Radiation Damage in Silicon Detectors
- An introduction for non-specialists -

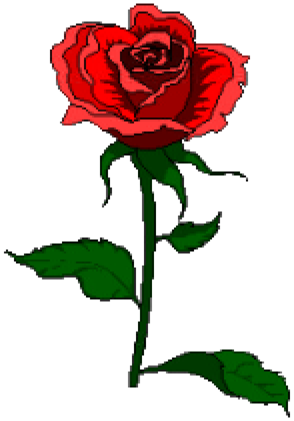
Michael Moll

CERN EP - Geneva

ROSE Collaboration (CERN RD48)

ROSE - Research and Development on Silicon Detectors for Future Experiments

http://www.cern.ch/rd48



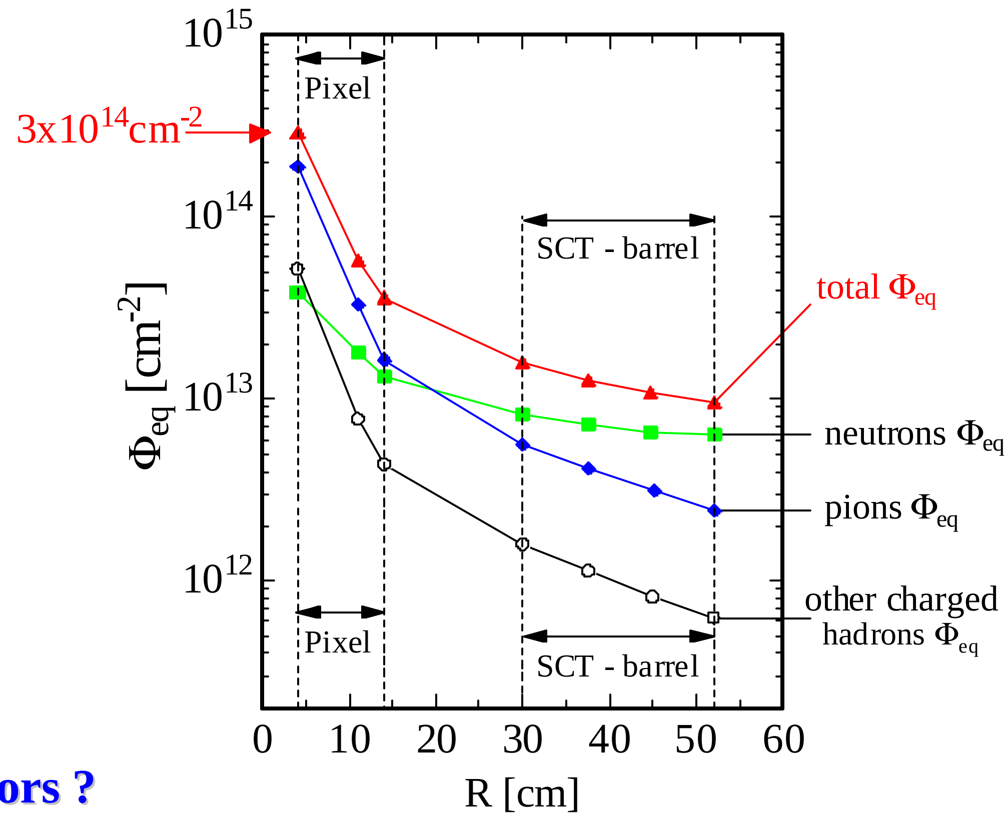
Outline

- **Motivation - The challenge of LHC-experiments**
- **Radiation induced changes in silicon detector properties**
  - Increase of leakage current
  - Change of effective doping concentration (depletion voltage)
  - Decrease of charge collection efficiency
- **Radiation hard silicon detectors**
  - Oxygen enriched silicon
- **Damage projections for LHC operation**
- **Microscopic defects in silicon**
- **Relation between microscopic and macroscopic properties of the damage**
- **Summary and Outlook**

Motivation

- ♦ **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

ATLAS - Inner Detector

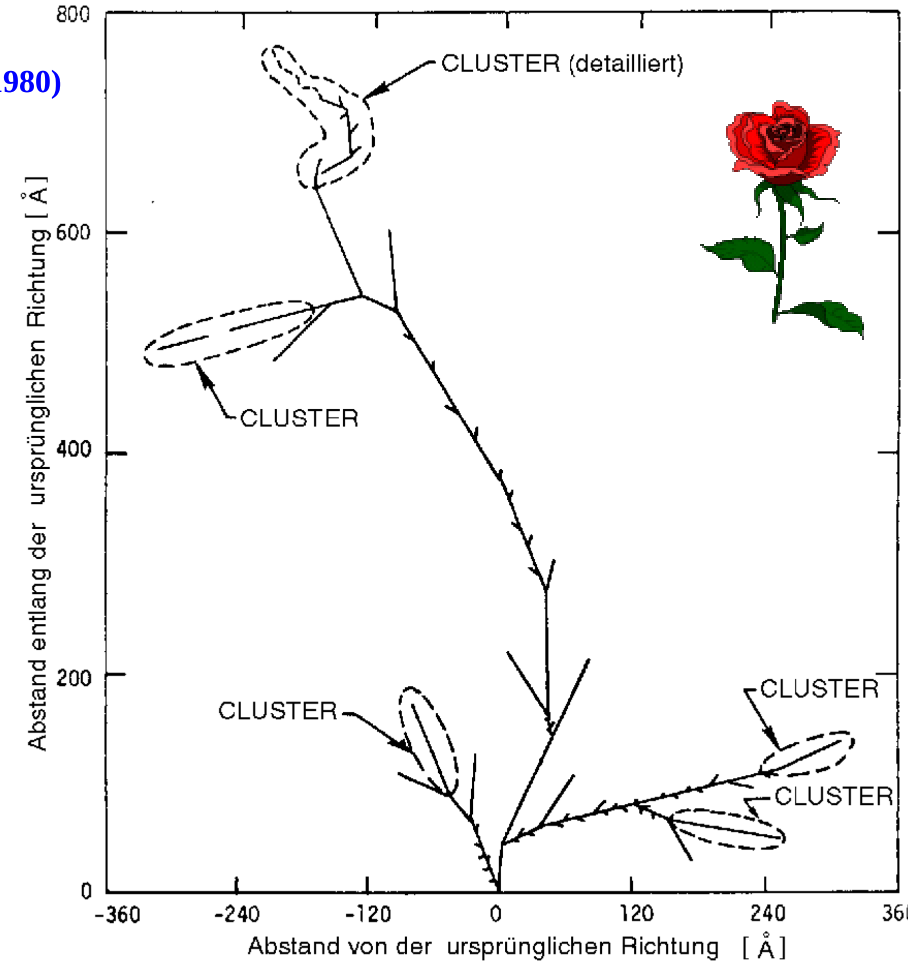


Þ **What is the impact on silicon detectors ?**

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

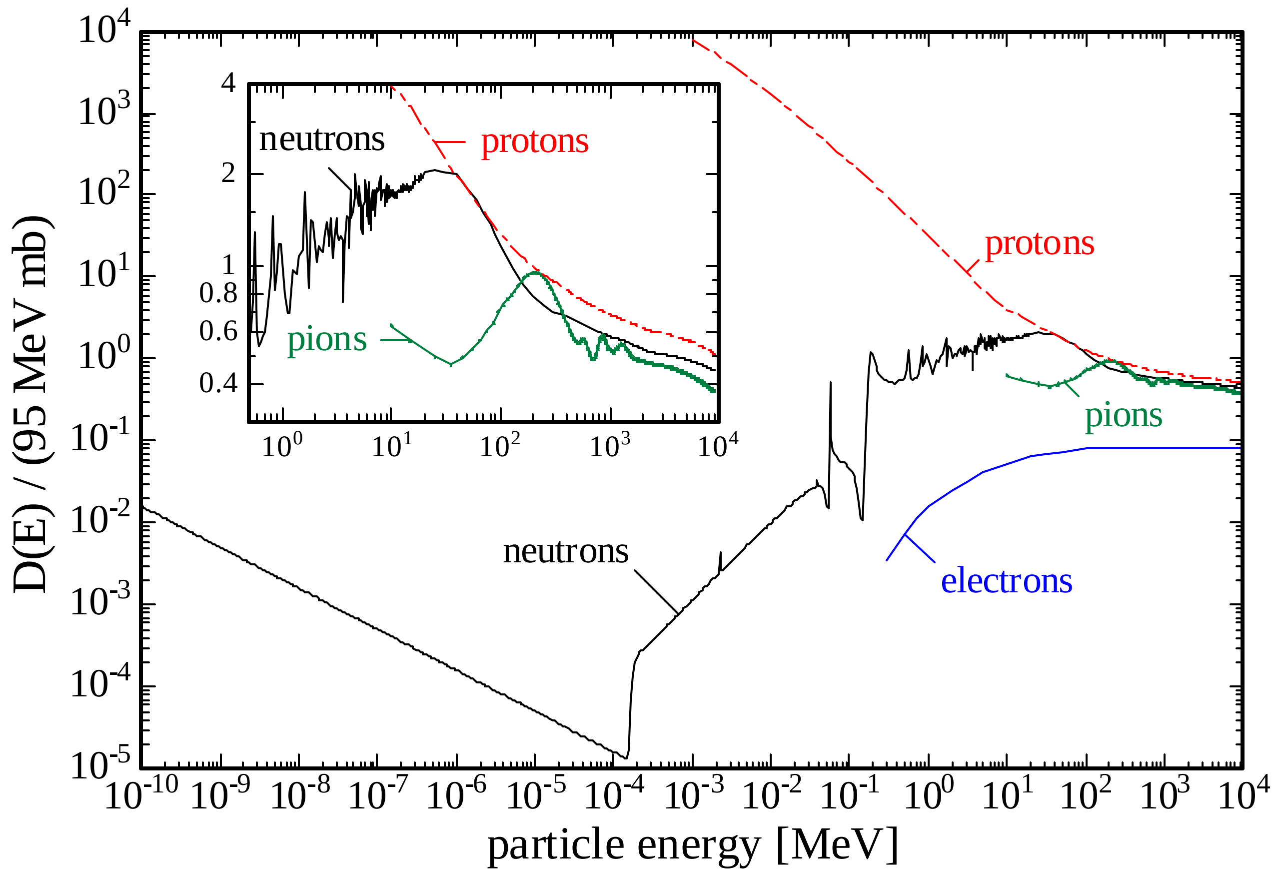
Primary Damage

- **PKA - Primary Knock on Atom**
- **Simulation** **(Fig.: van Lint 1980)**
  - **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)**

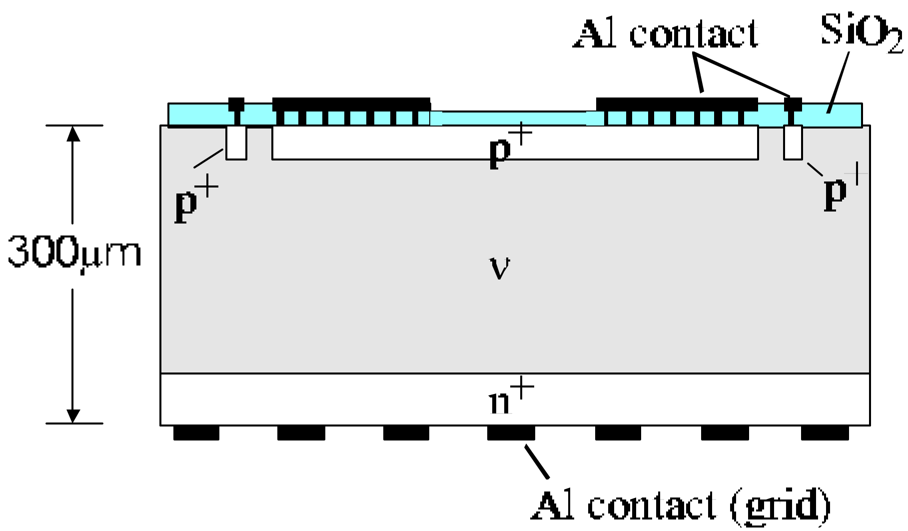
Displacement damage functions

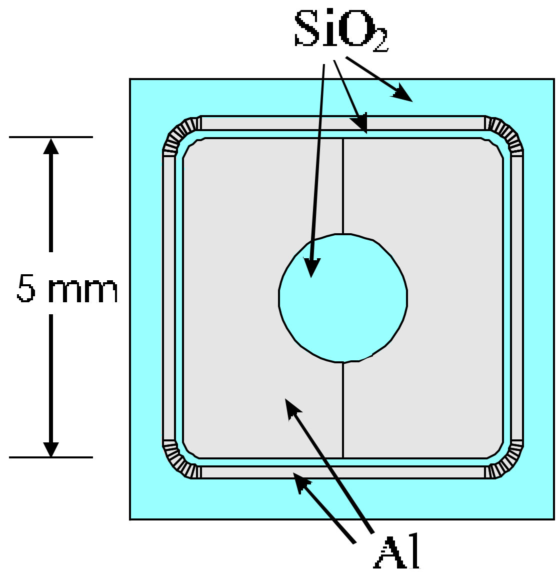


For Silicon:
100 MeVmb
= 2.14 keVcm^2/g

- **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)

Testing Structures - Simple Diodes





Example: Test structure from ITE

- **Very simple structures in order to concentrate on the bulk features**
  - Typical thickness: 300µm
  - Typical active area: 0.5×0.5 cm^2
- **Openings in front and back contact**
  - optical experiments with lasers or LED
- **Different producers used** (by the ROSE Collaboration)
  - ITE (Warsaw), Sintef(Oslo), MPI-Halbleiterlabor Munich, ELMA (Moscow), Canberra (Olen,Belgium), Diotec (Radosina, Slovakia), Schottky-diodes (Hamburg), ST Microelectronics (Catania, Italia), CIS (Erfurt)

Standard Measurements

- **Irradiation**
  - MeV neutrons – Reactor, Be(d,n) or T(d,n)
  - 10MeV, 23 GeV protons
  - 192 MeV pions
  - ^{60}Co-gammas

- **Measurements** Þ **Extracted Parameters**
  - C/V at room temperature Þ depletion voltage U_{dep} µ N_{eff}
  - I/V at room temperature Þ current at depletion voltage $I(U_{dep})$
  - DLTS (Deep Level Transient Spectroscopy) Þ microscopic defect parameters
  - TSC (Thermally Stimulated Currents) Þ microscopic defect parameters

- **Annealing Experiments**
  - Isothermal annealing studies at 20°C…120°C
  - Isochronal annealing studies 20°C…400°C

Þ Temperature dependent modeling Þ Damage Scenarios for HEP-Experiments

Understanding of microscopic defect kinetics Þ Defect Engineering

Radiation induced changes in detector properties

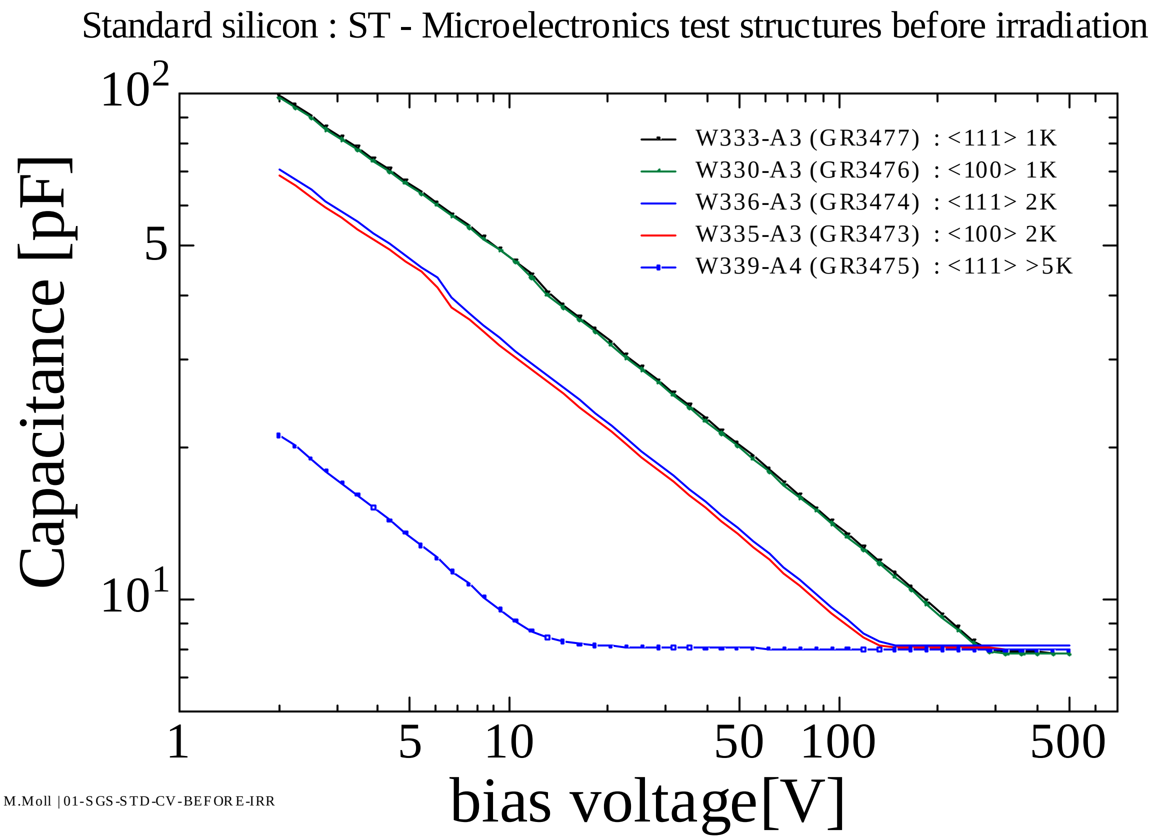
- **Change of depletion voltage**
  - Due to defect levels that are charged in the depleted region
    Þ most problematic !

- **Increase of leakage current**
  - Bulk current due to generation/recombination levels

- **Decrease of charge collection efficiency**
  - Due to damage induced trapping centers

ST Microelectronics - standard diodes

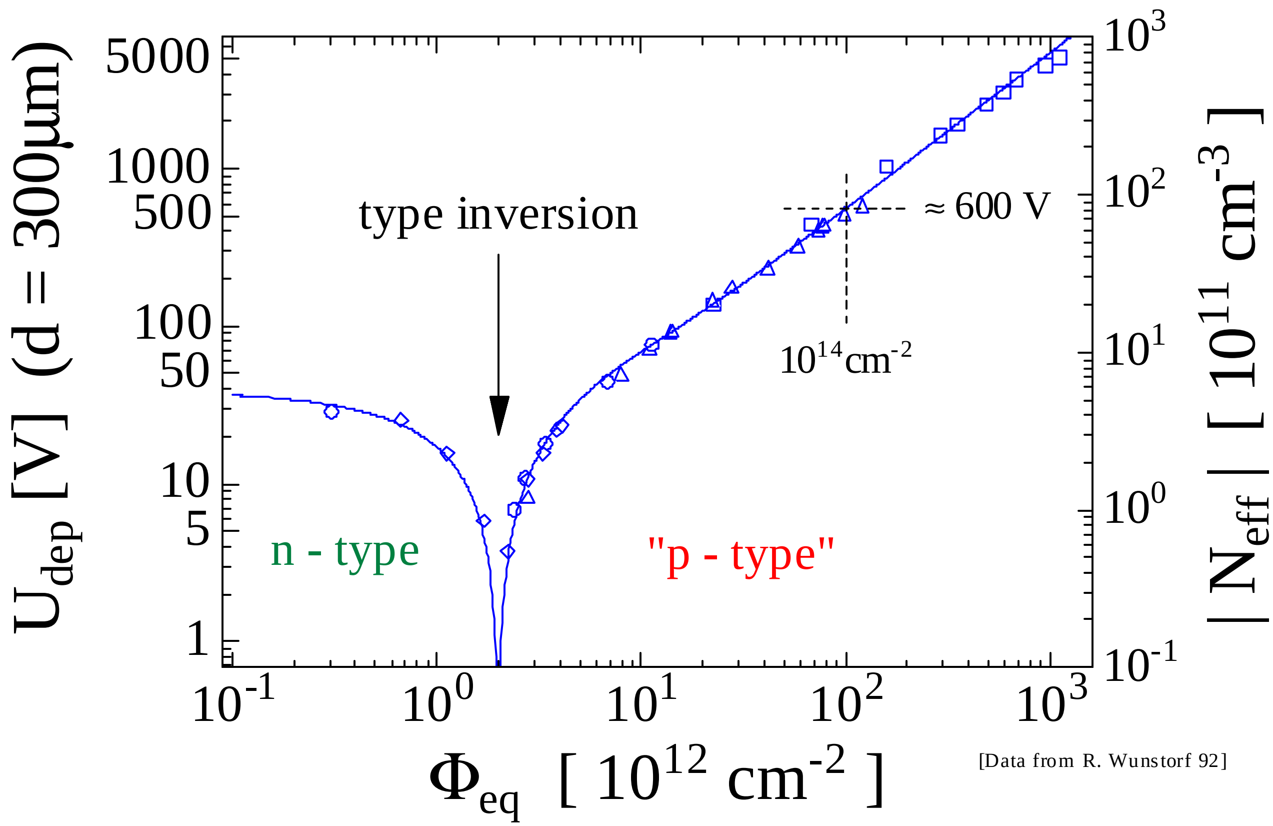
- **Different orientations** (<111> and <100>) **and resistivities**
- **CV measurements before irradiation**



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**



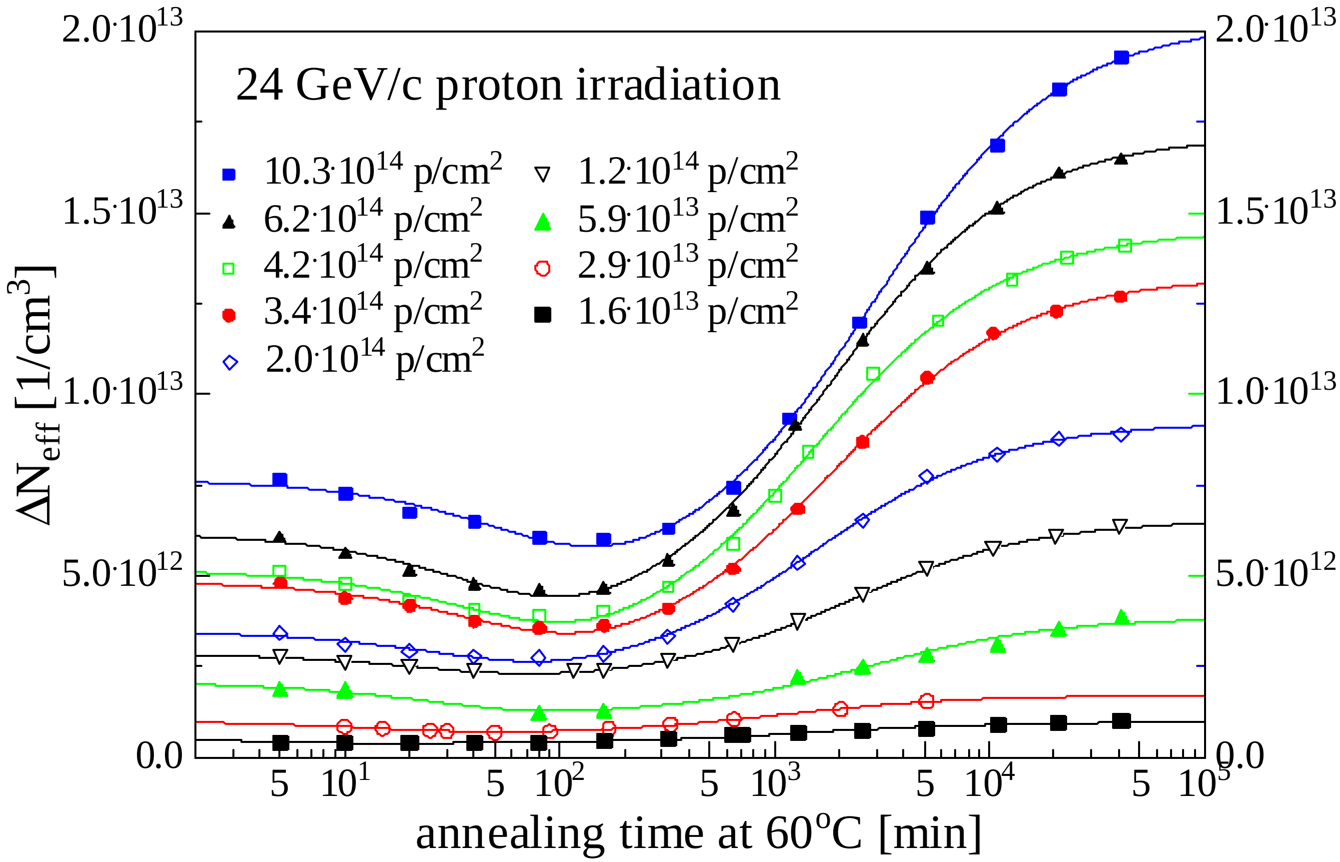
[Data from R. Wunstorf 92]

Systematic analysis of annealing data

Example: oxygen enriched silicon after 24 GeV/c proton irradiation

Instead of depletion voltage plot the change in the effective space charge ΔN_{eff}

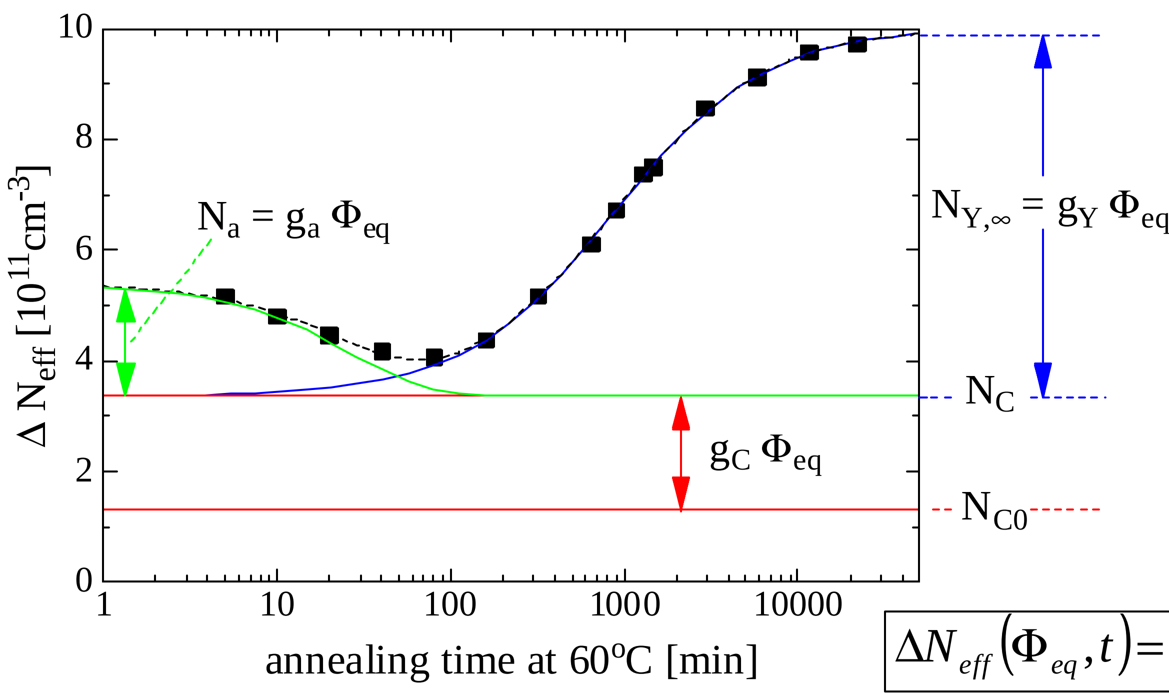
$$\Delta N_{eff}\left(\Phi_{eq},t\right) = N_{eff\,0} - N_{eff}\left(\Phi_{eq},t\right)$$



Annealing behavior of N_{eff} - Hamburg model -

$$\Delta N_{eff}(\Phi_{eq},t) = N_{eff\,0} - N_{eff}(\Phi_{eq},t)$$

ΔN_{eff} = Change of N_{eff} with respect to $N_{eff\,0}$ (value before irradiation)



[long term reverse annealing:]

$$N_Y = N_{Y,\infty} \cdot \left(1 - \frac{1}{1 + t/t_y}\right)$$

second order parameterization (with $N_{y,\infty} = g_y \times \Phi_{eq}$).gives best fit

But:

τ_y independent of Φ_{eq}

$\Rightarrow$ underlying defect reaction based on **first order** process!

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

short term annealing:

$$N_a = \Phi_{eq} \times \sum_i g_{ai} \times \exp\left(-\,{}^{t}\!/_{t_i}\right)$$

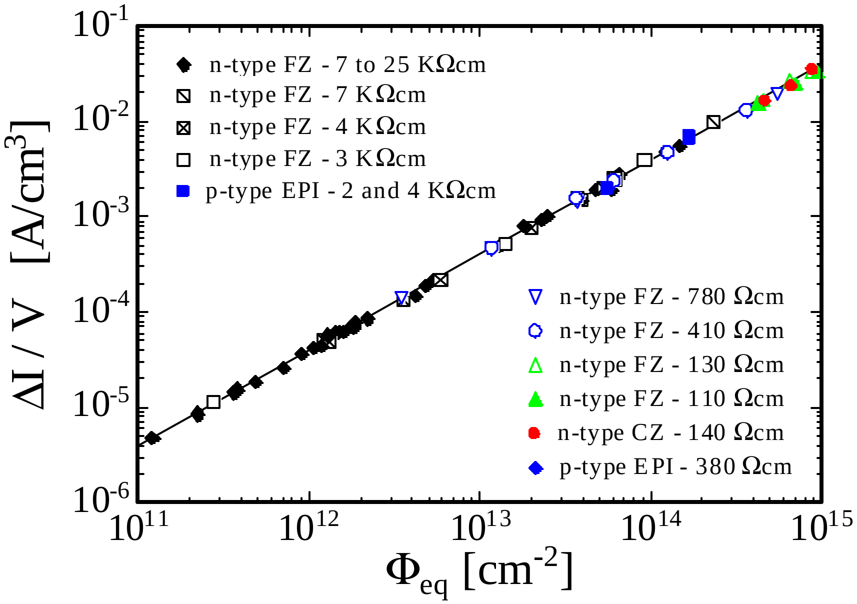
first order decay of acceptors introduced proportional to Φ_{eq} during irradiation

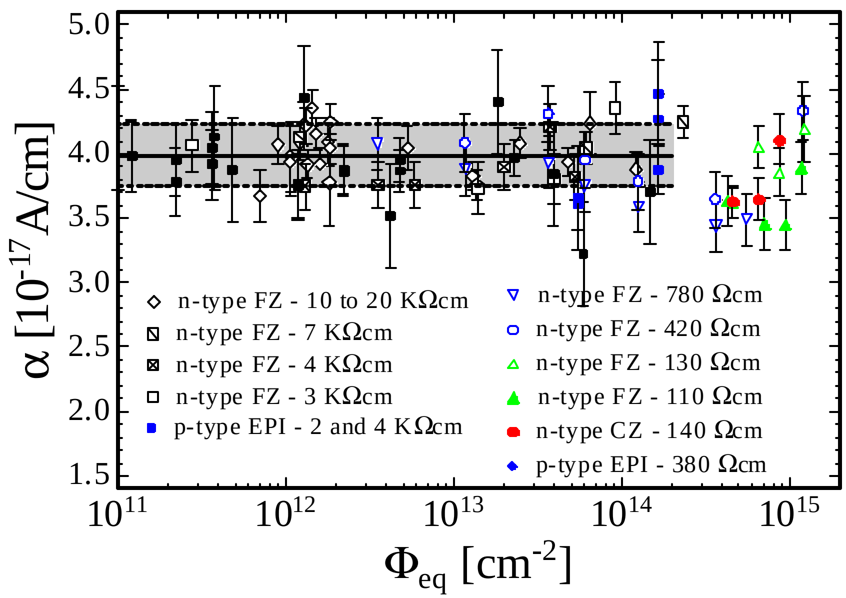
stable damage:

$$N_C = N_{CO} \cdot \left(1 - \exp(-c \cdot \Phi_{eq})\right) + g_C \cdot \Phi_{eq}$$

incomplete „donor removal“
+ introduction of stable acceptors

Increase of Leakage Current





- ♦ **Increase of leakage current independent of:**
  - Conduction type (p or n), resistivity
  - oxygen and carbon content
  - crystal orientation <111>, <100>
- ♦ **Temperature dependence:**

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

cooling strongly reduces current

- ♦ **Damage parameter a**
  - definition:

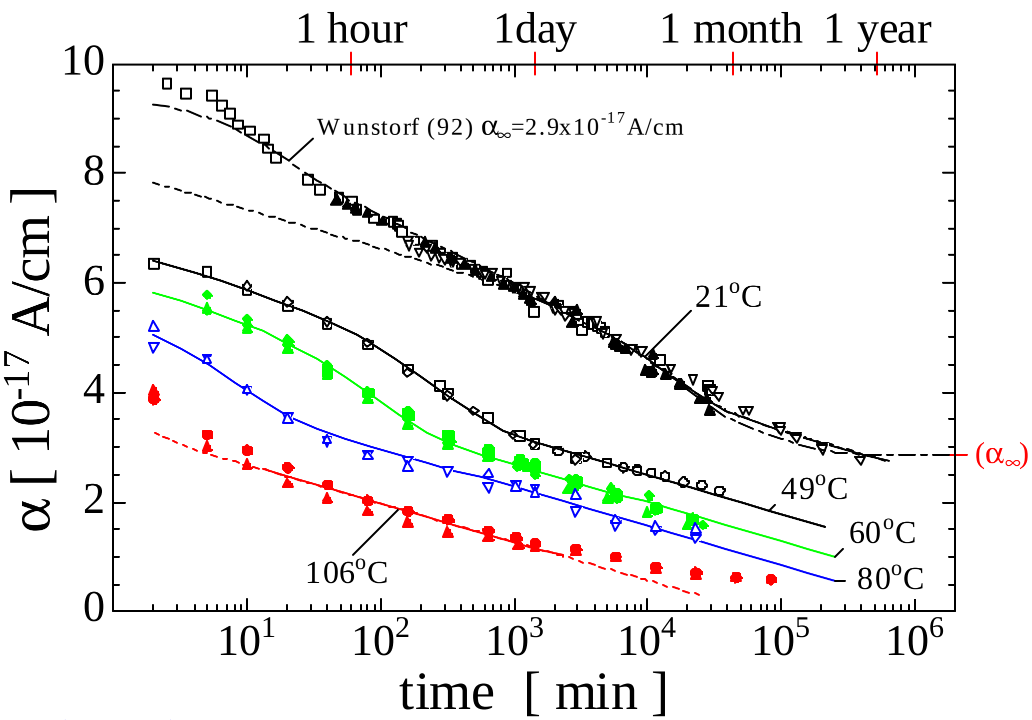
$$a = \frac{\Delta I}{V \cdot \Phi_{eq}}$$

  - measured after 80min at 60C:

$a_{80/60}$ = (3.99 ± 0.03)10^{-17} A/cm

  - used for fluence (NIEL) calibration

Annealing of leakage current



- **Annealing at RT (21°C):**
  - **good agreement with previous parameterization** (Wunstorf 92, parameters for non inverted detectors)
- **Annealing at higher temperature (long term at RT):**
  - **new parameterization:** $$a(T,t) = a_1 \cdot \exp\left(-t/t_1(T)\right) + \left(a_0 - b \cdot \ln(q(T) \cdot t/t_0)\right)$$
  - **exponential term:** activation energy: E_A = 1,11eV , $\nu = 1.2\times10^{13}\ s^{-1}$
    correlated with defect at E_C-0.46eV (DLTS)
  - **logarithmic term:** acceleration factor $\theta(T) \propto \exp(1.3\ eV / k_B T)$ ⇒ **no saturation value ! (no a_∞)**

The ROSE Collaboration CERN-RD48

(R&D On Silicon for future Experiments)

1995: formed by the Co-Spokespersons:

F.Lemeilleur (CERN, now retired), G.Lindström (Hamburg, now retired), S.Watts (Brunel,London)

2000: Final report to LEB - Oxygenated silicon will be used for the pixel detectors of ATLAS/CMS

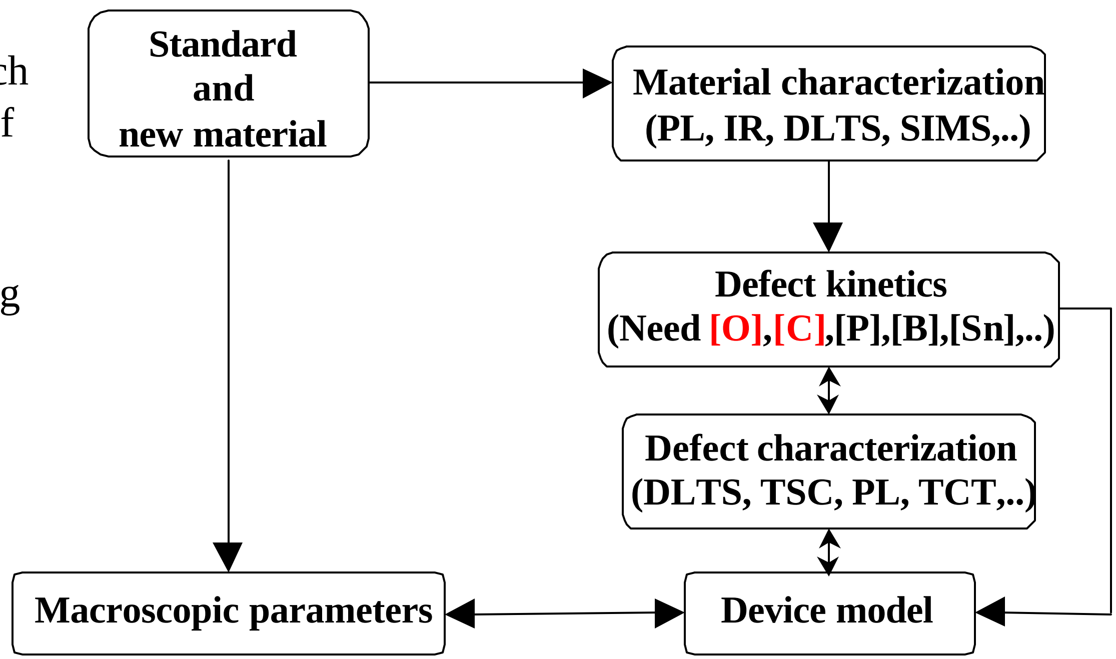
38 HEP- and Semiconductor groups (125 persons), 7 associated companies and many observers

For detailed information: http://cern.ch/rd48

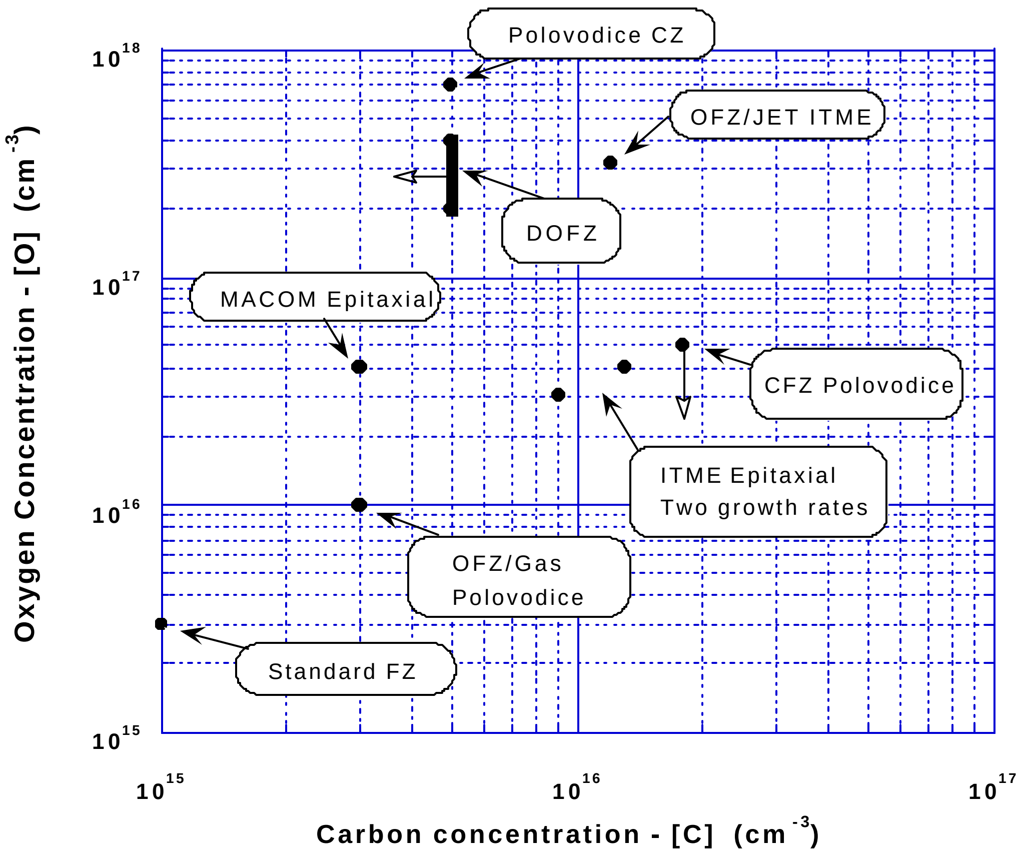
Objectives:

- **develop radiation hard detectors** which ensure operation for the whole lifetime of the Large Hadron Collider (LHC) experimental program
- **interact with industry** both for growing and defect engineering the appropriate detector grade material as for processing diodes in the most optimal way
- **exchange know how with the LHC experiments** both as to the experimental demands as to recommendations from results of the ROSE-studies

Defect engineering strategy :

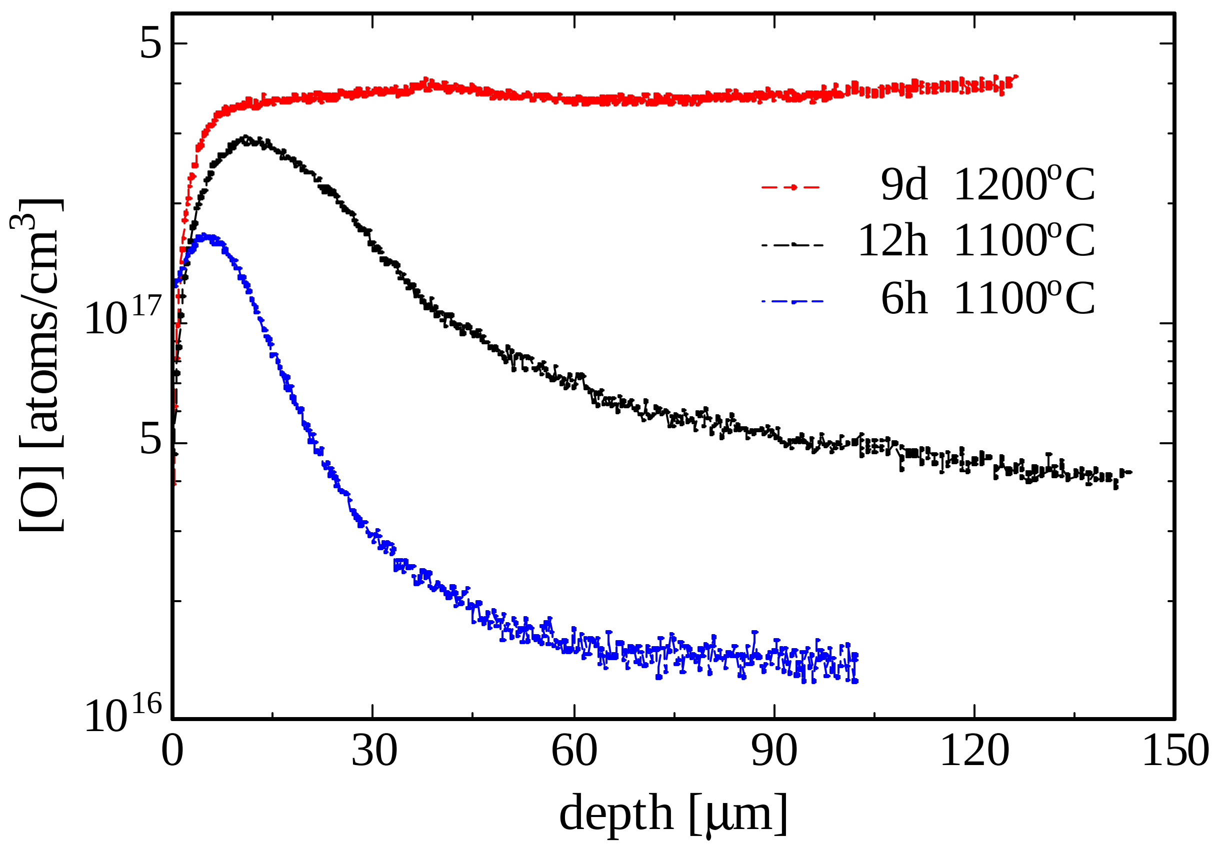


Oxygen and Carbon
- the key ingredients -



- ♦ **DOFZ - Diffusion Oxygenated Float Zone Silicon**
  - Controlled introduction of oxygen, easily included in manufacturing process, low cost

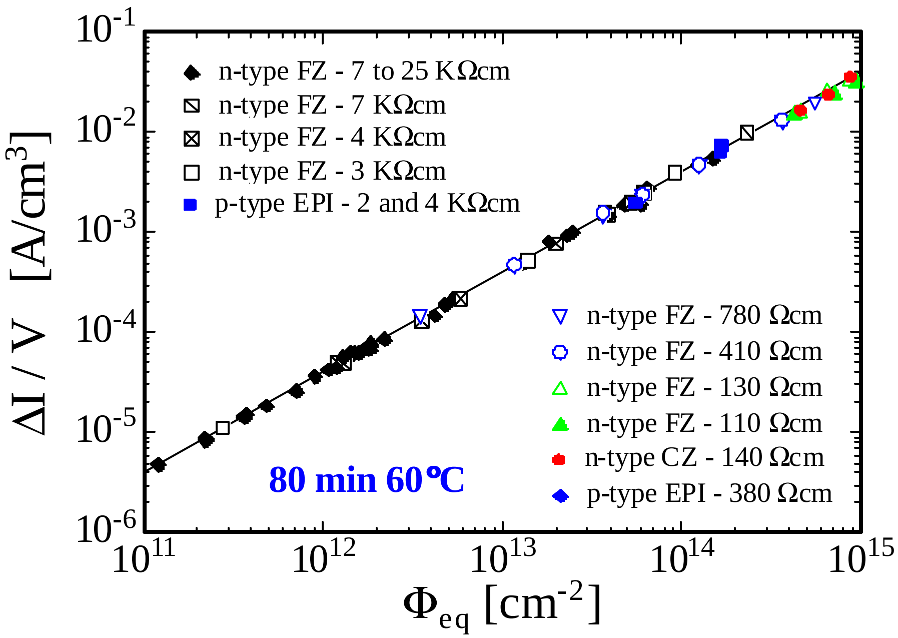
Oxygen diffusion

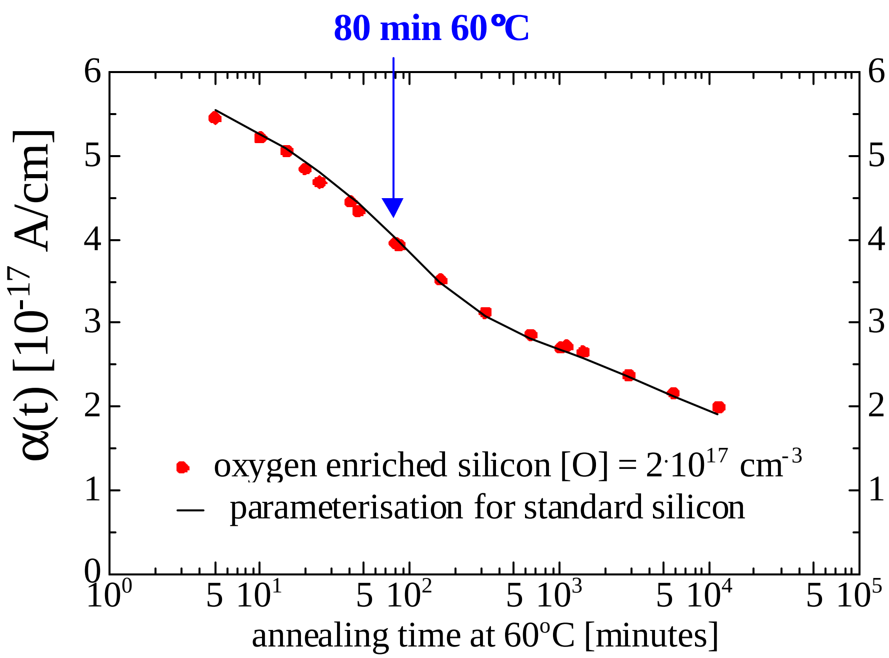


♦ **DOFZ - Diffusion Oxygenated Float Zone**

- Profiles measured by SIMS (Secondary Ion Emission Spectroscopy)
- Open question: Which is the minimum diffusion time/ oxygen concentration needed to get the beneficial effect ?

Leakage Current Annealing - Oxygenated Silicon

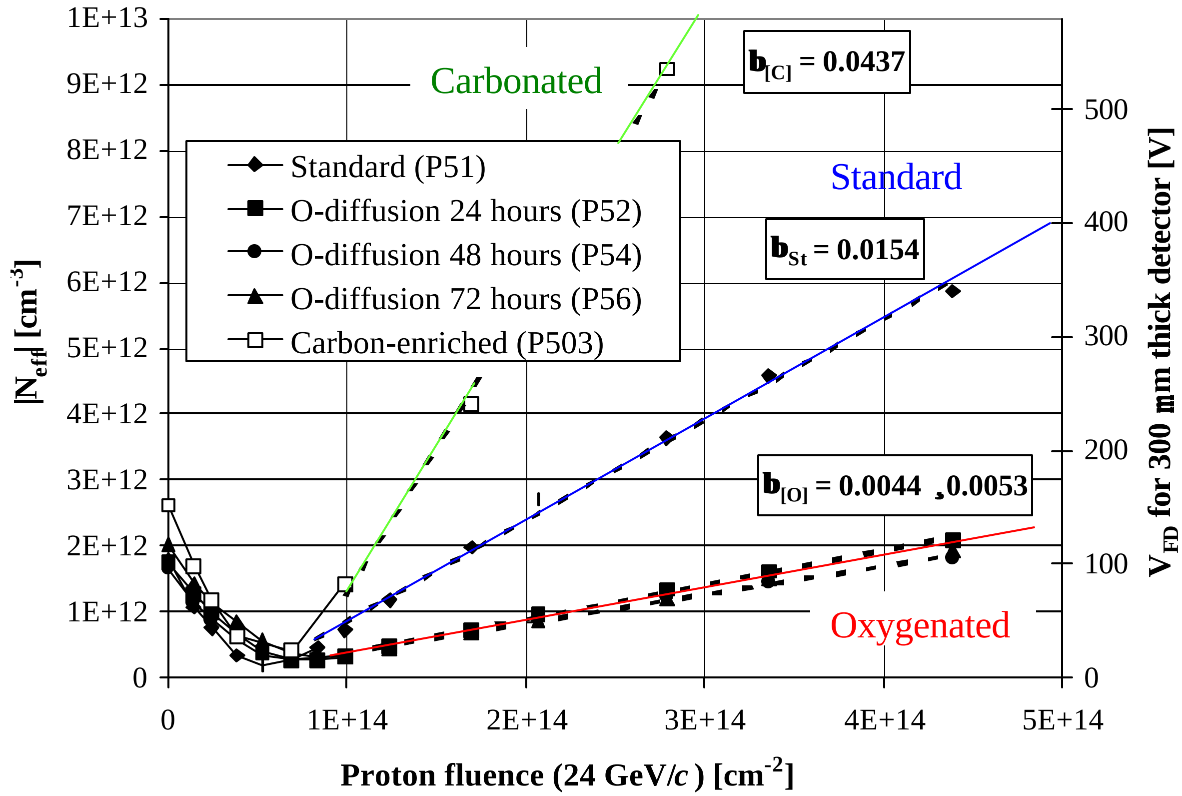




- **Damage parameter a:** $a = \frac{\Delta I}{V \cdot \Phi_{eq}}$ **independent of F_{eq}, used for fluence (NIEL) calibration**
- **Oxygenated and Standard Silicon show same annealing**

Influence of Carbon and Oxygen concentration

24 GeV/c proton irradiation

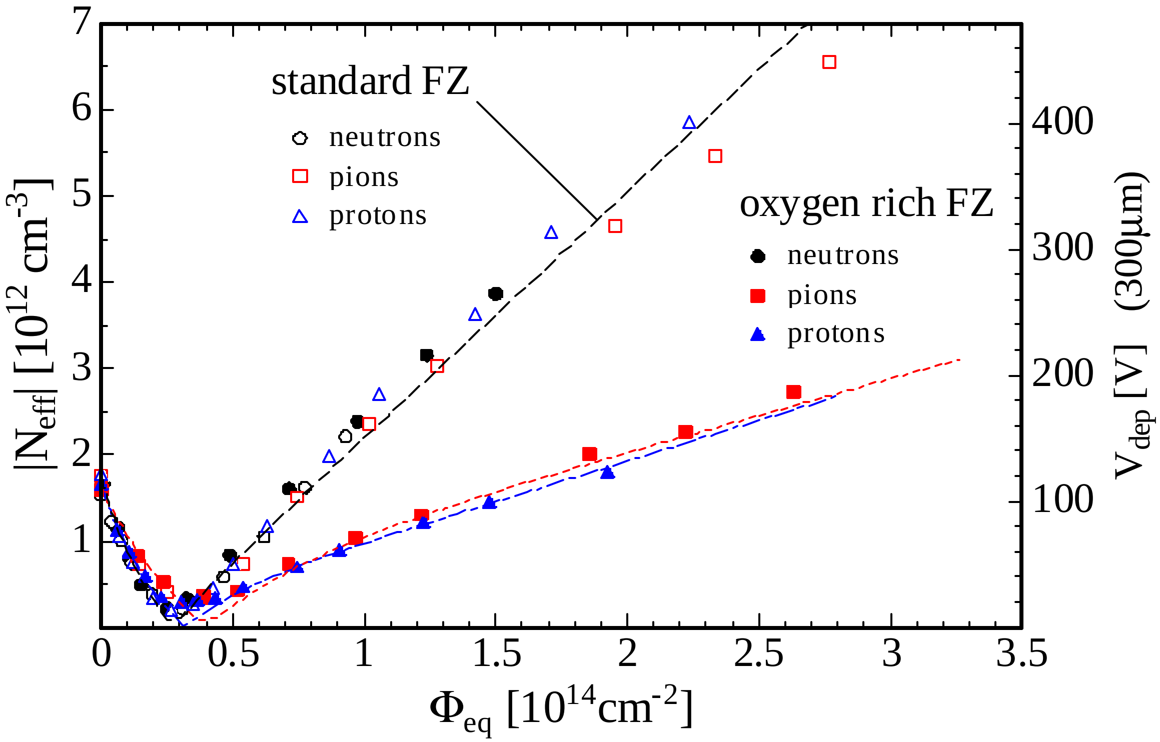


Compared to standard silicon:

- **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

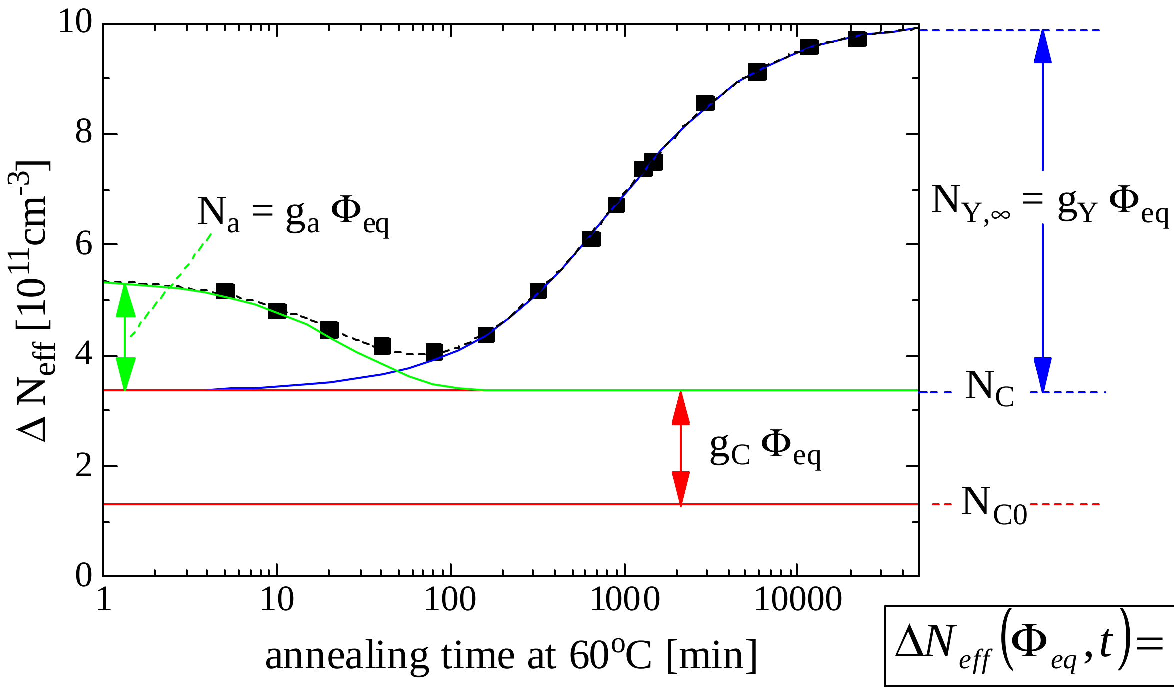


- **Strong improvement for pions and protons**
- **Almost no improvement for neutrons**

Annealing behavior of N_{eff} - Hamburg model -

$$\Delta N_{eff}(\Phi_{eq},t) = N_{eff\,0} - N_{eff}(\Phi_{eq},t)$$

ΔN_{eff} = Change of N_{eff} with respect to $N_{eff\,0}$ (value before irradiation)



long term reverse annealing:

$$N_Y = N_{Y,\infty}\cdot\left(1-\frac{1}{1+t/t_y}\right)$$

second order parameterization (with $N_{y,\infty}=g_y\times\Phi_{eq}$).gives best fit

But:

τ_y independent of Φ_{eq}

⇒ underlying defect reaction based on **first order** process!

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

short term annealing:

$$N_a = \Phi_{eq}\times\sum_i g_{ai}\times\exp\left(-\,{}^{t}\!/_{t_i}\right)$$

first order decay of acceptors introduced proportional to Φ_{eq} during irradiation

stable damage:

$$N_C = N_{CO}\cdot\left(1-\exp\left(-c\cdot\Phi_{eq}\right)\right) + g_C\cdot\Phi_{eq}$$

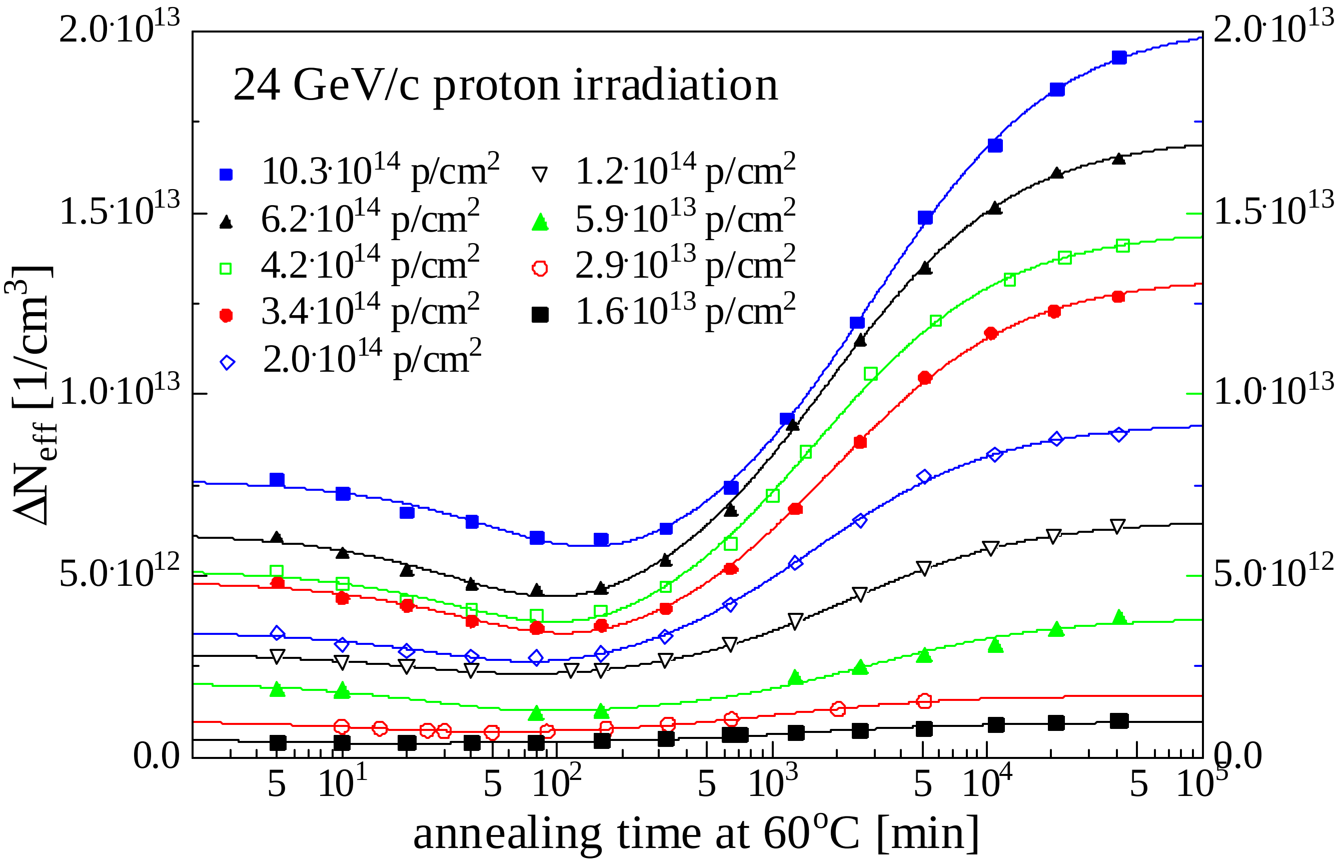
incomplete „donor removal“
+ introduction of stable acceptors

Systematic analysis of annealing data

Example: oxygen enriched silicon after 24 GeV/c proton irradiation

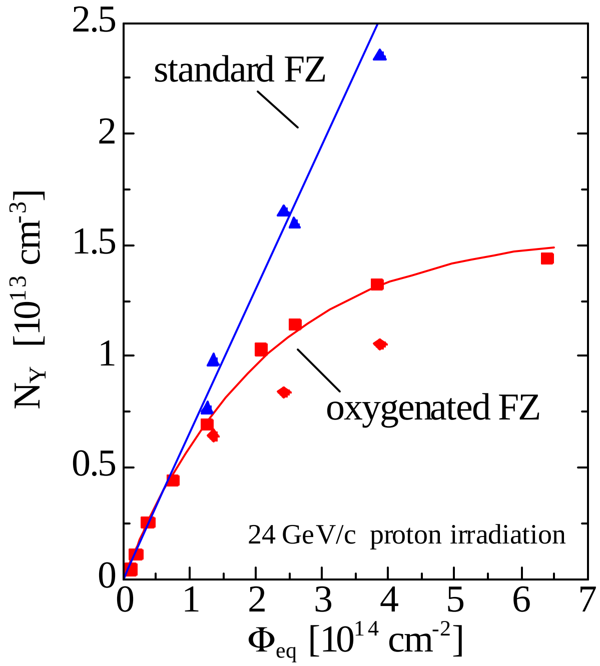
Instead of depletion voltage plot the change in the effective space charge ΔN_{eff}

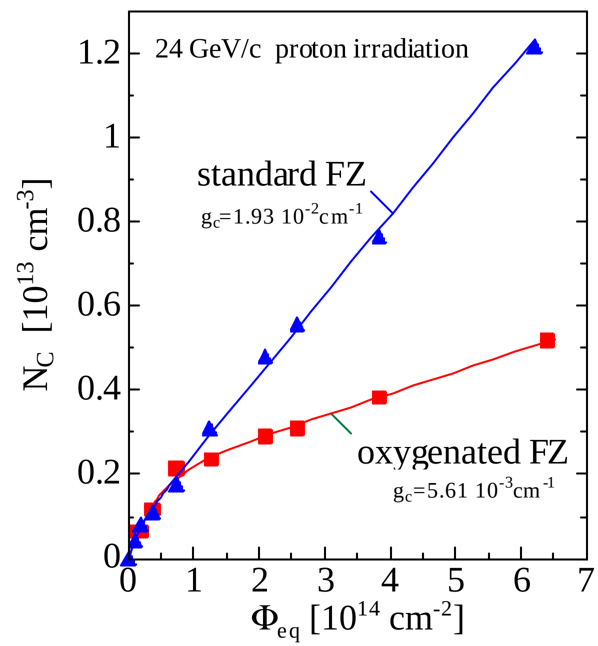
$$\Delta N_{eff}(\Phi_{eq}, t) = N_{eff\,0} - N_{eff}(\Phi_{eq}, t)$$



Extraction of damage parameters

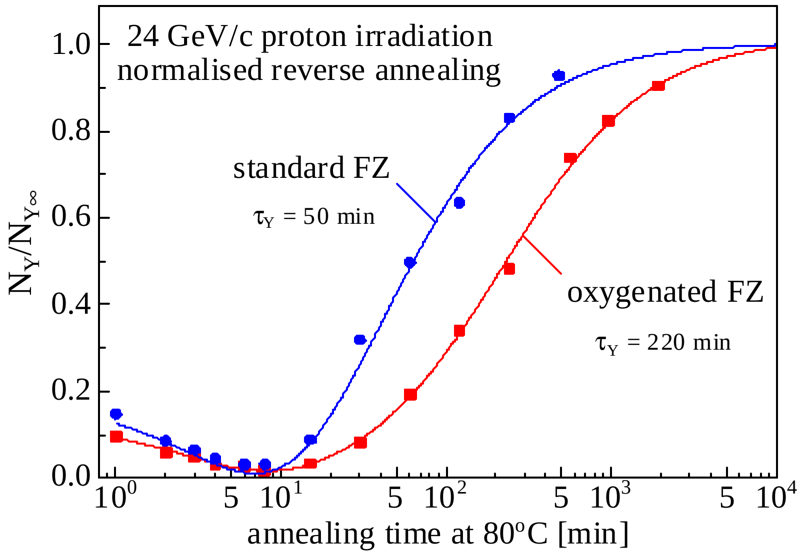
Reverse annealing amplitude N_Y





Stable damage parameter N_C

Reverse annealing time constant τ_Y

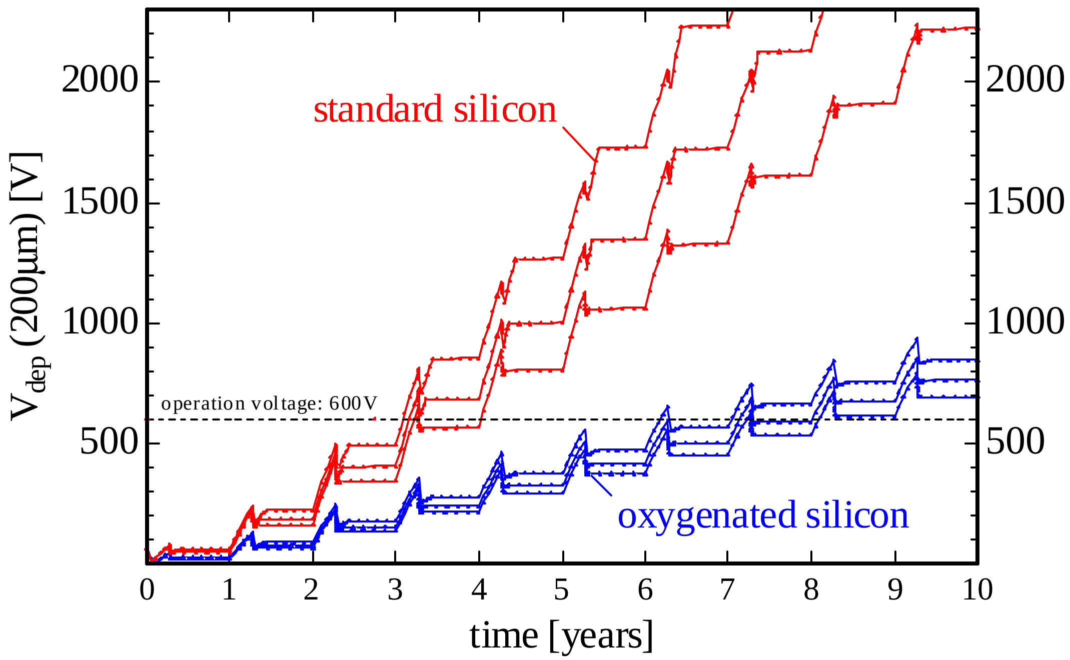


- **24 GeV/c proton irradiated** **O-enriched diodes**
- **g_c improved by a factor of 3**
- **saturation of reverse annealing**
- **delayed reverse annealing**

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

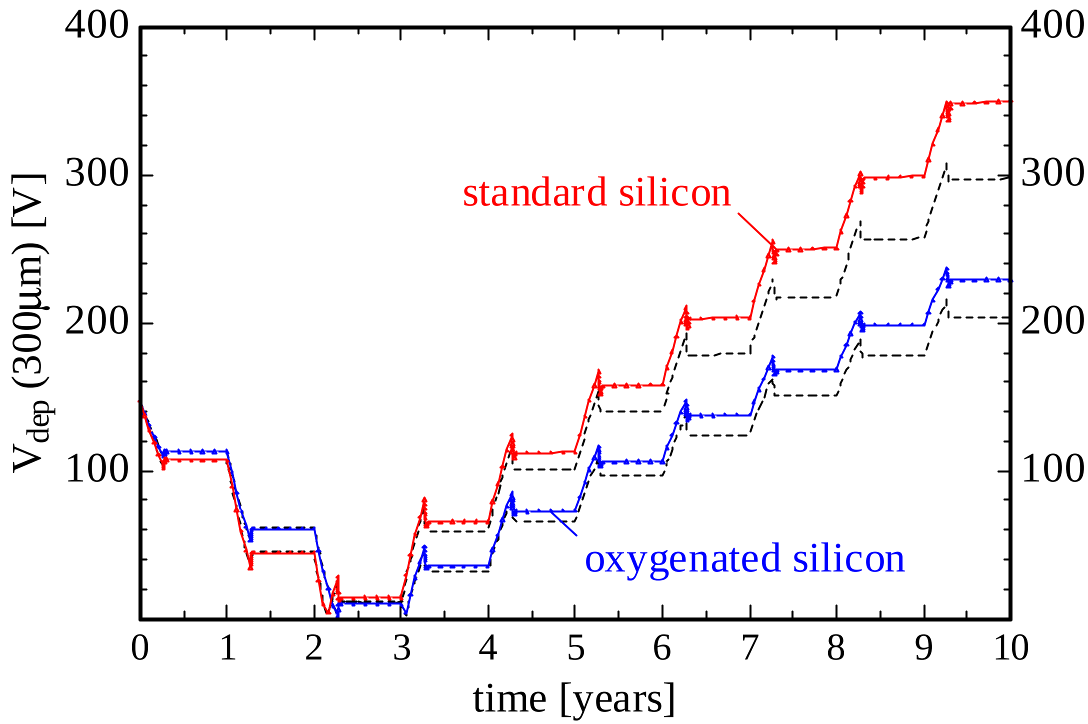
- **Radiation level:**
  - **Φ_{eq}(year) = 3.5 × 10^{14} cm^{-2}** (full luminosity)
    > 85% charged hadrons

- **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)



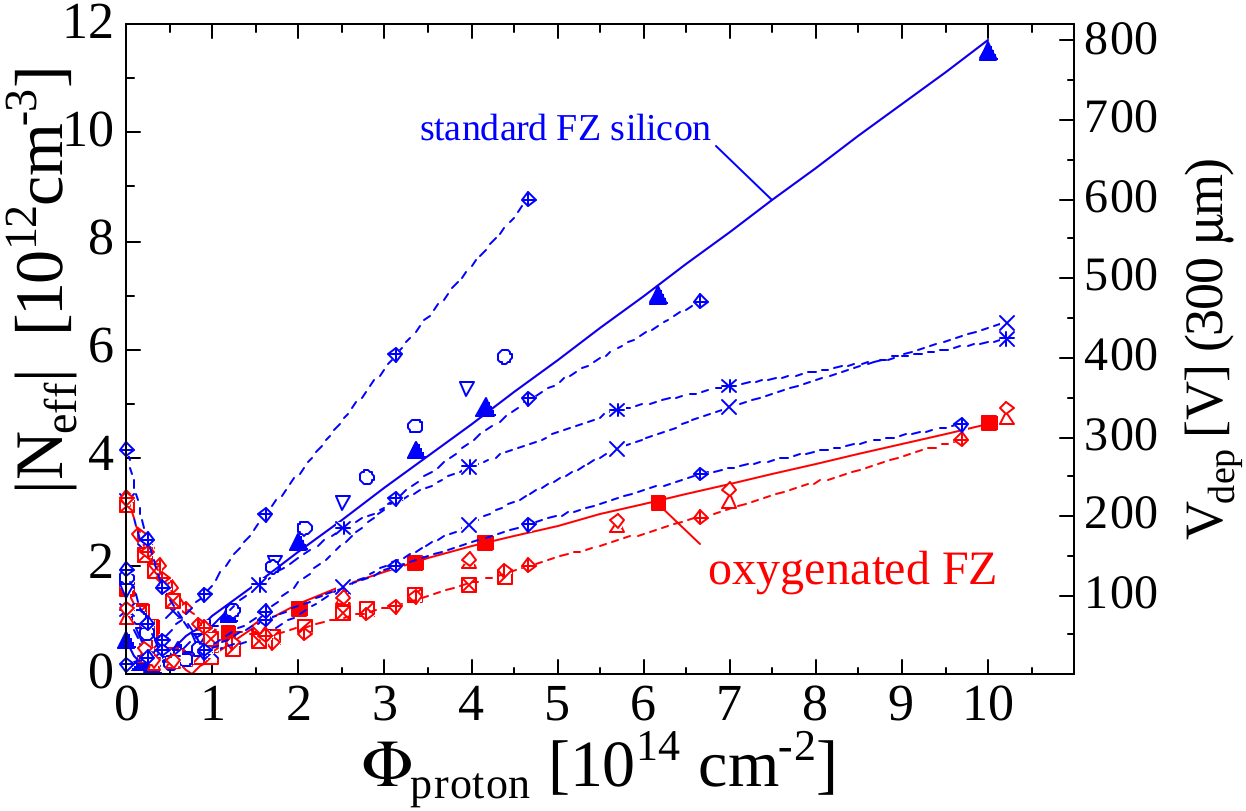
Damage Projection - Strip Detector - 30 cm

- **Radiation level:**
  - **F_{eq}(10years) = 2 ´ 10^{14} cm^{-2}**
    » 50% charged hadrons
- **Scenario:**
  - **1 year = 100 days beam (-7°C)**
    14 days 20°C
    251 days no beam (-7°C)



Dashed line - 2 days 20°C and
14 days 14°C warm-up

Warning: Variation of “standard material”



- ♦ **Strong variation of standard silicon**
- ♦ **Reproducible results for oxygenated silicon**

Summary (1/4) - Leakage Current

♦ NIEL - Non Ionizing Energy Loss

- **NIEL - Hypothesis** (damage parameters scale with NIEL) **has to be used very carefully !**
  (e.g. not valid for changes in V_{dep} of oxygenated and standard silicon detectors)

♦ Devices used for investigations

- Very simple diodes in order to concentrate on the bulk damage effects

♦ Macroscopic Damage Effects - Leakage Current

- **Strong increase of leakage current** after irradiation ⇒ Cooling of detectors necessary
- **Leakage current damage parameter α**
  - material independent (no impurity, resistivity or conduction type dependence)
  - scaling with NIEL for fast neutrons, pions and protons
- **Leakage current annealing** after irradiation same for all type of materials
- **^{60}Co-gamma irradiation**: No leakage current (bulk current!)
  annealing observed at room temperature !

Summary (2/4) - Depletion Voltage

♦ Macroscopic Damage Effects - Depletion Voltage - (N_{eff})

- In general the space charge becomes more negative after irradiation (**type inversion**).
  The initial n-type silicon inverts to a quasi "p-type" silicon
  The main depletion zone evolves from the back electrode (n^+) after type inversion

- **Changes in N_{eff}** consists of three basic components (neutrons, pions, protons):
  - **Short term** or beneficial **annealing** (Decrease of depletion voltage for inverted detectors)
  - **Stable damage** (No change in time after irradiation)
  - **Reverse annealing** (Increase of depletion voltage for inverted detectors)

- **^{60}Co-gamma irradiation:** No beneficial and no reverse annealing !

- Determination of all damage parameters (Hamburg model + many isothermal annealing experiments) allows for the simulation of **damage projections** in the LHC experiments under various operational conditions.

- **Annealing experiments** (macroscopic parameters - V_{dep}, α) isothermal and isochronal give already some very useful hints about the microscopic defects / defect reactions underlying the change of the macroscopic parameters !

Summary (3/4) - Microscopic Defects

♦ Damage at the Microscopic Level

- **DLTS** and **TSC** measurements reveal many electrical active defects
- Most of the defects are not charged in the space charge region (no influence on V_{dep} !!)
- Comparison between ^{60}Co-gamma and neutron/proton irradiated silicon allows for determination between **point defects** and defects related to **defect clusters**.
- Annealing experiments (isochronal and isothermal) reveal correlation's between single defects and macroscopic parameters - reverse annealing and leakage current annealing
- Defect introduction rates and defect parameters can be used for the modeling of the overall defect kinetics in the silicon (including fluence ranges where DLTS technique is not applicable any more)

♦ Defect kinetics modeling

- Modeling of the defect kinetics suggests that oxygen rich silicon is radiation harder (**V_2O-model**)
- Model can explain experimental data for gamma irradiated silicon
  (change of depletion voltage)
- Model gives qualitatively the macroscopic findings for hadron irradiated silicon detectors (depletion voltage). However, all models are so far incomplete.

Summary (4/4) - Oxygenated Silicon

- **Oxygen enriched silicon - technological results**
  - Oxygen enrichment by diffusion is most effective / less cost intensive method
  - Detectors produced on oxygen enriched silicon do not show any change in detector properties besides the improved radiation hardness (surface properties, performance before irradiation,etc.)
  - Diffusion technology has been successfully transferred to several silicon detector manufacturers (SINTEF, Micron, ST, CiS) and full-scale microstrip detectors produced
- **Oxygen enriched silicon - scientific results**
  - Effective doping changes can be improved by oxygenation of the material (**factor 3 for stable damage parameter gc**). 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 for the process is larger by a factor of 2-4** allowing detectors to remain at room temperature for longer periods during maintenance periods: **additional safety margin**.
- **Many open questions – Further work on oxygenated/standard Silicon needed !**
  - The proton – neutron puzzle: Violation of NIEL ?
  - Why does the reverse annealing saturate in oxygenated silicon ?
  - Which defect is responsible for the differences observed after proton and neutron irradiation ? (V_2O ?)
  - …more open questions and details……see ROSE status reports ….

The ROSE Collaboration

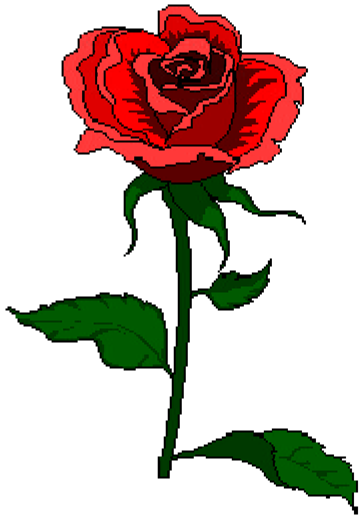
Visit our web-site for…

… more information

… status reports, preprints,

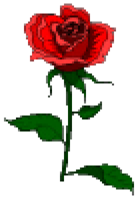
… publications,

…related conferences, etc….



http://cern.ch/rd48

Remember, today is
Valentines Day !



A good day for ROSES ?