ROSE – oxygenated silicon

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for the

CERN RD48 (ROSE) collaboration

ROSE: R&D On Silicon for future Experiments

- **Founded in 1995, formally approved by LHCC in 1996, ended successfully in December 2000**
  39 collaborating institutes, 7 associated companies, 3 observers

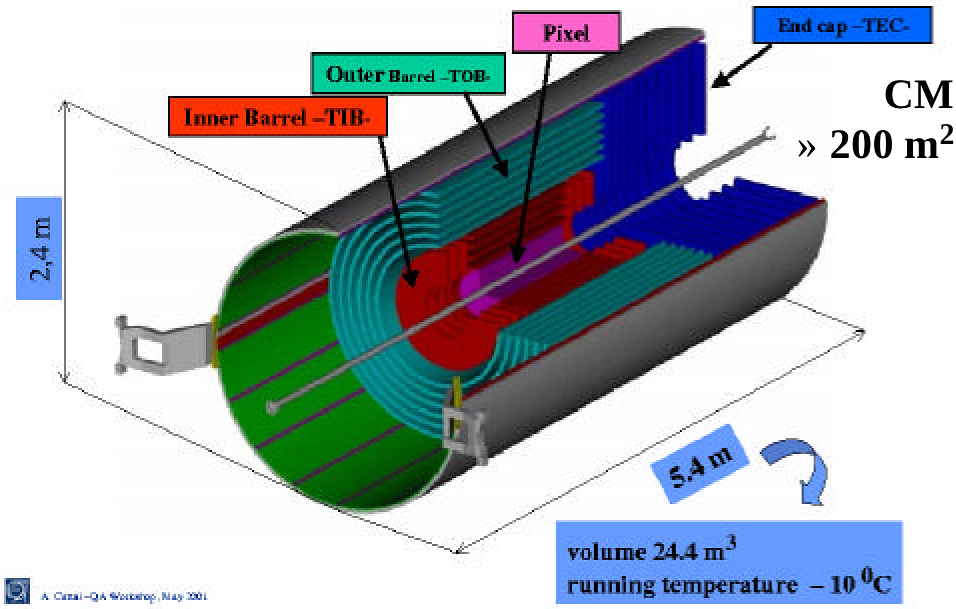
- **Final report CERN/LHCC 2000-09**
  Latest summarising publications:
  Hiroshima 2000, Pixel-2000, Vertex-2001

- **Goals:**
  - ❖ **Development of radiation hard Si-detectors operable beyond the limits of 1996-state of the art devices, ensuring operation for whole lifetime of LHC experimental program**
  - ❖ **Recommendations to experiments on optimum Si and quality control to ensure radiation tolerance**

- **Main focus:**
  - ❖ **Defect engineering by DOFZ Oxygen enrichment: Diffusion of oxygen during manufacturing process ensures cost effectiveness**
  - ❖ **Radiation hardness issues:**
    Tolerable depletion voltage, good charge collection;
    Leakage current by cooling
  - ❖ **Dependence on material and particle type, NIEL scaling?**
  - ❖ **Understanding on microscopic scale, using DLTS and similar methods for detection of defects, studying kinetics and correlations with macroscopic behaviour**

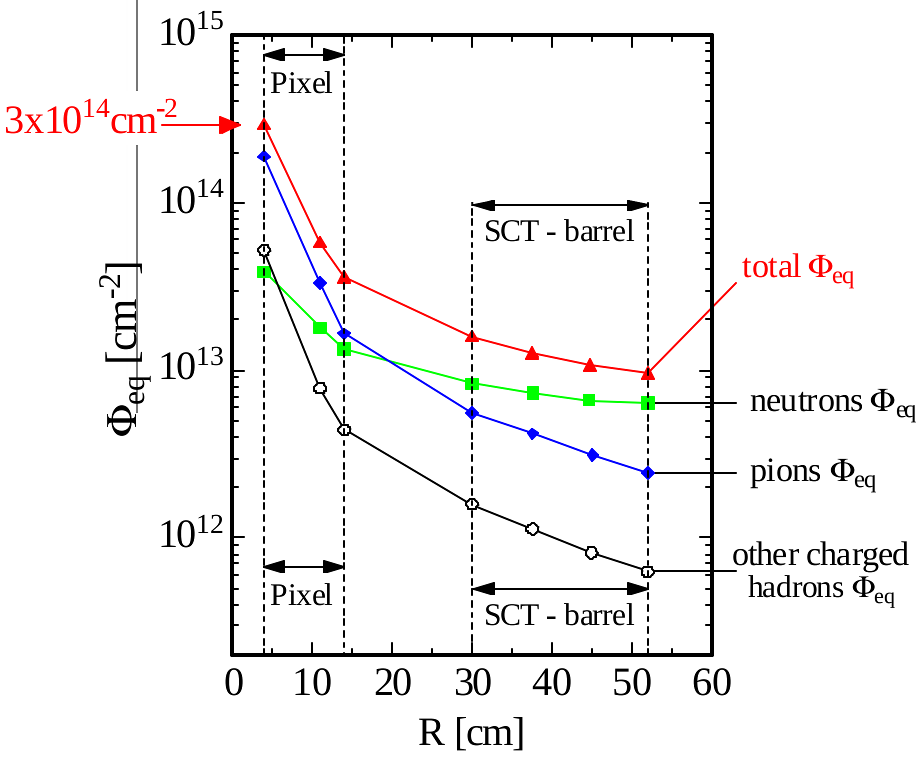
Motivation

The CMS Tracker



CMS Tracker
» 200 m^2 silicon sensors

ATLAS - Inner Detector

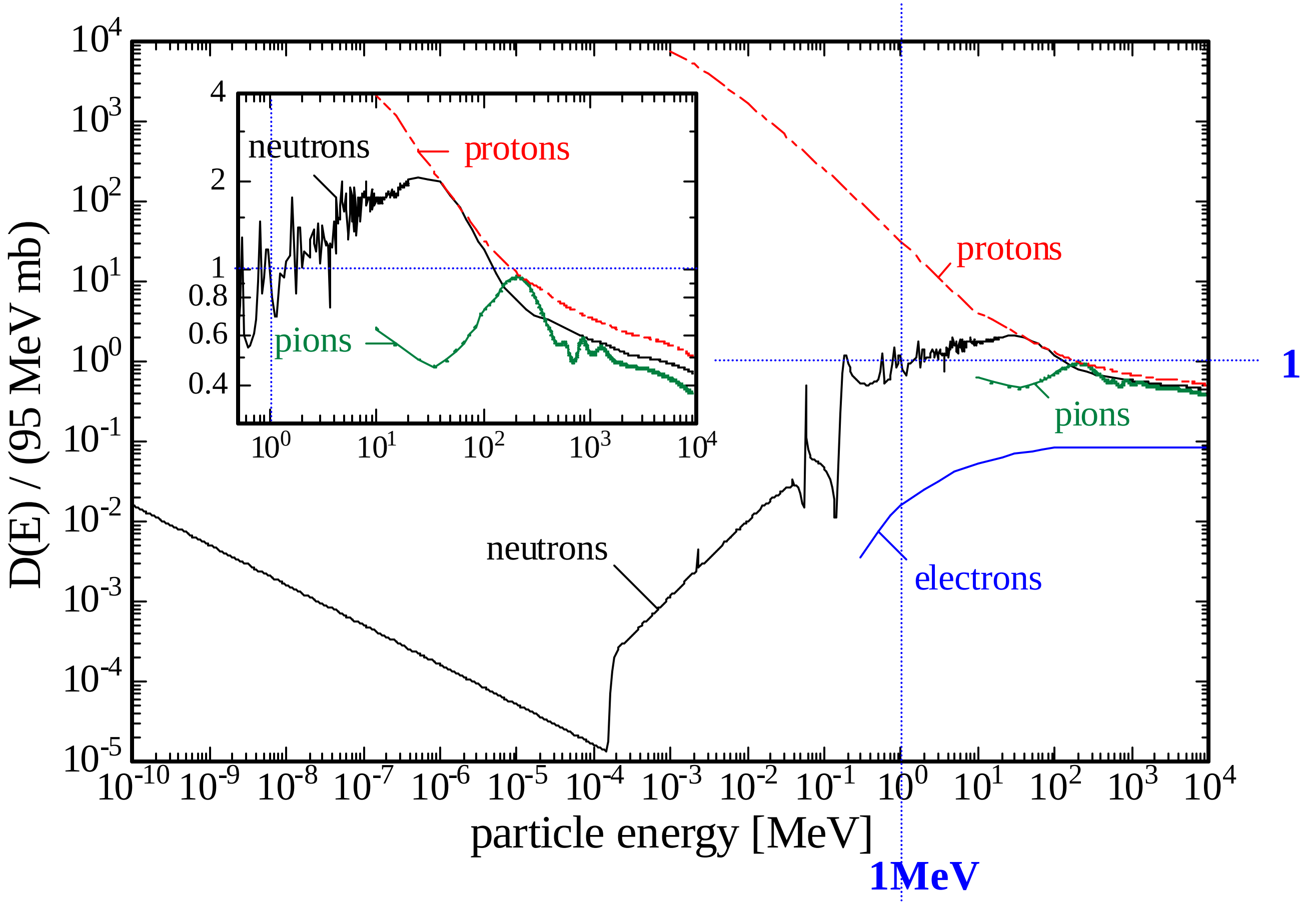


- ♦ **Promising new physical results are related to some very rarely produced particles**
  - High event rate (10^9/s at LHC), very good spatial resolution and fast signal read out required, can be fulfilled with silicon detectors, however:
- ♦ **Detectors and electronics will be harshly irradiated !**
  - ATLAS - Inner Detector: Φ_{eq} up to $3\times10^{14}cm^{-2}$ per operational year
  - 10 years of operation have to be guaranteed

Þ **What is the impact on silicon detectors ?**

Þ **How can we make silicon radiation harder ?**

Displacement damage functions



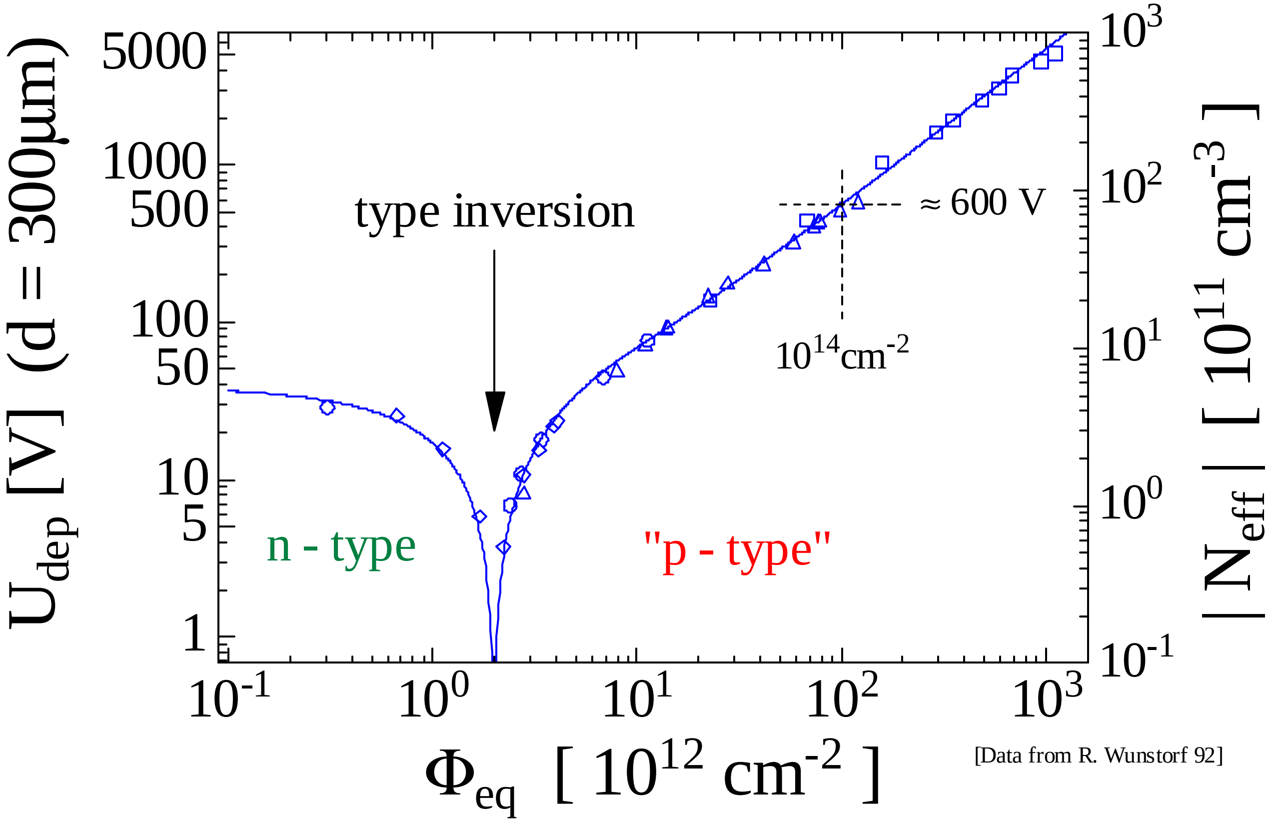
1 MeV neutron equivalent damage

- ♦ **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)

N_{eff} - effective doping concentration

$$\left|N_{eff}\right| \propto \frac{V_{dep}}{d^2}$$

- **N_{eff} positive - n-type silicon** (e.g. Phosphorus doped - Donor)
- **N_{eff} negative - p-type silicon** (e.g. Boron doped - Acceptor)
- **$|N_{eff}|$ proportional to depletion voltage and 1/(device thickness)^2**



[Data from R. Wunstorf 92]

The ROSE Collaboration CERN-RD48

(R&D On Silicon for future Experiments)

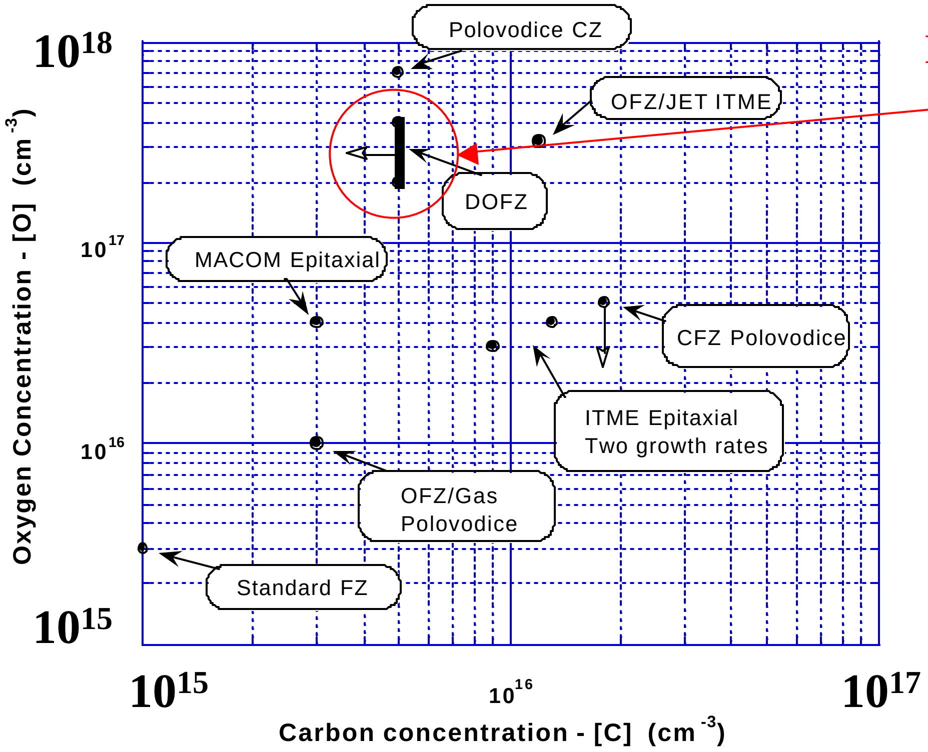
http://cern.ch/rd48

Formed 1995 and completed in 12/2000

38 HEP- and Semiconductor groups (125 persons), 7 associated companies and many observers.

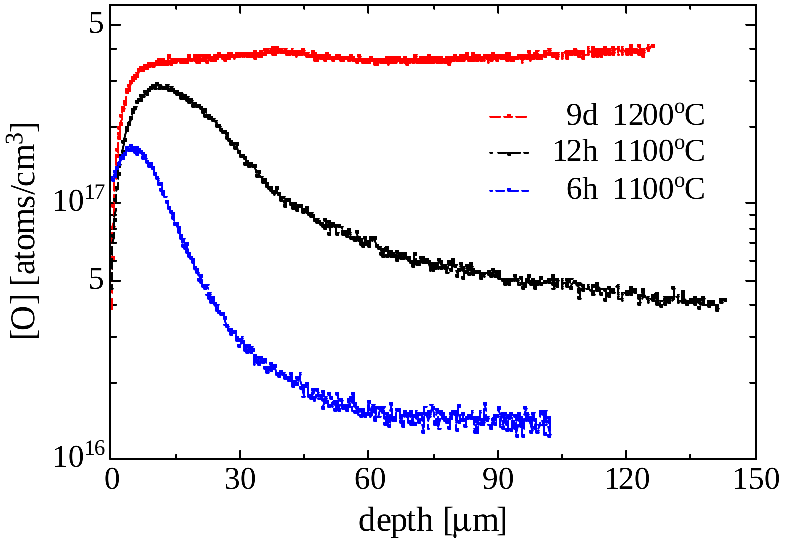
Success ⇒ Oxygenated silicon will be used for the pixel detectors of ATLAS (and CMS ?)

Defect engineering strategy : modify the defect kinetics in irradiated silicon in such a way that less macroscopic damage is produced ⇒ Oxygen and Carbon are main impurities



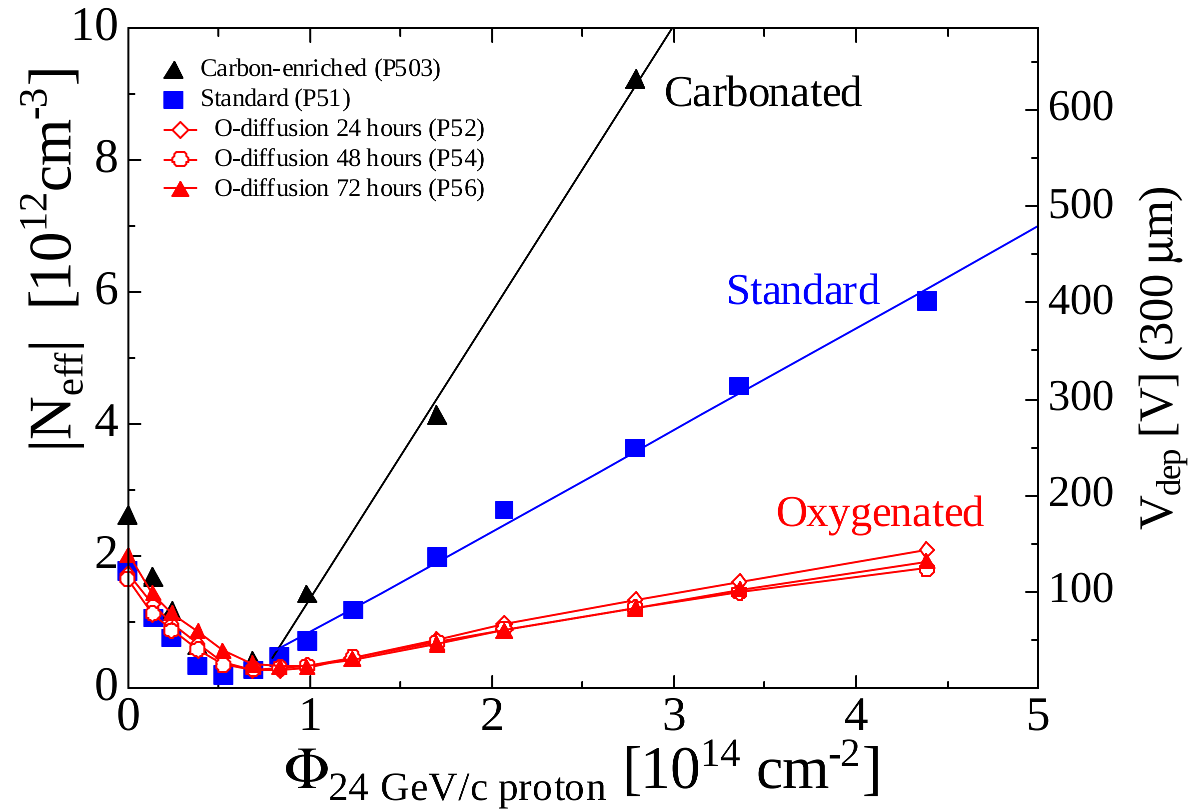
DOFZ - Diffusion Oxygenated Float Zone Silicon

Controlled introduction of oxygen,easily included in manufacturing process, low cost



Influence of Carbon and Oxygen concentration

24 GeV/c proton irradiation

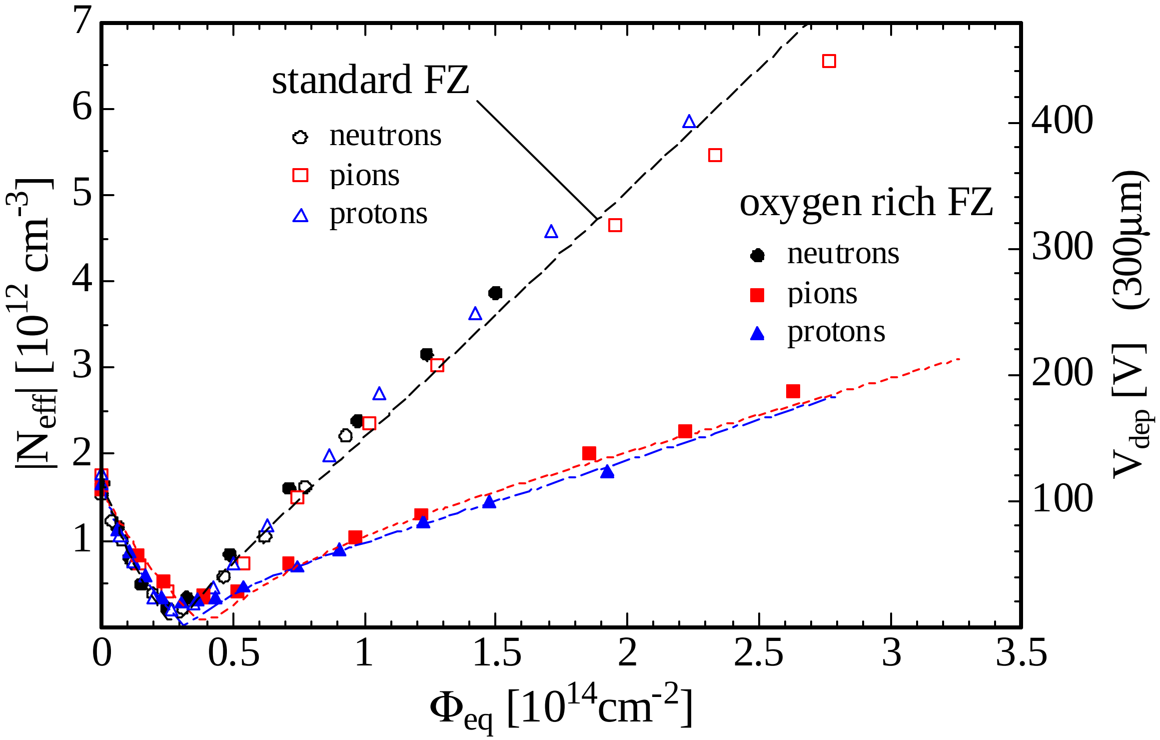


Compared to standard silicon:

- **High Carbon** Þ **less radiation tolerant**
- **High Oxygen** Þ **more radiation tolerant**

Oxygen and standard silicon
- Particle dependence -

23 GeV protons - 192 MeV pions - reactor neutrons

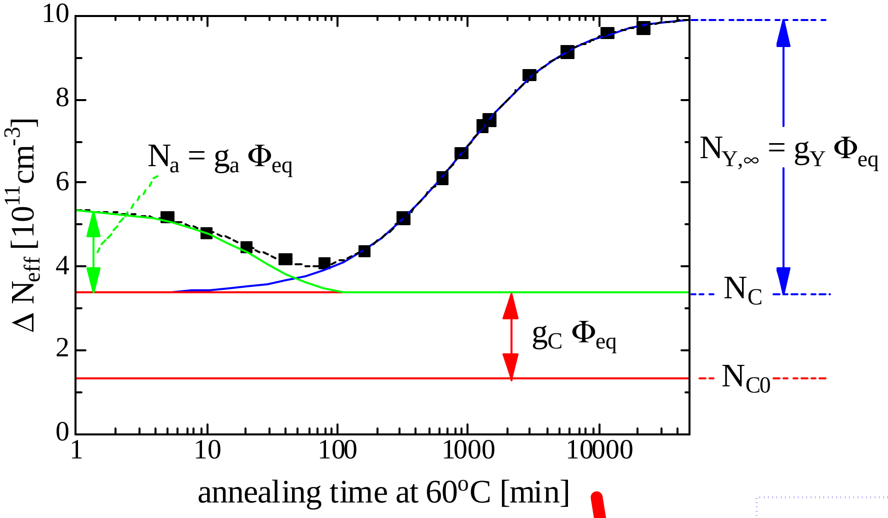


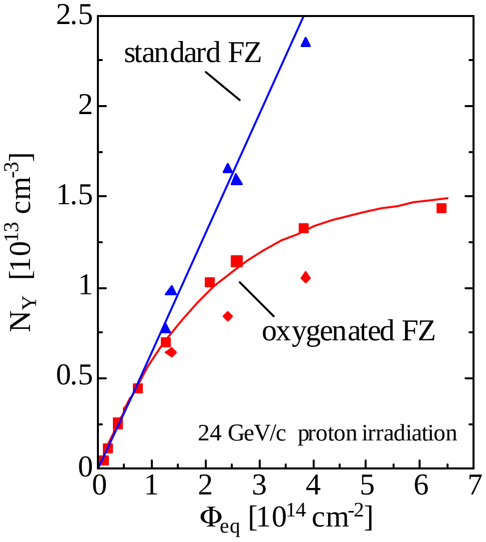
- ♦ **Strong improvement for pions and protons**
- ♦ **Almost no improvement for neutrons Þ <u>“Proton-Neutron-Puzzle”</u>**

Annealing after 24 GeV/c proton irradiation

$$\Delta N_{eff}\left(\Phi_{eq},t\right)=\underline{N_a\left(\Phi_{eq},t\right)}+\underline{N_C\left(\Phi_{eq}\right)}+\underline{N_Y\left(\Phi_{eq},t\right)}$$

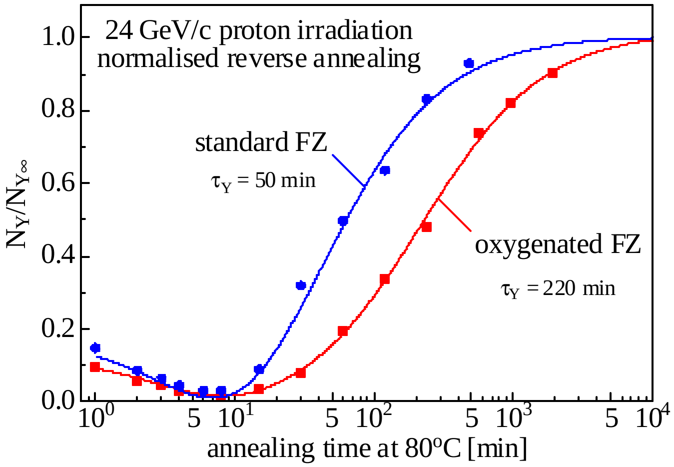
beneficial annealing / stable damage / reverse annealing

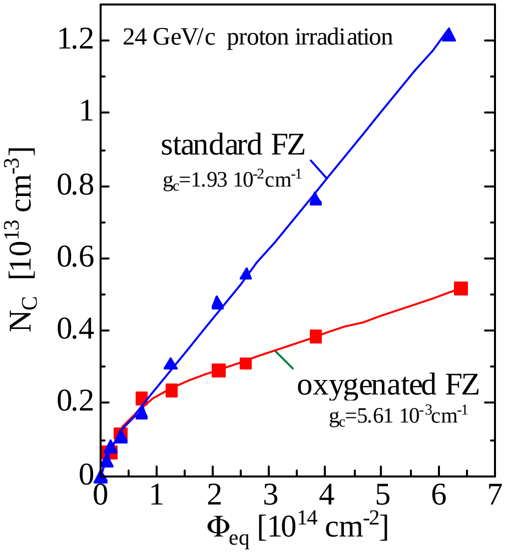




Saturation of reverse annealing

delayed reverse annealing





Stable damage reduced by a factor of 3

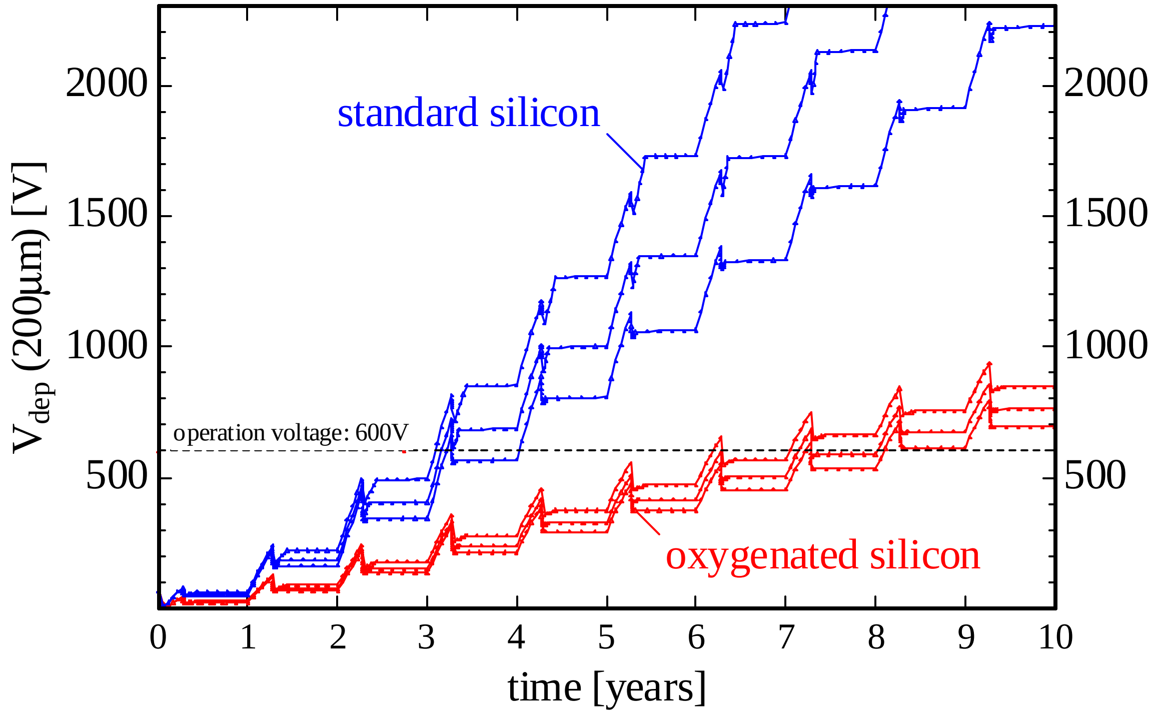
Damage Projection - ATLAS Pixel Detector - B-layer (4cm)

♦ **Radiation level:**

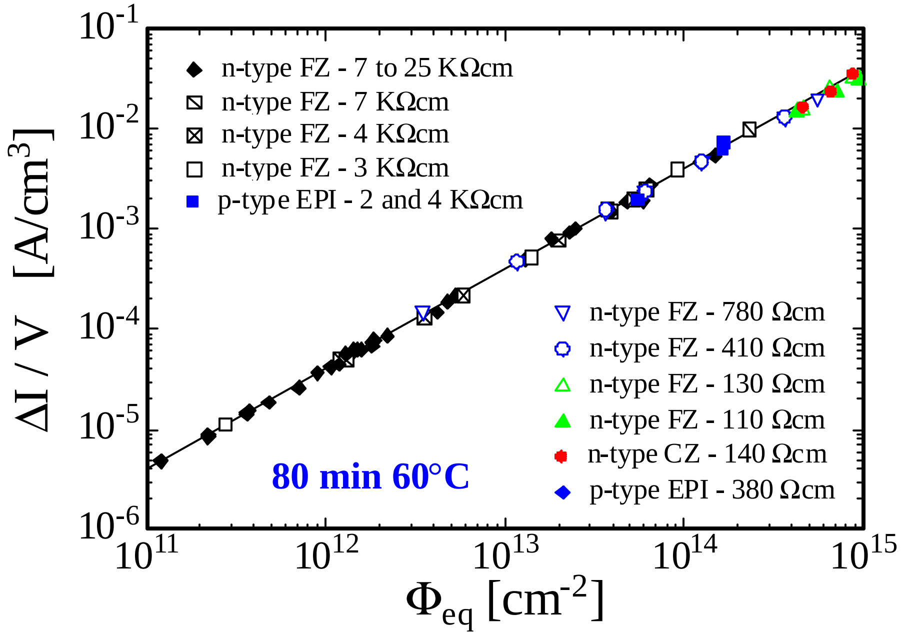
- F_{eq}**(year) = 3.5 ´ 10^{14} cm^{-2}** (full luminosity)
  > 85% charged hadrons

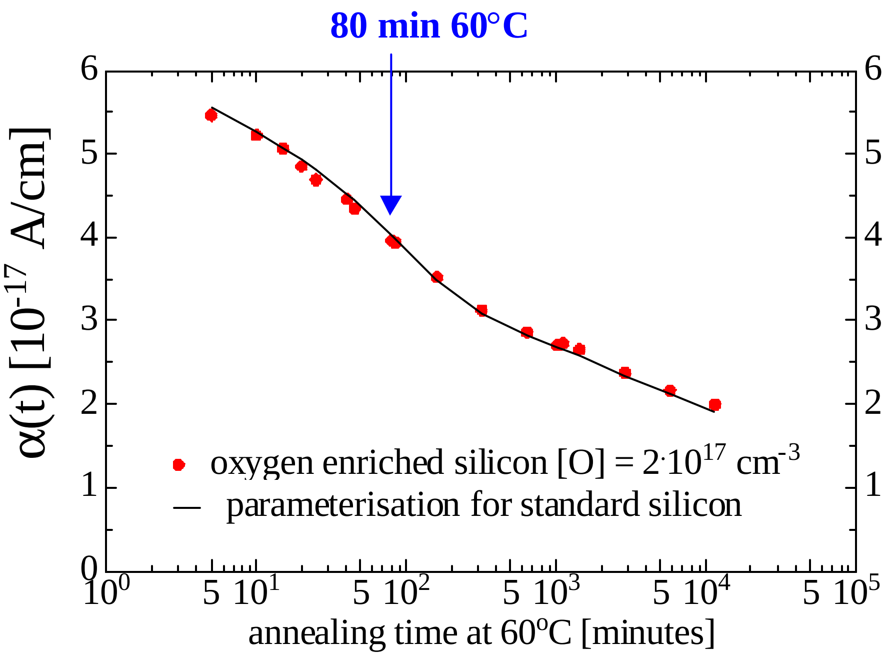
♦ **Three scenario:**

- **1 year = 100 days beam (-7°C)**
  (1) 3 days 20°C and 14 days 17°C
  (2) 30 days 20°C
  (3) 60 days 20°C
  Rest of the year: no beam (-7°C)



Leakage Current Annealing - Oxygenated Silicon



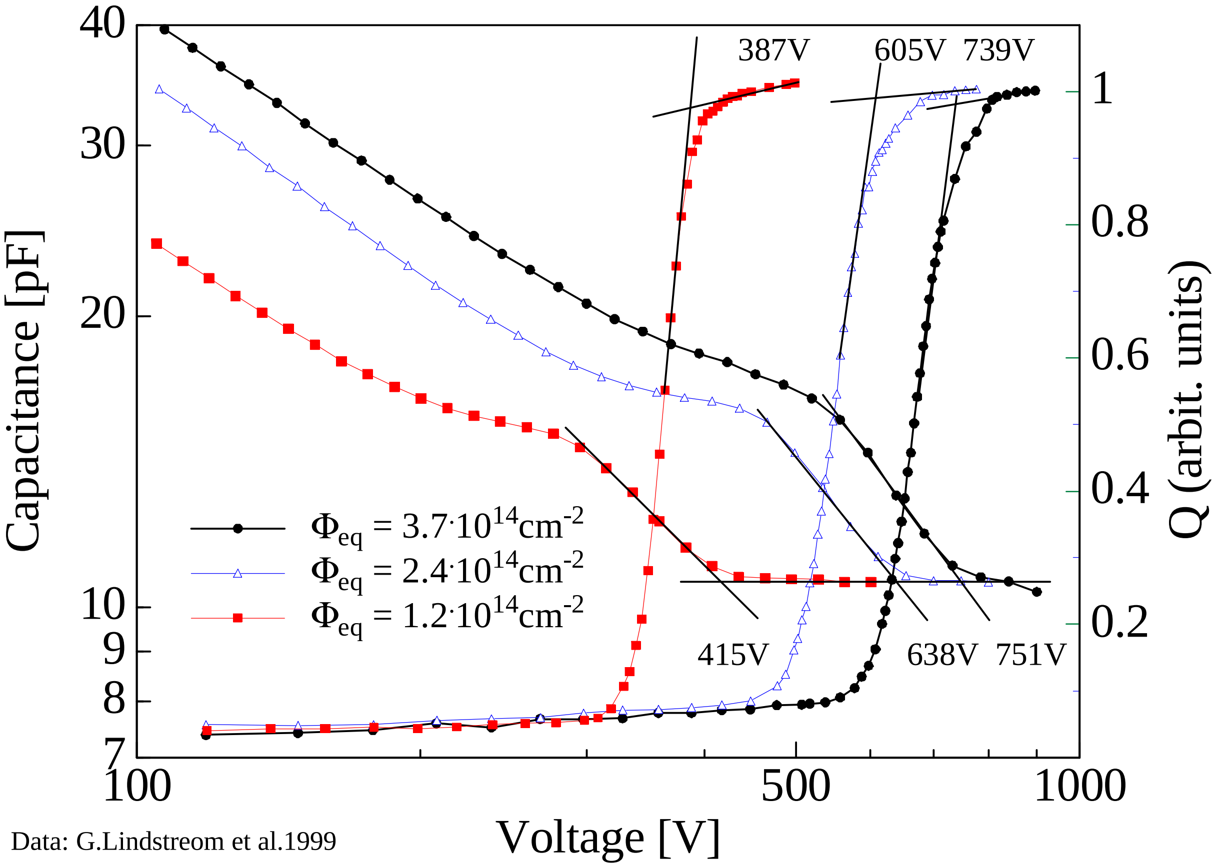


- **Damage parameter α:** $\alpha = \dfrac{\Delta I}{V \cdot \Phi_{eq}}$ **independent of Φ_{eq}, used for fluence (NIEL) calibration**
- **Oxygenated and Standard Silicon show same annealing**

TCT and CV measurements

TCT - Transient Charge Technique

- proton irradiated oxygenated silicon -

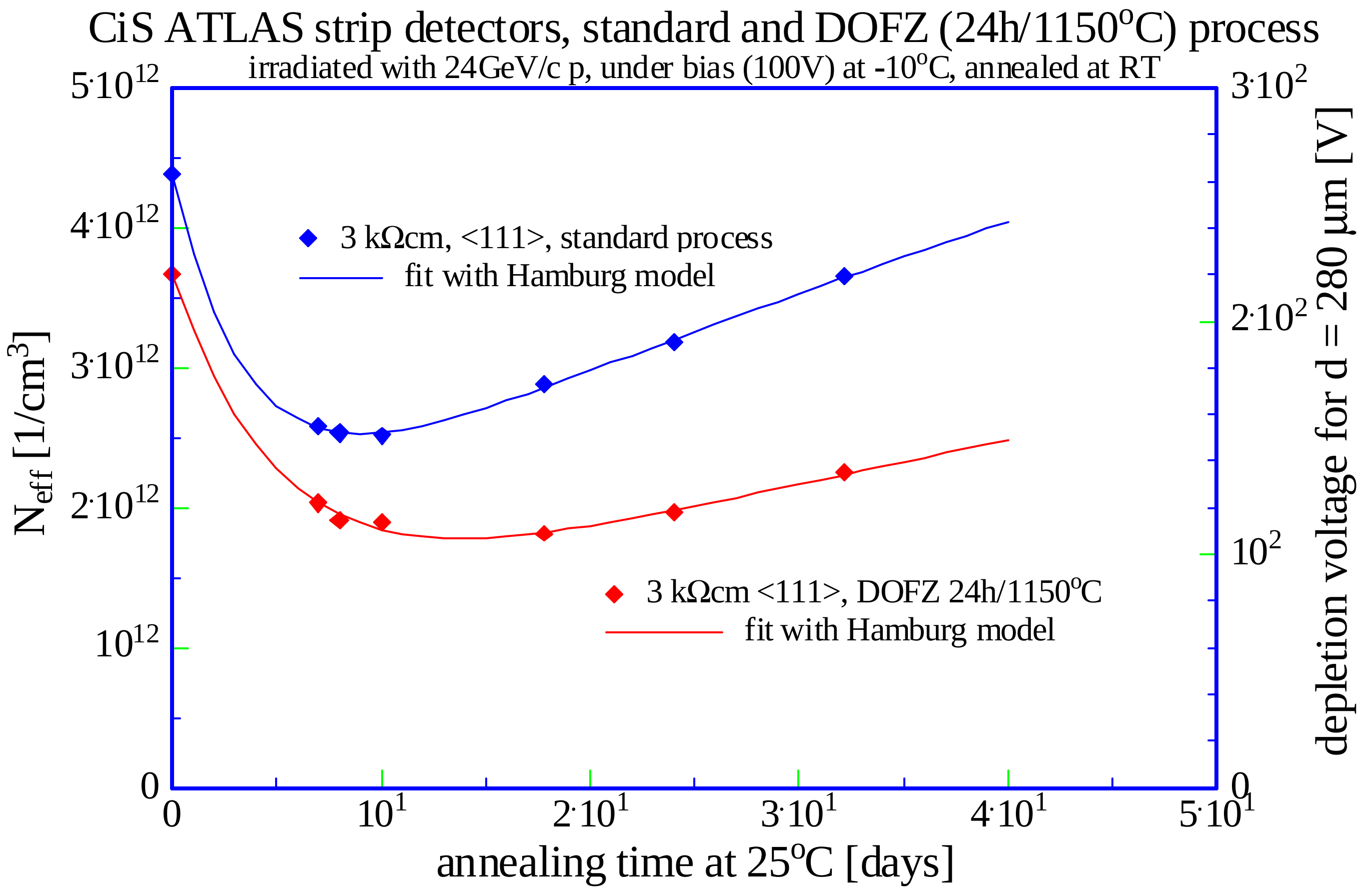


Data: G.Lindstreom et al.1999

- Measured after complete annealing (type inverted detector)
- V_{dep}: Coincidence between CV and TCT
- TCT: 670nm, front illumination

Oxygenated and Standard Strip Detectors

3´ 10^{14} p/cm^2 (24 GeV/c protons)



data from L. Andricek, MPI Munich

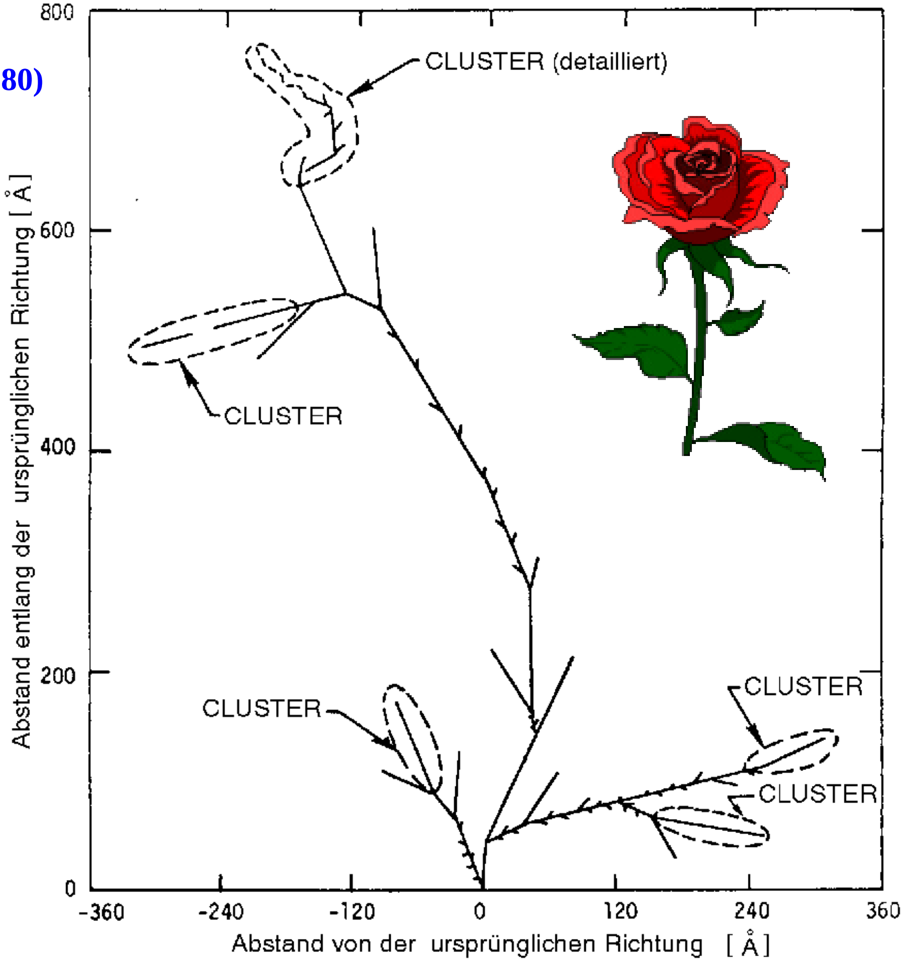
Charge Collection Efficiency: oxygenated and standard 92%

(Sr90, SCT 128a, analogue, 20ns rise time)

Primary Damage

- **PKA - Primary Knock on Atom**
- **Simulation**
  - **50 KeV PKA** (average recoil energy for PKA produced by 1 MeV neutrons)
- **Displacement threshold in Silicon:**
  - **Single lattice atom (Frenkel pair):** **E_d » 25 eV**
  - **Defect cluster** **E_C » 5 keV**
- **Neutrons (elastic scattering)**
  - **E_n > 185 eV for single displacement**
  - **E_n > 35 keV for cluster**
- **Electrons**
  - **E_e > 255 keV for single displacement**
  - **E_e > 8 MeV for cluster**
- **60Co-gammas**
  - **Compton Electrons with max. E_g »1 MeV (no cluster production)**

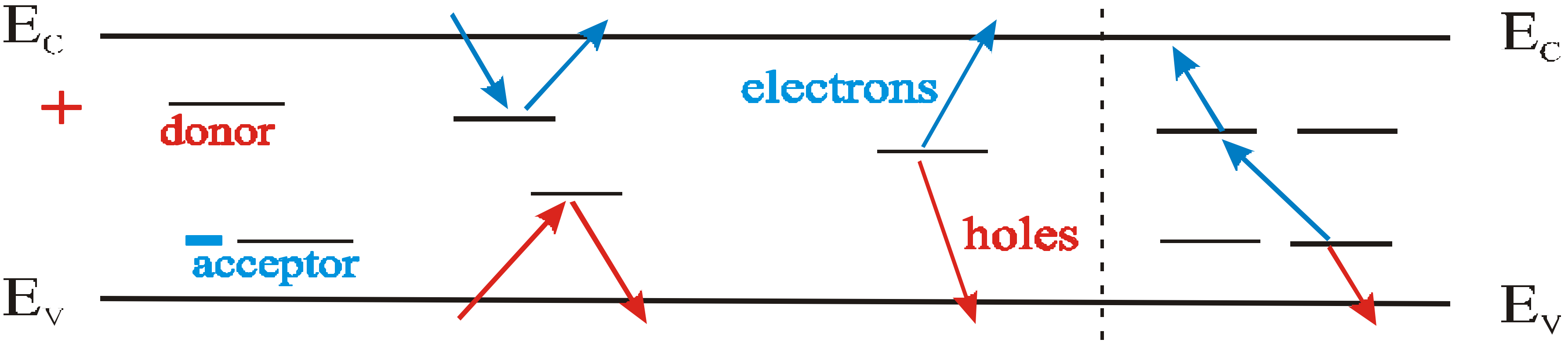
(Fig.: van Lint 1980)



Impact of Defects on Detector properties

Shockley-Read-Hall statistics
(standard theory)

Inter-center charge
transfer model
(inside clusters only)



charged defects
⇒ **N_{eff} , V_{dep}**
e.g. donors in upper and acceptors in lower half of band gap

Trapping (e and h)
⇒ **CCE**
shallow defects do not contribute at room temperature due to fast detrapping

generation
⇒ **leakage current**
Levels close to midgap most effective

enhanced generation
⇒ **leakage current**
⇒ **space charge**

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

$\sigma_{n,p}$: cross sections **ΔE : ionization energy** **N_t : concentration**

Microscopic understanding
- simplified ! -

♦ V_2O-model

Higher oxygen content Þ less negative space charge

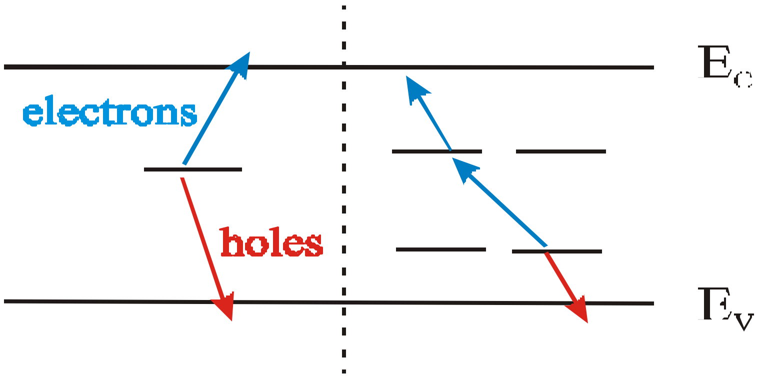
V → **O** ⟶ **VO** **(not harmful at room temperature)**

V → **VO** ⟶ **V_2O** **(negative space charge)**

♦ Intercenter charge transfer – model

Enhanced charge carrier generation inside clusters
Þ **depending strongly on the <u>defect density in the clusters</u>**

Shockley-Read-Hall
statistics
(standard theory)

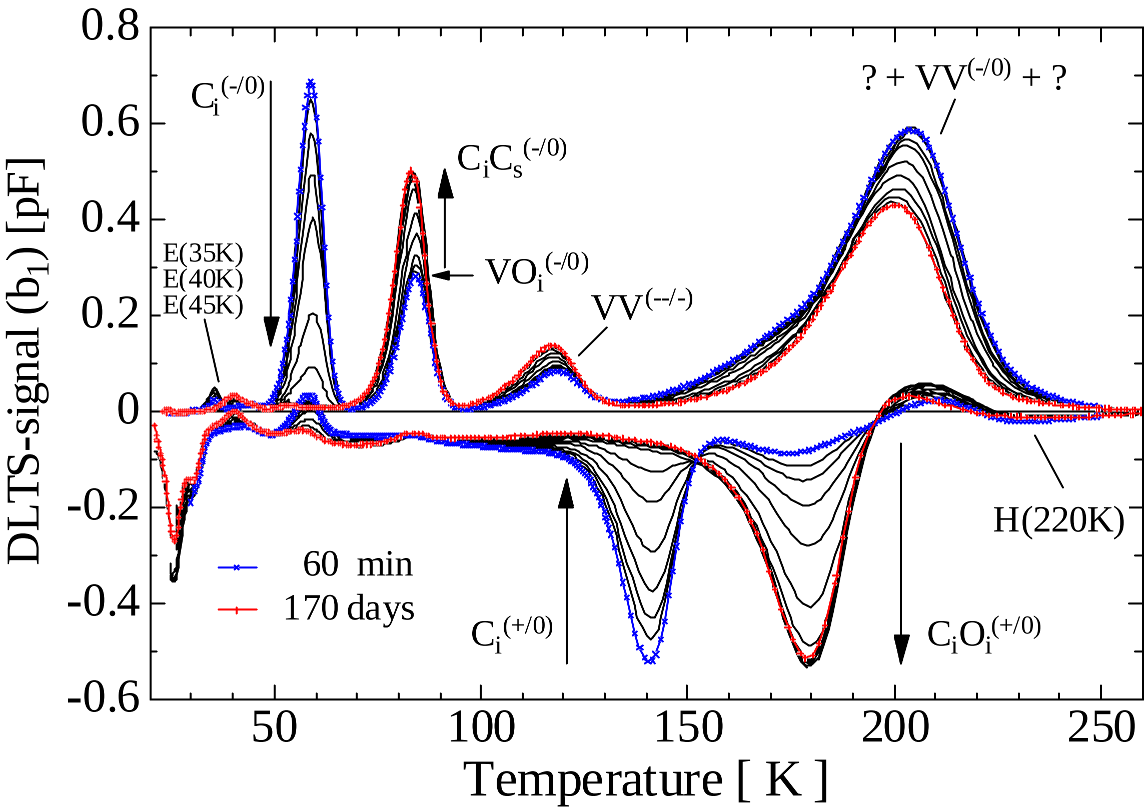


Inter-center charge
transfer model
(inside clusters only)

Example of defect spectroscopy

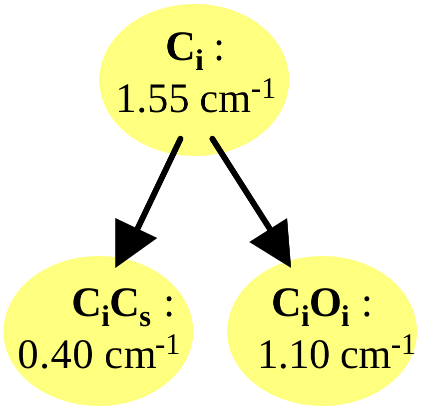
- DLTS, room temperature annealing -

- neutron irradiated -



Introduction Rates

N_t/F_{eq}:



C_i : 1.55 cm^{-1}

C_iC_s : 0.40 cm^{-1}

C_iO_i : 1.10 cm^{-1}

- **Introduction rates of main defects** » **1 cm^{-1}**
- **Introduction rate of negative space charge** » **0.05 cm^{-1}**

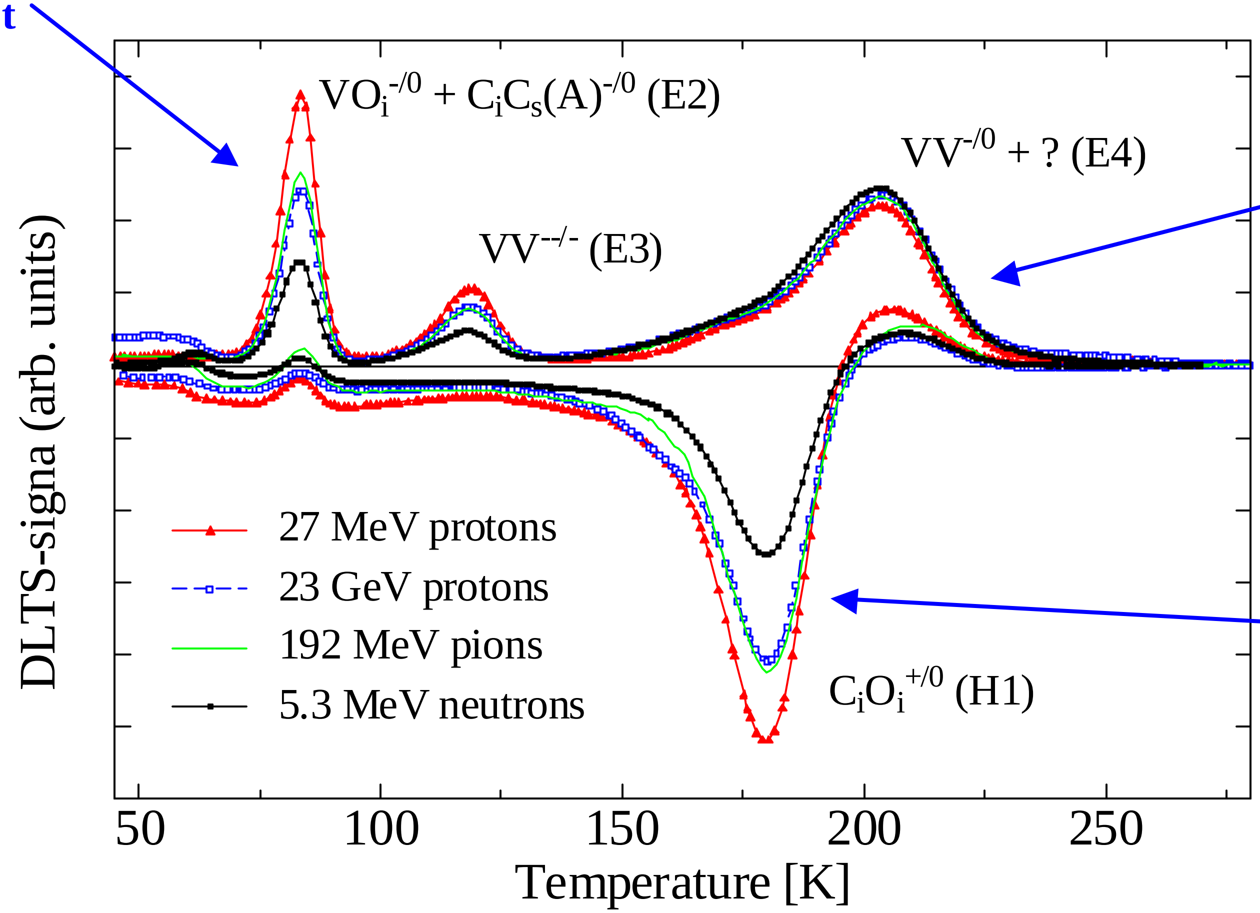
example : F_{eq} = 1´ 10^{14} cm^{-2}

defects » 1´ 10^{14} cm^{-3}

space charge » 5´ 10^{12}cm^{-3}

Dependence on Particle Type

Point defect



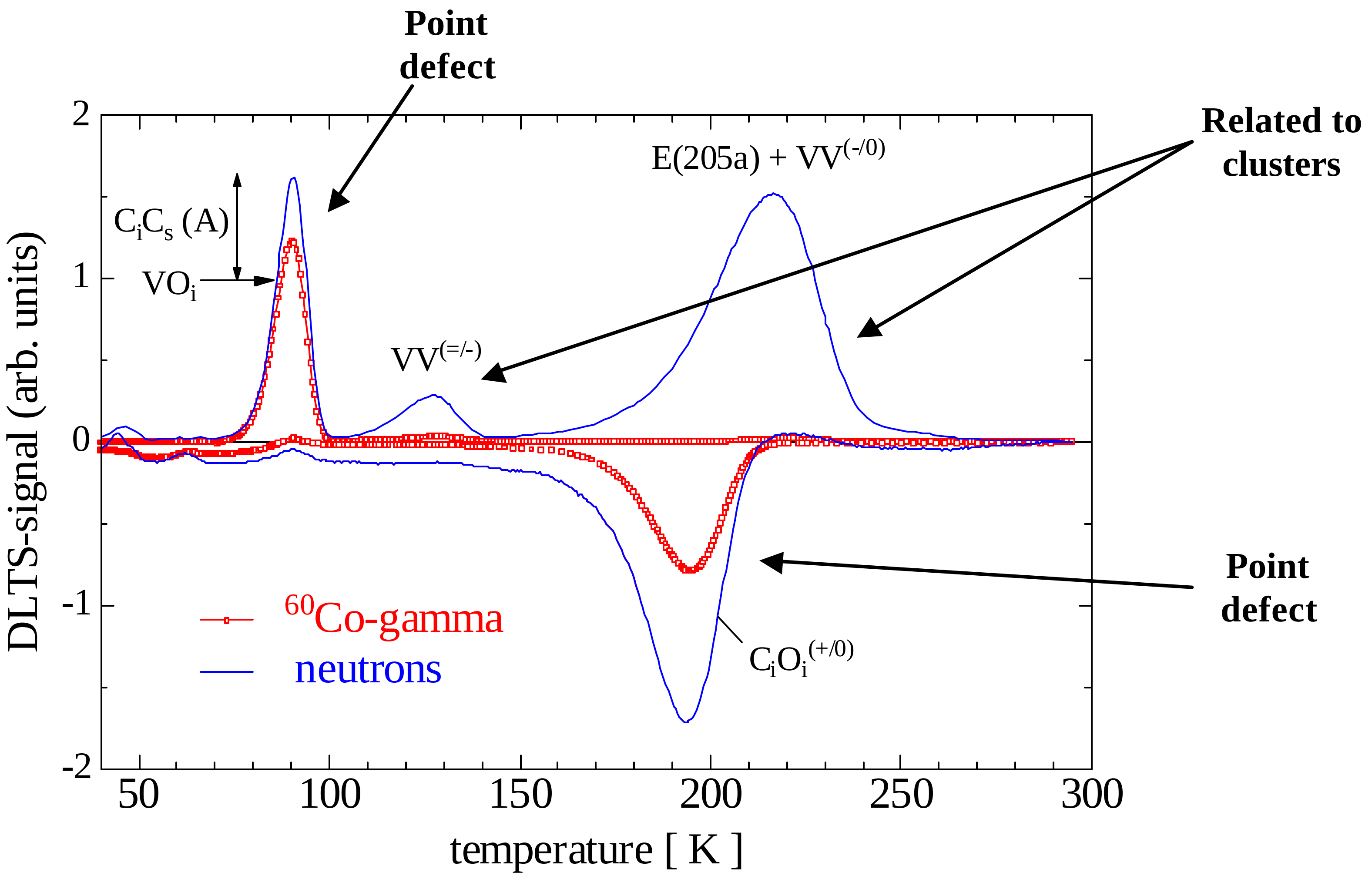
Related to clusters

Point defect

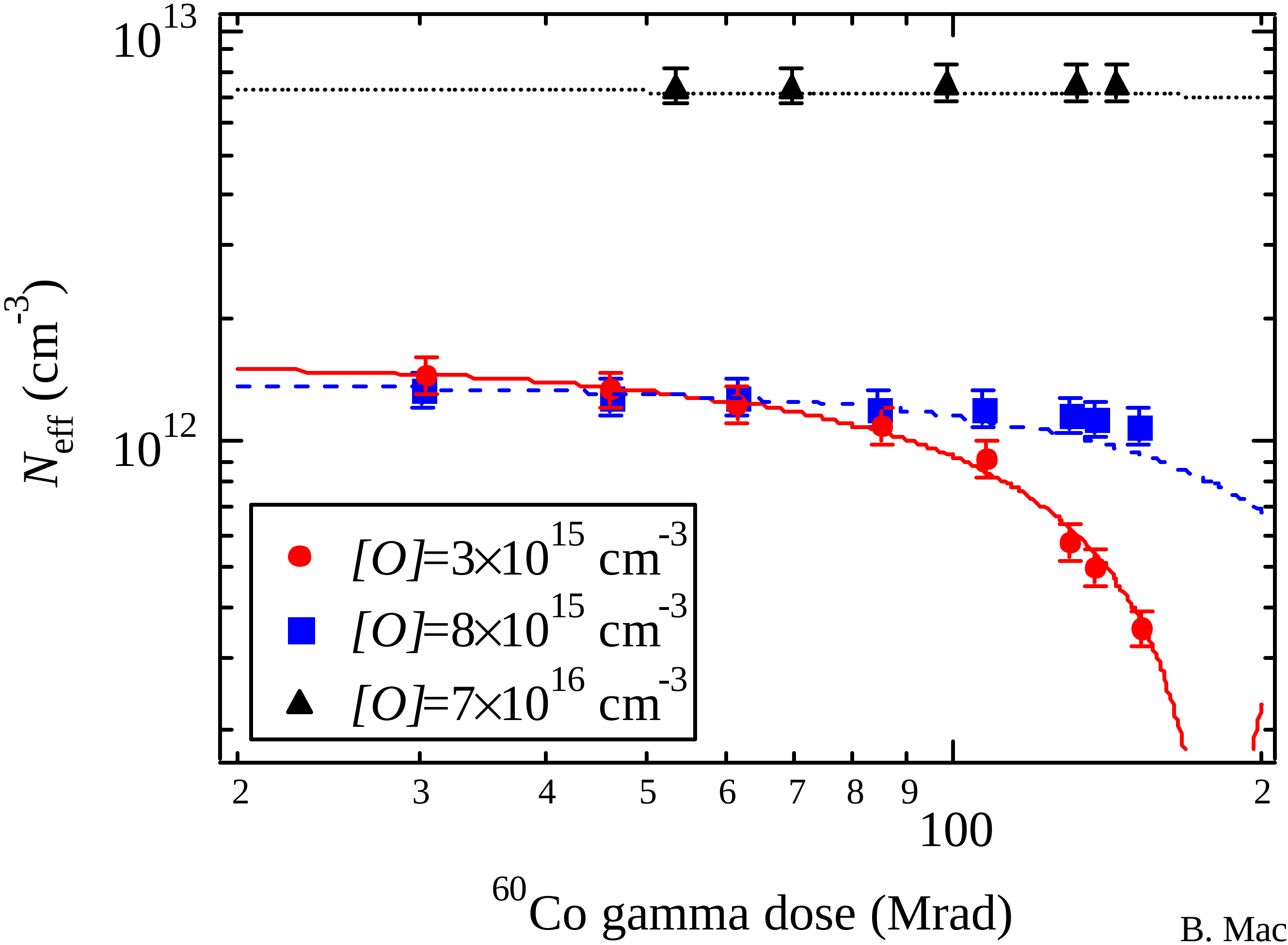
- **Charged hadrons create more point defects than neutrons**
- **27 MeV protons create more point defects than 23 GeV protons**

Gamma-irradiation Û Neutron-irradiation

only point defects Û cluster and point defects

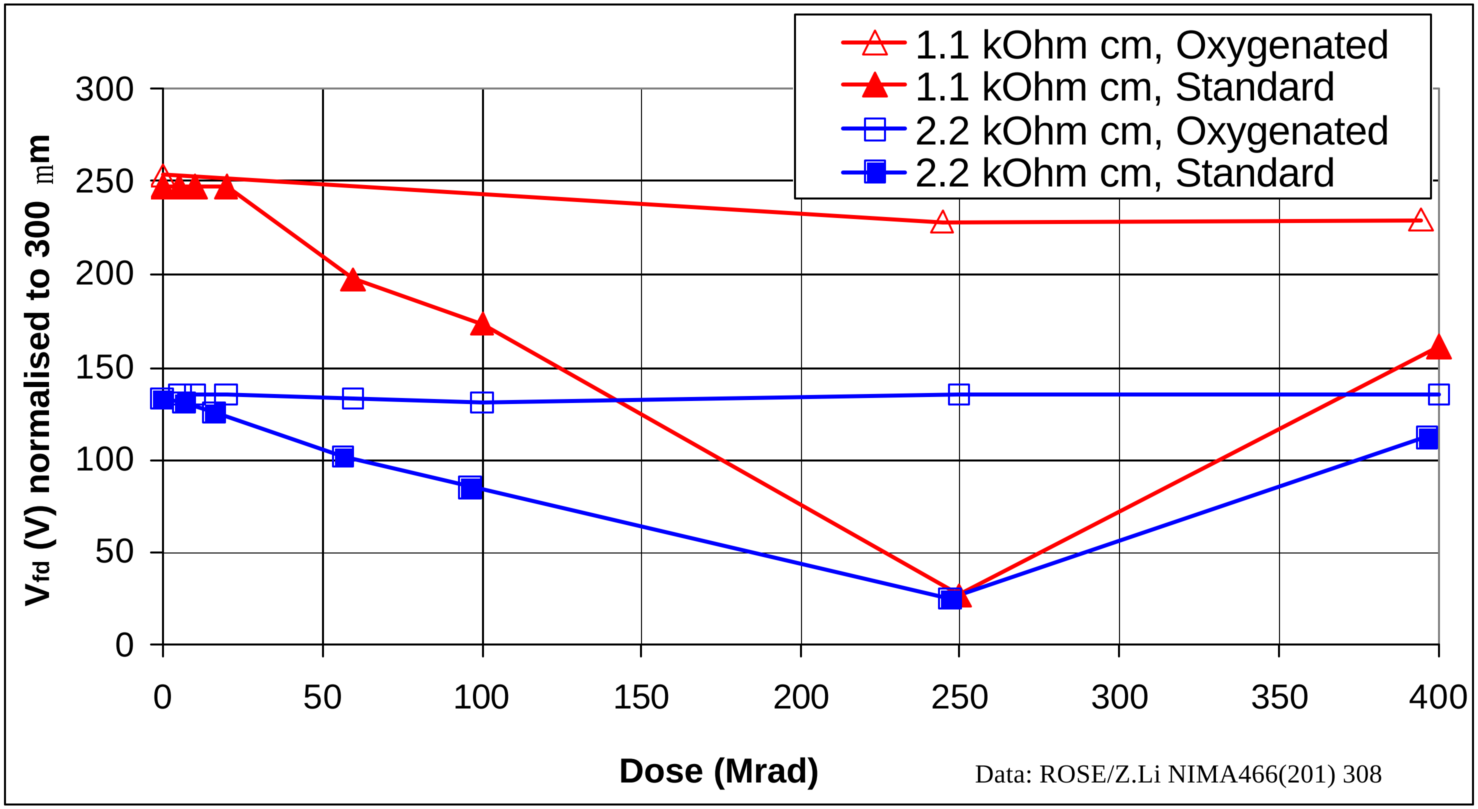


^{60}Co gamma irradiation
- Model predictions and experimental data -



B. MacEvoy et al.

^{60}Co-g Irradiation



Data: ROSE/Z.Li NIMA466(201) 308

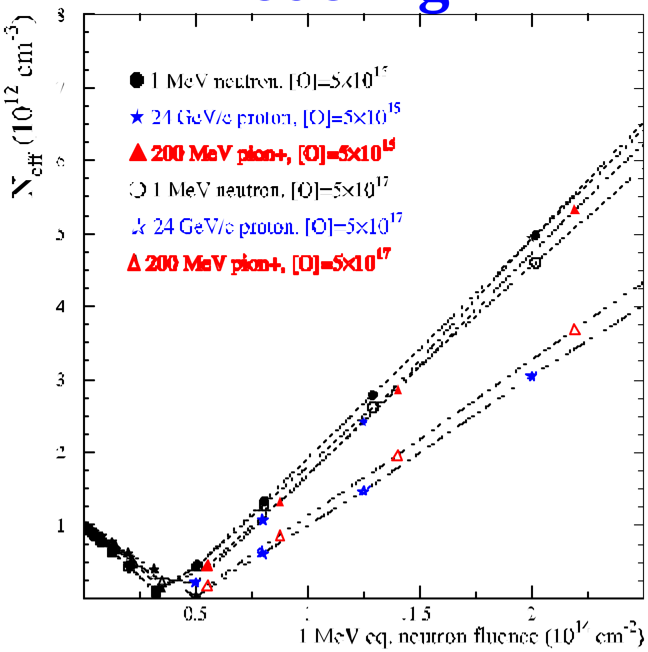
- **For DOFZ silicon Vdep (resp. N_{eff}) remains constant whereas standard silicon shows type inversion**
- For both: There is no annealing at room temperature !

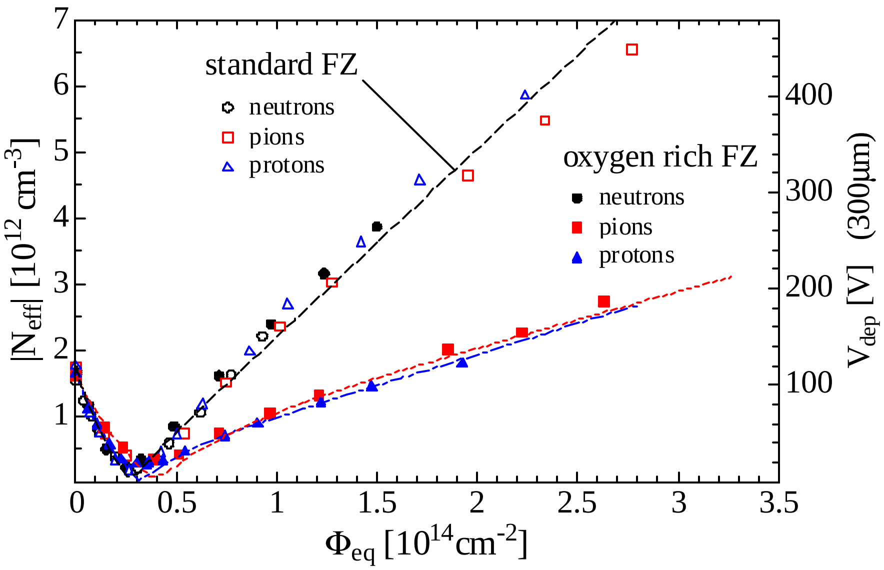
Simulations of NIEL and Defect Formation

Mika Huhtinen (CERN) - **ROSE/TechnicalNote/2001-02 - http://cern.ch/rd48**

<u>Complex</u> modeling of: 1. Hadronic interactions (FLUKA, …)
2. Transport of recoil ions (TRIM)
3. Defect formation within primary damage region (clusters)
4. Defect production outside of clusters (point defects)
5. Macroscopic detector properties
(V$_2$O and intercenter charge transfer models)

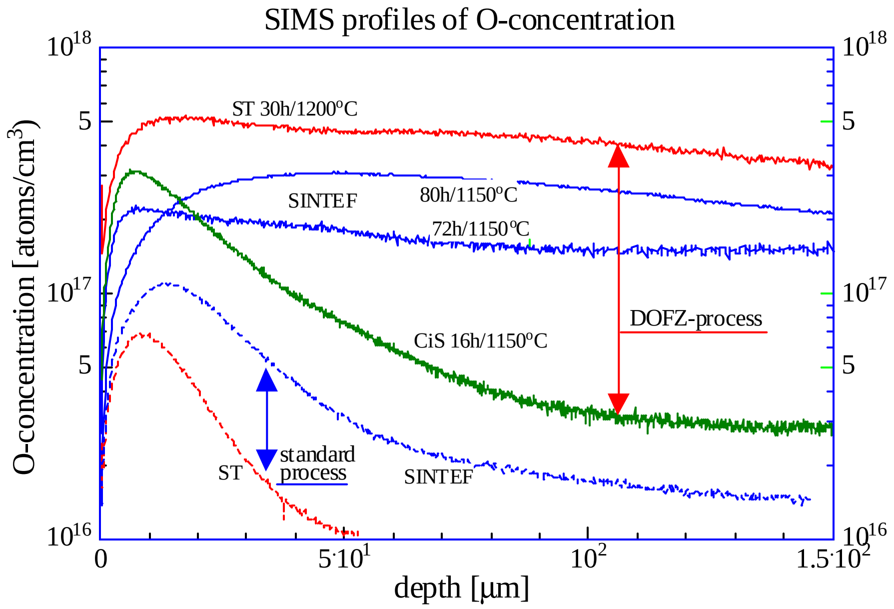
Modeling Û **Measurement**

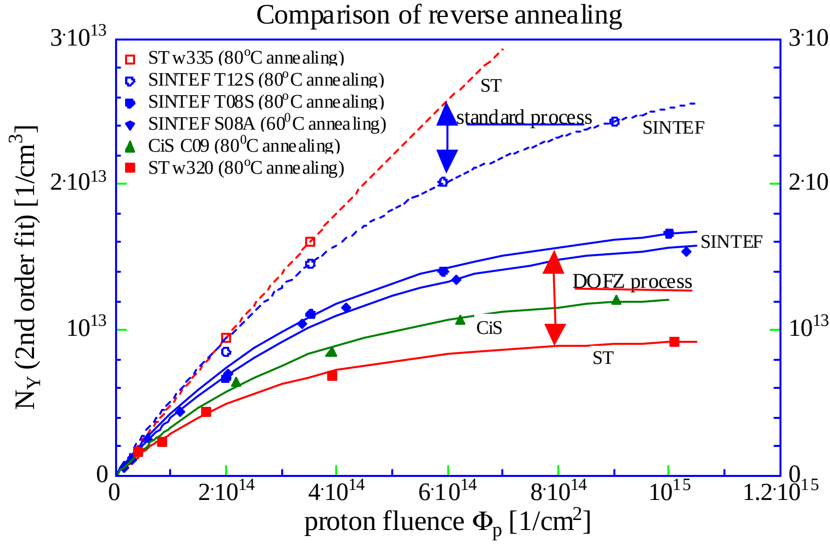




♦ **“Proton - Neutron - Puzzle” can be explained qualitatively by model**

Influence of oxygenation on reverse annealing for processing by different manufacturers


SIMS profiles of O-concentration


Comparison of reverse annealing

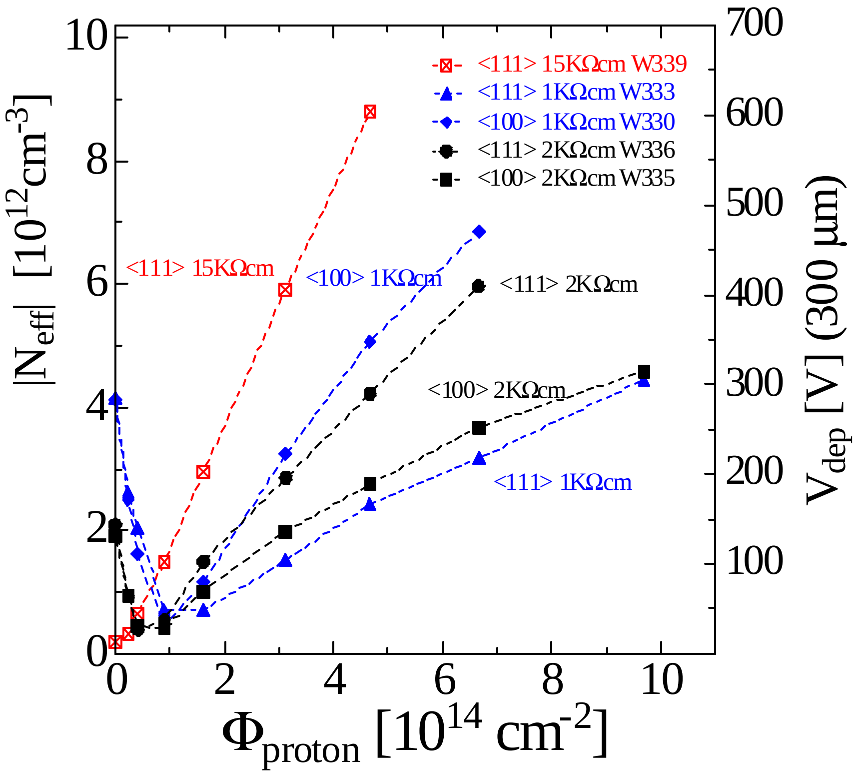
- **Oxygenation leads to large reduction of reverse annealing**

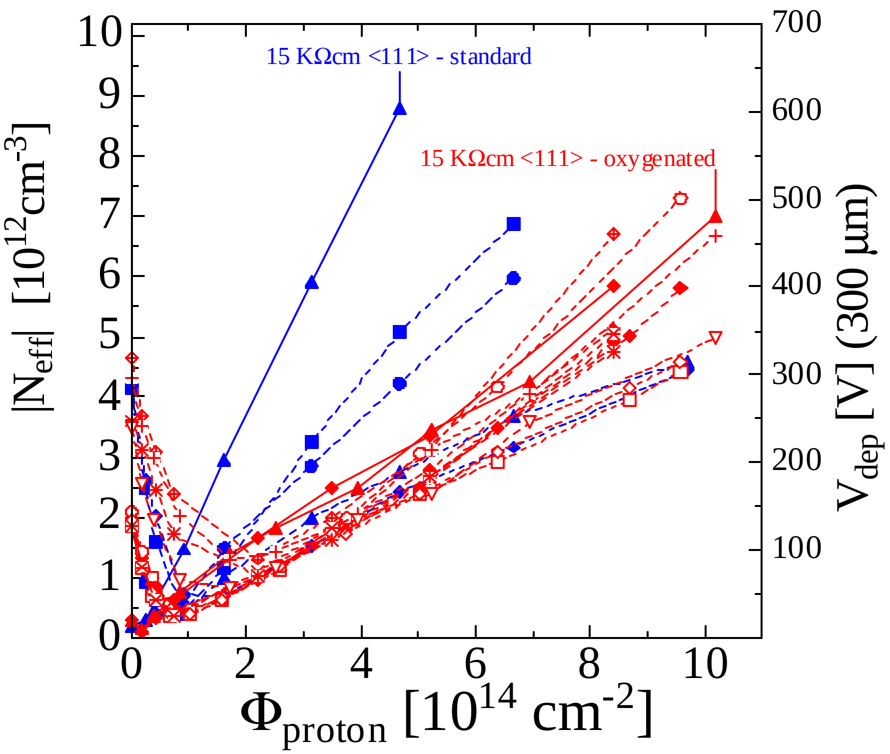
Silicon: Wacker FZ; <111> and <100> ; 1, 2 and 15 KWcm
Devices: ST Microelectronics; ROSE - mask

Variation of standard silicon

Oxygen diffusion

Homogeneity of oxgenated silicon





- **Strong variation of standard silicon observed**
- **Most probable reason** (indicated by SIMS-measurements): **Carbon content**
- **After oxygenation (same material!) only small variation**

Summary: Key scientific results

♦ Macroscopic Damage Effects

- **Leakage current** damage parameter is material independent (no impurity, resistivity or conduction type dependence)
- Effective doping changes can be improved by oxygenation of the material (**factor 3 for stable damage parameter g_c**). Such improvement is only observed when the radiation environment contains a significant charged particle component.
- **Reverse annealing saturates** at high fluences (2×10^{14}p/cm^2) for oxygen enriched silicon. **Time constant larger by a factor of 2-4** allowing detectors to remain at room temperature for longer periods during maintenance periods: **additional safety margin**

♦ Damage at the Microscopic Level / Simulations

- **Reverse annealing** and **leakage current** are **linked to defect clusters**
- Correlations between microscopic defects and macroscopic parameters found
- **Charged particle irradiation produces more point defects** than irradiation with reactor energy neutrons
- **Defect kinetics models** and device models can **predict macroscopic behavior qualitatively. However, some model predictions have to be proved.**

Summary: Key technological results

DOFZ – Diffusion Oxygenated Float Zone

♦ Oxygen enrichment

- Many oxygenation techniques tested. Final solution: Diffusion of oxygen from Si/SiO$_2$-interface using high temperature drive in (1150°C in Quartz, up to 1200°C in SiC-tube), method applicable for any wafer as part of normal process.
- Diffusion Technology has been successfully transferred to several silicon detector manufacturers (SINTEF, Micron, ST, CiS, ..) and full-scale microstrip detectors produced.

♦ Quality of DOFZ-detectors vs. standard process:

- Diffusion Oxygenated Float Zone wafers produce detectors which prior to irradiation are no different to those produced on standard material.
- Irradiated standard and oxygenated test structures show **same increase in interface generation current and oxide charges**.
- **Trapping:** Up to a fluence of 2 x 10^{14} cm^{2} (24GeV/c p) **no difference** between DOFZ and FZ observed (ATLAS strip detector).

Open Questions

- **Which O diffusion is optimal ?**
  - Optimization of the DOFZ process (diffusion temperature and duration) in correlation with resulting radiation hardening needs more study (collaboration with manufacturers).
- **Reason for the strong variation of standard silicon ?**
  - After proton irradiation a broad variation with respect to the radiation hardness of “standard silicon” has been observed while oxygenated silicon showed reproducible results.
- **Saturation of reverse annealing ?**
  - The beneficial effect of oxygen on the reverse annealing needs more work. As this effect is crucial to the maximum maintenance period that can be used by the experiments, it needs further investigation. This work is extremely time consuming.
- **Transfer of results to real strip and pixel detectors ?**
  - The physics of bulk damage should be the same in full-scale detectors as in simple diodes. Nevertheless, comparisons between both types of devices esp. regarding the charge collection efficiency need more study.
- **The proton – neutron puzzle: Violation of NIEL ?**
  - The violation of NIEL by charged hadrons in oxygenated material needs further study. Testing with radiation sources that better represent the environment in the LHC experiments needs to be performed. The neutron spectrum in the LHC experiments extends to much higher energy than for reactor sources.
- **Which defects are responsible for the different macroscopic changes ?**