Recent Results by the ROSE / CERN RD48 Collaboration

Research and development On Silicon for future Experiments

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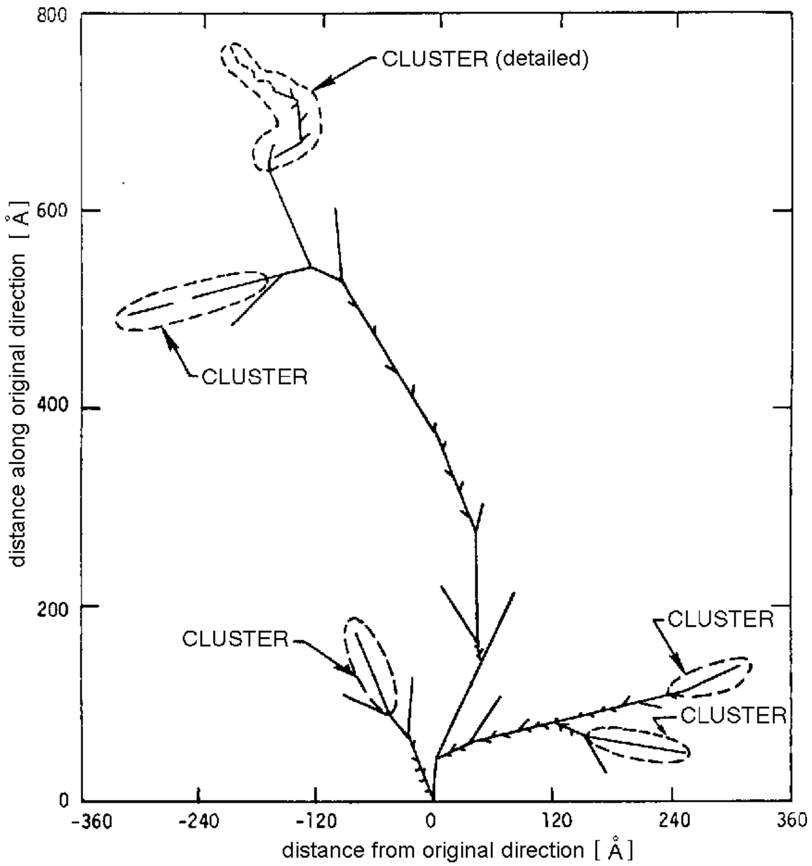
on behalf of

The ROSE Collaboration / CERN RD48

http://cern.ch/rd48



The 'ROSE': damage cascade
simulated by V.A.J. van Lint

RD48 Objectives

Develop more radiation tolerant silicon

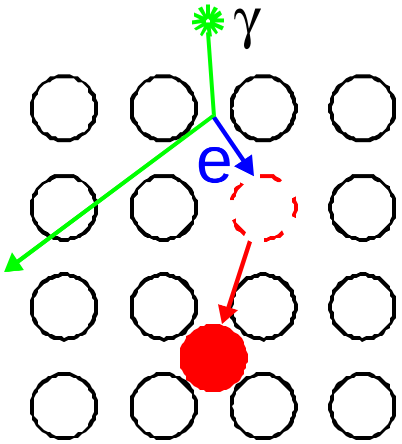
- characterize radiation defects at the microscopic level
- deliberately add impurities, choices motivated by microscopic models
- establish affordable procedures with manufacturers for the materials modification

Make reliable predictions for operation in rad. environment

- in-depth studies of the macroscopic damage effects, including aging studies
- proof transferability of test-structure results to actual strip/pixel detectors
- fluence normalization issues

Displacement Damage in Silicon

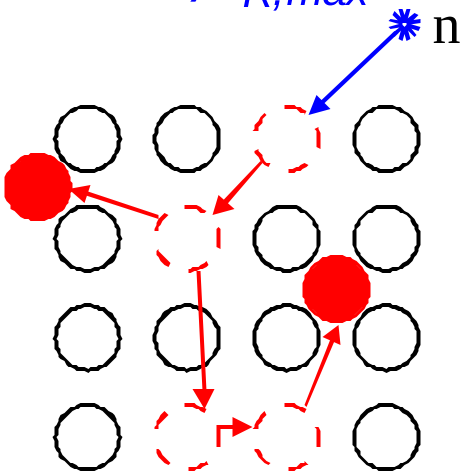
^{60}Co-γ, $E_{R,max}$=150eV



only Frenkel-pairs:
interstitial + vacancy
Si_i ● V ◌

Threshold E_d = 25 eV

1 MeV n, $E_{R,max}$=130keV



Frenkel-pairs,
cascades,
higher order defects
(e.g. divacancy),
disordered regions
at cascade terminals

Defect Reactions in Silicon

$I+C_s \rightarrow C_i$

$I+CC \rightarrow CCI$

$I+CCI \rightarrow CCII$

$I+CO \rightarrow COI$

$I+COI \rightarrow COII$

$I+VO \rightarrow O$

$I+V_2O \rightarrow VO$

$I+V_2 \rightarrow V$

$I+VP \rightarrow P$

$V+V \rightarrow V_2$

$V+V_2 \rightarrow V_3$

$V+O \rightarrow VO$

$V+VO \rightarrow V_2O$

$V+P \rightarrow VP$

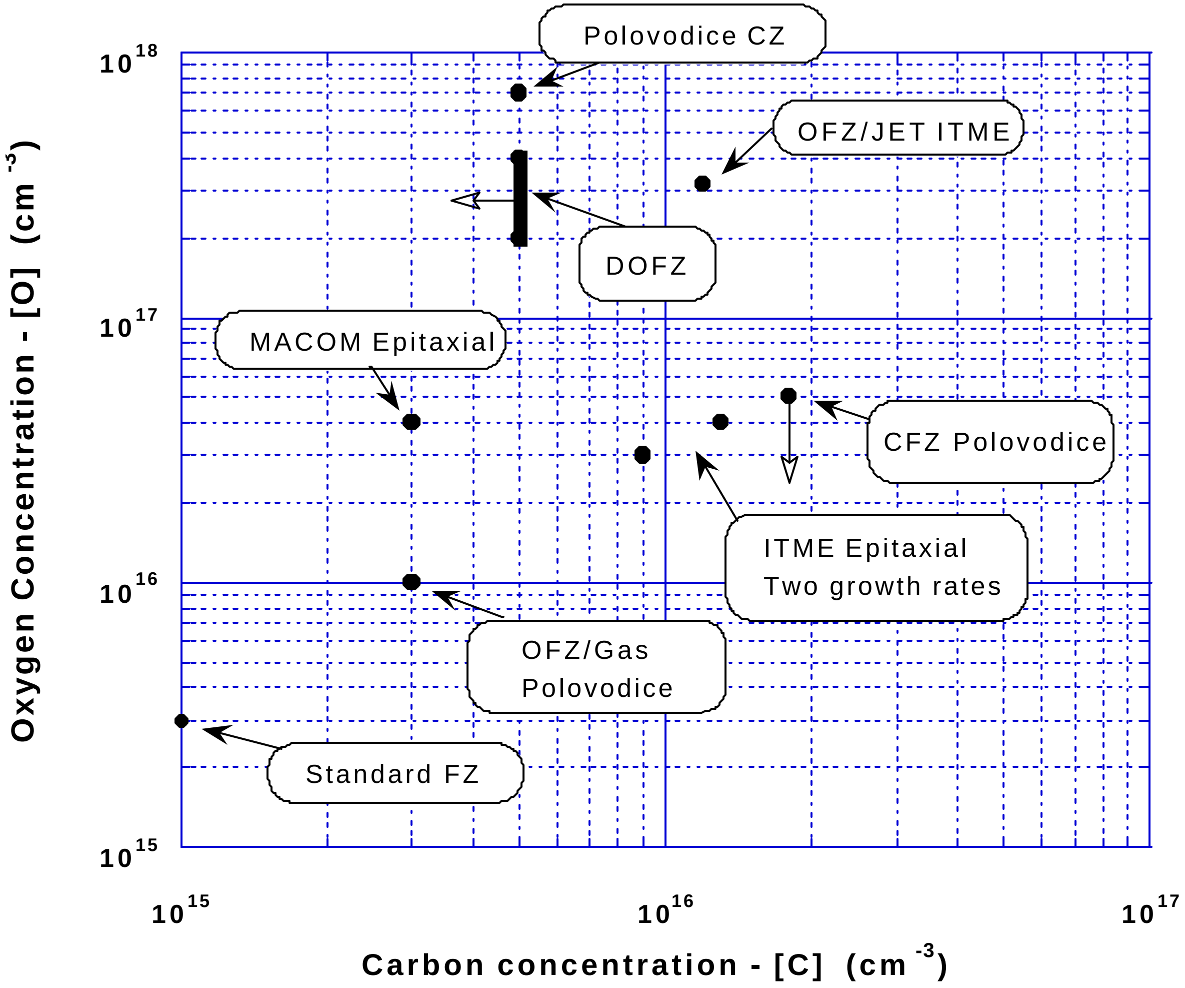
$C_i+C_s \rightarrow CC$

$C_i+O \rightarrow CO$

I: Interstitial
V: Vacancy
C_i: Carbon, interstitial
C_s: Carbon, substitutional
O: Oxygen, always interstitial
P: Phosphorus

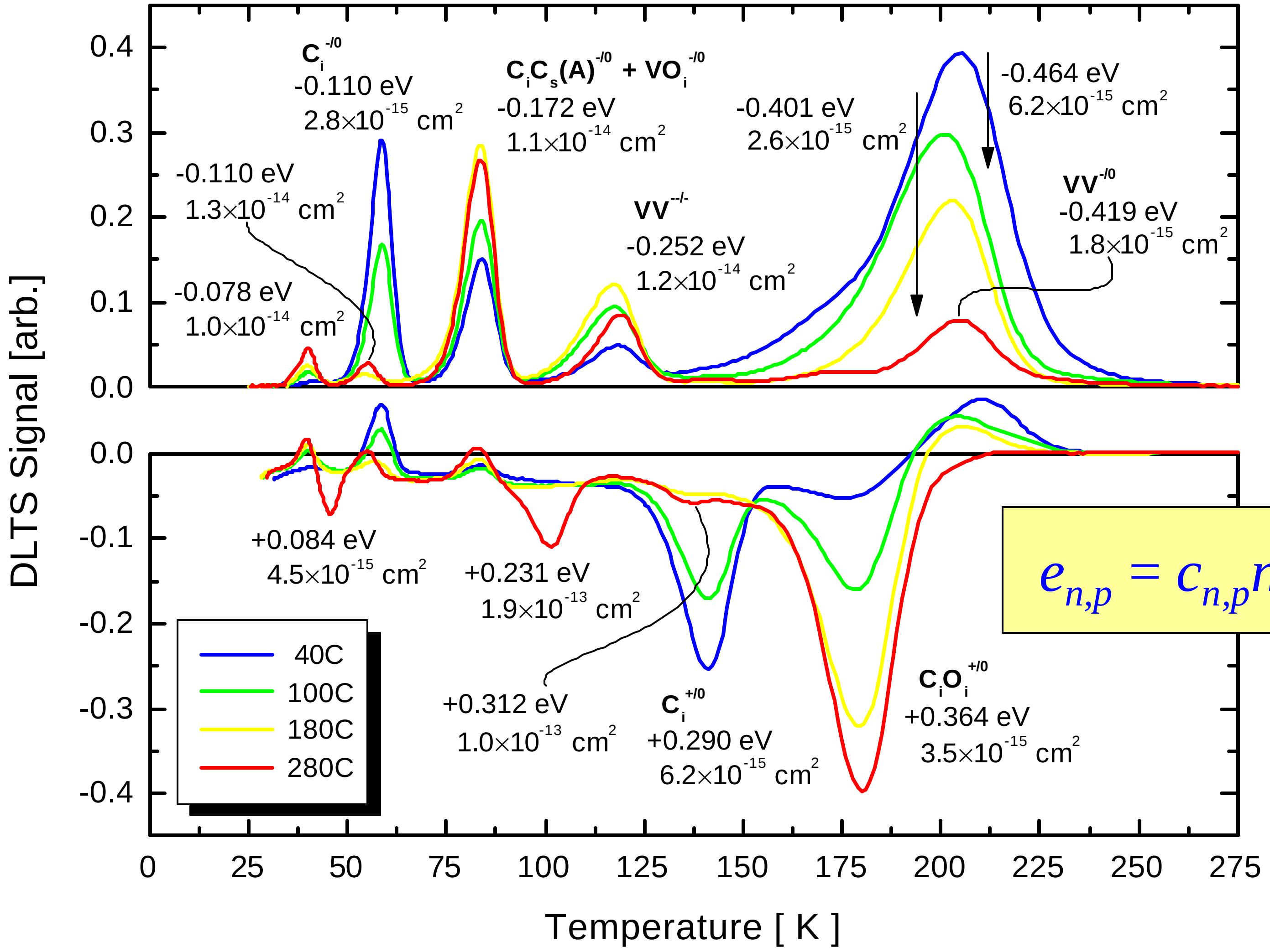
In Silicon self-interstitials and vacancies are highly mobile and cause complex quasichemical defect reactions.

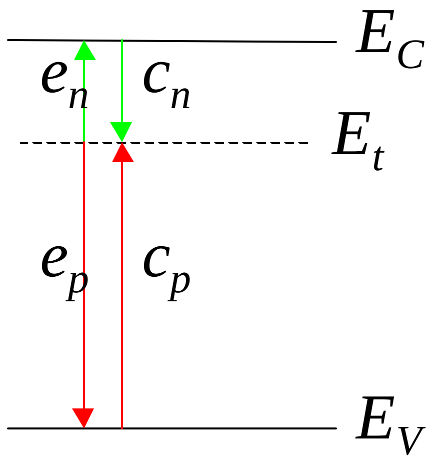
Oxygen and Carbon, Key Ingredients



Various materials were specially grown, and unusual materials have been considered. Impurity concentrations were determined (SIMS, FTIR), and thorough defect studies and macroscopic characterizations were carried out.

Deep-Level Transient Spectroscopy

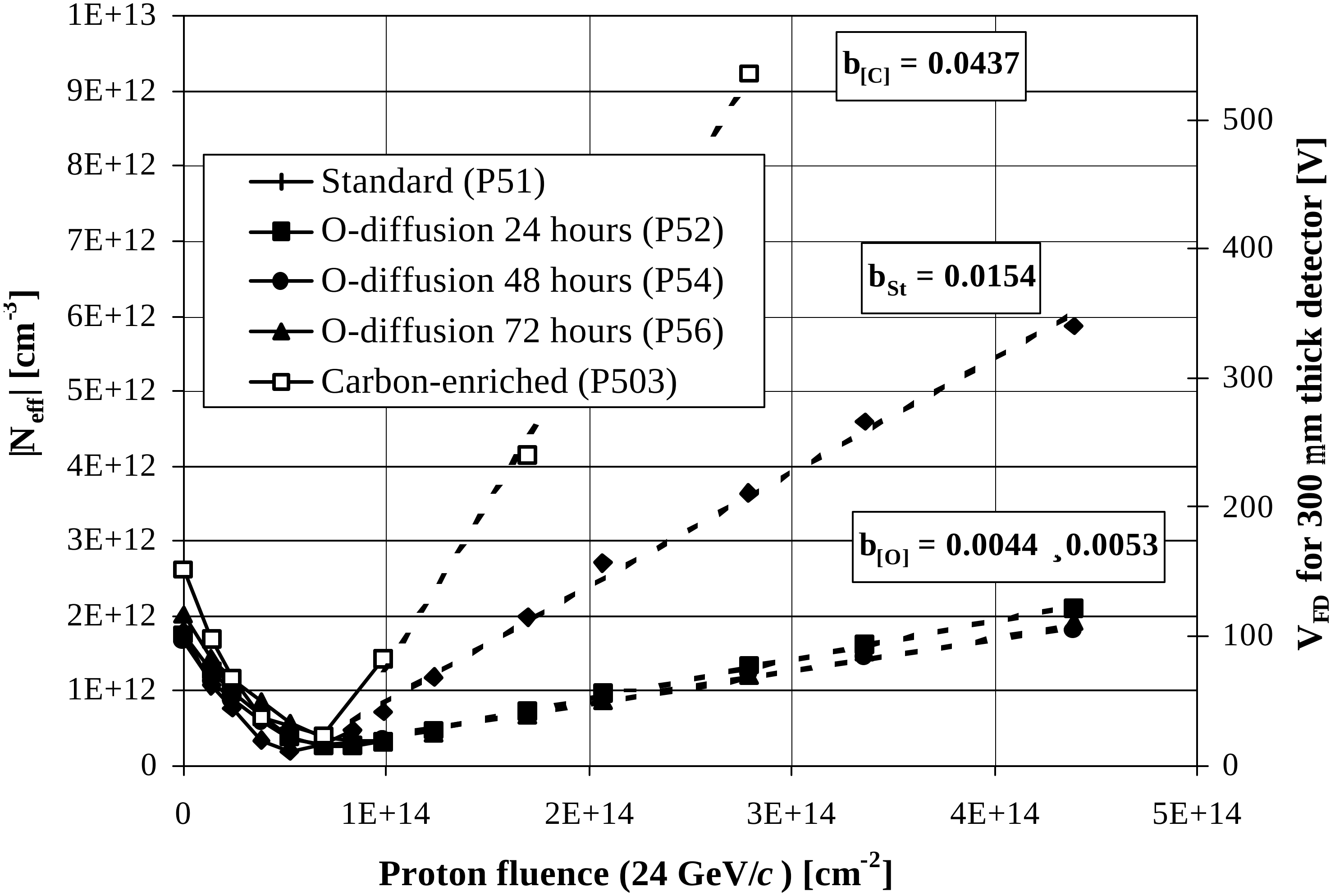




$$e_{n,p} = c_{n,p} n_i \exp(\pm(E_t-E_i)/kT)$$

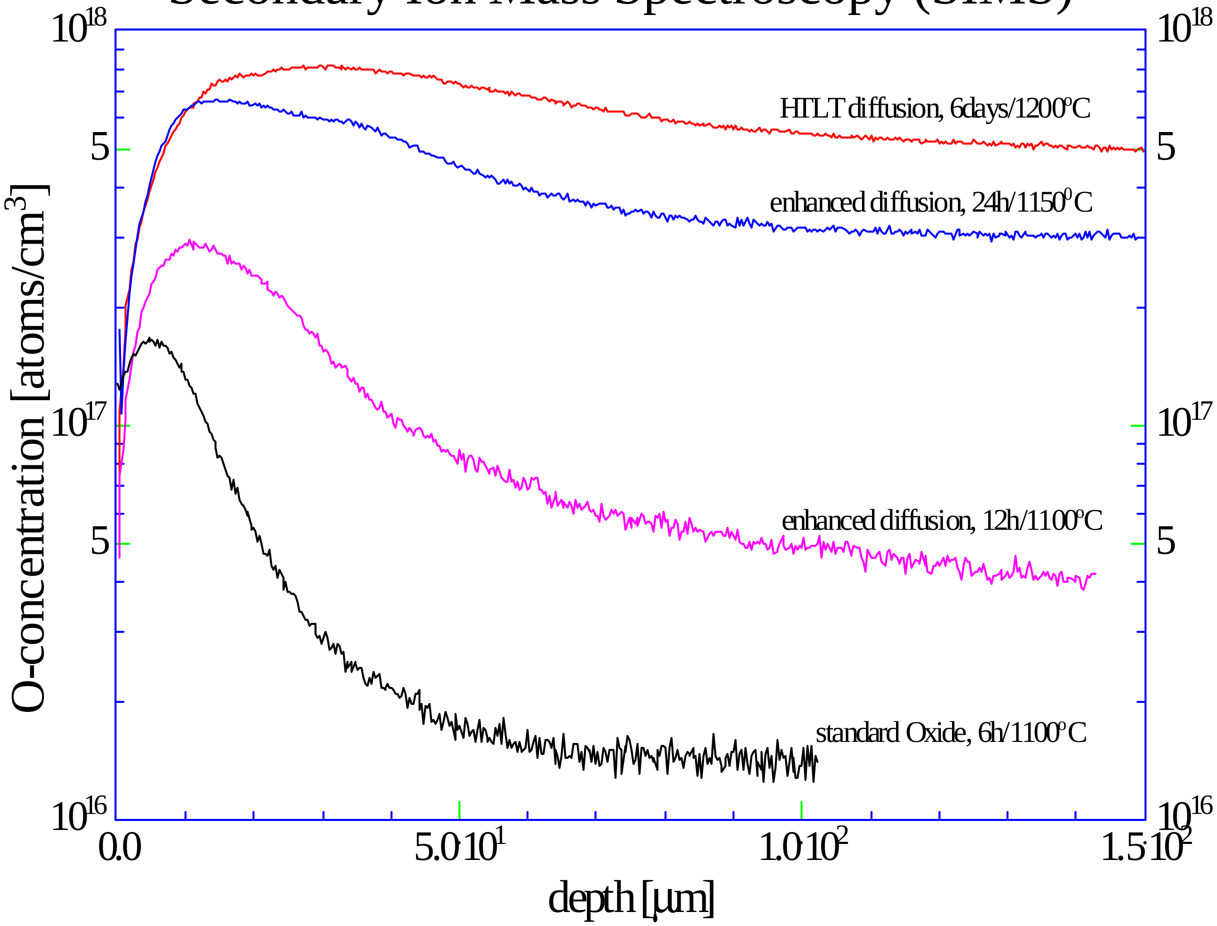
F_{eq} = 2.32×10^{11} cm^{-2},
Dt = 20 min, DT = 20^{o}C,
900 Ωcm n-type EPI,
[P_s] = 4.8×10^{12} cm^{-3},
[O_i] = 6×10^{16} cm^{-3},
[C_s] = 3×10^{15} cm^{-3}

Oxygen is Good, Carbon is Bad



Diffusion-Oxygenated Float Zone (DOFZ)

Secondary Ion Mass Spectroscopy (SIMS)



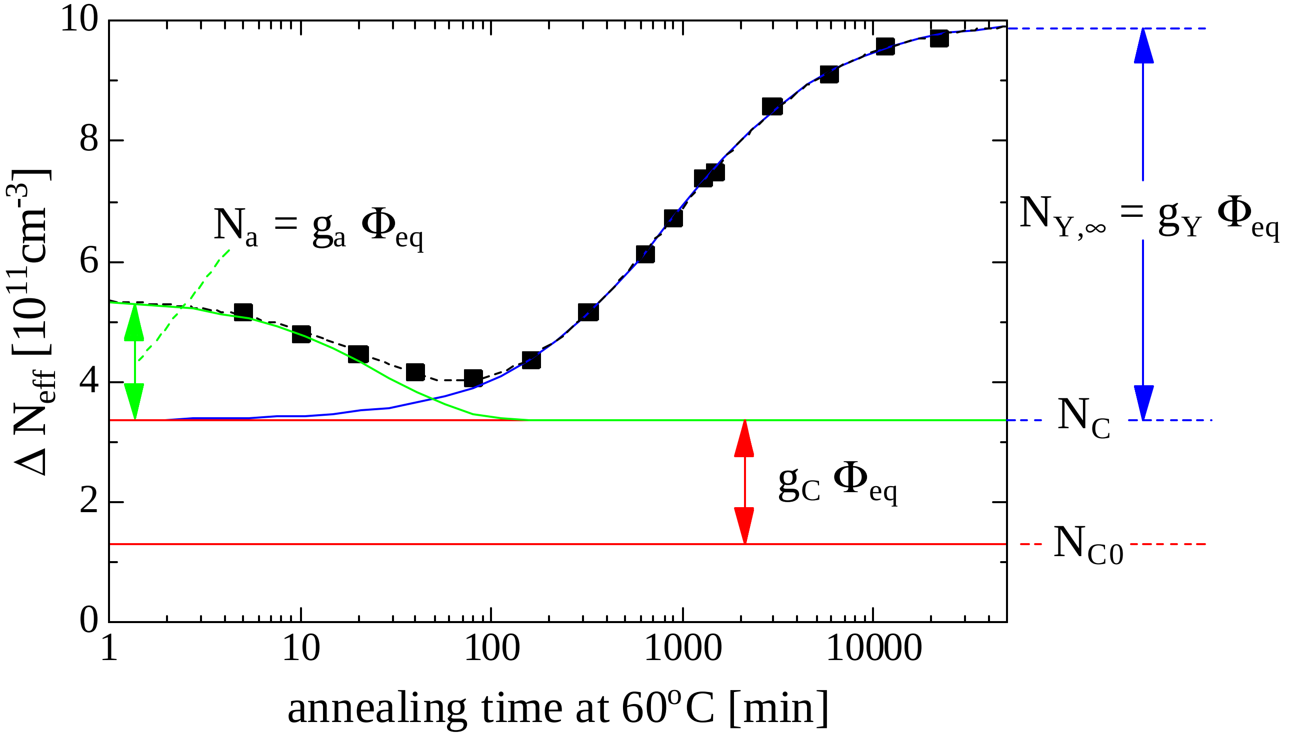
Controlled introduction of oxygen into silicon bulk

Easily included in manufacturing process

Low cost

Adopted by SINTEF, CiS, Micron, ST Microelectronics, CNM-CSIC, BNL Instr. Div.

Systematic Studies on DOFZ Material



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

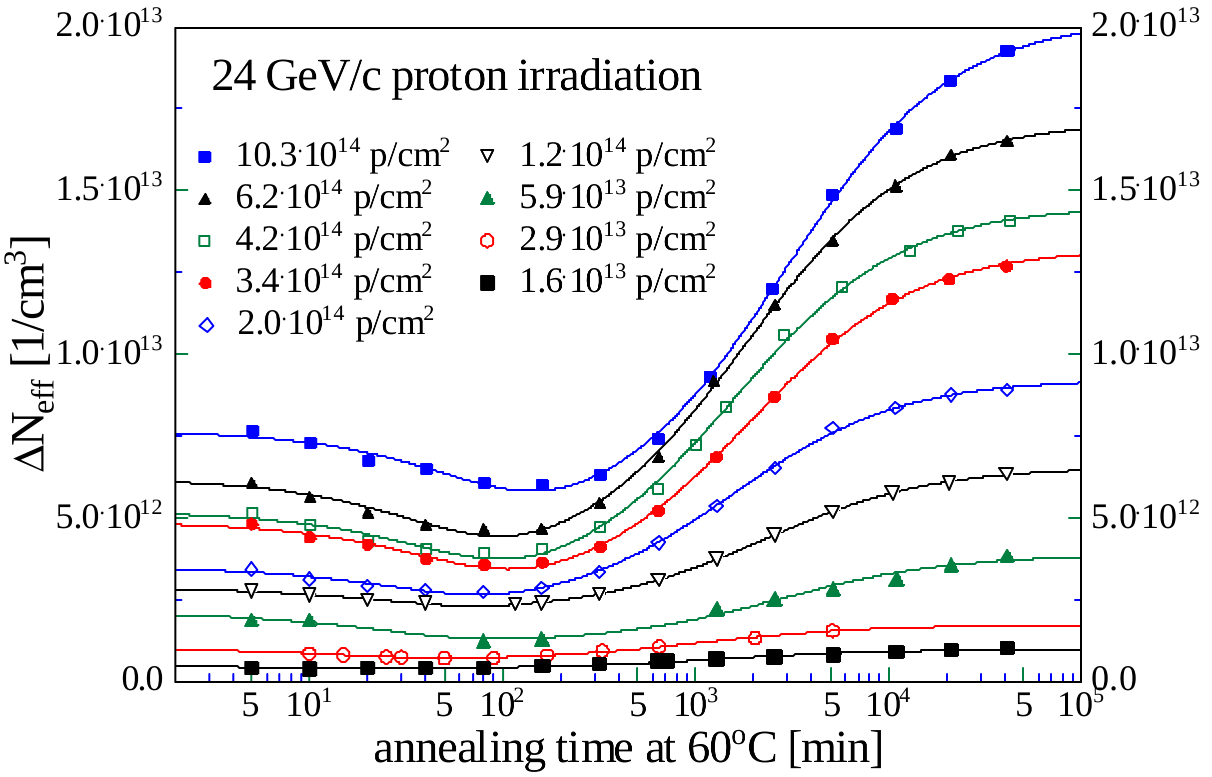
$$\boxed{DN_{eff}\left(F_{eq},t\right) = \underline{N_a\left(F_{eq},t\right)} + \underline{N_C\left(F_{eq}\right)} + \underline{N_Y\left(F_{eq},t\right)}}$$

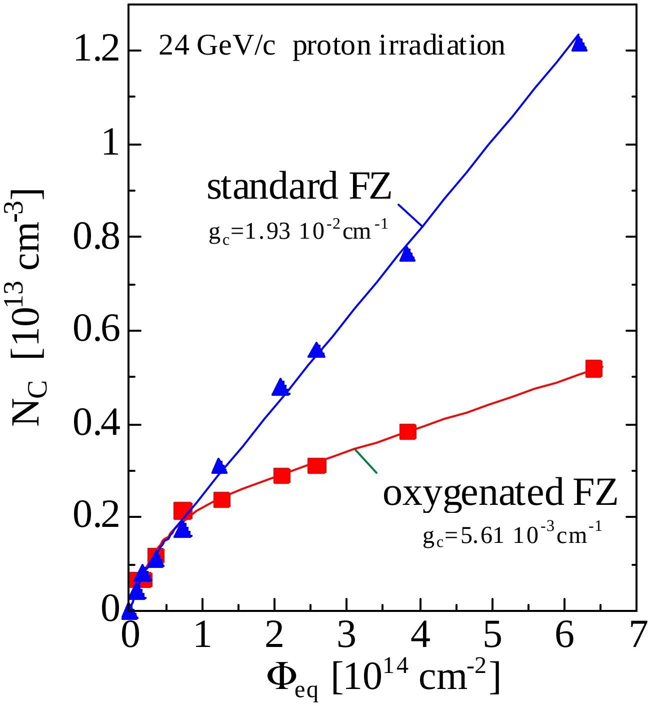
short term annealing

stable damage

long term reverse annealing

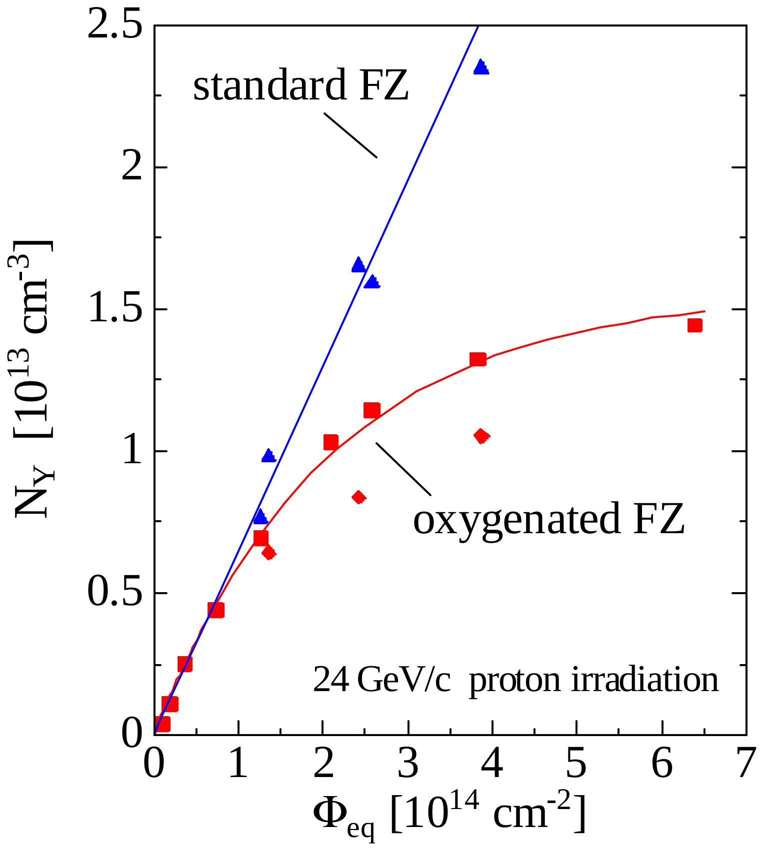
1st Benefit of DOFZ Material

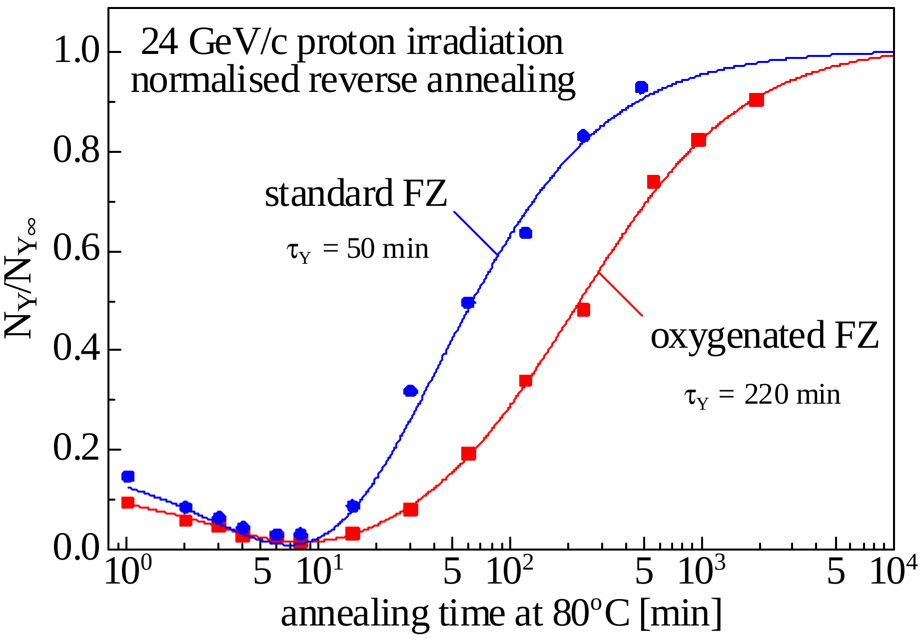




g_c improved by a factor of 3!

2^{nd} Benefit of DOFZ Material

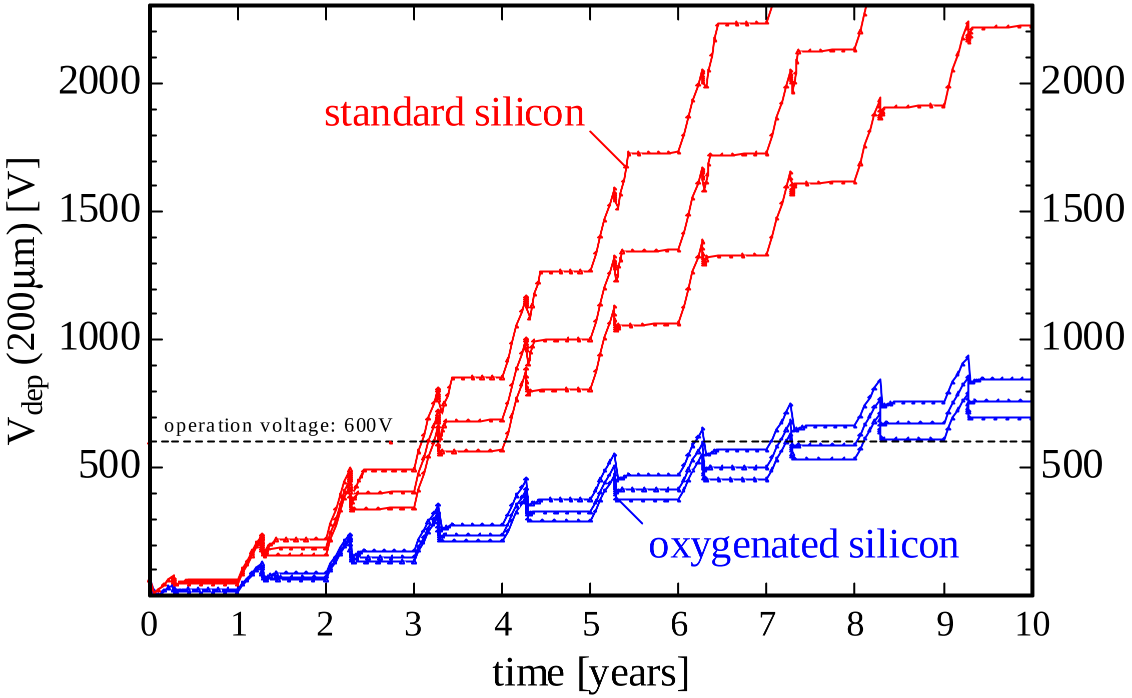




Reverse annealing saturates, and
Reverse annealing is delayed!

Damage Projection - ATLAS Pixel Detector - B-Layer

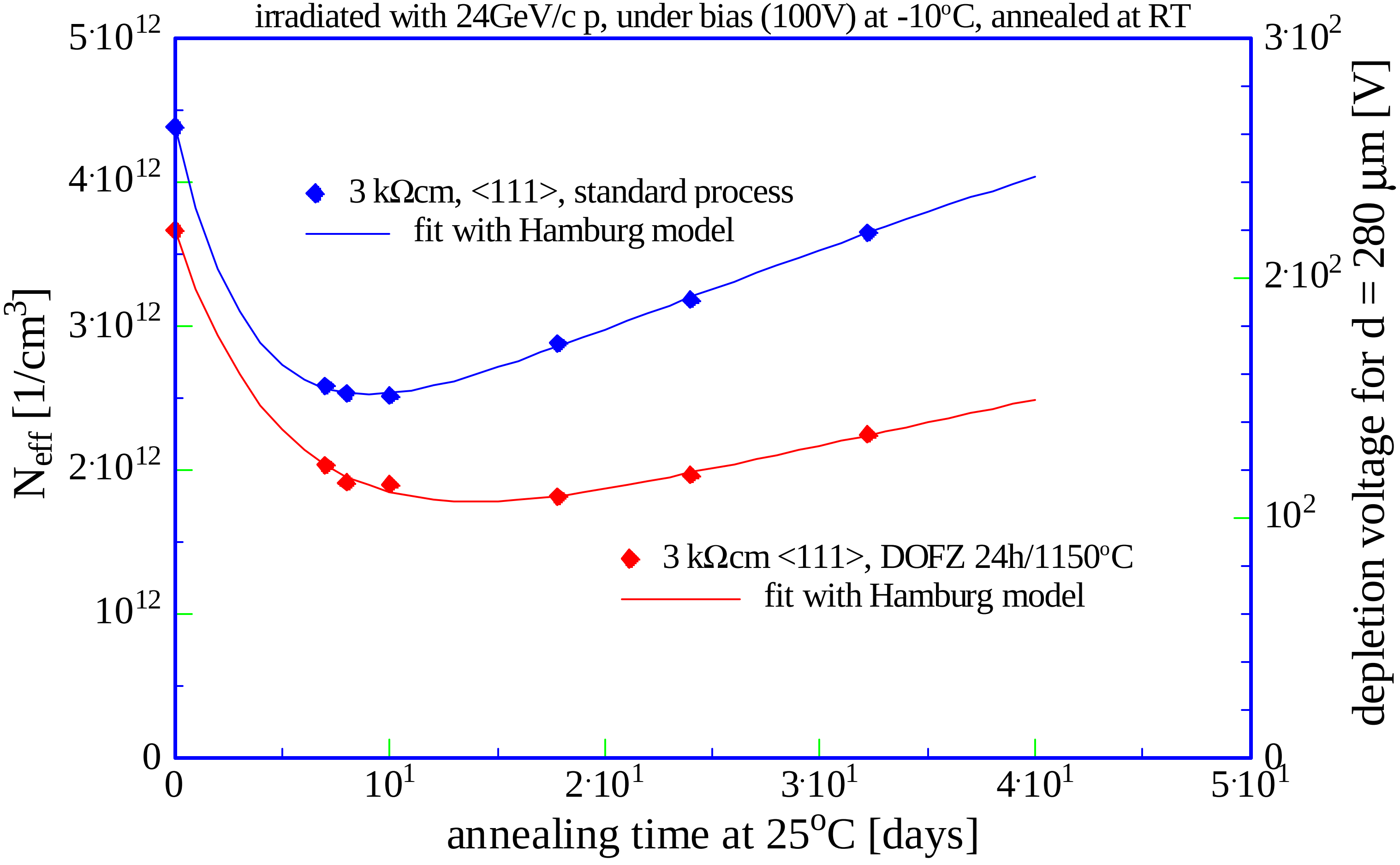
- **Radiation level for B-Layer :**
  - Φ_{eq}(year) = 3.5 × 10^{14} cm^{-2} (full luminosity)
    > 85% charged hadrons
- **Three scenarios :**
  - 1 year = 100 days beam (-7°C)
    (1) 3 days 20°C and 14 days 17°C
    (2) 30 days 20°C
    (3) 60 days 20°C
    Rest of the year: no beam (-7°C)



Simulation of Maintenance Warm-Up

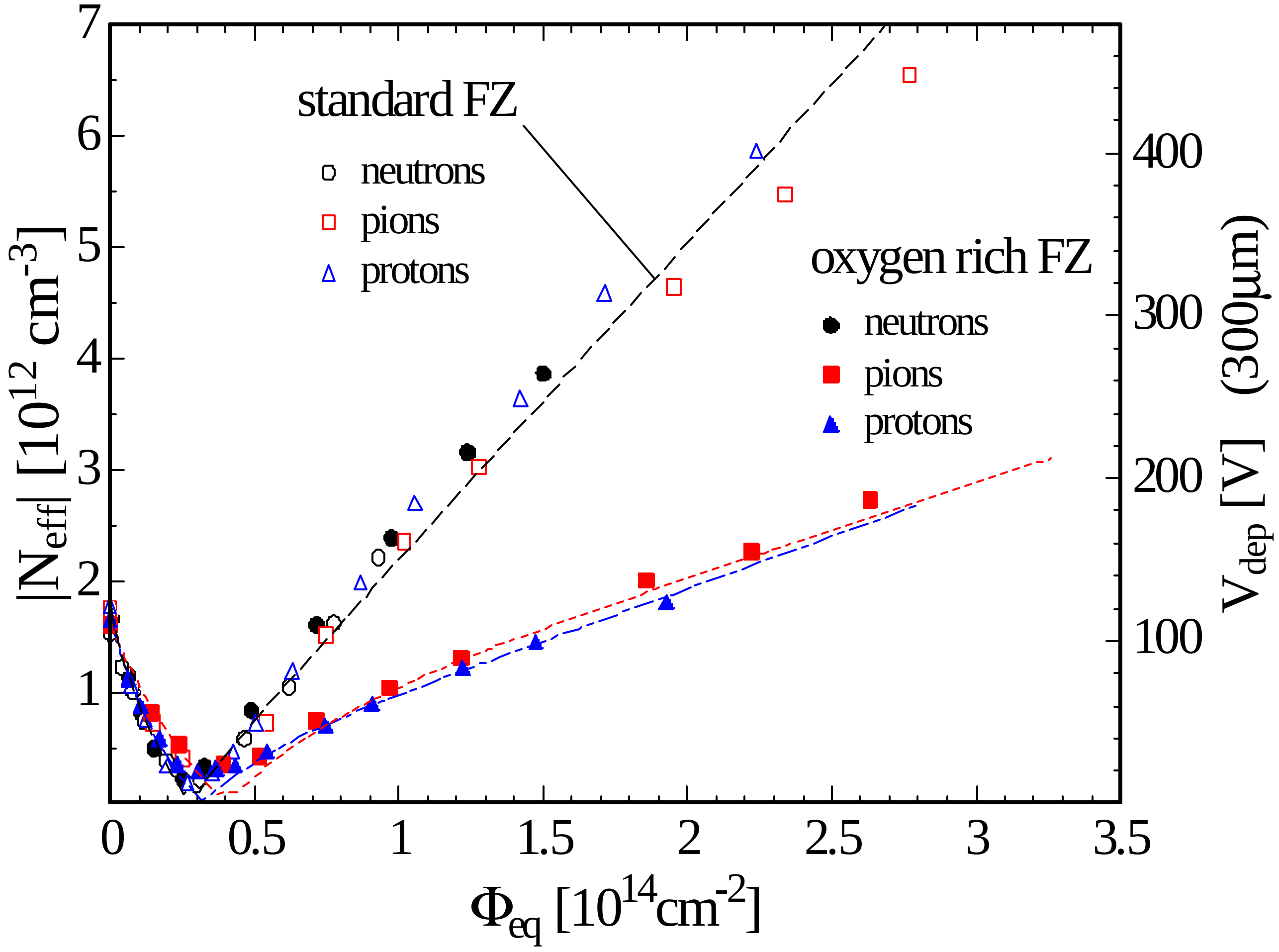
CiS ATLAS strip detectors, standard and DOFZ (24h/1150°C) process

irradiated with 24GeV/c p, under bias (100V) at -10°C, annealed at RT



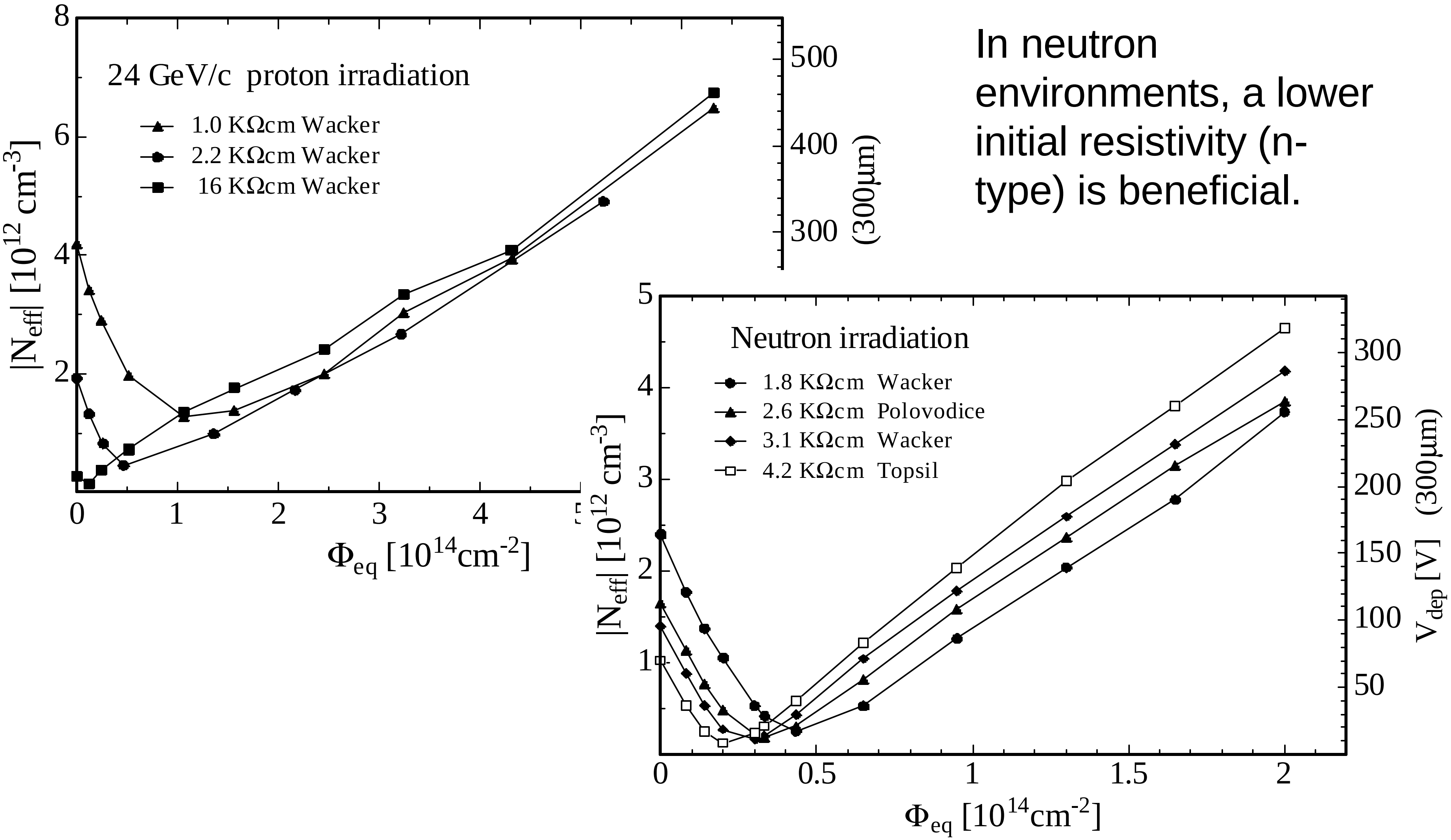
data from L. Andricek, MPI Munich

The Neutron-Proton Puzzle



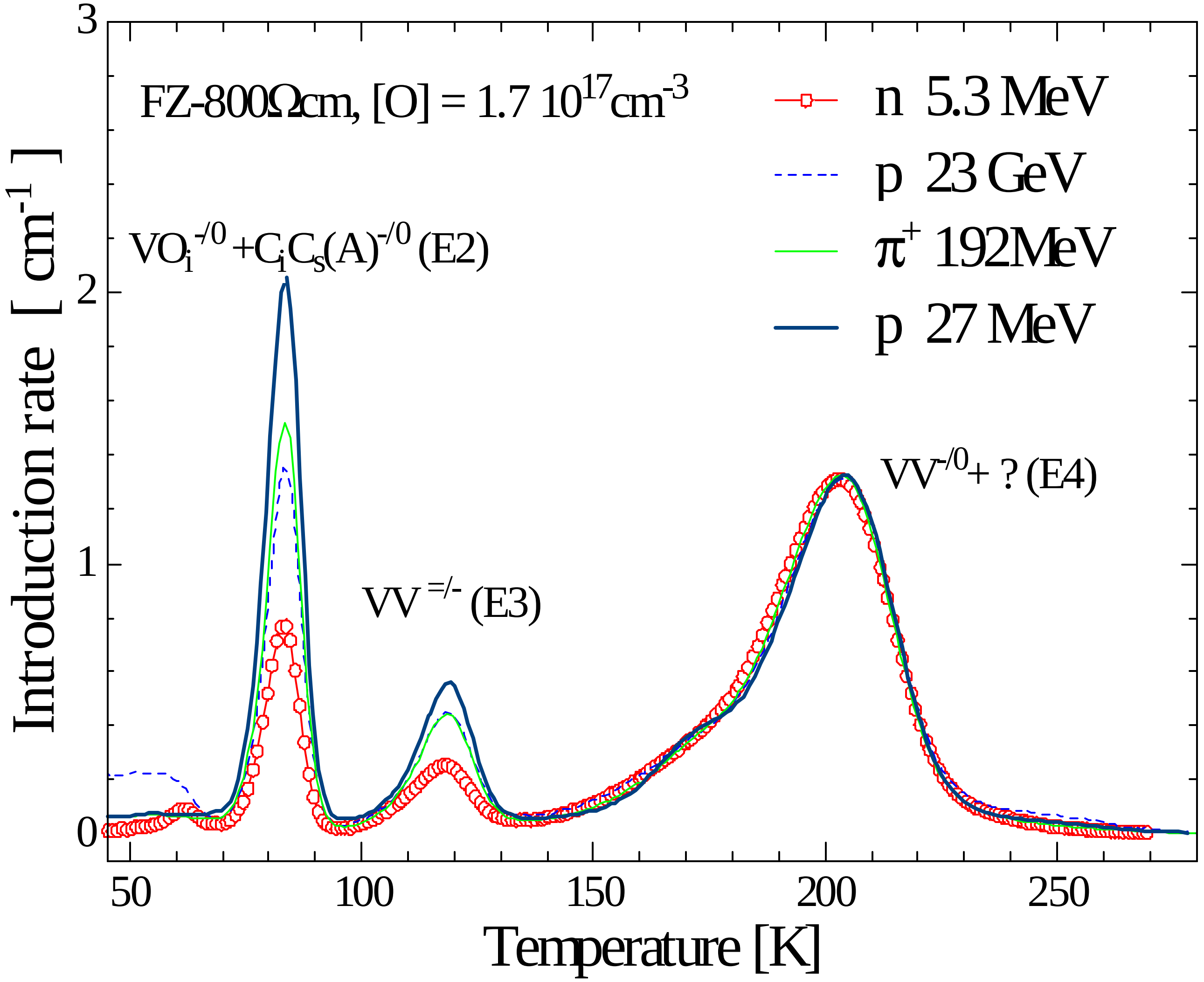
No benefit of the DOFZ material is observed for neutron irradiation

Initial Resistivity



In neutron environments, a lower initial resistivity (n-type) is beneficial.

Particle-Dependent DLTS Spectra

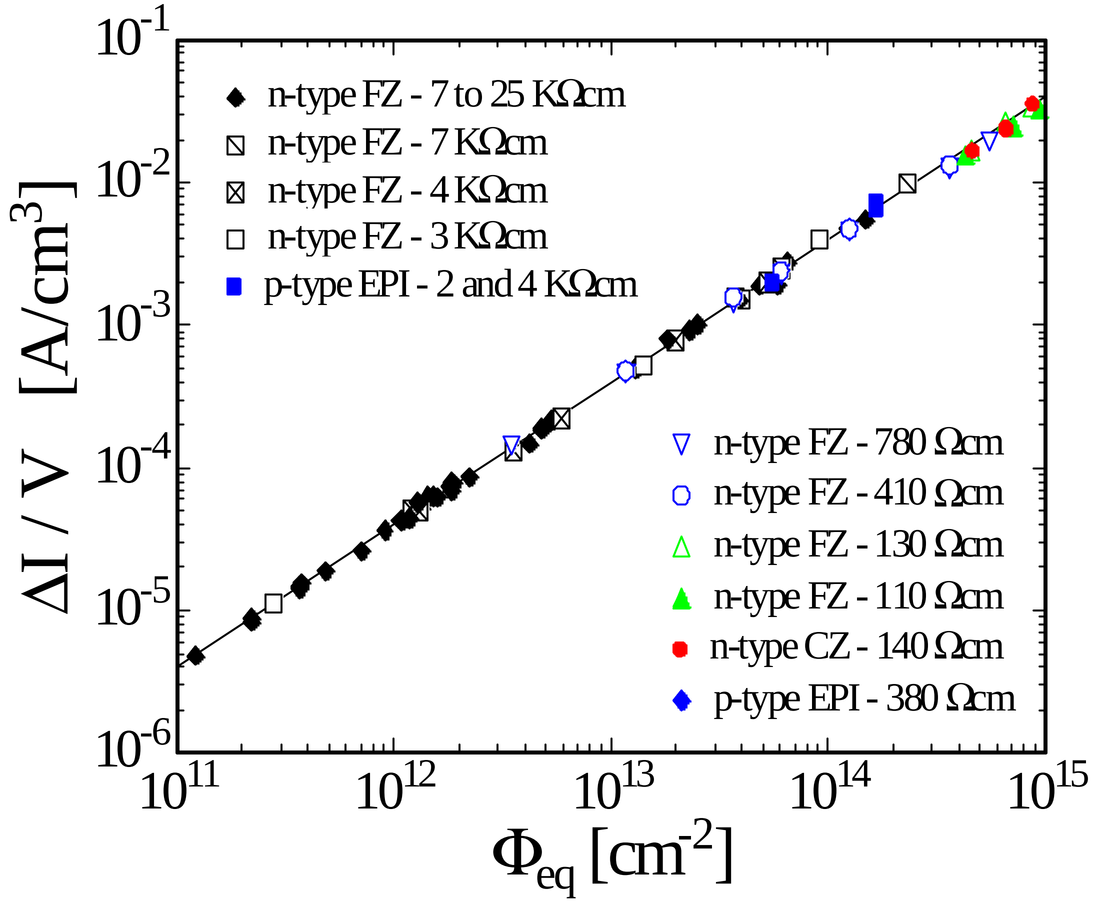


'Cluster' peak at 200K is alike for all types of particle irradiation

-

point defect-related peaks are not.

Leakage Current



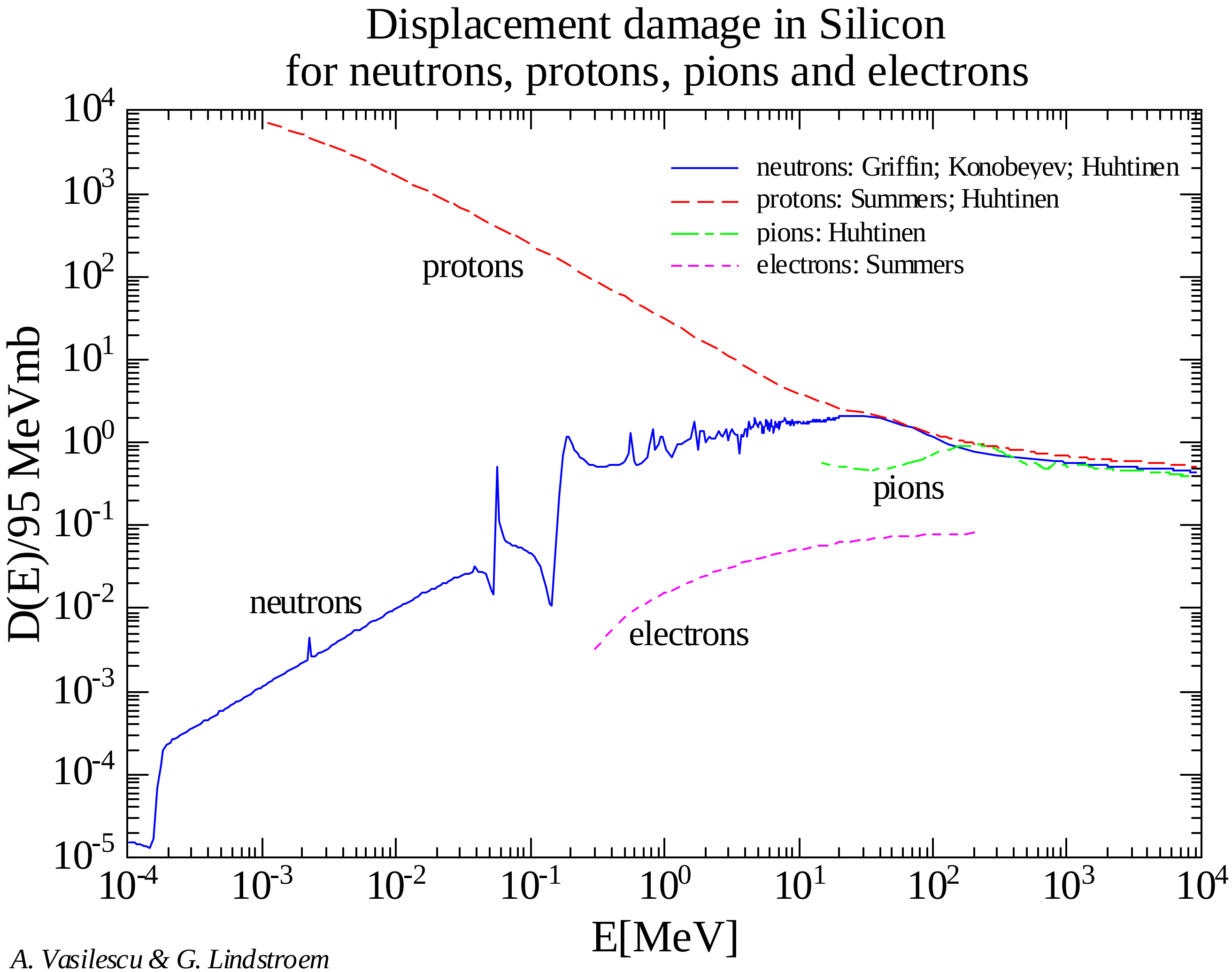
$$a = \frac{\Delta I}{V \cdot \Phi_{eq}}$$

The increase in leakage current does not depend on the initial resistivity or impurity content.

The value measured after 80 min annealing at 60 C is used for 1-MeV n equivalent fluence determination

$\alpha_{80min/60C} = 4.0 \times 10^{-17}$ A/cm

Non-Ionizing Energy Loss


Displacement damage in Silicon
for neutrons, protons, pions and electrons

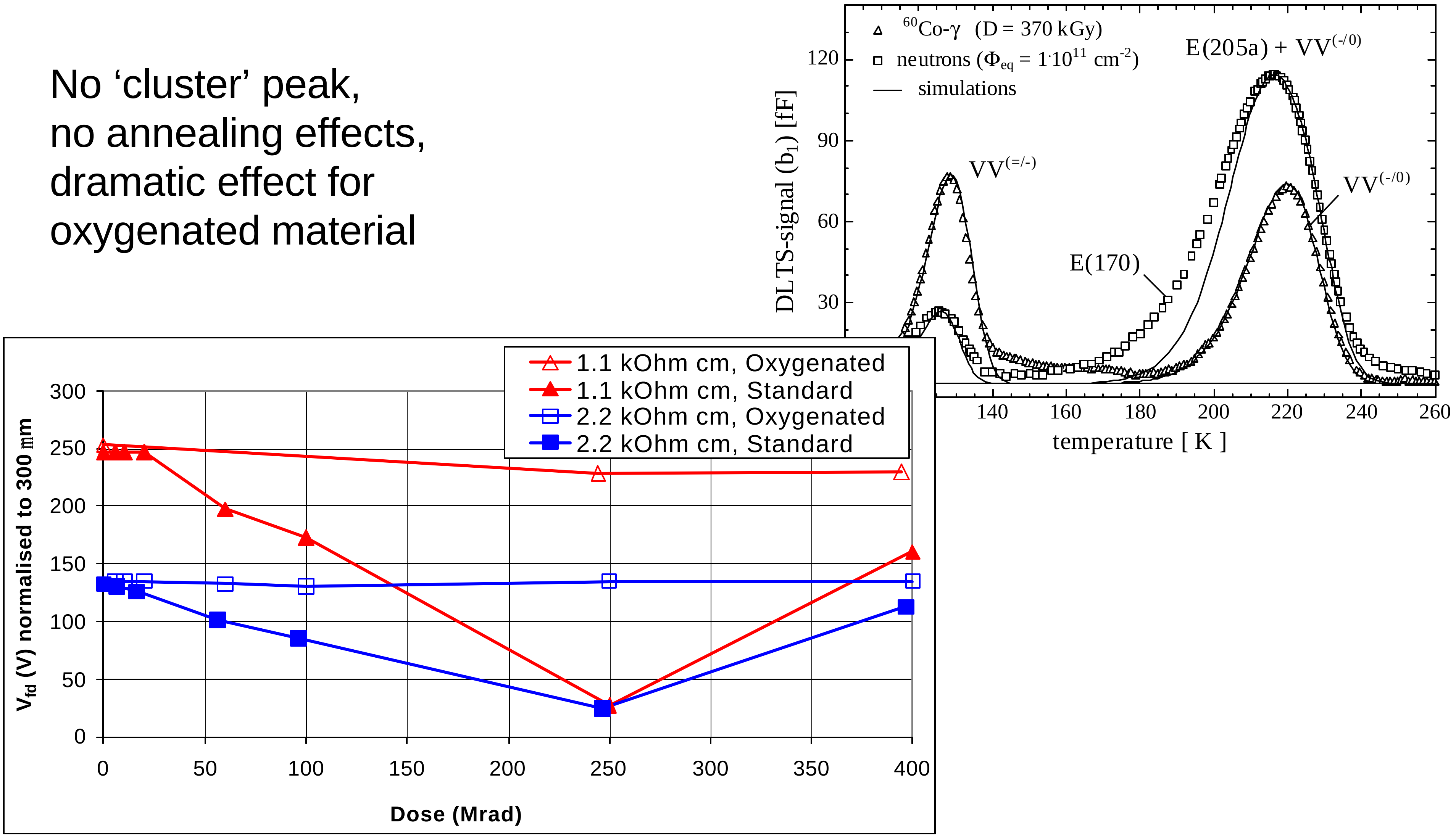
A. Vasilescu & G. Lindstroem

NIEL functions specify the amount of energy going into mechanical displacements, disregarding the spatial distribution of the primary damage.

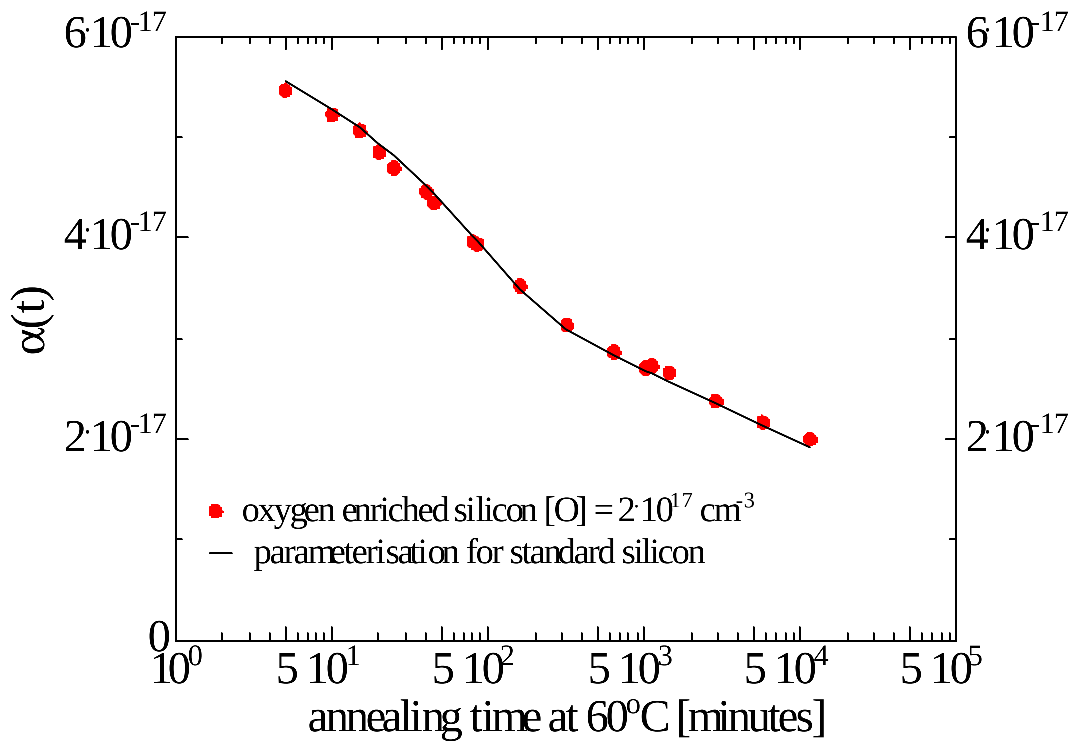
Coulomb interaction causes relatively more low-energy transfers, i.e., more point defects / less clusters.

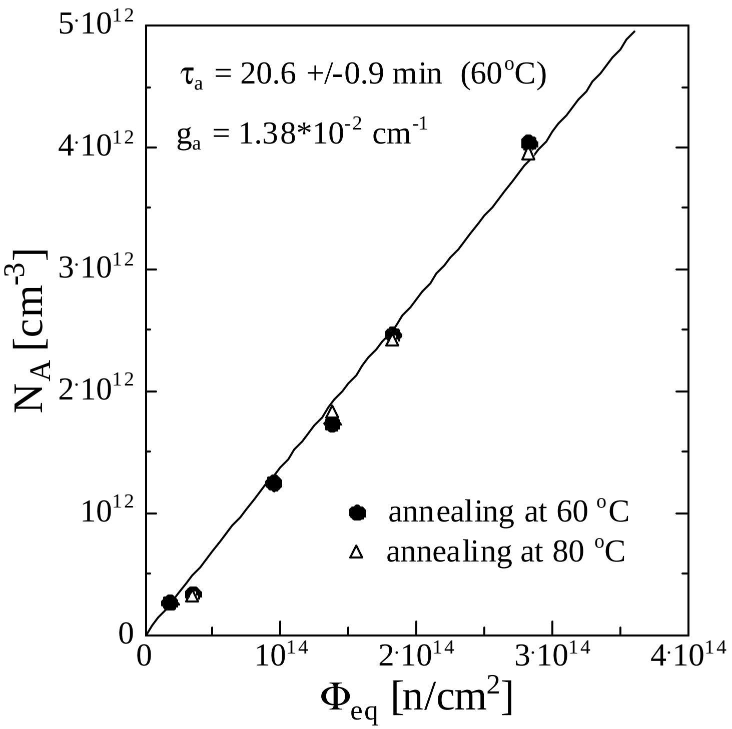
Gamma Irradiation

No ‘cluster’ peak,
no annealing effects,
dramatic effect for
oxygenated material



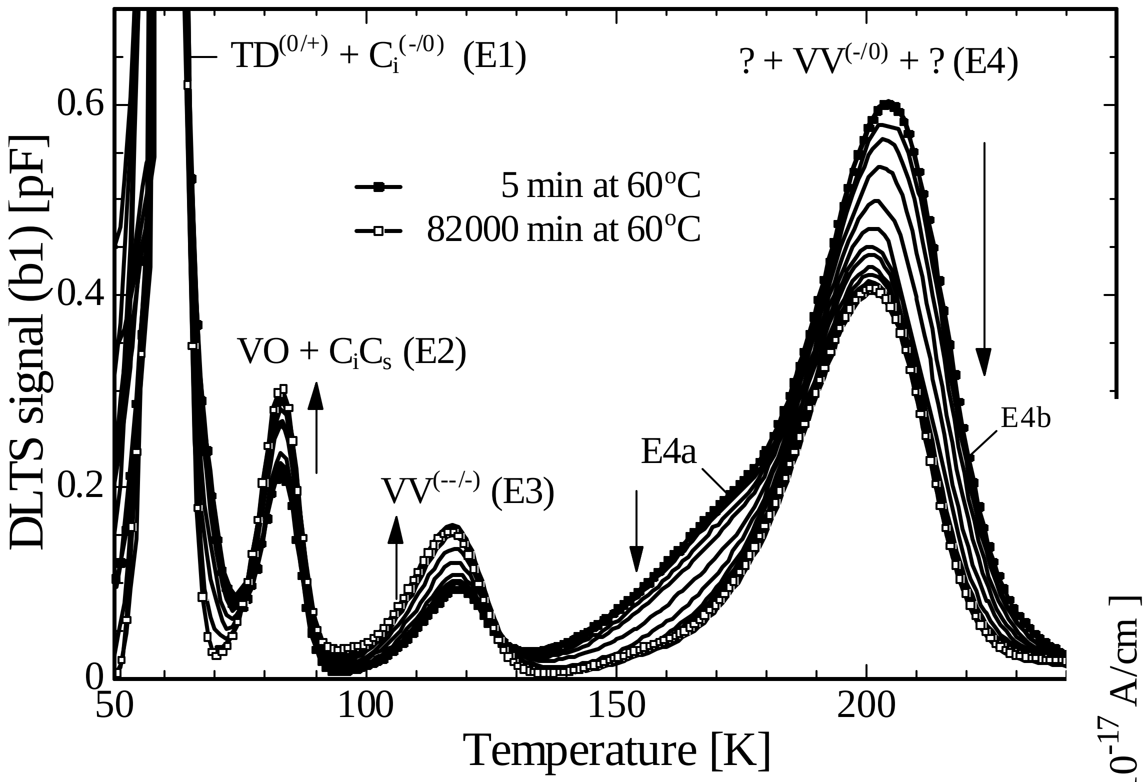
Short Term Annealing



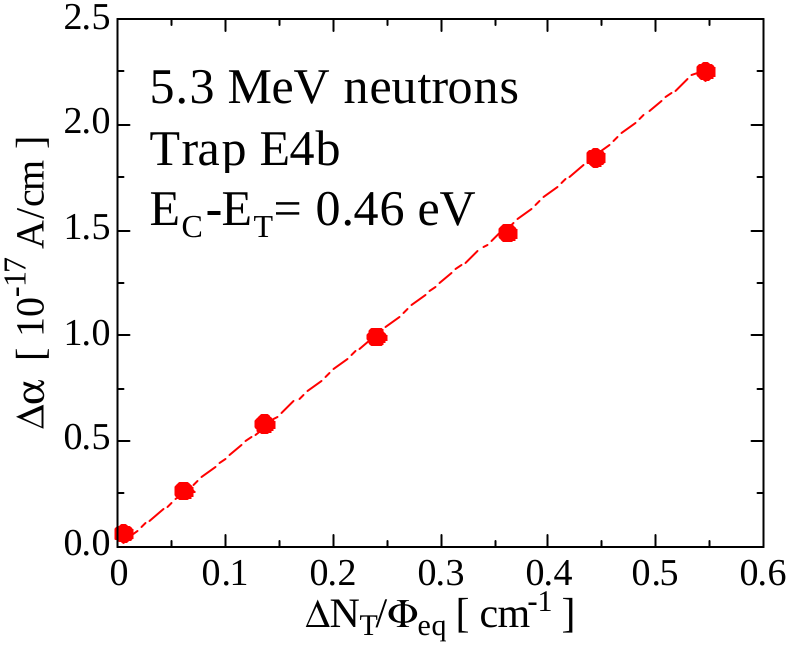


The activation energy of the short term annealing is about 1.1 eV for both doping and leakage current. Common cause!

The Right-Hand Shoulder of the 'Cluster' Peak



Unambiguous correlation between DLTS annealing and leakage current annealing.



Summary

Main Result:
DOFZ technology has proven to be both technologically feasible (transfer to industry successful) and detectors manufactured this way show superior radiation hardness

◆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.
- **Lower resistivity material is beneficial** for detectors that operate in a radiation environment dominated by reactor energy **neutrons**.
- **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

- **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**