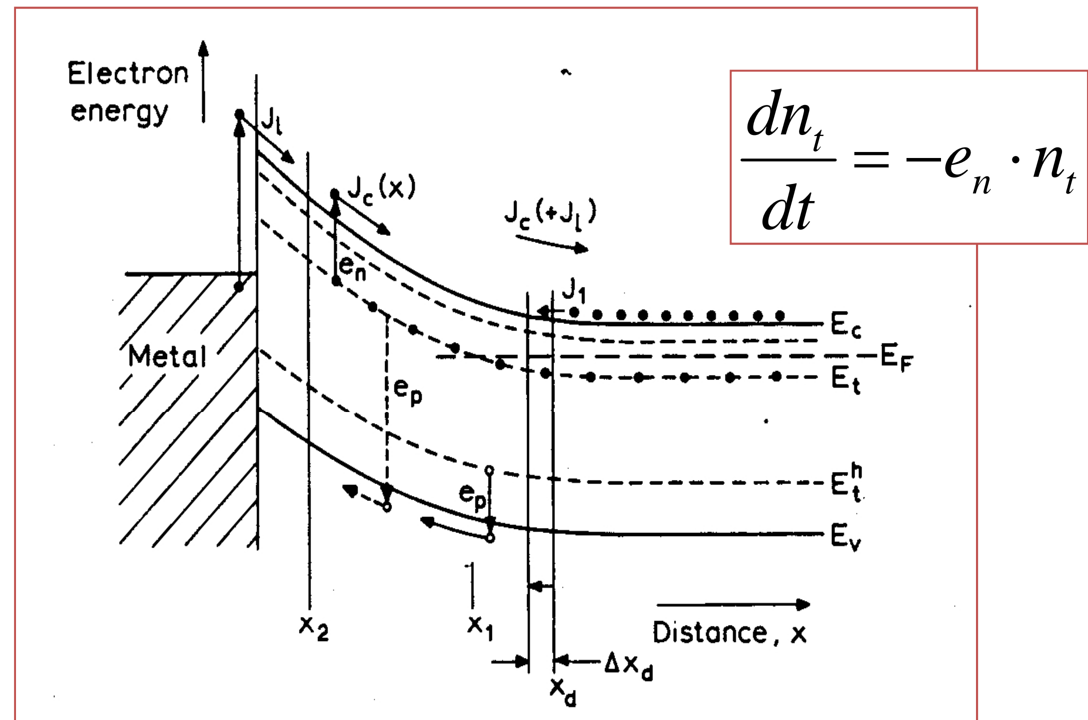
Emission coefficient:

$$e_n = N_c \sigma_n v_{th} \cdot e^{-\frac{E_c - E_t}{KT}}$$

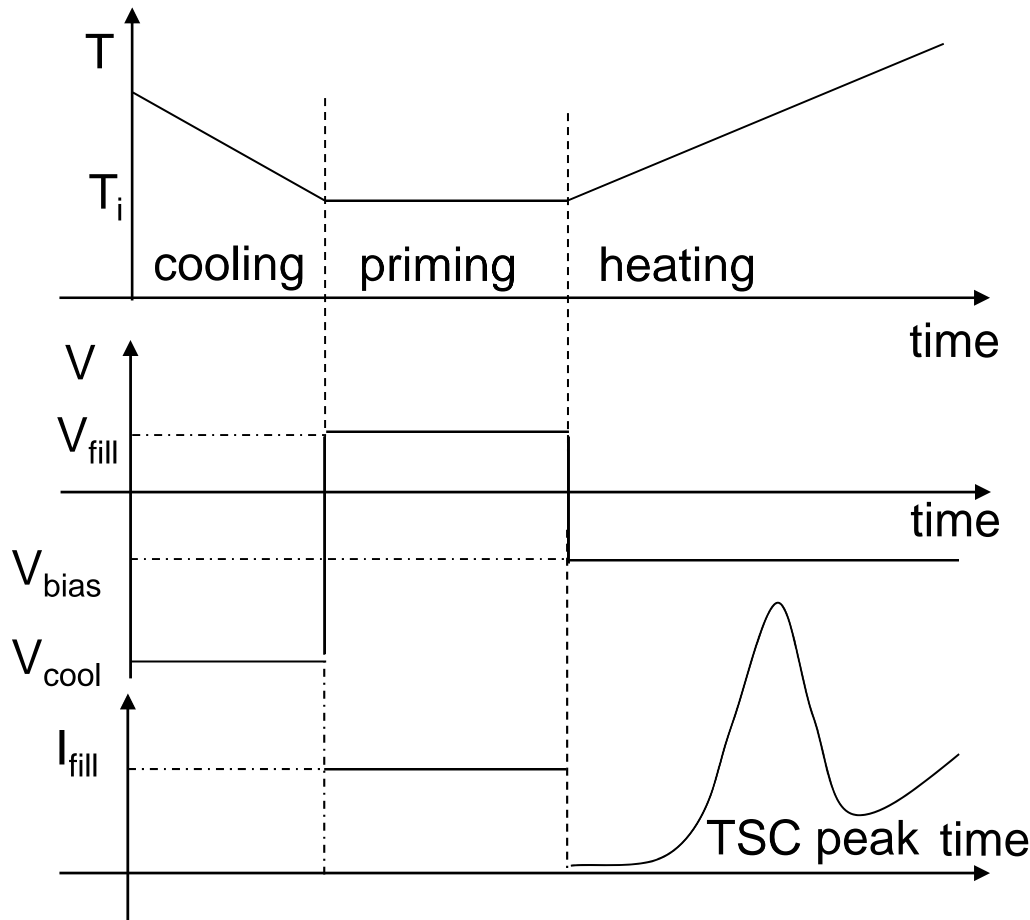
Capture coefficient :

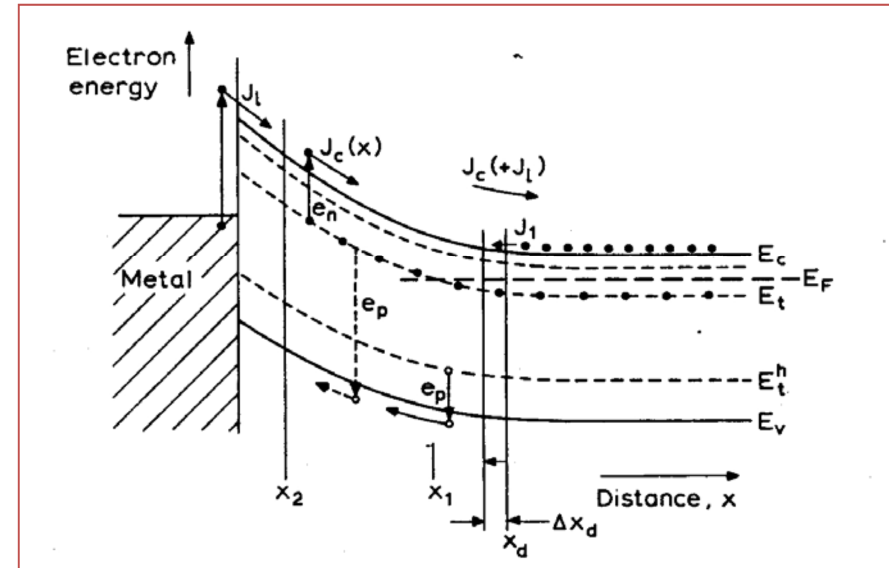
$$c_n = n \sigma_n v_{th}$$

$$\frac{dn_t}{dt} = -e_n \cdot n_t$$



Thermally Stimulated Current: TSC





-Cooling with applied reverse V_{cool} or null bias

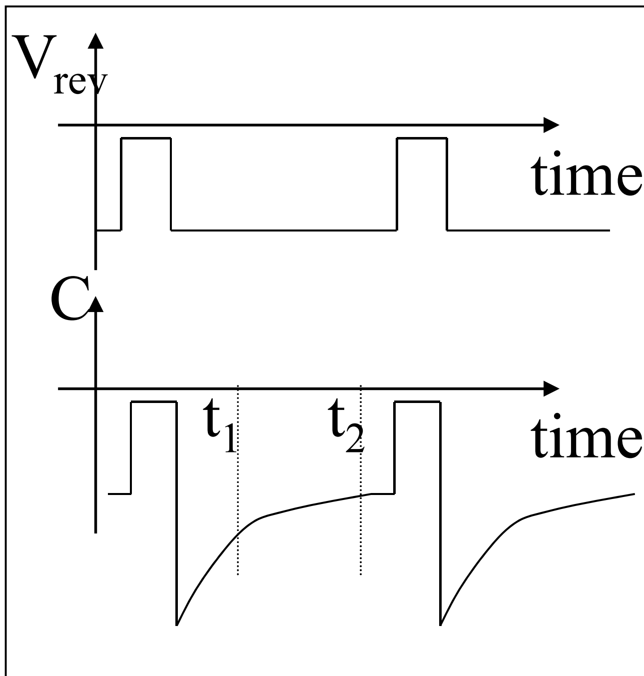
-Forward voltage applied V_{fill} at T_i or illumination with optical source

- V_{bias} applied

-Thermally stimulated current read-out

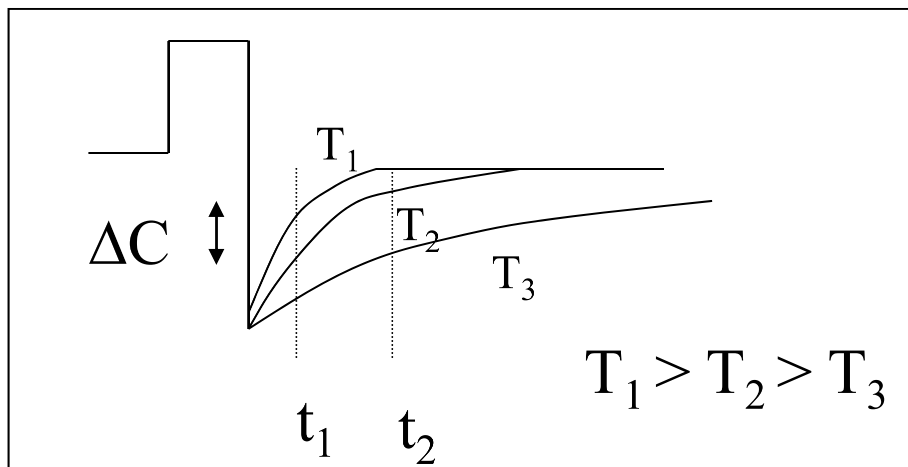
$$I_{TSC}(T) = -\frac{1}{2} q \cdot A \cdot N_t \cdot W \cdot e_n(T) \exp\left(-\frac{1}{b}\int_{Ti}^{T} e_n(T)\,dT\right)$$

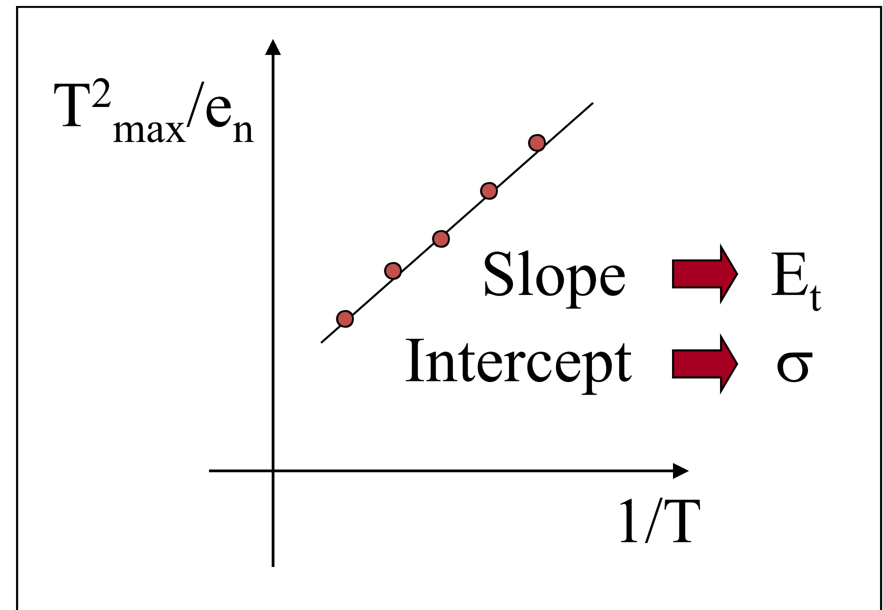
Deep Level Transient Spectroscopy DLTS



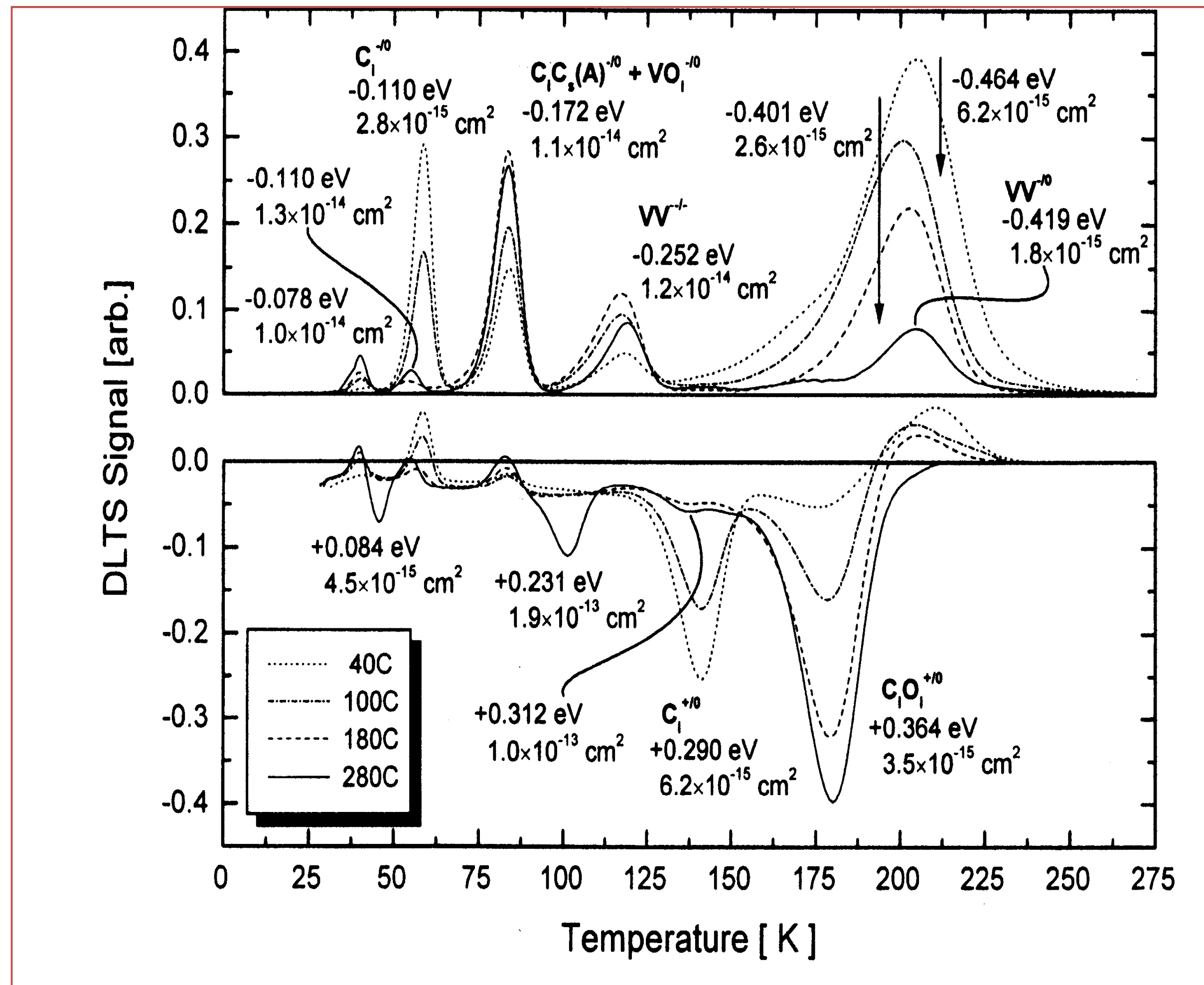
$$S = \Delta C_0 \left(e^{-e_n(T)t_1} - e^{-e_n(T)t_2} \right)$$

$$e_n(T_{max}) = \frac{t_2 - t_1}{\ln(t_2/t_1)} \alpha T_{max}^2 \cdot e^{-E_t/KT_{max}}$$





DLTS more powerful than TSC because <u>can distinguish between acceptor-like and donor-like behaviour of traps</u> BUT can be used <u>only</u> in the low fluence range due to insensitivity of capacitance at high fluence to high frequency signals



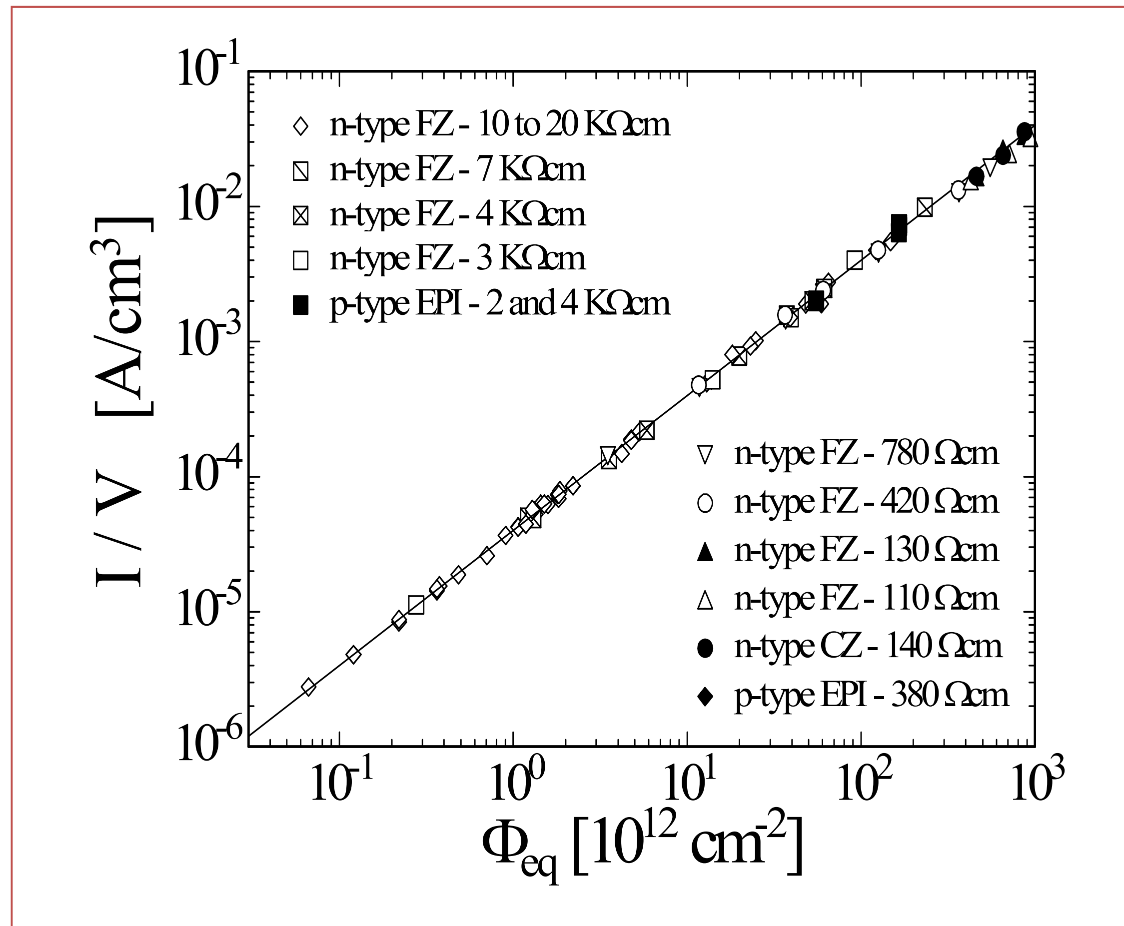
DLTS

f $=10^{11}$ ncm^{-2}

ROSE Coll. NIM A 466 (2001) 308

Radiation Damage: macroscopic parameters

I. Increase of leakage current with the fluence



- **Damage parameter α (slope in figure): Leakage current per unit volume and particle fluence**

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

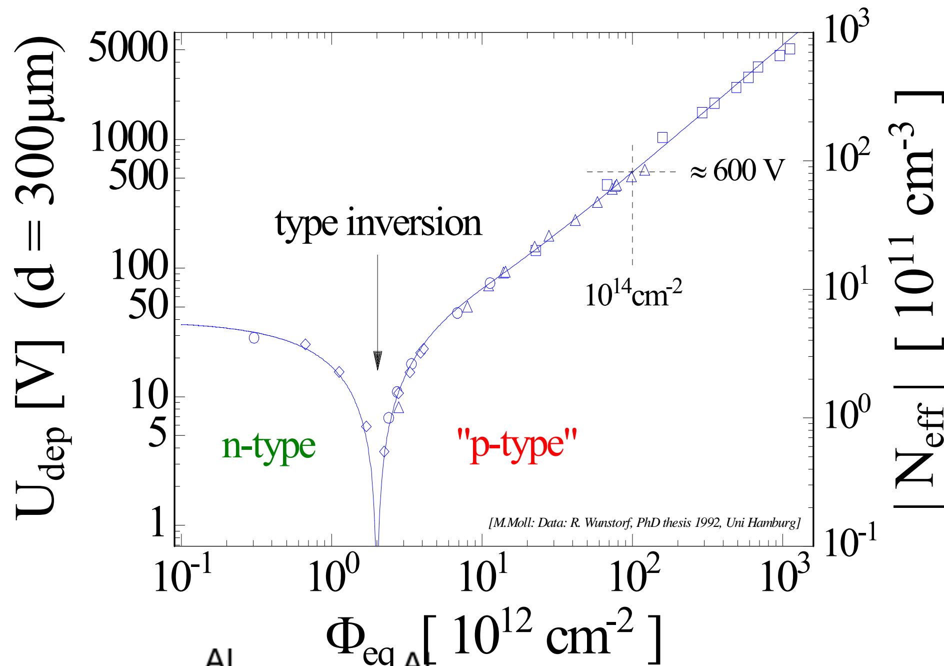
α independent of Φ_{eq} and impurities ⇨ used for fluence calibration (NIEL-Hypothesis)

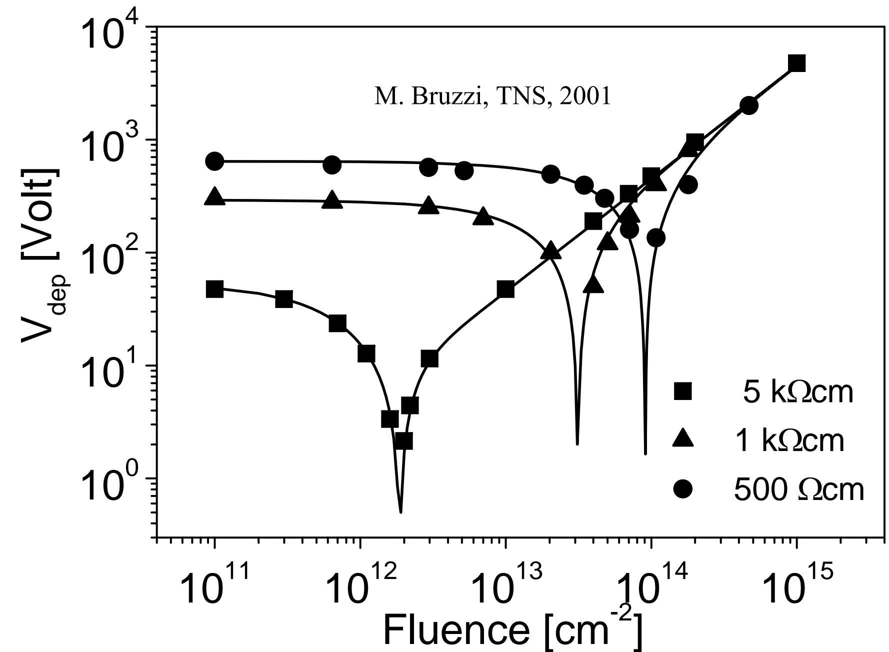
II. Change of V_{fd} and N_{eff} with fluence

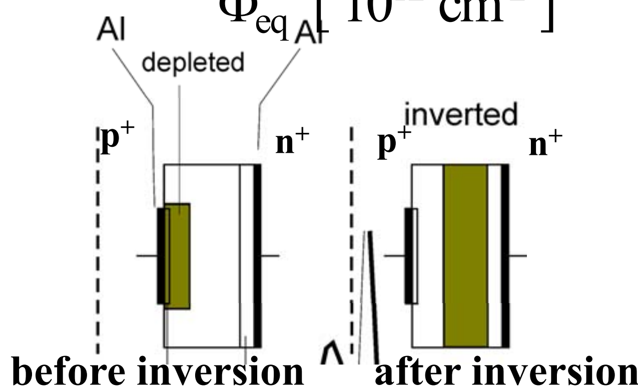
$$\Delta N_{eff}(\Phi) = | N_{C0}(1 - e^{-c\Phi}) - \beta \cdot \Phi |$$

Production of acceptor like defect

Removal of the shallow dopant level

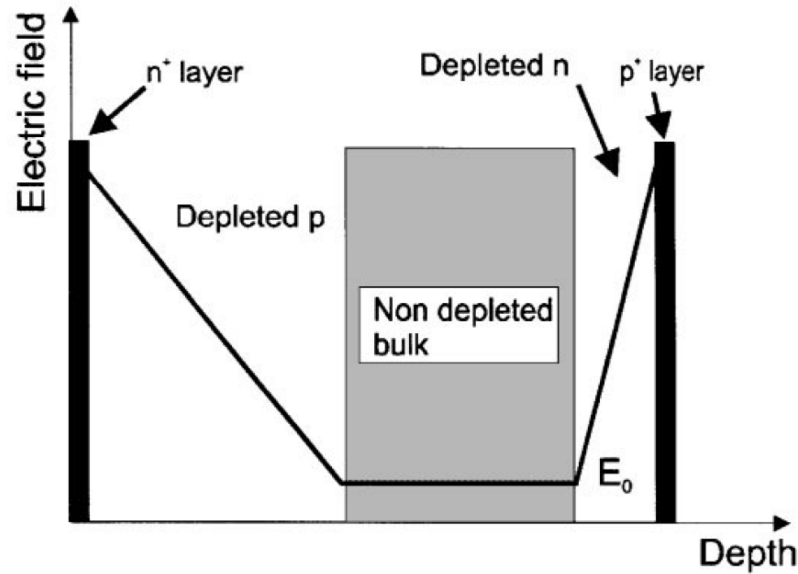






V_{dep} vs. fluence plot indicates an inversion of the Space Change Sign at high fluences

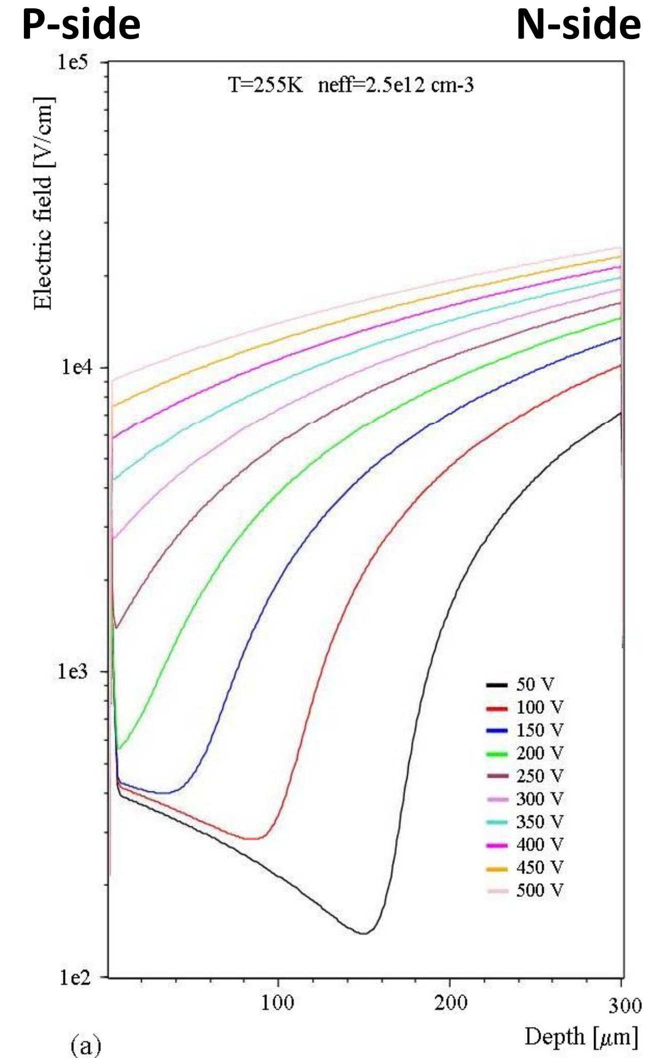
Double Junction



In reality, after irradiation electric fields show a double junction structure with a non-depleted bulk in the middle of the sensor below the full depletion voltage

See G. Casse, et. al., NIMA 426 (1999) 140-146 and G. Kramberger, et. al., NIMA 579 (2007) 762-765 for details

P-side **N-side**

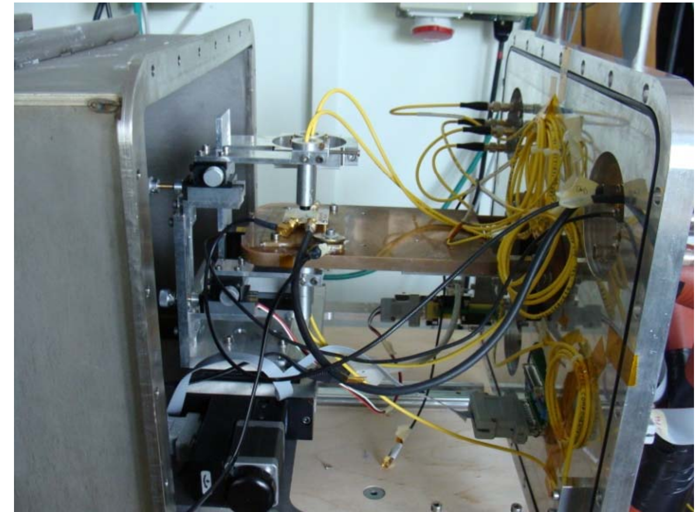


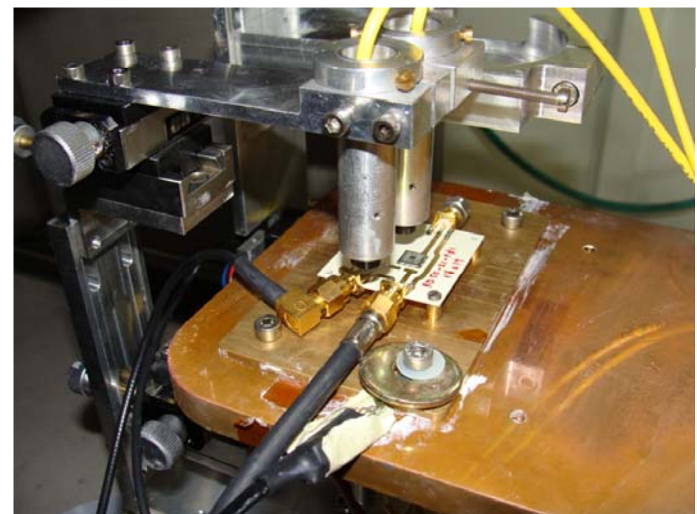
ISE-TCAD simulation after 6. 10^{14} p cm^{-2}

Experimental technique to analyze electric field Transient Current Technique: TCT

- Cooling to -35±0.5 C
- Red (665 nm) and Infrared (1060 nm) laser illumination
- FWHM pulse width 80 ps
- Miteq 1.5 GHz 44 dB low noise amplifier
- Agilent 2.5 GHz oscilloscope
- Detector bonded on thermally conductive PCB
- Front biasing, decoupling with 12 GHz BW Bias-Tee
- Laser delivery system with 4 focusers (front/back, red/IR)
- Humidity controlled: dry air atmosphere with dew point < -50C

More on Laboratory :
Laser induced Signals
By Nicola Pacifico (CERN)
Gregor Kramberger (JSI, Ljubljana)





CERN TCT system

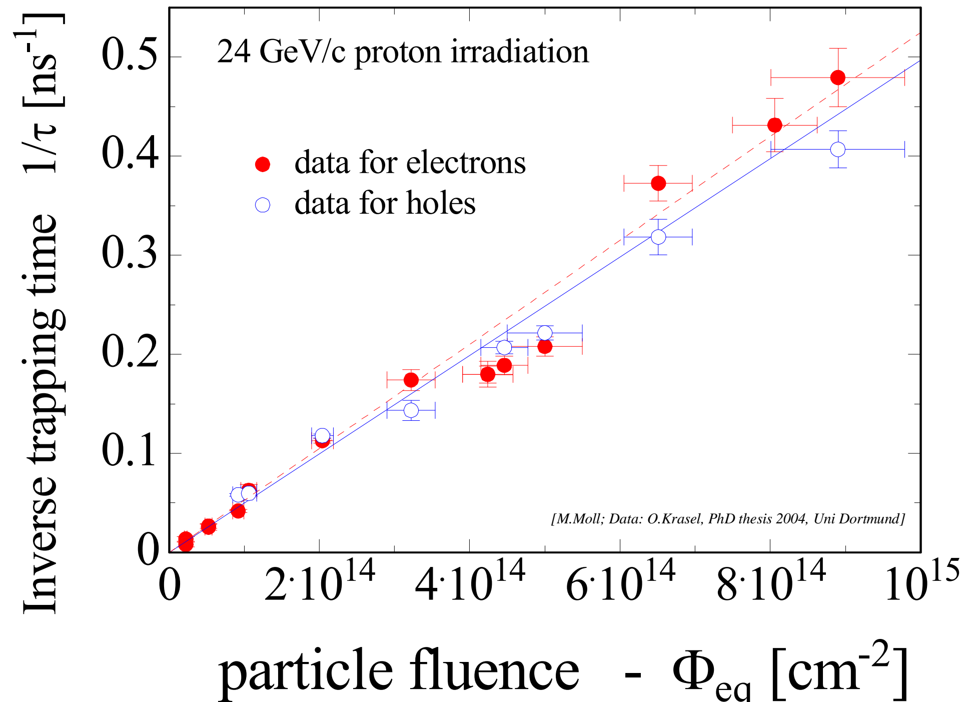
III. Charge Collection Efficiency (CCE) degradation due to trapping

CCE degradation is mainly due to partial depletion and trapping.

Effective trapping time τ_{eff} for electrons and holes:

$$Q_{e,h}(t) = Q_{0e,h} \exp\left(-\frac{1}{\tau_{eff\ e,h}} \cdot t \right) \quad \textbf{where} \quad \frac{1}{\tau_{eff\ e,h}} \propto N_{defects}$$

Increase of inverse trapping time (1/τ) with fluence



Expected signal from charge trapping

Effect of trapping on the Charge Collection Distance:

$Q_{tc} \cong Q_0 \exp(-t_c/\tau_{tr})$, $1/\tau_{tr} = \beta\Phi$.

$v_{sat,e} \times \tau_{tr} = \lambda_{av}$

$\beta_e = 4.2E-16$ cm^{-2}/ns

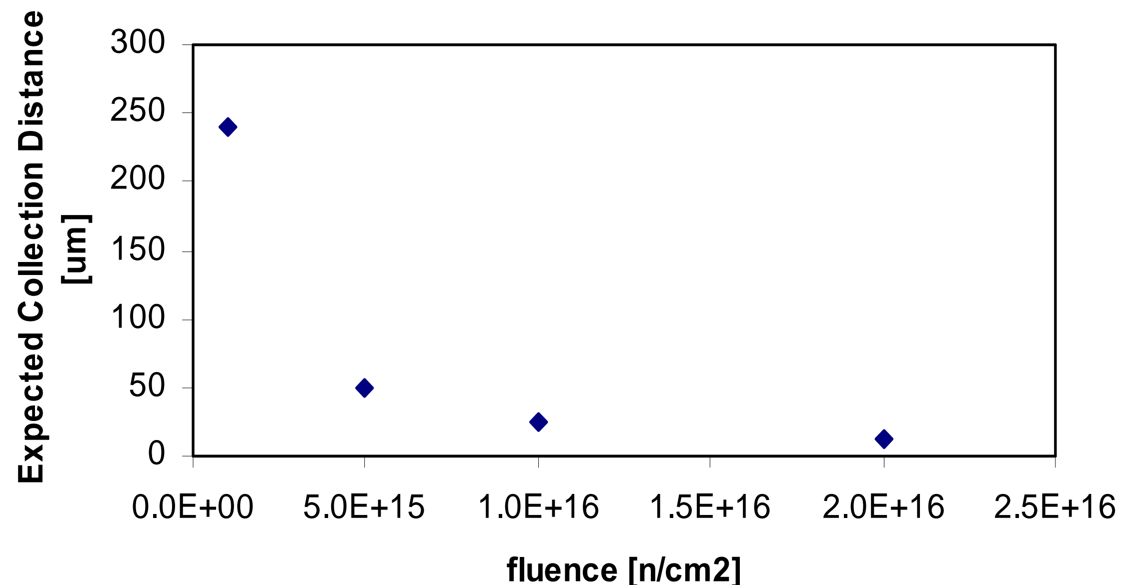
$\beta_h = 6.1E-16$ cm^{-2}/ns

G. Kramberger et al., NIMA 476(2002), 645-651.

Expected collection distance at saturation velocity λ_{av} :

after 1×10^{15} n_{eq} cm^{-2}: 240µm expected charge ~19ke.

λ_{av} after 1×10^{16} n_{eq} cm^{-2}: 25µm expected charge <1.3ke.

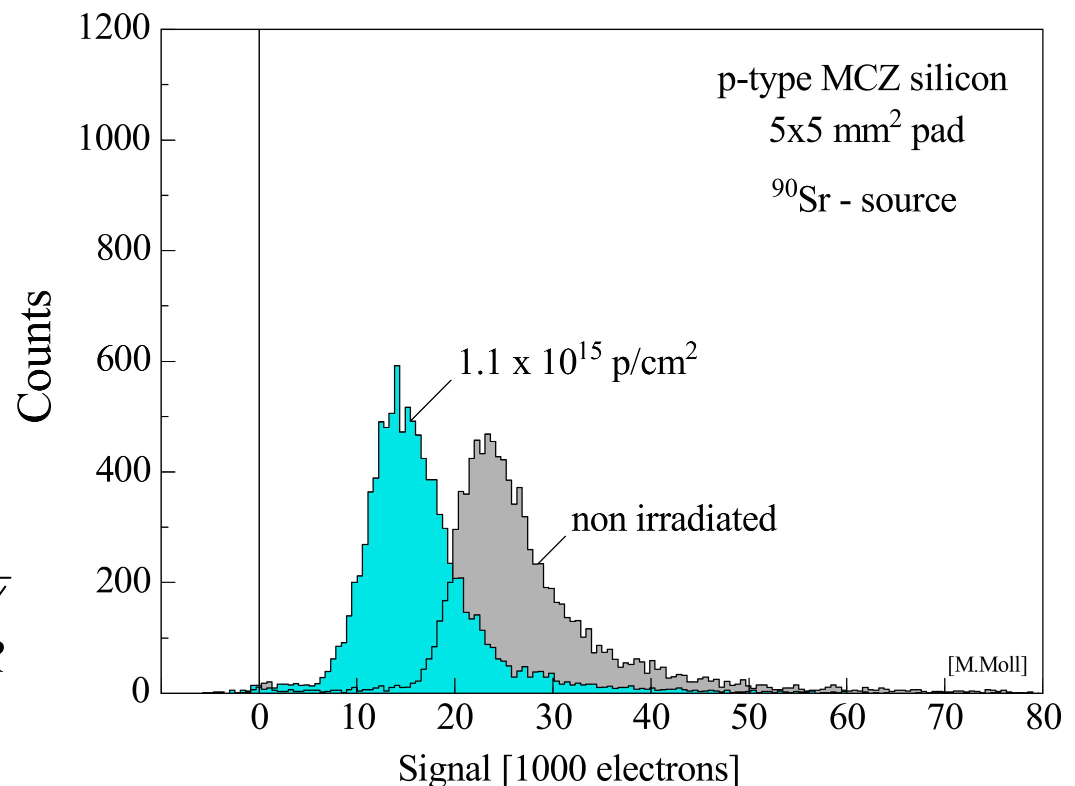


Noise increase with irradiation

Figure of Merit: Signal-to-Noise Ratio S/N. Radiation damage severely degrades the S/N.

Noise sources:

- **Capacitance** $ENC \propto C_d$
- **Leakage Current** $ENC \propto \sqrt{I}$
- **Thermal Noise (bias resistor)** $ENC \propto \sqrt{k_B T / R}$

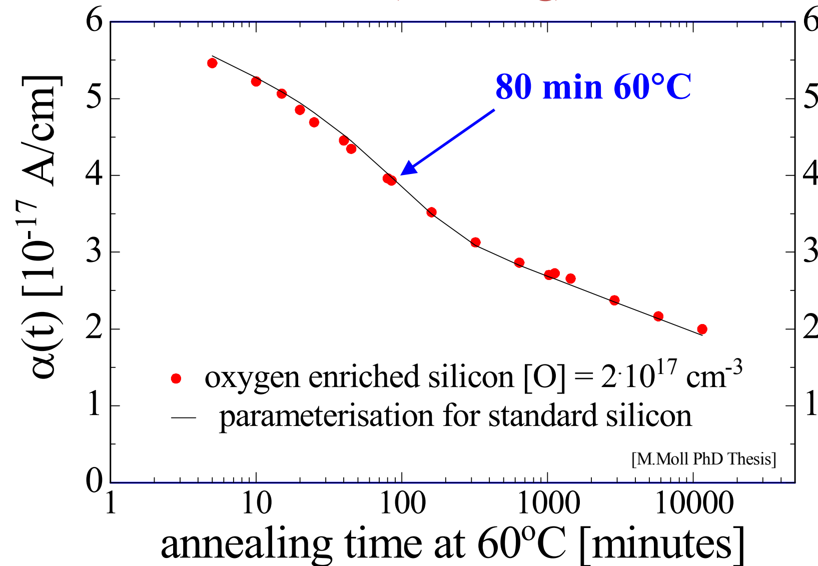


(ENC = Equivalent Noise Charge)

Changes with time and temperature after irradiation (annealing)

- **Leakage Current and N_{eff} (after hadron irradiation)**

…. with time (annealing):



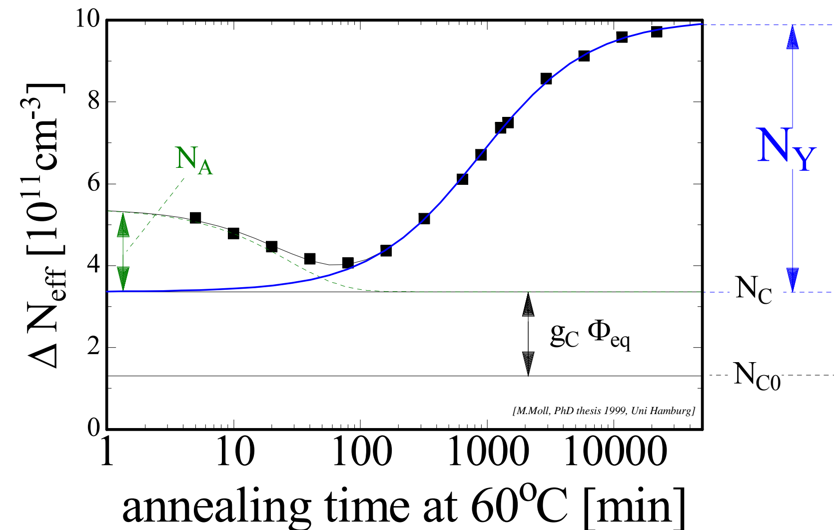
- **Leakage current decreasing in time (depending on temperature)**
- **Strong temperature dependence**

$$I \propto \exp\left(-\frac{E_g}{2k_B T}\right)$$

Consequence:

Cool detectors during operation!
Example: *I*(-10°C) ~1/16 *I*(20°C)

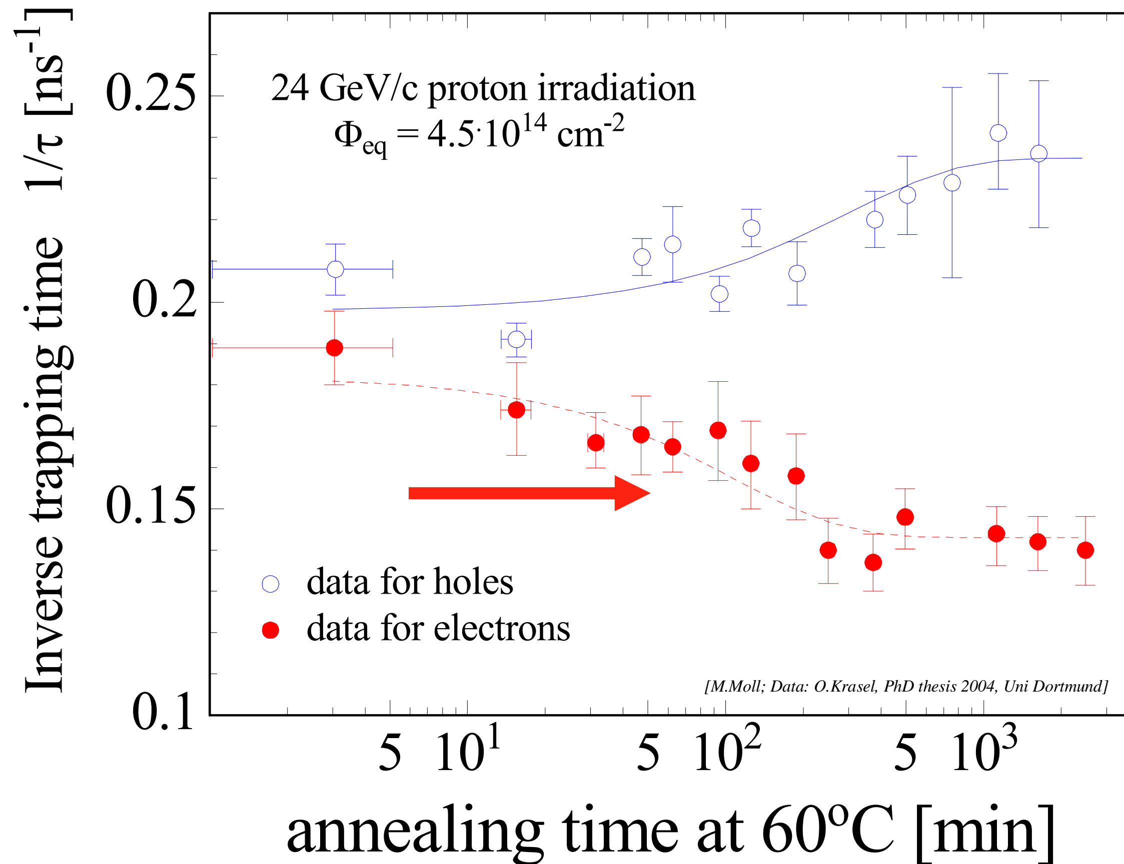
…. with time (annealing):



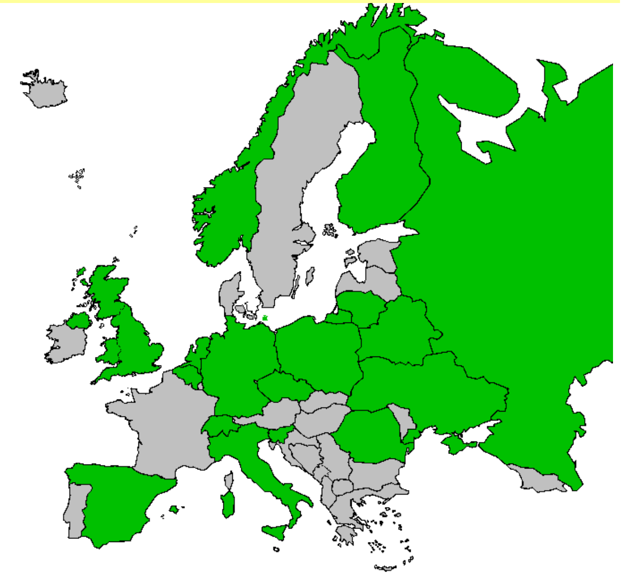
- Short term: "**Beneficial annealing**"
- Long term: "**Reverse annealing**"
  - **time constant depends on temperature:**
    - **~ 500 years (-10°C)**
    - **~ 500 days (20°C)**
    - **~ 21 hours (60°C)**
  - Consequence: **Detectors must be cooled even when the experiment is not running!**

Change of inverse trapping time

Decrease of inverse trapping time ($1/\tau$) with annealing for electrons

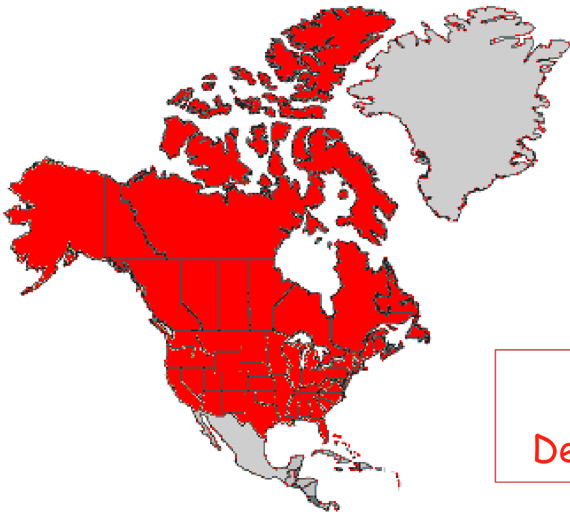


RD50 - Development of Radiation Hard Semiconductor Devices for High Luminosity Colliders



38 European institutes

Belarus (Minsk), Belgium (Louvain), Czech Republic (Prague (3x)), Finland (Helsinki, Lappeenranta), Germany (Dortmund, Erfurt, Freiburg, Hamburg, Karlsruhe, Munich), Italy (Bari, Florence, Padova, Perugia, Pisa, Trento), Lithuania (Vilnius), Netherlands (NIKHEF), Norway (Oslo (2x)), Poland (Warsaw(2x)), Romania (Bucharest (2x)), Russia (Moscow, St.Petersburg), Slovenia (Ljubljana), Spain (Barcelona, Valencia), Switzerland (CERN, PSI), Ukraine (Kiev), United Kingdom (Glasgow, Lancaster, Liverpool)



8 North-American institutes

nada (Montreal), USA (BNL, Fermilab, New Mexico, Purdue, Rochester, Santa Cruz, Syracuse)

1 Middle East institute

Israel (Tel Aviv)

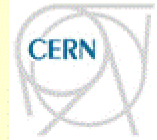
257 Members from 47 Institutes

Detailed member list: http://cern.ch/rd50

RD50

Scientific Organization of RD50

Development of Radiation Hard Semiconductor Devices for High Luminosity Colliders



Co-Spokespersons

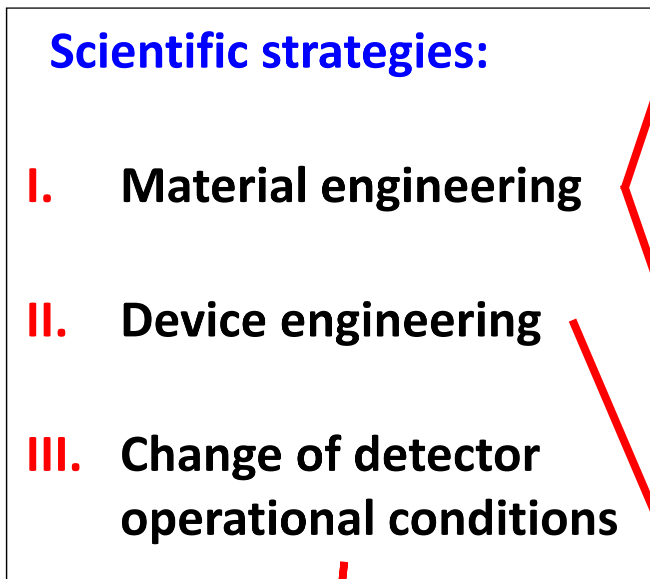
Gianluigi Casse and *Michael Moll*

University of Liverpool — CERN PH-DT

Defect / Material Characterization *Mara Bruzzi* (INFN and Uni Florence)	Defect Engineering *Eckhart Fretwurst* (Hamburg University)	Pad Detector Characterization *Gregor Kramberger* (Ljubljana University)	New Structures *Richard Bates* (Glasgow University)	Full Detector Systems *Gianluigi Casse* (Liverpool University)
Characterization of microscopic properties of standard-, defect engineered and new materials pre- and post-irradiation ▪ Wodean – Workshop on Defect Analysis in Silicon Detectors (G.Lindstroem)	Development and testing of defect engineered silicon: - Epitaxial Silicon - High res. CZ, MCZ - Other impurities H, N, Ge, … - Thermal donors - Pre-irradiation ▪ Wafer procurement (M.Moll)	▪Test structure characterization IV, CV, CCE ▪NIEL ▪Device modeling ▪Operational conditions ▪Common irradiations ▪Standardisation of measurements (A.Chilingarov) ▪ New Materials (E. Verbitskaya)	▪3D detectors ▪Thin detectors ▪Cost effective solutions ▪3D (R.Bates) ▪Semi 3D (Z.Li) ▪Thinned detectors (M.Boscardin)	▪LHC-like tests ▪Links to HEP ▪Links to R&D of electronics ▪Comparison: pad-mini-full detectors ▪Comparison of detectors made by different producers

CERN contact: Michael Moll

Approaches to develop radiation harder solid state tracking detectors



CERN-RD39
"Cryogenic Tracking Detectors"
operation at 100-200K
to reduce charge loss

- **Defect Engineering of Silicon**

  Deliberate incorporation of impurities or defects into the silicon bulk to improve radiation tolerance of detectors

  - **Needs:** Profound understanding of radiation damage
    - microscopic defects, macroscopic parameters
    - dependence on particle type and energy
    - defect formation kinetics and annealing
  - **Examples:**
    - Oxygen rich Silicon (DOFZ, Cz, MCZ, EPI)
    - Oxygen dimer & hydrogen enriched Si
    - Pre-irradiated Si
    - Influence of processing technology

- **New Materials**
  - Silicon Carbide (SiC), Gallium Nitride (GaN)
  - Diamond (CERN RD42 Collaboration)
  - Amorphous silicon

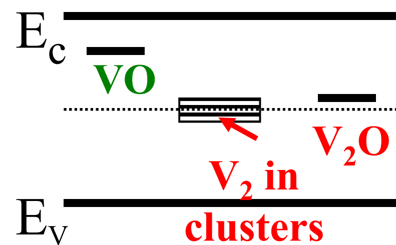
- **Device Engineering (New Detector Designs)**
  - p-type silicon detectors (n-in-p)
  - thin detectors, epitaxial detectors
  - 3D detectors and Semi 3D detectors, Stripixels
  - Cost effective detectors
  - Monolithic devices

Oxygen Enrichment for Radiation Hardening

RD48 (ROSE) and RD50 CERN Collaborations

Main Hypothesis: Oxygen beneficial as sink of vacancies

$V\text{-}O_i$ complex concentration increase → reduction of deeper levels mainly divacancy related



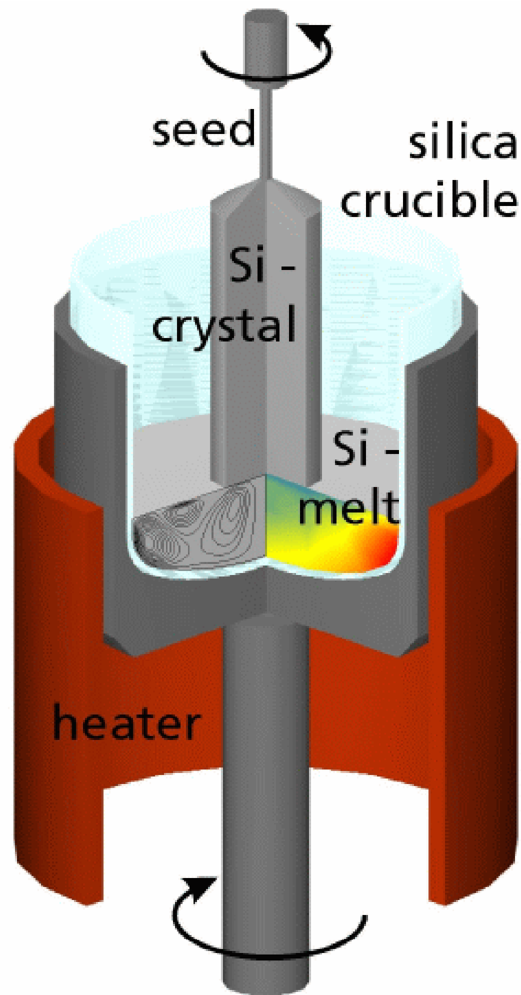
Typical oxygen concentration in Si:

-FZ [Oi] $10^{15}cm^{-3}$
-Diffusion oxygenated FZ : DOFZ [O_i] 10^{16}-$10^{17}cm^{-3}$
-Czochralski Si: [O_i] up to $10^{18}cm^{-3}$

Note: as VO is a point defect the beneficial effect of oxygen is expected especially when cluster formation by irradiation is less important than point defect formation.

Czochralski silicon (Cz) & Epitaxial silicon (EPI)

Czochralski silicon



- Pull Si-crystal from a Si-melt contained in a silica crucible while rotating.
- Silica crucible is dissolving oxygen into the melt ⇨ high concentration of O in CZ
- Material used by IC industry (cheap)
- Recent developments (~5 years) made CZ available in sufficiently high purity (resistivity) to allow for use as particle detector.

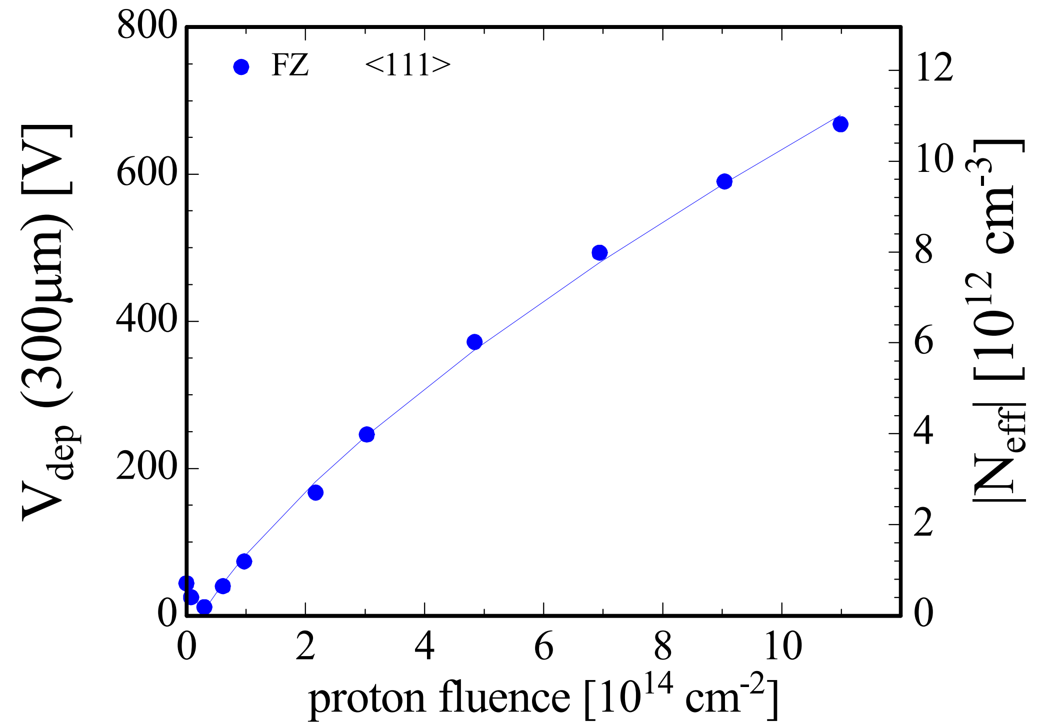
Epitaxial silicon

- Chemical-Vapor Deposition (CVD) of Silicon
- CZ silicon substrate used ⇨ **in-diffusion of oxygen**
- growth rate about 1μm/min
- excellent homogeneity of resistivity
- up to 150 μm thick layers produced (thicker is possible)
- price depending on thickness of epi-layer but not extending ~ 3 x price of FZ wafer

Standard FZ, DOFZ, MCz and Cz silicon

24 GeV/c proton irradiation

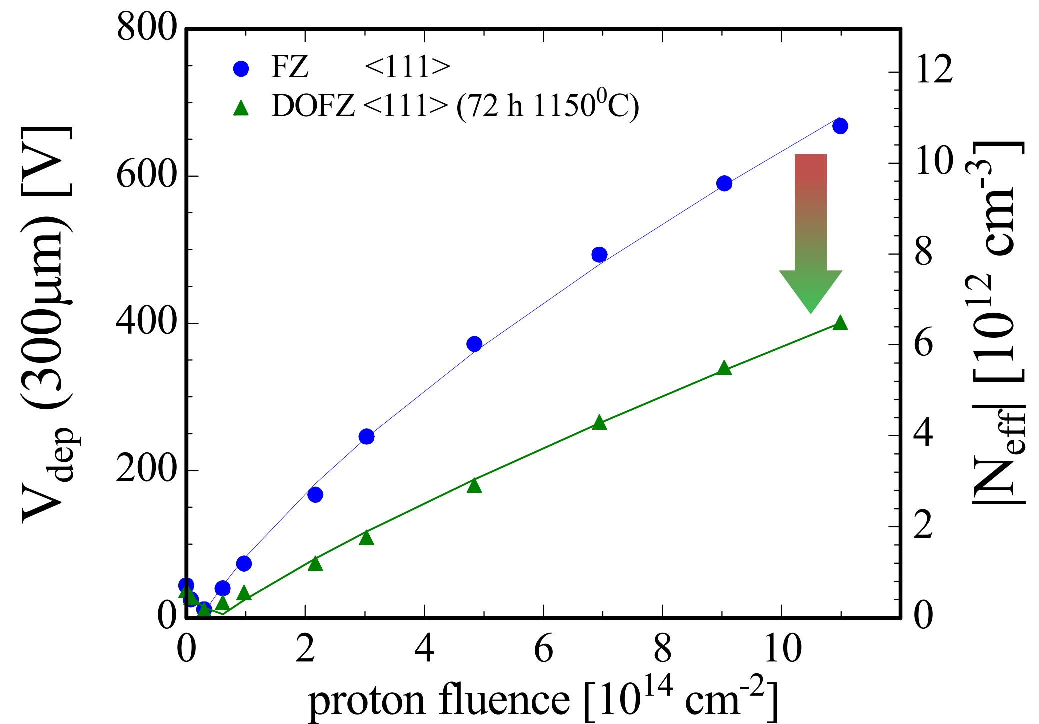
- **Standard FZ silicon**
  - type inversion at ~ 2×10^{13} p/cm^2
  - strong N_{eff} increase at high fluence



Standard FZ, DOFZ, MCz and Cz silicon

24 GeV/c proton irradiation

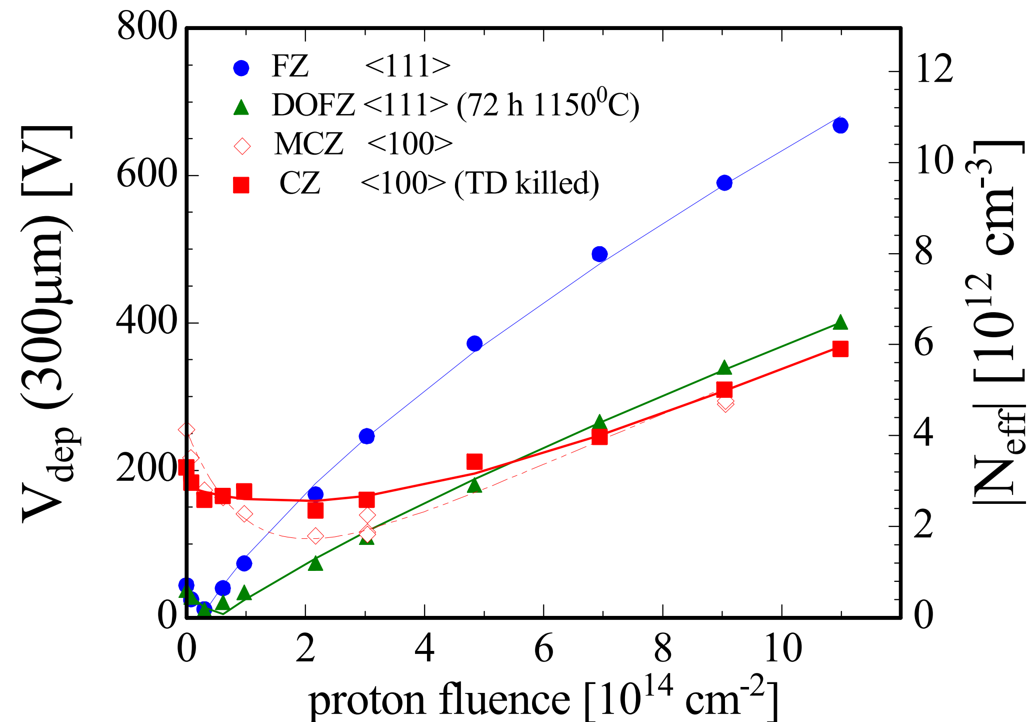
- **Standard FZ silicon**
  - type inversion at ~ 2×10^{13} p/cm^2
  - strong N_{eff} increase at high fluence
- **Oxygenated FZ (DOFZ)**
  - type inversion at ~ 2×10^{13} p/cm^2
  - reduced N_{eff} increase at high fluence



Standard FZ, DOFZ, MCz and Cz silicon

24 GeV/c proton irradiation

- **Standard FZ silicon**
  - type inversion at ~ 2×10^{13} p/cm^2
  - strong N_{eff} increase at high fluence
- **Oxygenated FZ (DOFZ)**
  - type inversion at ~ 2×10^{13} p/cm^2
  - reduced N_{eff} increase at high fluence
- **CZ silicon and MCZ silicon**
  - "no type inversion" in the overall fluence range

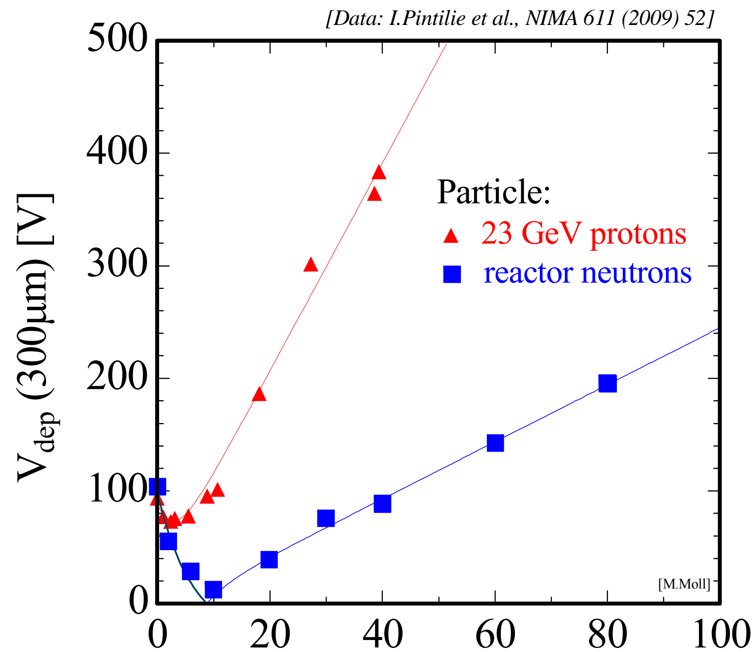


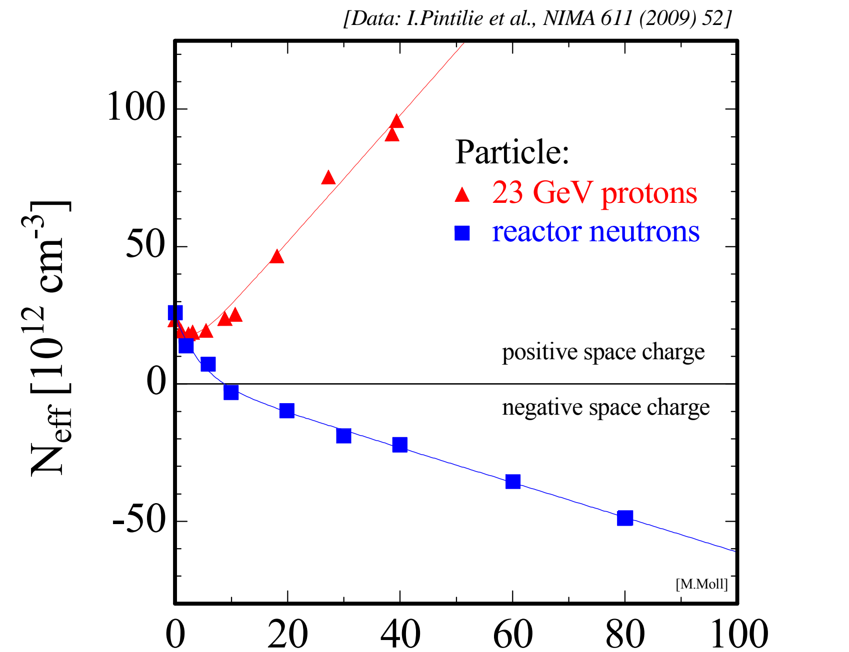
(for experts: there is no "real" type inversion, a more clear understanding of the observed effects is obtained by investigating directly the internal electric field; look for: TCT, MCZ, double junction)

- **Common to all materials** *(after hadron irradiation, not after γ irradiation)*:
  - **reverse current increase**
  - **increase of trapping (electrons and holes) within ~ 20%**

Proton vs. Neutron irradiation of oxygen rich silicon

- Epitaxial silicon *(EPI-DO, 72μm, 170Ωcm, diodes)*
  irradiated with <u>23 GeV protons</u> or <u>reactor neutrons</u>





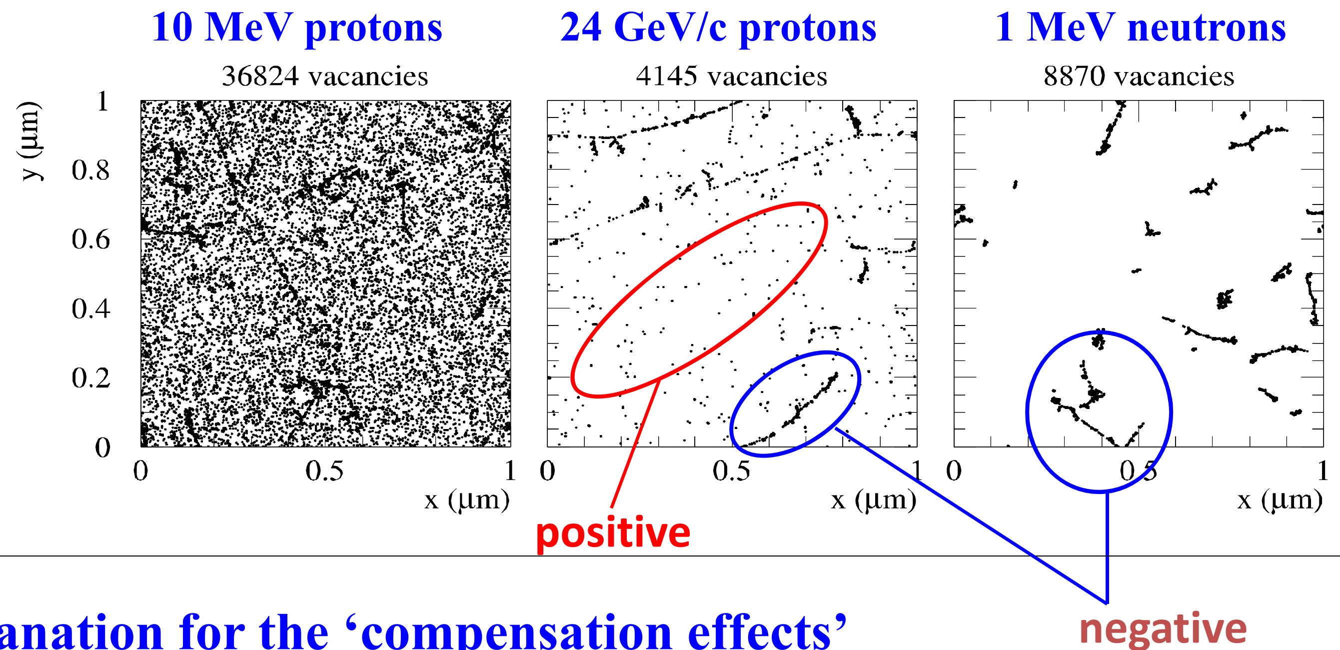
depletion voltage → $$V_{dep} = \frac{q_0}{\varepsilon\varepsilon_0} \cdot |N_{eff}| \cdot d^2$$ ← ***absolute effective space charge density***

Why is proton and neutron damage different?

Simulation:

Initial distribution of vacancies in $(1\mu m)^3$ after 10^{14} particles/cm^2

[Mika Huhtinen NIMA 491(2002) 194]

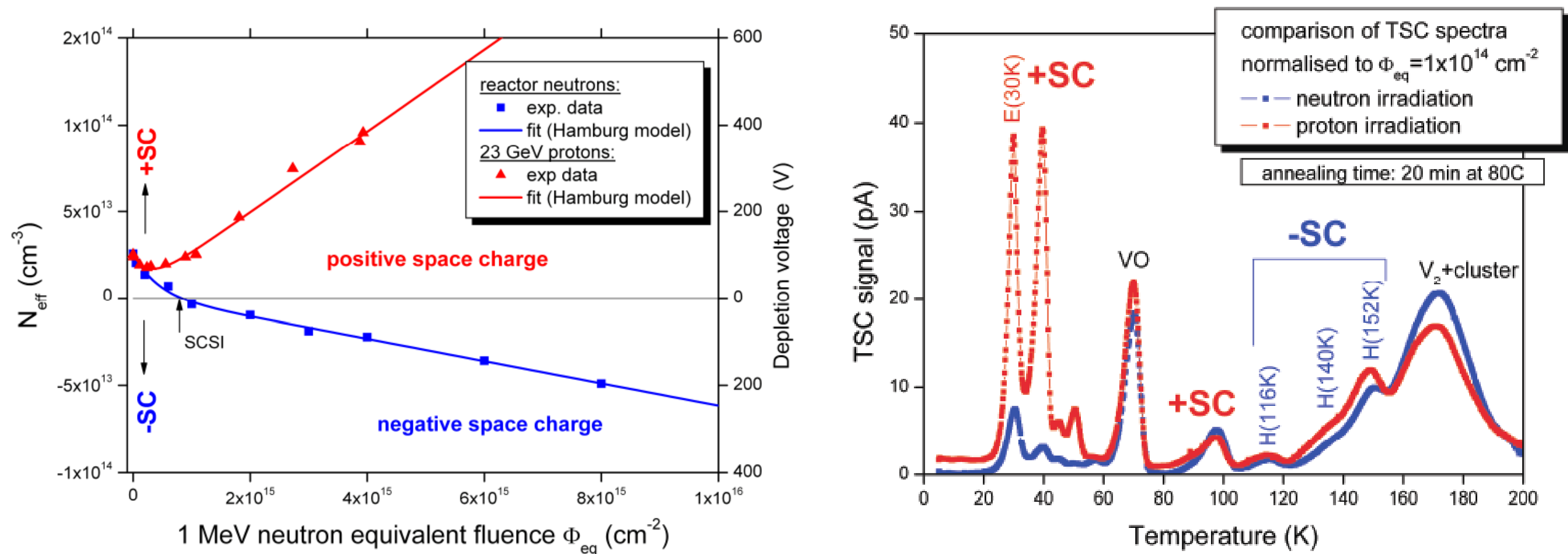


- **A 'simplified' explanation for the 'compensation effects'**
  - Defect clusters produce predominantly **negative space charge**
  - Point defects produce predominantly **positive space charge** (in 'oxygen rich' silicon)

Note:NIEL violation

From microscopic to macroscopic: N_{eff} changes explained with TSC

Epi-Si irradiated with 23 GeV protons and reactor neutrons



[Pintilie, Lindstroem, Junkes, Fretwurst, NIM A 611 (2009) 52–68]

- SCSI "Type Inversion" after neutrons but not after protons
- donor generation enhanced after proton irradiation

Main Defects Affecting the Device Properties

[I.Pintilie et al., Appl. Phys. Lett.92 024101,2008]

Point defects

- $E_i^{BD} = E_c - 0.225$ eV
- $\sigma_n^{BD} = 2.3 \cdot 10^{-14}$ cm^2

- $E_i^{I} = E_c - 0.545$ eV
  - $\sigma_n^{I} = 1.7 \cdot 10^{-15}$ cm^2
  - $\sigma p^{I} = 9 \cdot 10^{-14}$ cm^2

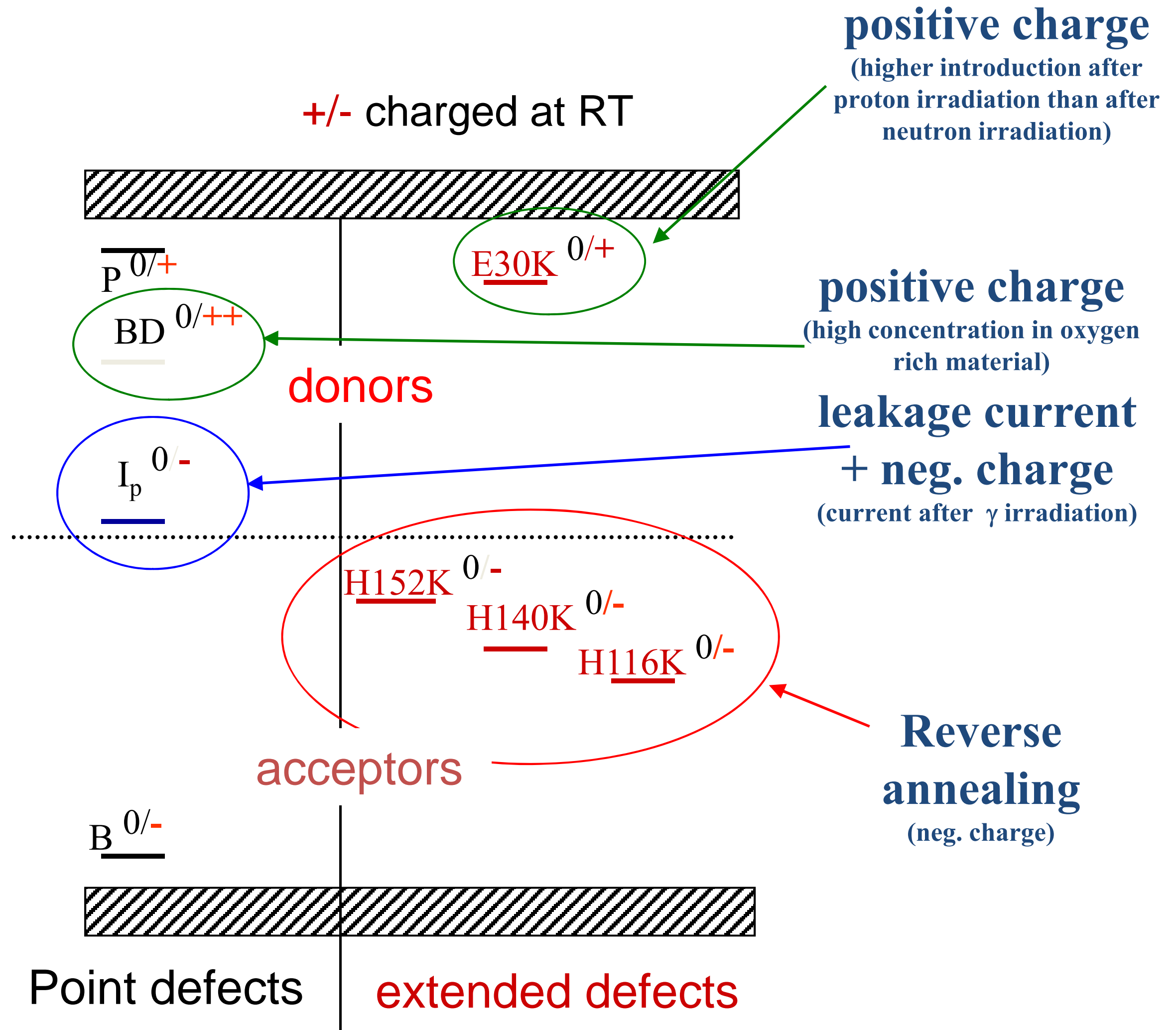
Cluster related centers

- $E_i^{116K} = E_v + 0.33$eV
- $\sigma_p^{116K} = 4 \cdot 10^{-14}$ cm^2

- $E_i^{140K} = E_v + 0.36$eV
- $\sigma_p^{140K} = 2.5 \cdot 10^{-15}$ cm^2

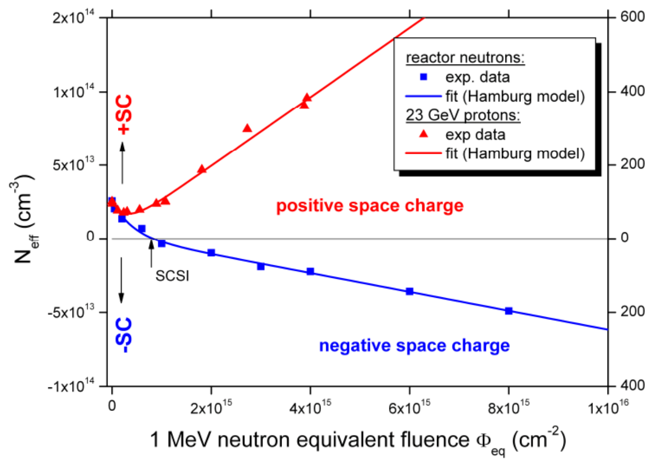
- $E_i^{152K} = E_v + 0.42$eV
- $\sigma_p^{152K} = 2.3 \cdot 10^{-14}$ cm^2

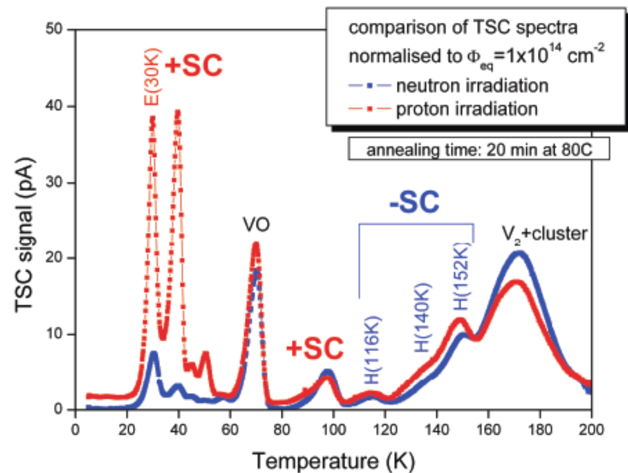
- $E_i^{30K} = E_c - 0.1$eV
- $\sigma_n^{30K} = 2.3 \cdot 10^{-14}$ cm^2

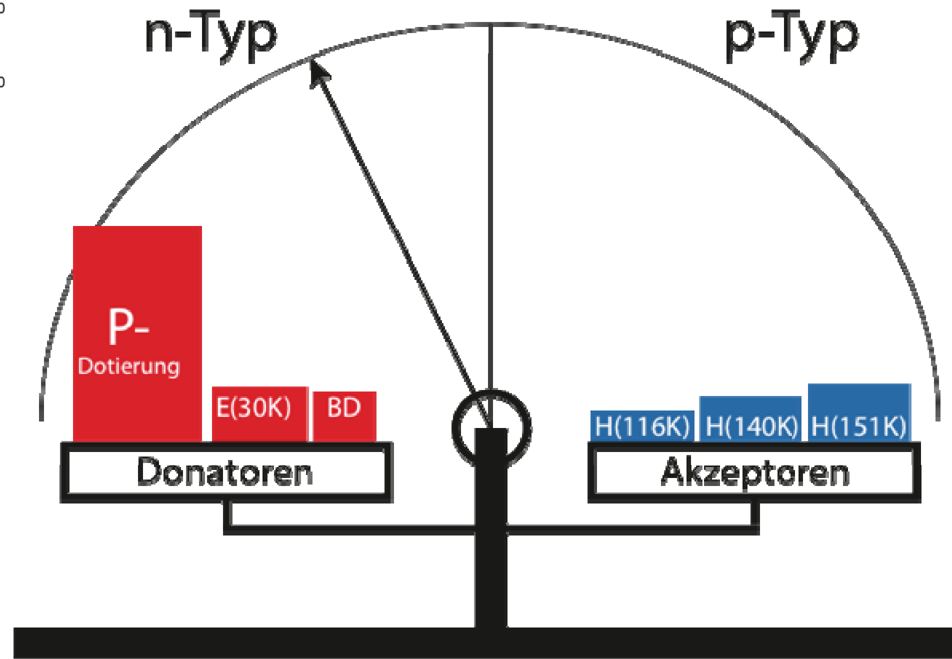


N_{eff}: Neutron irradiation

Epitaxial silicon (***EPI-DO, 72μm, 170Ωcm, diodes)*** irradiated with reactor neutrons







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1E13

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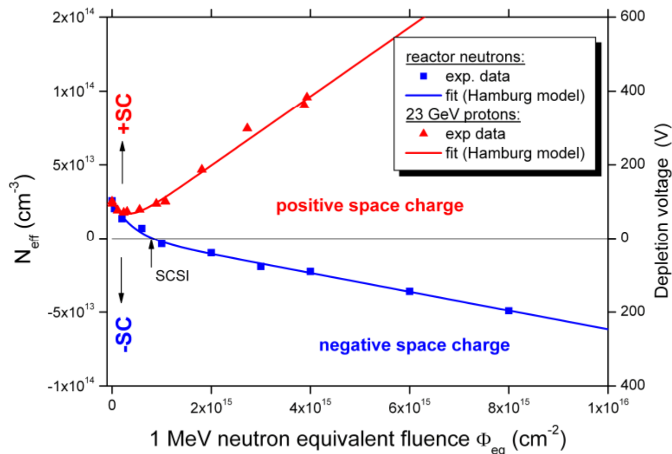
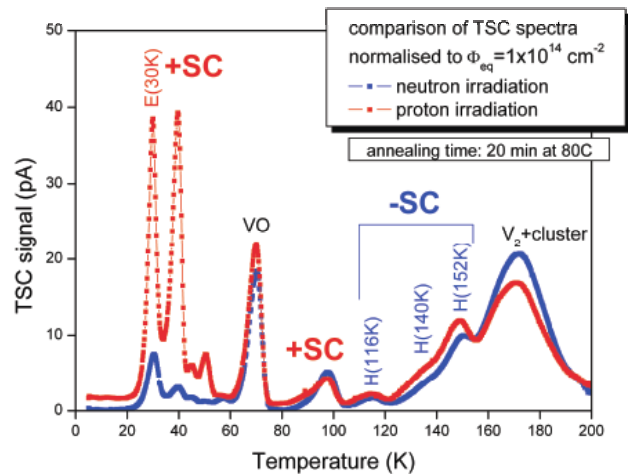
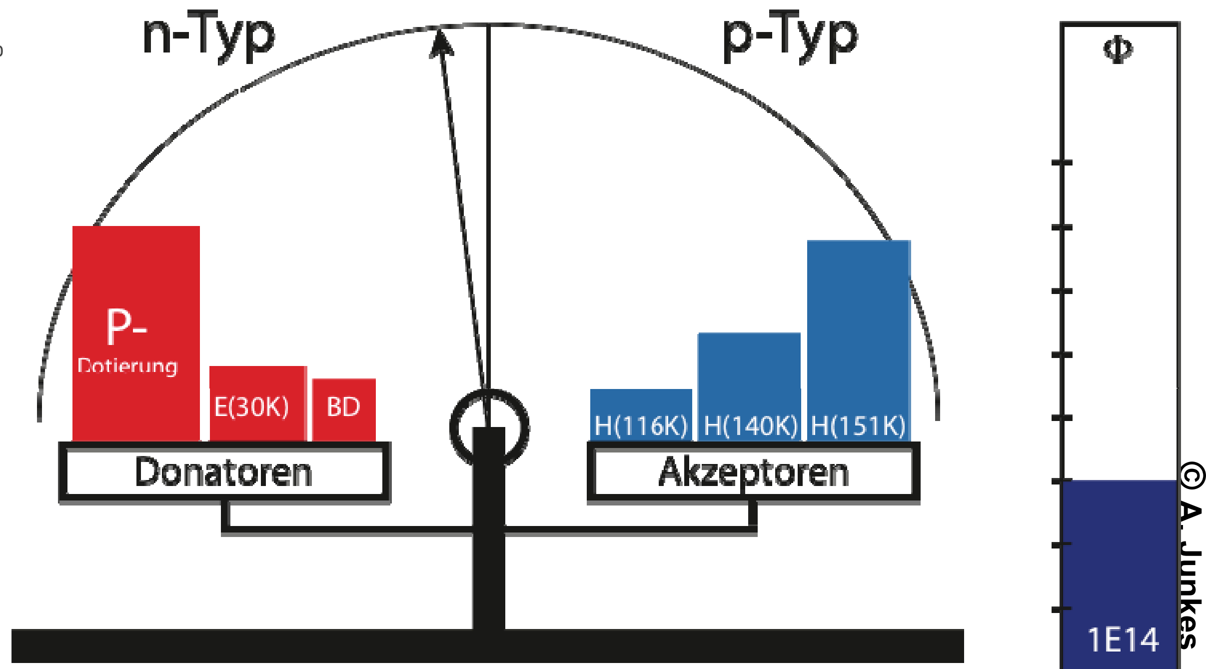
N_{eff}: Neutron irradiation



Epitaxial silicon (***EPI-DO, 72μm, 170Ωcm, diodes)*** irradiated with reactor neutrons





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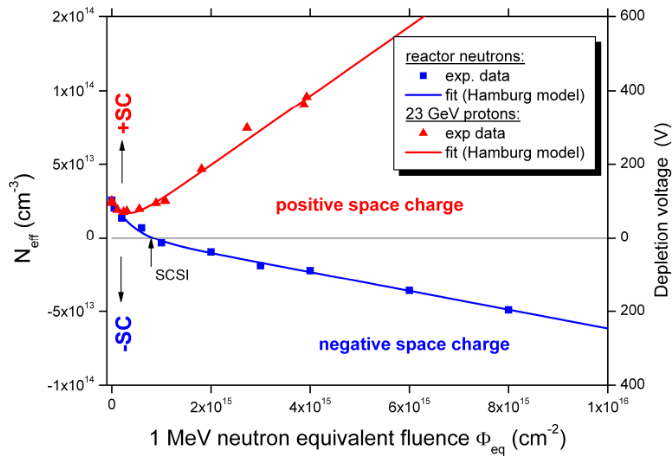
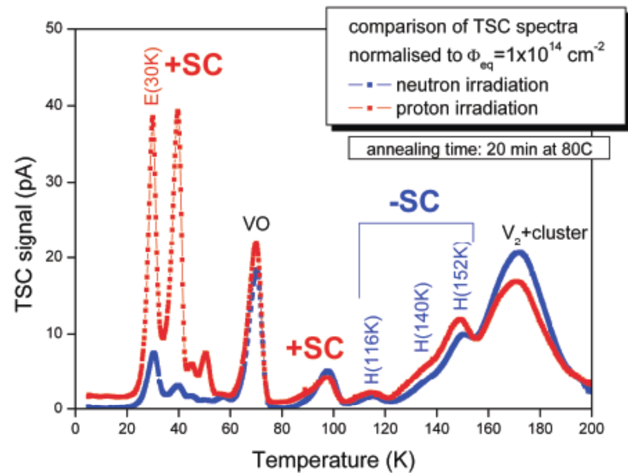
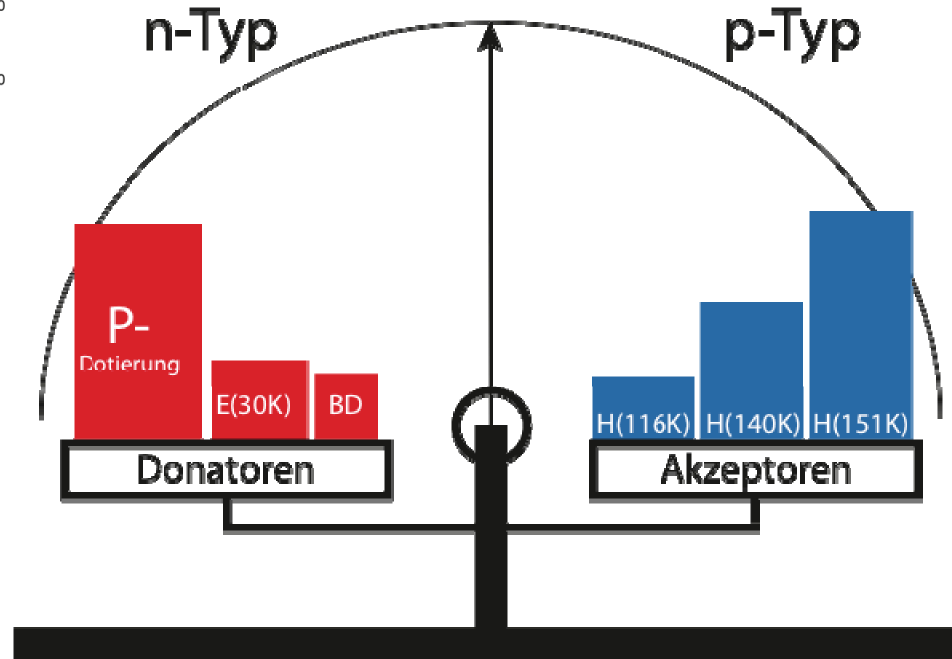
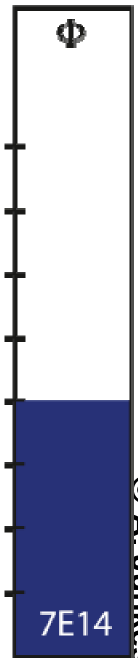
N_{eff}: Neutron irradiation





Epitaxial silicon (***EPI-DO, 72μm, 170Ωcm, diodes)*** irradiated with reactor neutrons





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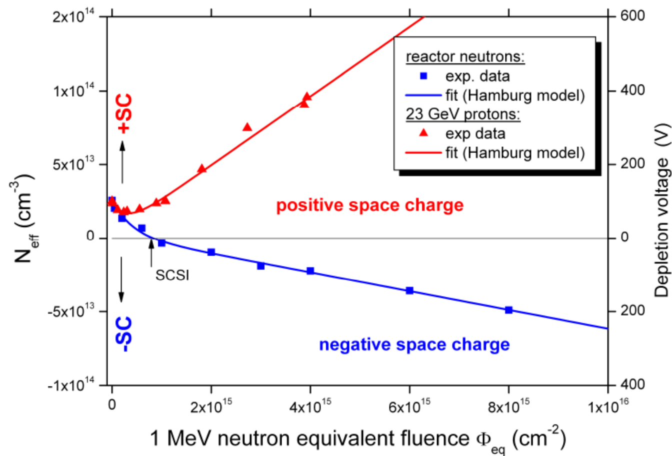
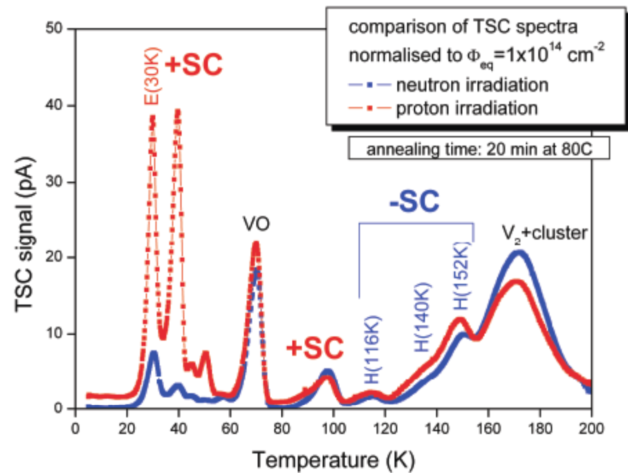
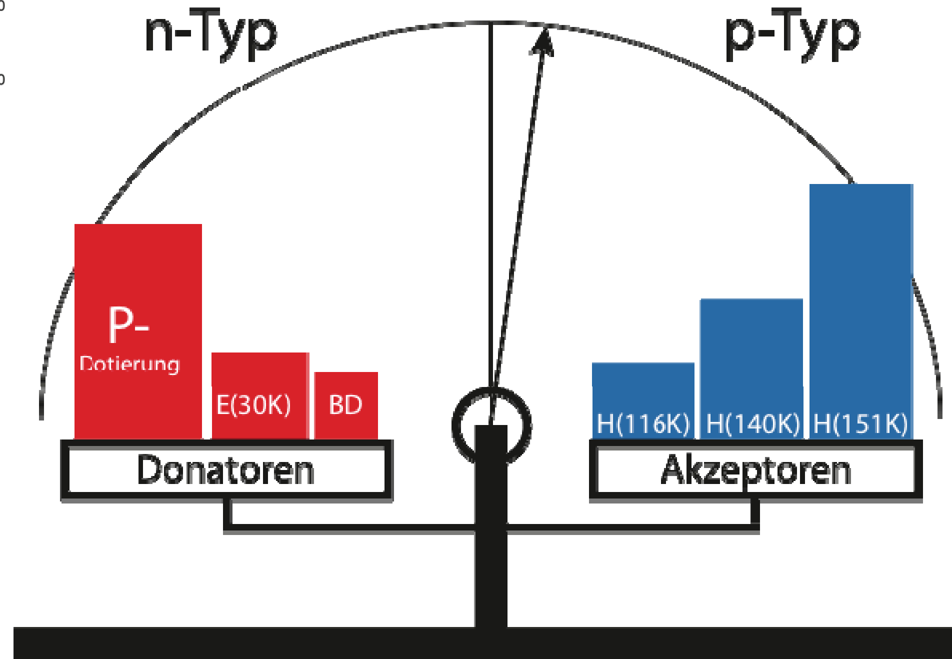
N_{eff}: Neutron irradiation





Epitaxial silicon (***EPI-DO, 72μm, 170Ωcm, diodes)*** irradiated with reactor neutrons



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1E15

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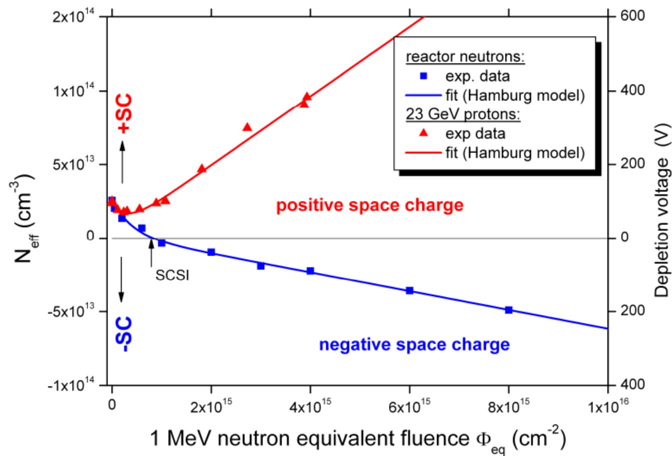
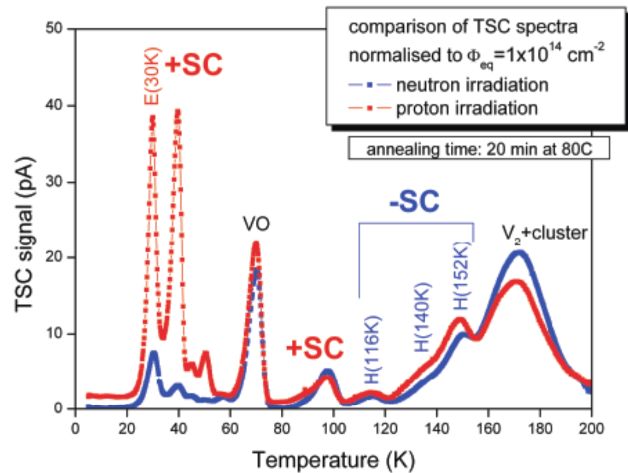
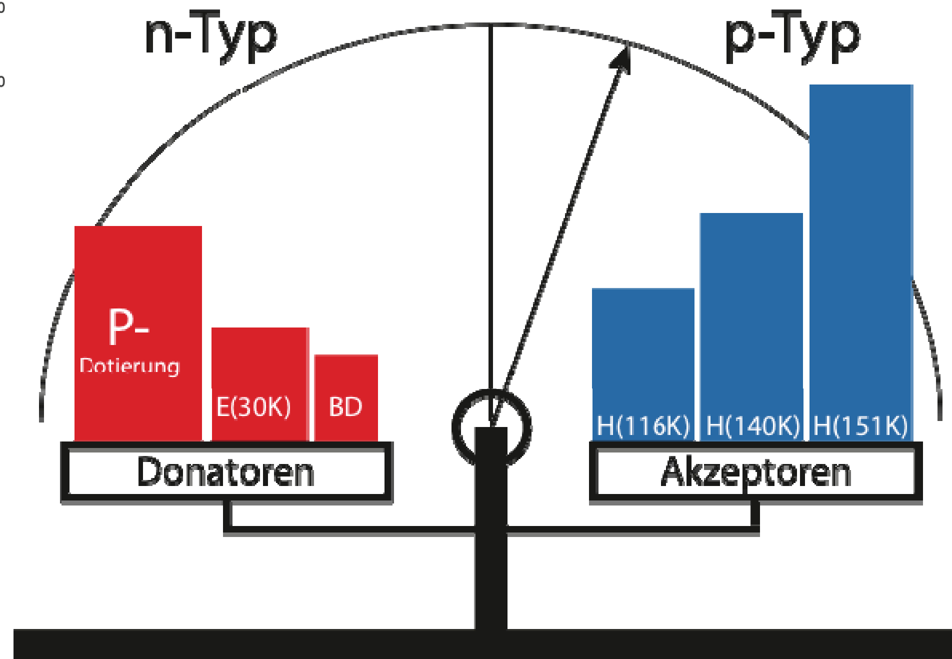
N_{eff}: Neutron irradiation





Epitaxial silicon (***EPI-DO, 72μm, 170Ωcm, diodes)*** irradiated with reactor neutrons



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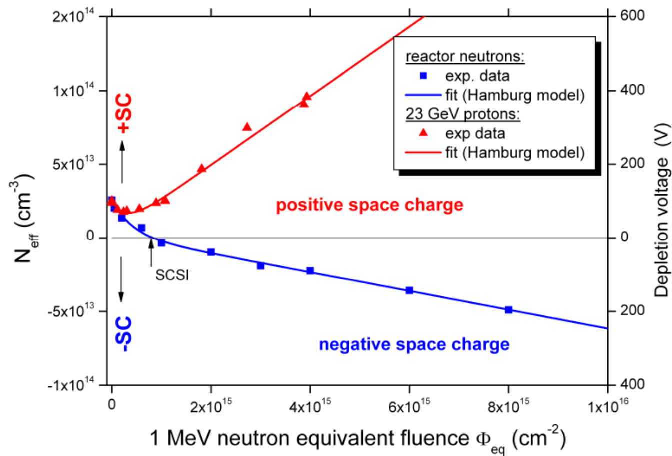
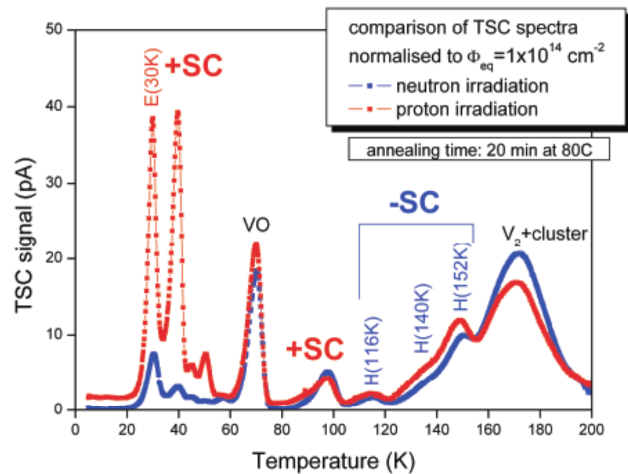
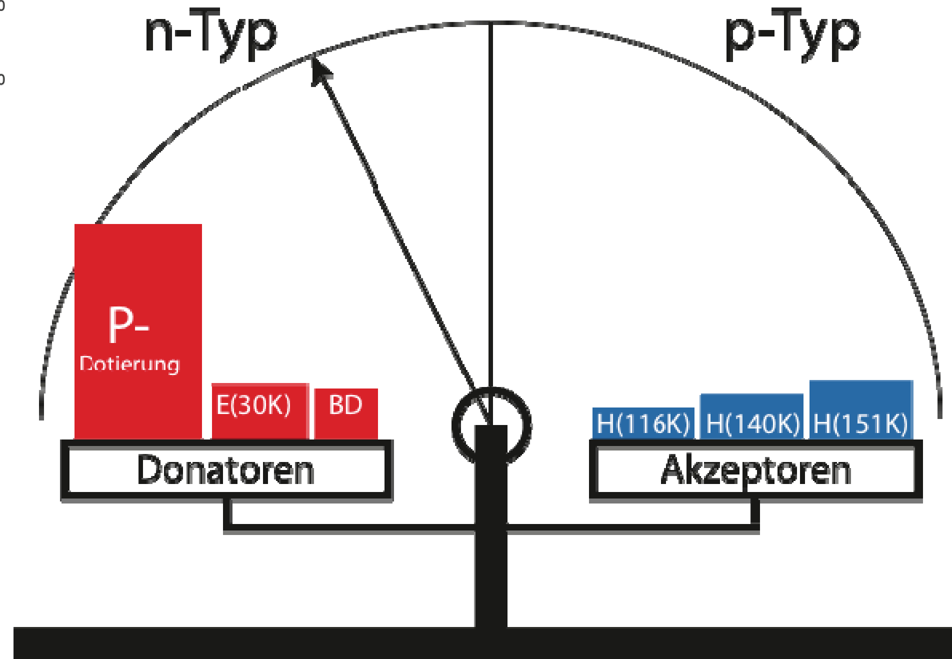
N_{eff}: Proton irradiation





Epitaxial silicon (***EPI-DO, 72μm, 170Ωcm, diodes)*** irradiated with <u>23 GeV Protons</u>



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1E13

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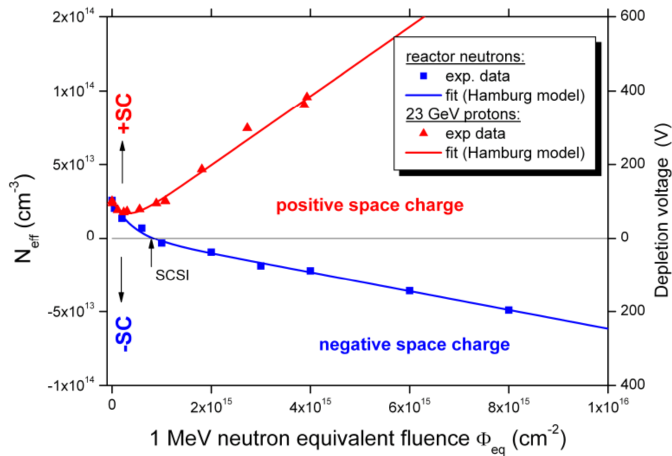
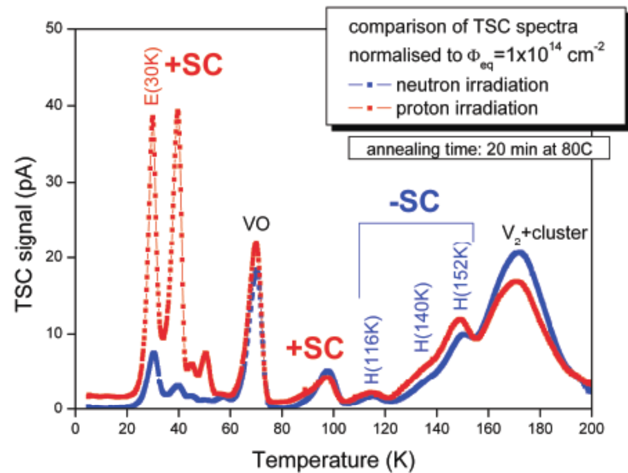
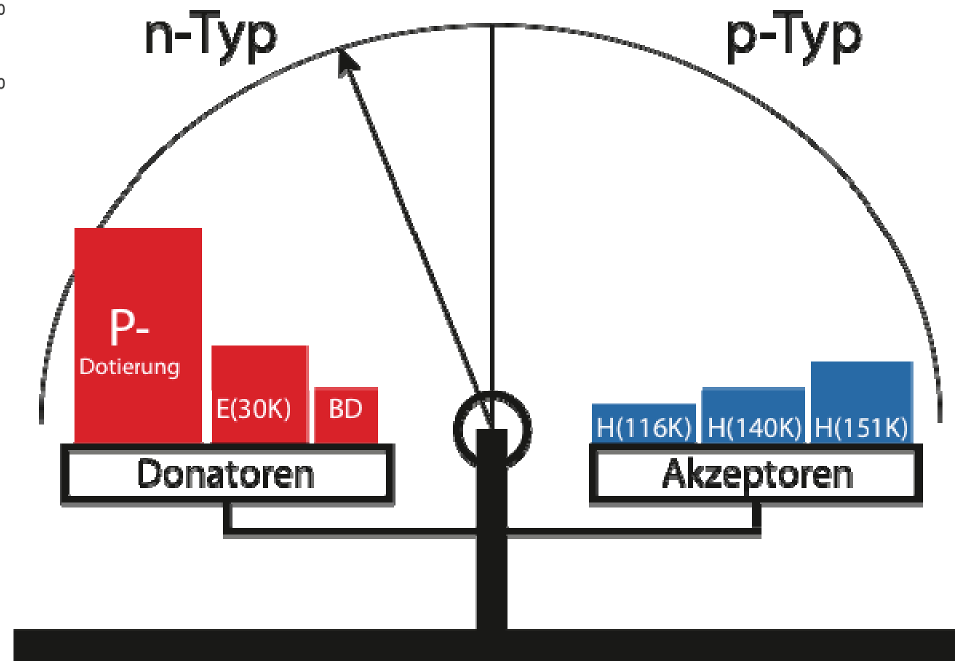
By A. Junkes, presented by U. Parzefal on behalf of the RD50 Collaboration, RESMDD10 , Oct. 2010, Florence

N_{eff}: Proton irradiation





Epitaxial silicon (***EPI-DO, 72μm, 170Ωcm, diodes)*** irradiated with 23 GeV Protons



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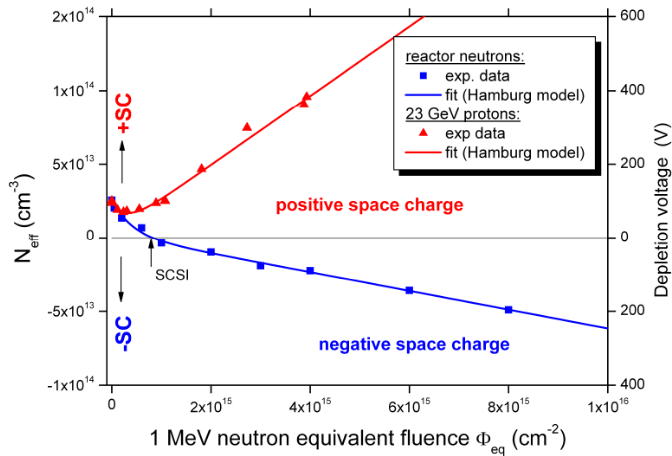

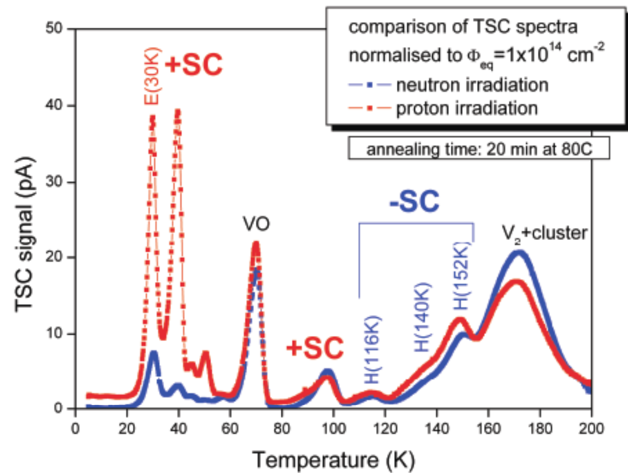

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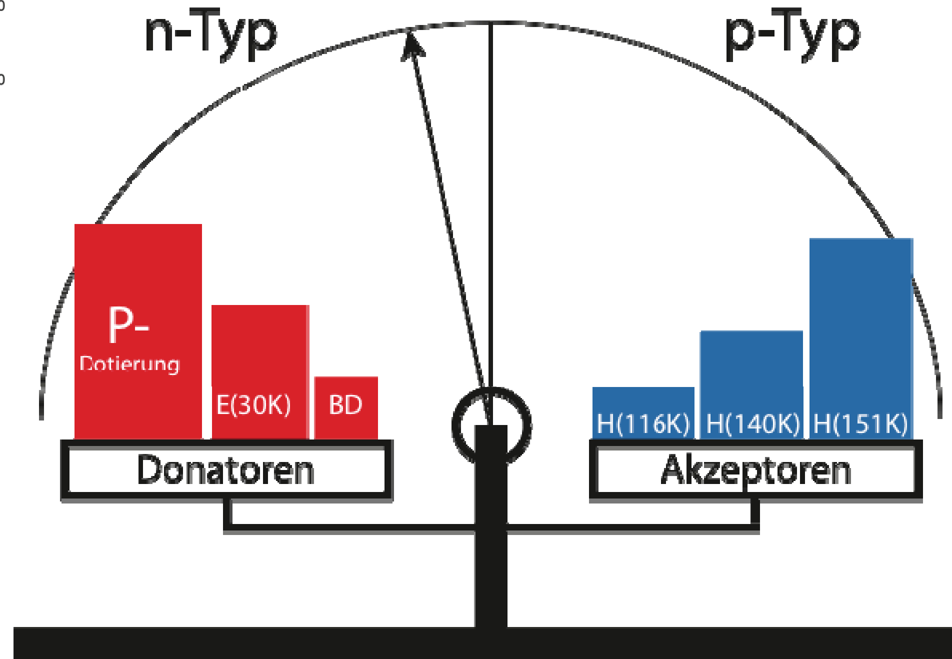

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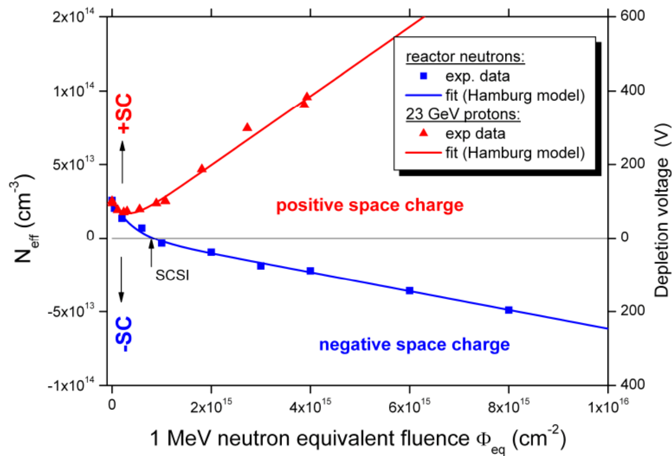

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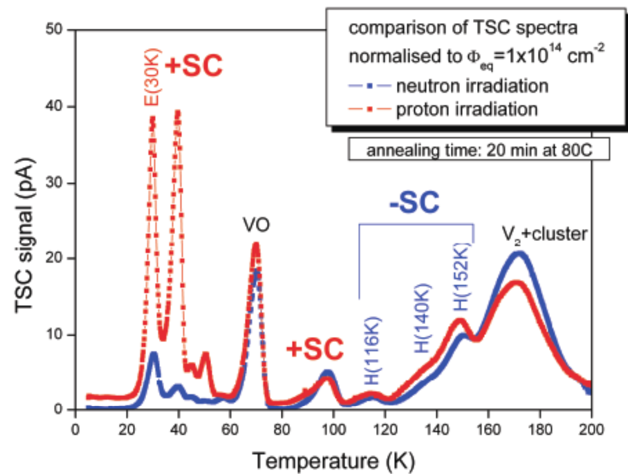

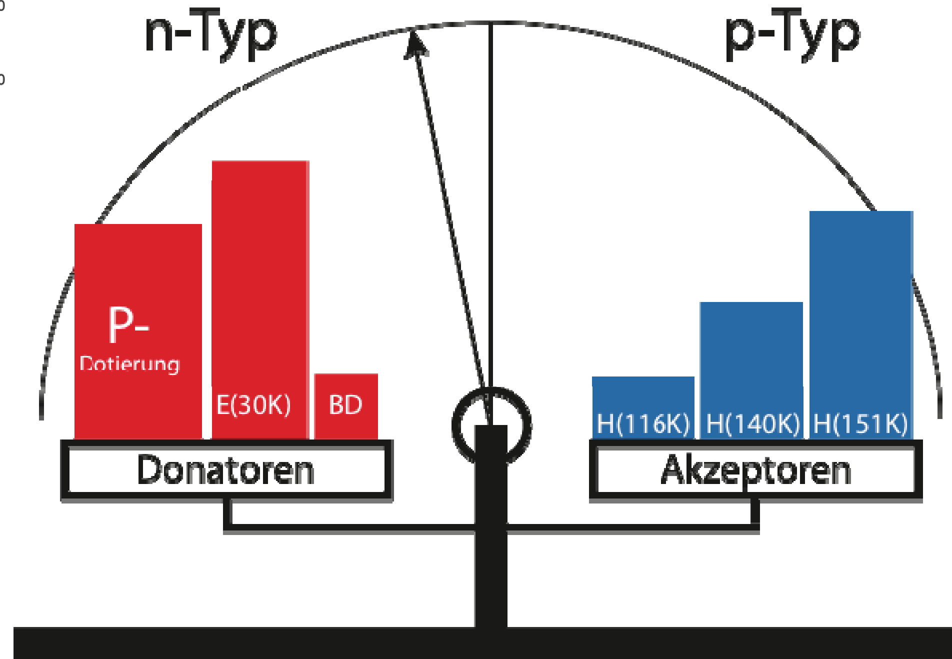

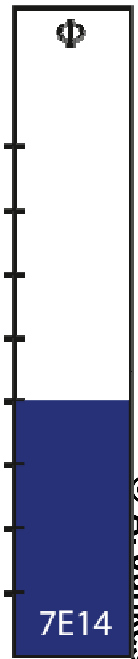

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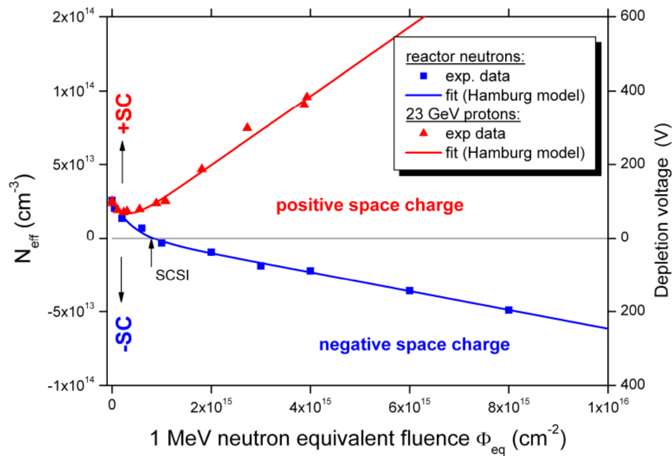

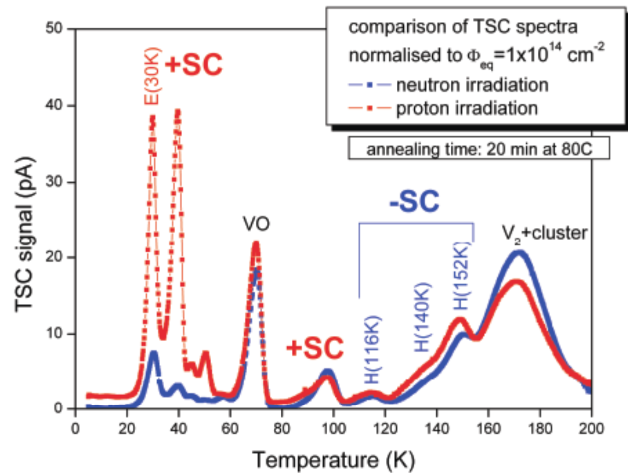

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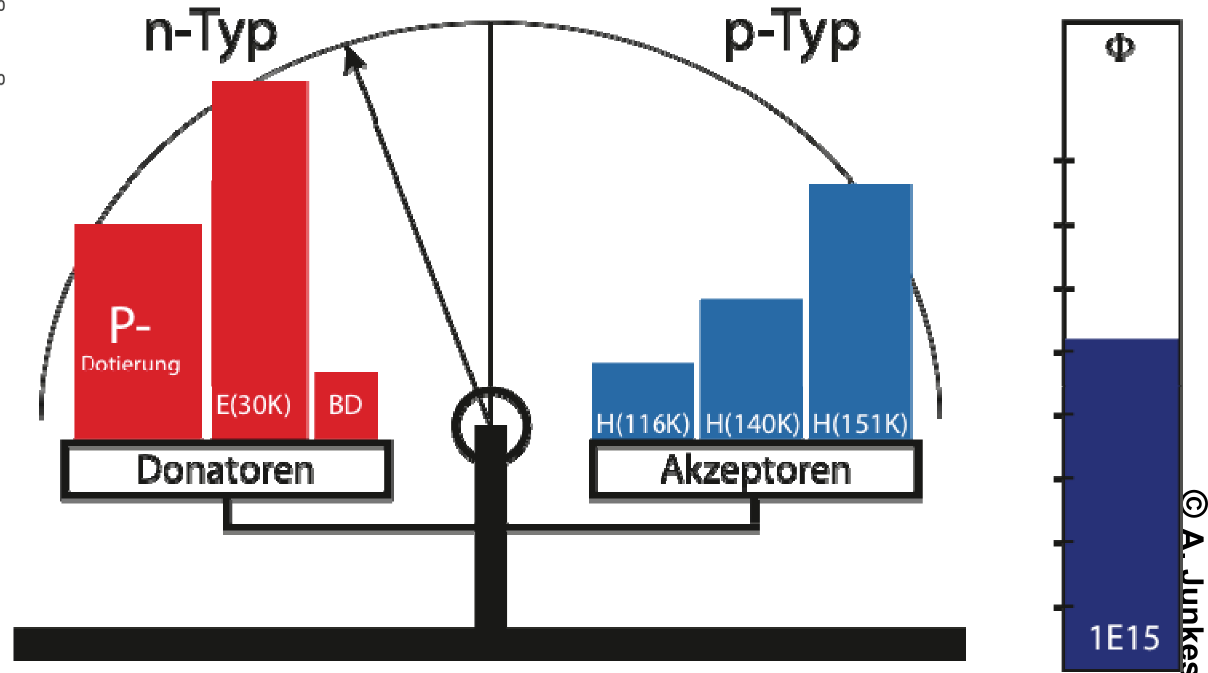

By A. Junkes, presented by U. Parzefal on behalf of the RD50 Collaboration, RESMDD10 , Oct. 2010, Florence

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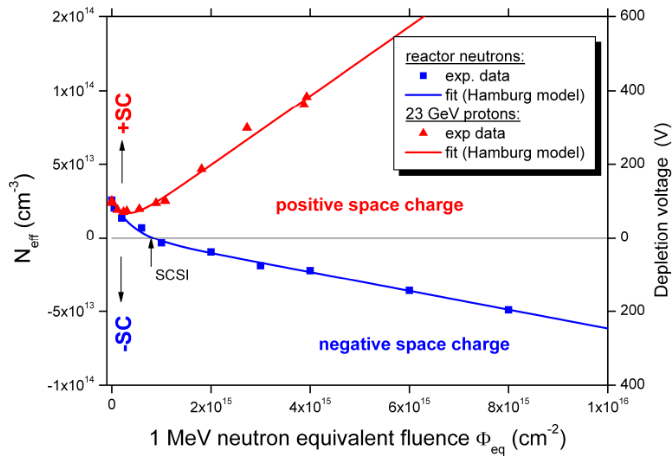

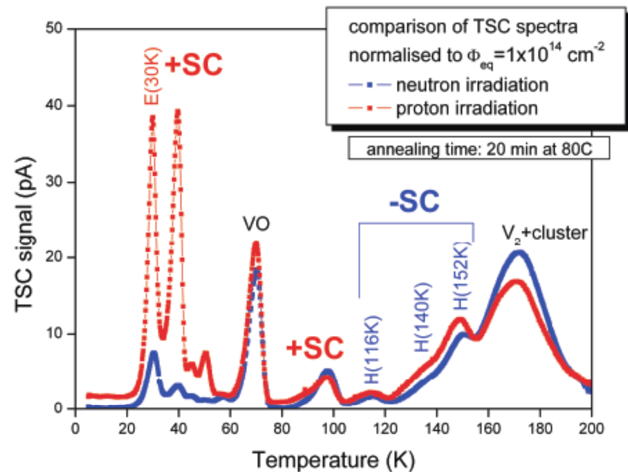

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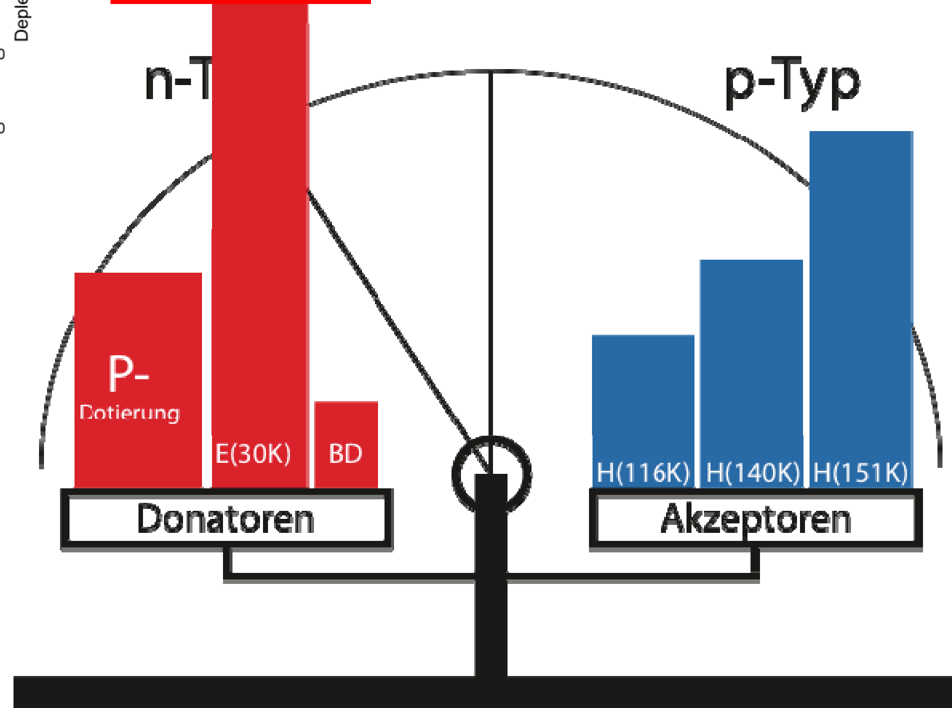

Φ

2E15

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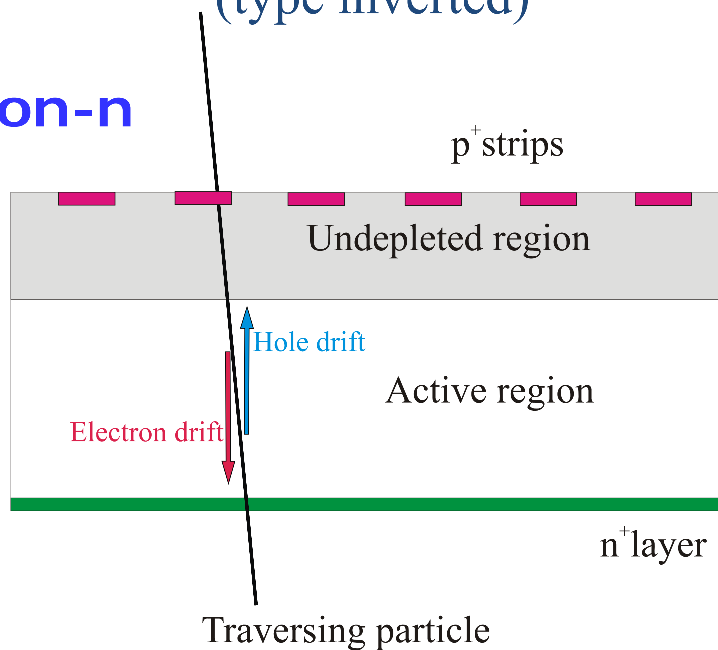
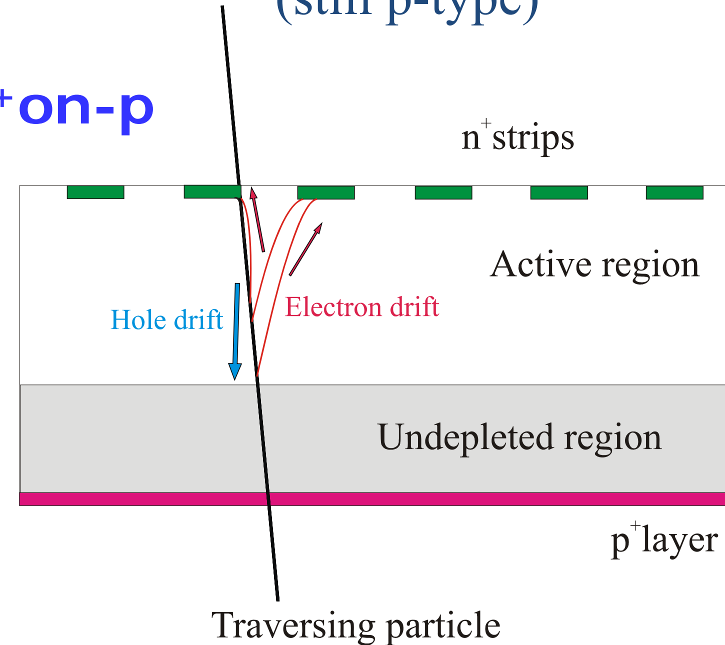
By A. Junkes, presented by U. Parzefal on behalf of the RD50 Collaboration, RESMDD10 , Oct. 2010, Florence

RD50: Device engineering

p-in-n versus n-in-p (or n-in-n) detectors





p-on-n silicon, under-depleted:

- **Charge spread – degraded resolution**
- **Charge loss – reduced CCE**

n-on-p silicon, under-depleted:

- **Limited loss in CCE**
- **Less degradation with under-depletion**
- **Collect electrons (3 x faster than holes)**

Comments:

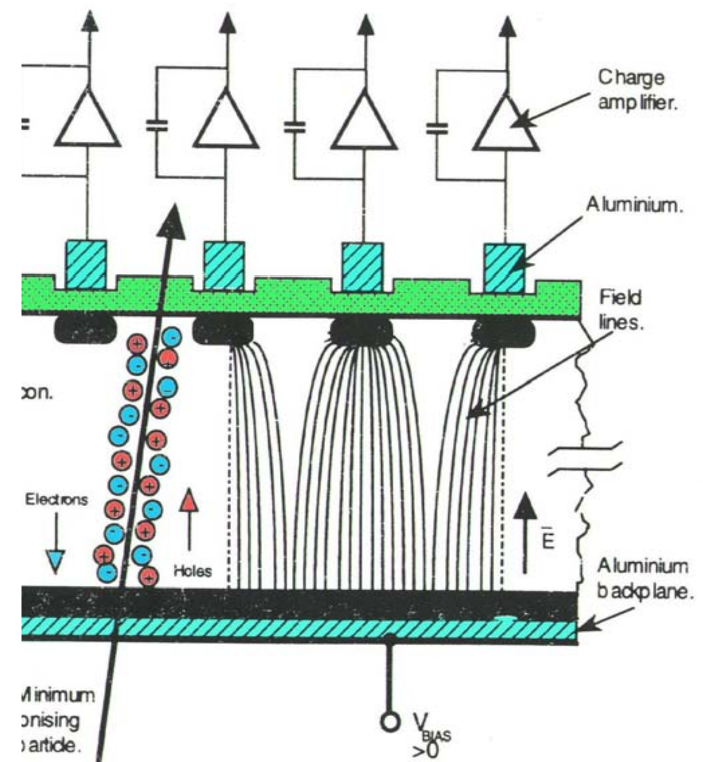
- Instead of n-on-p also n-on-n devices could be used

Charge Multiplication by impact ionization

Charge collected at electrodes in a semiconductor can not only be generated by ionising radiation but also by the acceleration of charge carriers by high electric fields, a phenomenon called impact ionization.

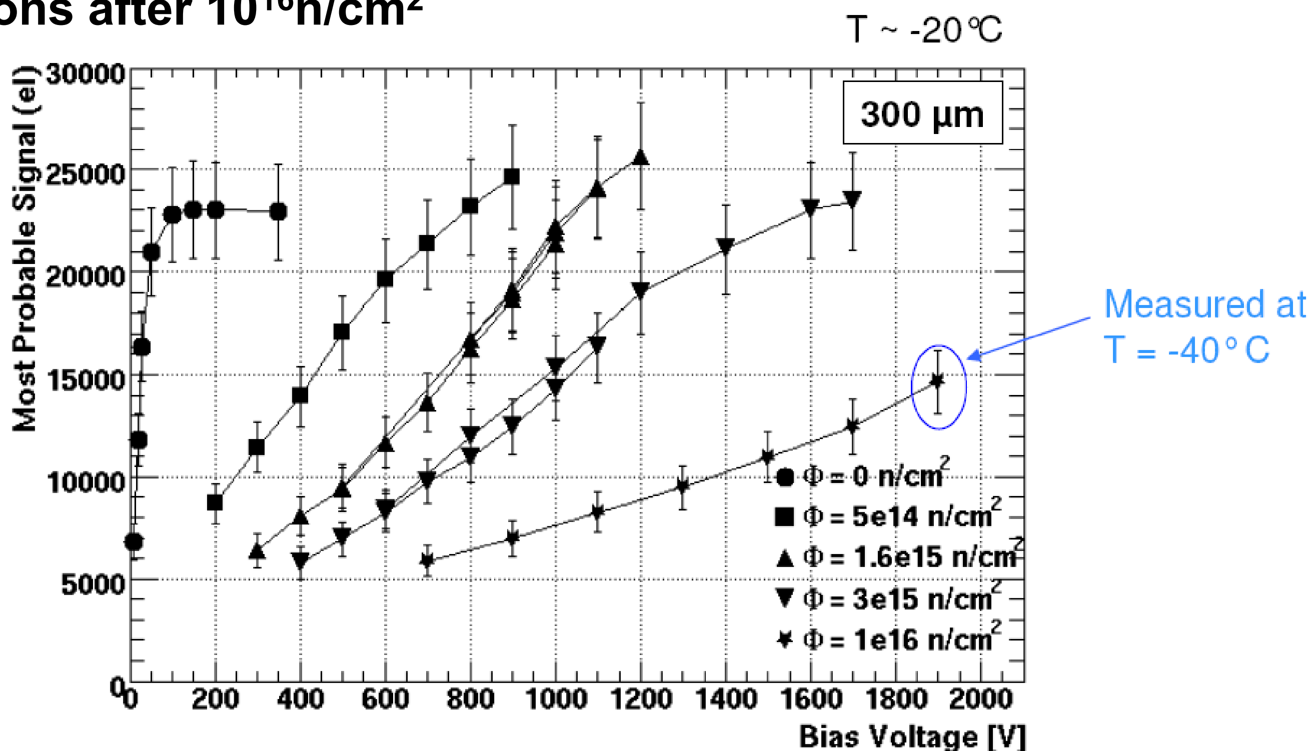
This way electrons and holes promoted in conduction/valence bands by ionising radiation (primary charge) attain enough energy to create new electron-hole pairs (secondary charge). This mechanism is also origin of current breakdown in diodes when very high reverse voltage are applied.

In a segmented device electric field is increased in the nearby of the collecting electrode due to accumulation of field lines. In irradiated devices the electric field is also enhanced by radiation induced defects.



Charge Multiplication

CCE measured with p-type Si microstrip detectors at very high fluences shows evidence of a charge multiplication effect: 100% CCE seen after 3x10^{15} n/cm^2, 15000 electrons after 10^{16}n/cm^2



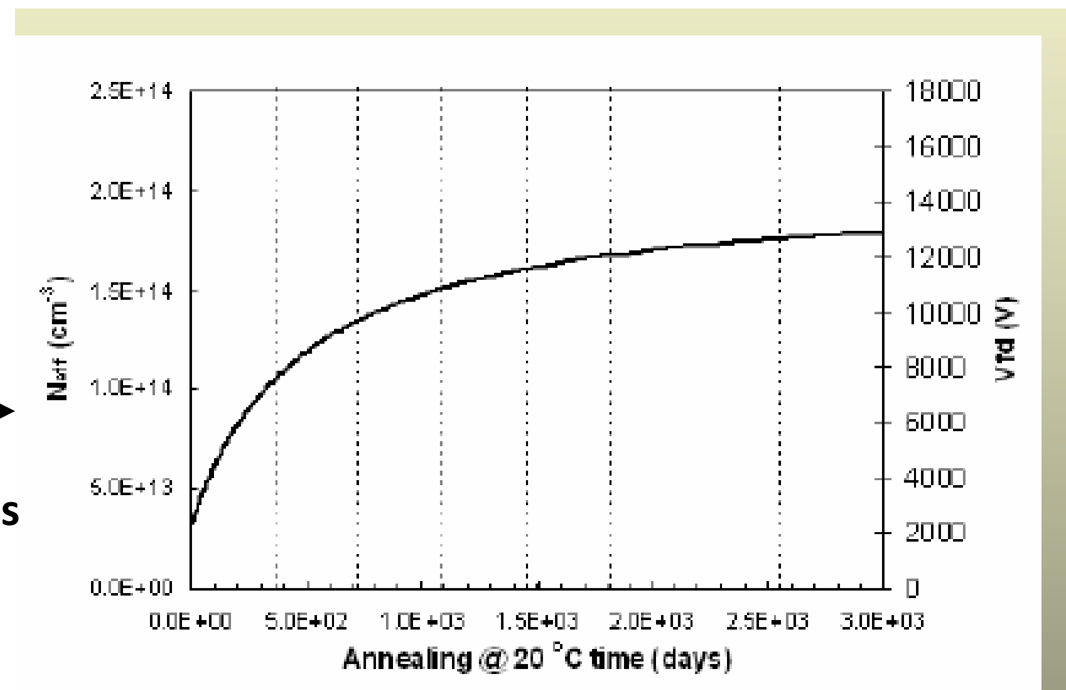
Origin: increase of the electric field close to the strips causing impact ionization/carrier when high concentrations of effective acceptors are introduced at very high fluences.

Annealing of irradiated microstrip detectors

Reverse annealing in irradiated Si microstrip detectors has been always considered as a possible cause of early failure in the experiments if not controlled by mean of low temperature (not only during operations but also during maintenance/shut down periods). This was originated by accurate measurements of the annealing behavior of the full depletion voltage in diodes measured with the CV method.

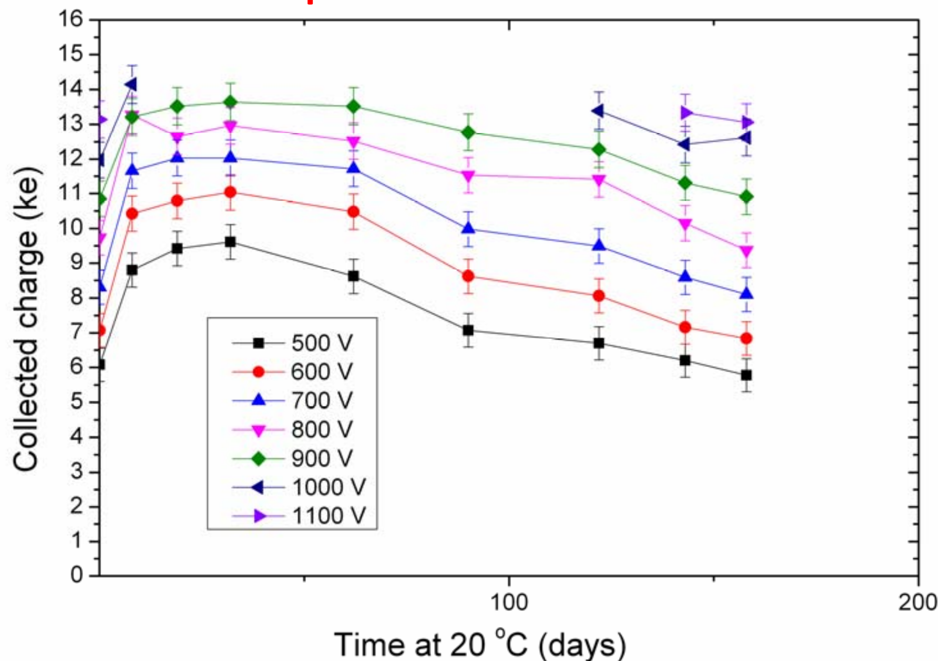
Expected changes of full depletion voltage with time after irradiation (as measured with the C-V method) for detector irradiated to 7.5 10^{15} p cm^{-2}.

Please notice that according to CV measurements the so called V_{FD} changes from <3kV to >12kV!

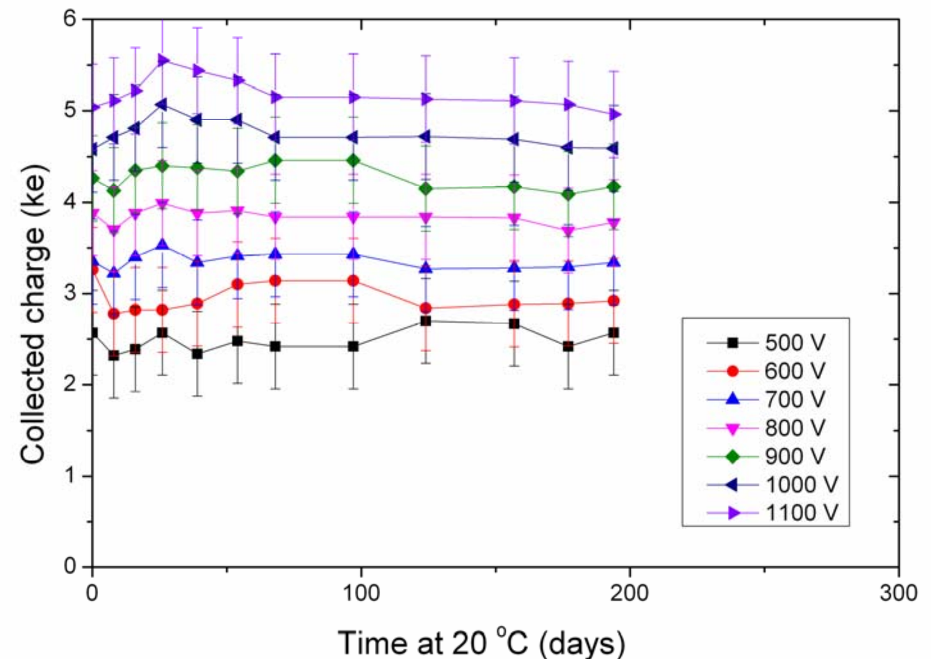


As a matter of fact, the annealing behaviour of the CCE measured with p-type Si microstrip detectors does not correspond to that measured by CV with diodes. No reverse annealing is visible in the CCE measurement.

HPK FZ n-in-p, 2E15 n cm^{-2} 26MeV p irradiation



HPK FZ n-in-p, 1E16 n cm^{-2} (26MeV p irradiation)

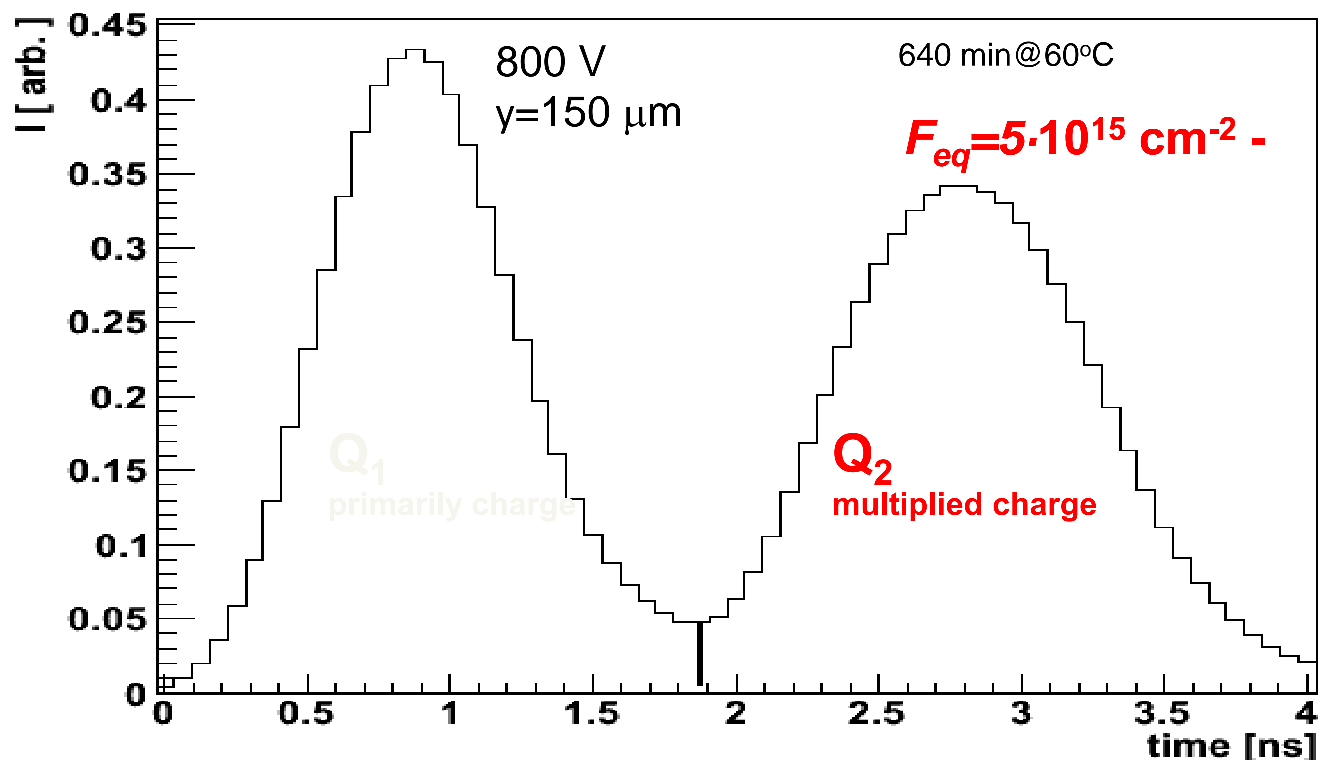


Origin of observed behaviour :

-Charge Multiplication due to increased electric field close to strips as concentration of acceptors grows with time/temperature;

-Reduction of the effective trapping probability of electrons with annealing.

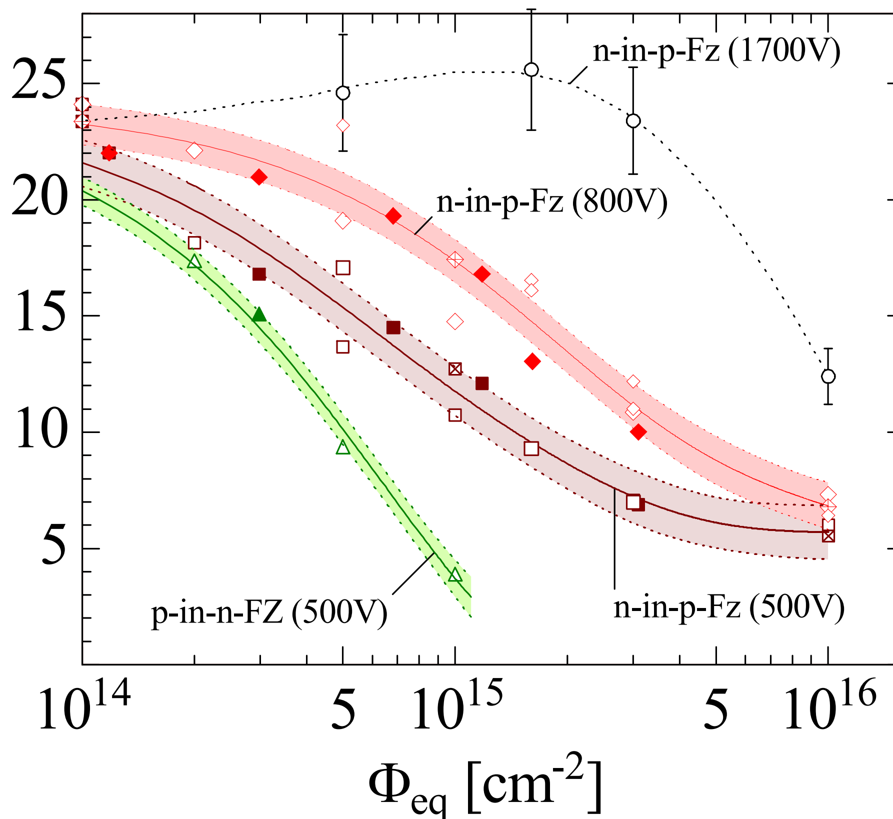
Edge TCT: a way to visualize *Multiplication profiles*



- 1st peak – current induced by the drift of primarily generated carriers
  - small change with annealing
- 2nd peak – current induced by the drift of multiplied holes
  - huge change with annealing

G. Kramberger, "Edge-TCT measurements with irradiated micro-strip silicon detectors", 8th RESMDD, Oct. 2010, Firenze, Italy

RD50 Planar Detector Compilation



FZ Silicon Strip Sensors

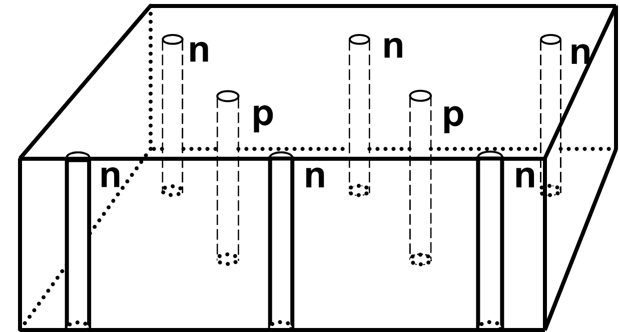
- n-in-p (FZ), 300µm, 500V, 23GeV p
- n-in-p (FZ), 300µm, 500V, neutrons
- n-in-p (FZ), 300µm, 500V, 26MeV p
- n-in-p (FZ), 300µm, 800V, 23GeV p
- n-in-p (FZ), 300µm, 800V, neutrons
- n-in-p (FZ), 300µm, 800V, 26MeV p
- n-in-p (FZ), 300µm, 1700V, neutrons
- p-in-n (FZ), 300µm, 500V, 23GeV p
- p-in-n (FZ), 300µm, 500V, neutrons

RD50 - M. Moll

- p-in-n fades away well before $10^{15}N_{eq}$
- n-in-p still gets 50% charge at $10^{16}N_{eq}$ at high bias voltages
- n-in-p benefits from charge multiplication (at high bias voltages)
- CM effect also seen for p-in-n (but less strong in partial depletion mode)
- n-in-p (n-in-n) superior material for high radiation environments

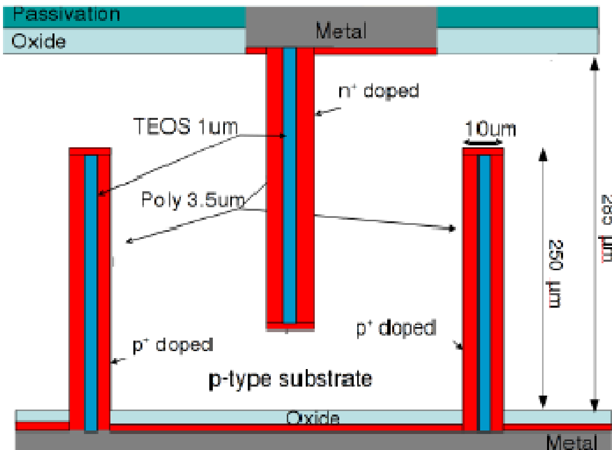
Device Engineering: 3D detectors

- Electrodes:
  - **narrow columns along detector thickness-“3D”**
  - **diameter:** 10μm **distance:** 50 - 100μm
- Lateral depletion:
  - **lower depletion voltage needed**
  - **thicker detectors possible**
  - **fast signal**
- Hole processing :
  - **Dry etching, Laser drilling, Photo Electro Chemical**



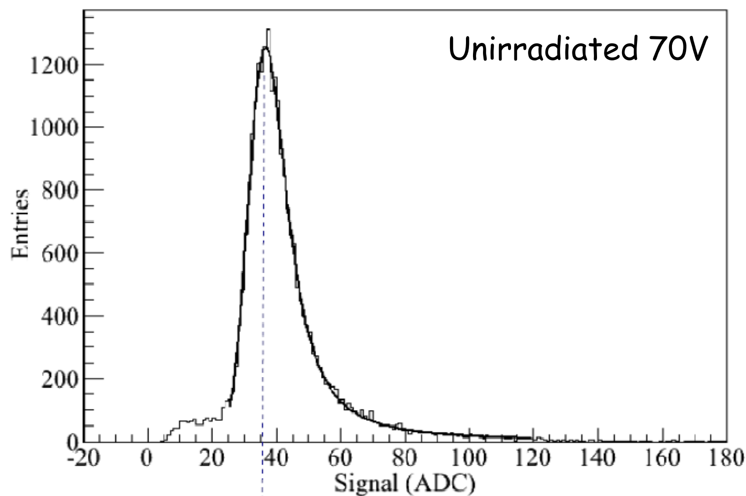
(*Introduced by S.I. Parker et al., NIMA 395 (1997) 328*)

Charge Collection of 3d Detectors: results from RD50

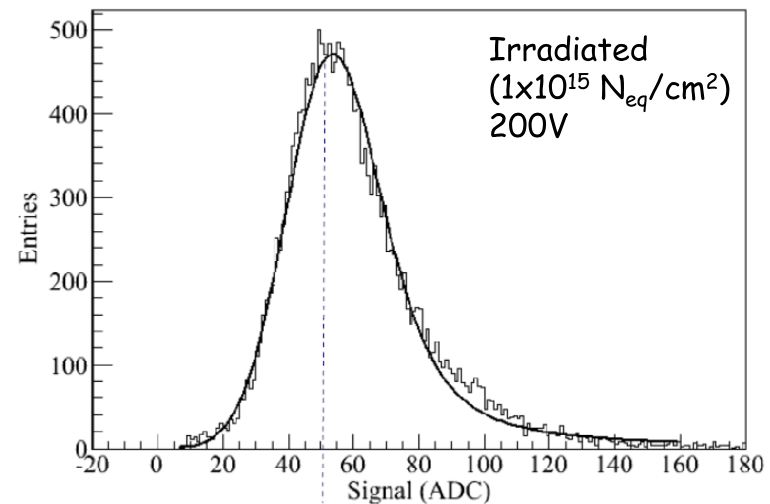


[M.Koehler et al., RD50 Workshop, May/June 2010]

- Double Sided 3d p-type sensors in SPS Testbeam
- Irradiation at the Karlsruhe cyclotron with 25MeV protons
- Higher signal after irradiation than before
  → Charge multiplication



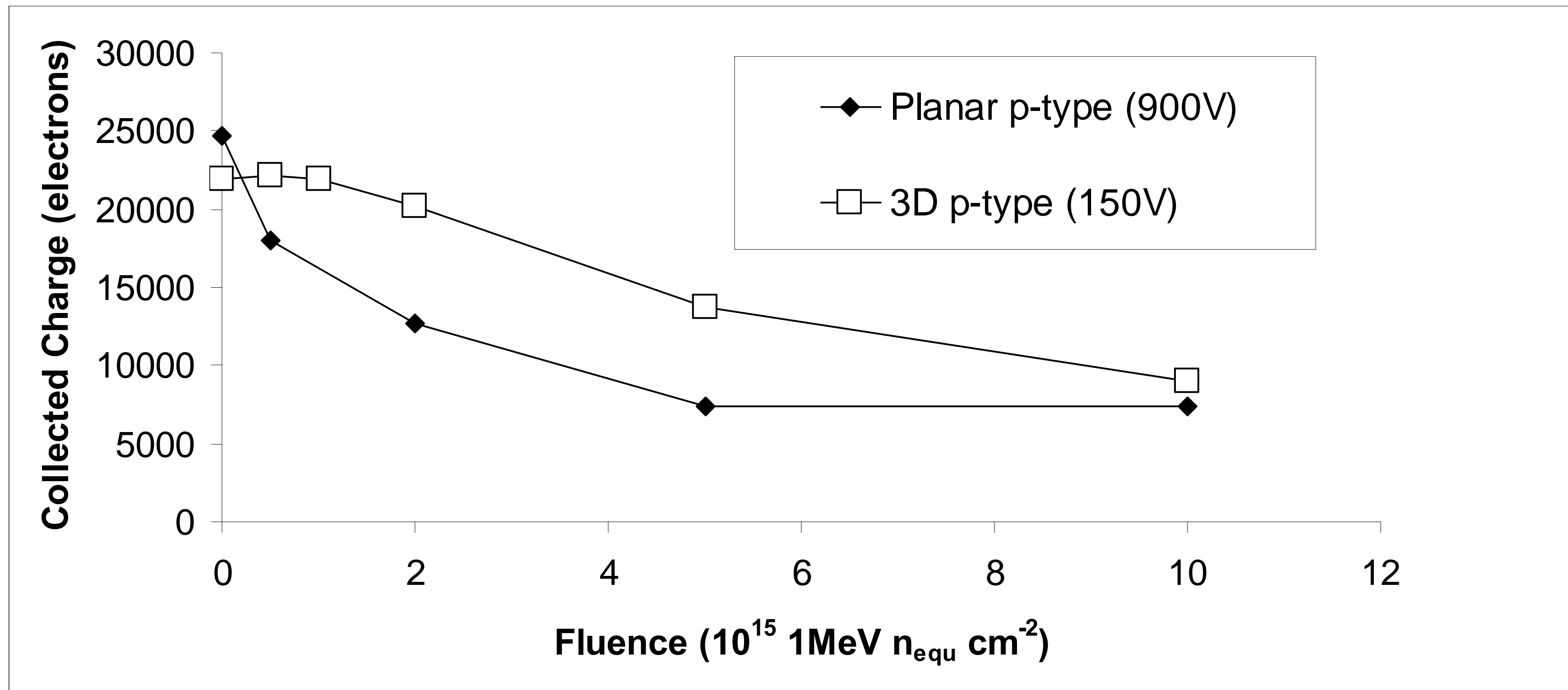
Landau MPV: 35 ADC



Landau MPV: 49 ADC

3D vs planar detectors

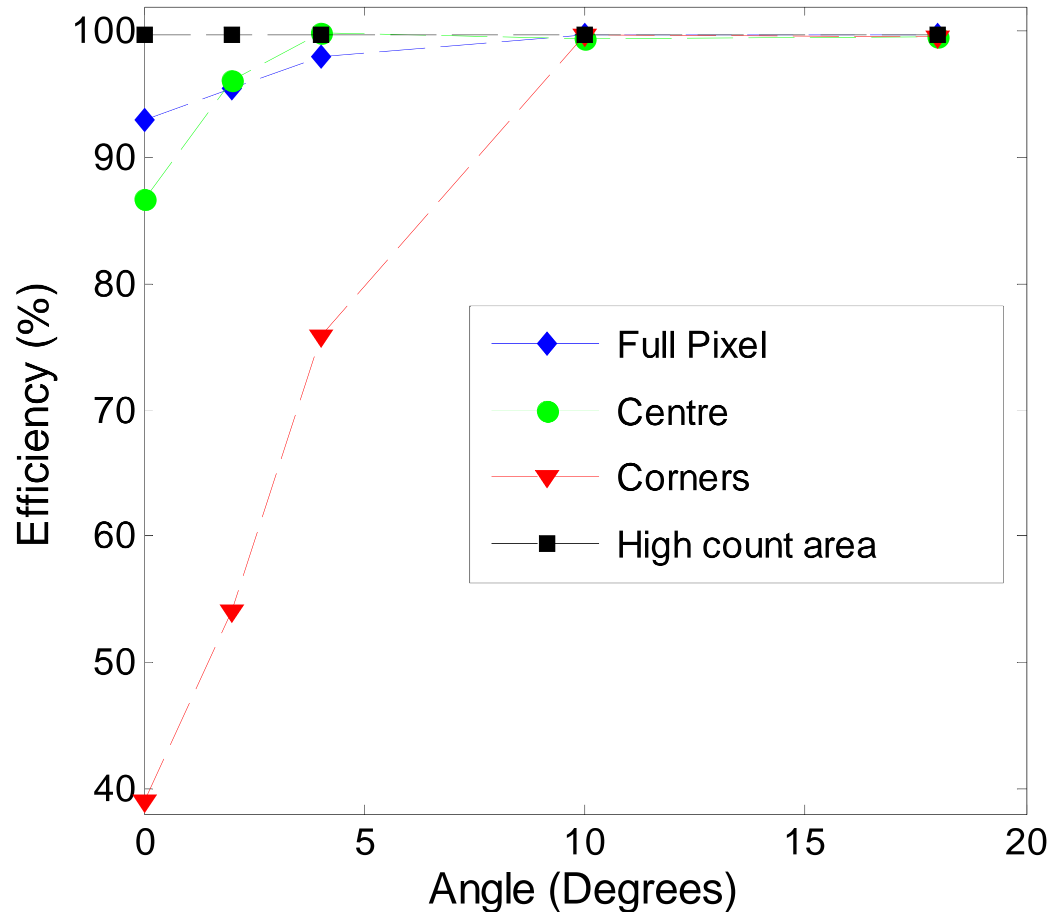
Collected charge as a function of fluence. Note 3D only 150V, high bias gets increase in charge due to multiplication

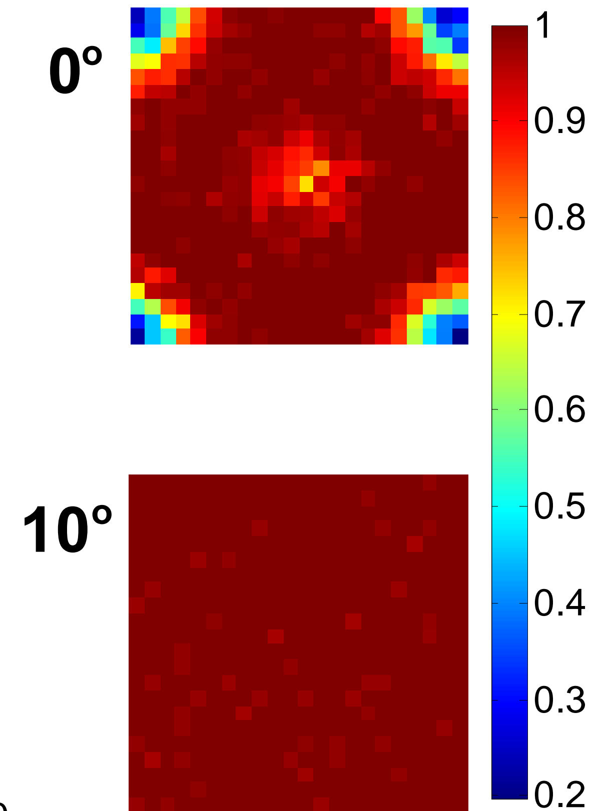


R. Bates et al. IEEE NSS 2009

R. Bates et al. IEEE Trans Nucl Sci To be published

Efficiency low in holes – reaches full efficiency at a track angle of 10degs





50um pitch (short side of ATLAS pixel)

C. Parkes et al. Submitted to JInst
P. Grenier et al. Submitted to NIMA

Conclusions

- Development of radiation-hard Silicon detectors for high-luminosity colliders, in particular the sLHC, is mandatory.
- RD50 is a forum to work on the subject inter-disciplinarly
- Microscopic view can explain radiation damage in detectors operative parameters. Large progress in understanding leakage current and effective doping concentration.
- Charge amplification and no annealing degradation observed on irradiated p-type Si microstrip sensors are beneficial to p-type Si detector performance especially at heavy fluence irradiations.
- N-on-p much better than standard n-on-p devices, good enough for most regions of the tracker.
- 3D Si can add extra radiation hardness if required for innermost sLHC tracking layer(s).