

Development of Radiation Hard Sensors

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And

On behalf of the CERN-RD48 (ROSE) Collaboration

OUTLINE

- ◆ **Semiconductor detector materials**

 - General remarks**

 - Properties**

 - Examples**

- ◆ **Development of rad hard silicon detectors – Results from CERN-RD48**

 - DOFZ silicon – macroscopic results**

 - Annealing Studies & Hamburg model**


 - LHC-projections**

 - Microscopic understanding**

 - Open questions**

- ◆ **Conclusions**

Possibilities for Improving the Radiation Tolerance of Tracking Detectors for HEP Experiments

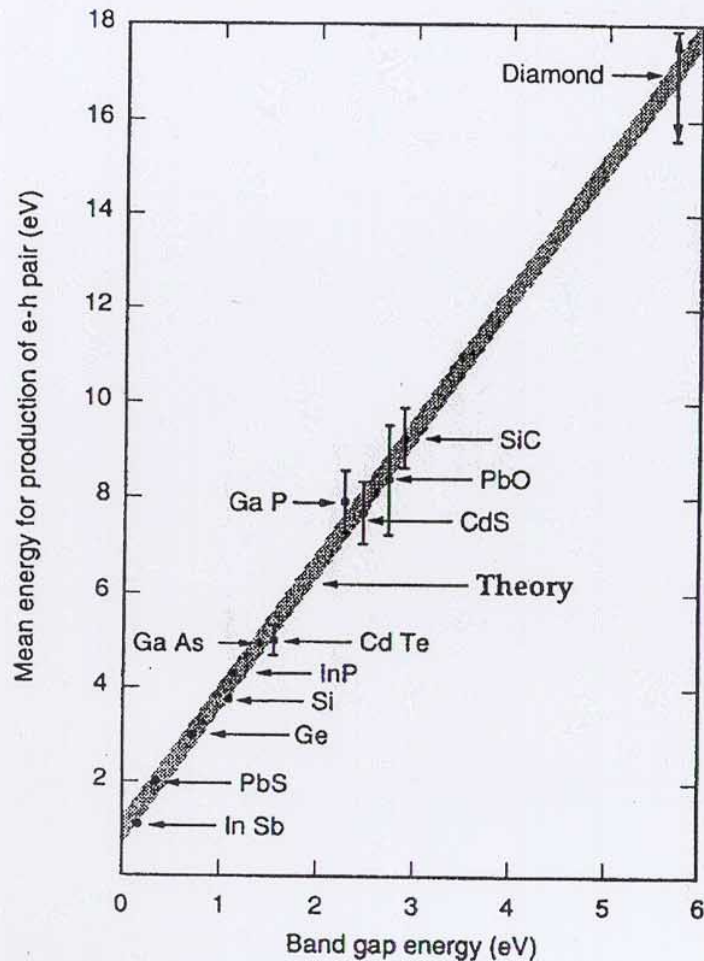
- ◆ **Selection of Detector Material** 
- ◆ **Detector Design (guard rings, 3D design,**)
- ◆ **Defect Engineering (impurities)**
- ◆ **Operational Conditions (cooling,.....)**

Criteria for Semiconductor Tracking Detectors

- ◆ **Bandgap larger than Silicon**
(Si: 1.12 eV) ⇒ **less cooling necessary**
- ◆ **Bandgap smaller than Diamond**
(C: 5.46 eV) ⇒ **lower ioniz. energy ⇒ good S**
- ◆ **Large Radiation Length \approx Silicon**
(Si: 9.4 cm) ⇒ **stable wafer thickness**
- ◆ **High e/h-mobilities \geq Silicon**
(Si: 1400/450 cm²/Vs) ⇒ **fast charge collection**
- ◆ **Low dielectric constant $<$ Silicon**
(Si: 11.7) ⇒ **low capacitance ⇒ low N**
- ◆ **Low trap concentration, monocrystalline**
(Si: \approx ideal) ⇒ **good charge collection**
- ◆ **Large displ. energy for PKA \geq Silicon**
(Si: 21 eV) ⇒ **less rad. damage ⇒ stable S/N**
- ◆ **Mechanical strength & heat conductance** ⇒ **good for process handling
stability as detector component**
- ◆ **Commercial product, standard process** ⇒ **large scale use, cost effective**

[S = signal height for mip's, N = noise]

A closer look at the bandgap



Ionization energy vs. bandgap energy
(from Dubbs et al., IEEE 98)

| | band gap [eV] | w/ehpair [eV] | R.Length X_0 [cm] | eh-pairs/ $0.3\%X_0$ |
|------------------------|---------------|---------------|---------------------|----------------------|
| Ge | 0.76 | 2.9 | 2.3 | 17 E3 |
| Si | 1.12 | 3.6 | 9.4 | 30 E3 |
| InP | 1.34 | 4.3 | 2.1 | 8.9E3 |
| GaAs | 1.42 | 4.2 | 2.3 | 10 E3 |
| CdZnTe | 1.5-2.2 | 5-7 | ? | ? |
| SiC | 2.9 | 9.3 | 8.1 | 16 E3 |
| C _(diamond) | 5.46 | 13 | 18.8 | 7.2E3 |

0.3% X_0 for Si = 280 μm

However optimization needed since:

- ◆ Low bandgap \Rightarrow low w but high current
- ◆ High bandgap \Rightarrow low current (SI!!) but small S

Electrical Properties – Some examples

| | ϵ | $E_{\text{break-down}}$ [V/cm] | μ_e [cm ² /Vs] | μ_h [cm ² /Vs] | $v_{\text{saturation}}$ [cm/s] | Thermal conductivity [W/cmK] |
|-------------|------------|-----------------------------------|----------------------------------|----------------------------------|-----------------------------------|---------------------------------|
| Si | 11.9 | $3 \cdot 10^5$ | 1350 | 480 | $8 \cdot 10^6$ | 1.5 |
| InP | 12.5 | $5 \cdot 10^5$ | 5400 | 200 | $3 \cdot 10^7$ | |
| GaAs | 13.1 | $4 \cdot 10^5$ | 8500 | 400 | $8 \cdot 10^6$ | 0.45 |
| SiC | 9.7 | $2 \cdot 10^6$ | 900 | 20 | $2 \cdot 10^7$ | 4.9 |
| C | 5.7 | 10^6 - 10^7 | 1800 | 1200 | $2 \cdot 10^7$ | 15 |

- ◆ Charge carrier mobilities depend on electric field and temperature, decreasing with increasing E and decreasing T, values are given for T=293K and zero (low) field
- ◆ The charge collection time t_c depends on the carrier type, the smaller μ -value governs the minimum achievable value. For low E $t_c = d^2/(\mu \cdot V)$, for high E look at details of transport properties
- ◆ Charge collection efficiency governed by $\mu\tau$ -product with τ = lifetime of e resp h-carriers.

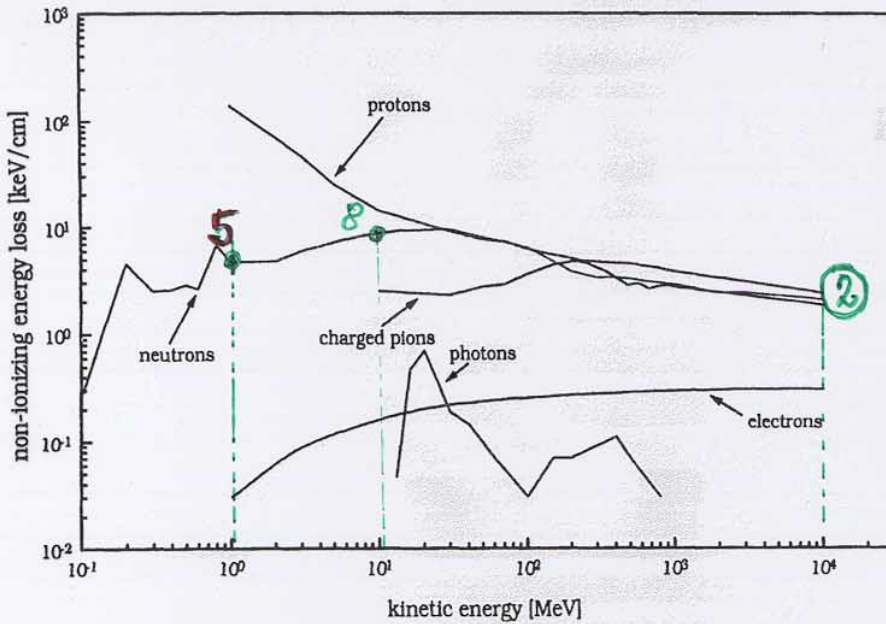
Main problems:

Crystalline imperfections (diamond), stoichiometry (abundance of one constituent in compounds)

Impurities acting as deep traps (also intentionally for compensation), polarization effects at surface

NIEL governed radiation damage

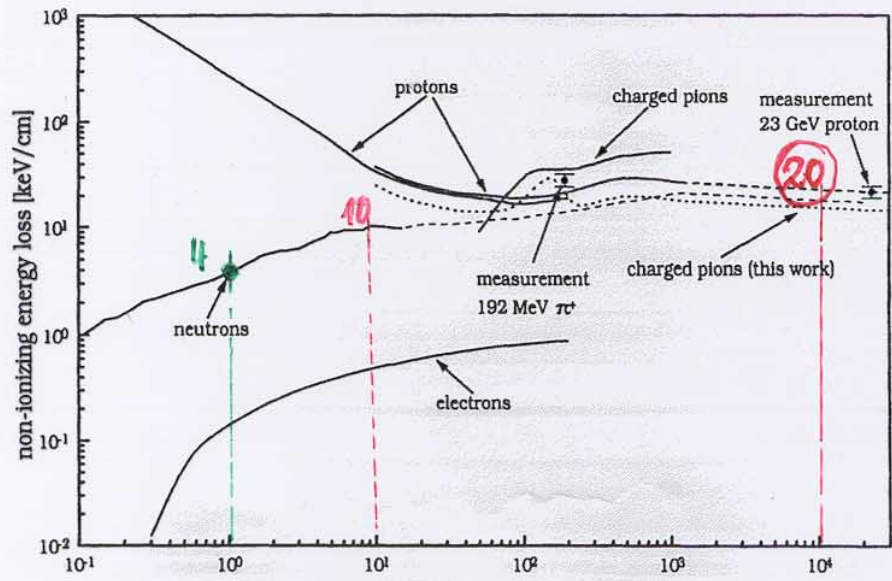
Comparison between Si and GaAs as example



monocrystalline, ideal
 large X_0
 largest $S(\text{mip}/X_0)$
 ideal charge collection
 has to be cooled!

Si

Displacement energy = 21 eV



large band gap
 usable at RT
 "faster" than Si
 not ideal ch. collection
 (deep traps)
 worse rad. damage than Si

GaAs

Displacement Energy = 10 eV

Curves taken from M. Rogalla, PhD thesis 1997

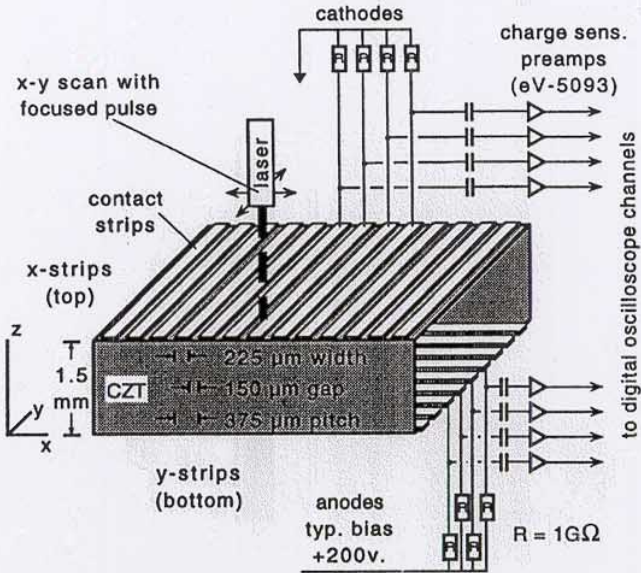
◆ The damage in GaAs at high proton energies is ~~1.5~~ x larger than in Si

10

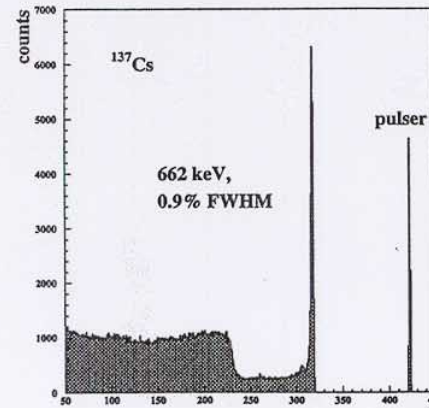
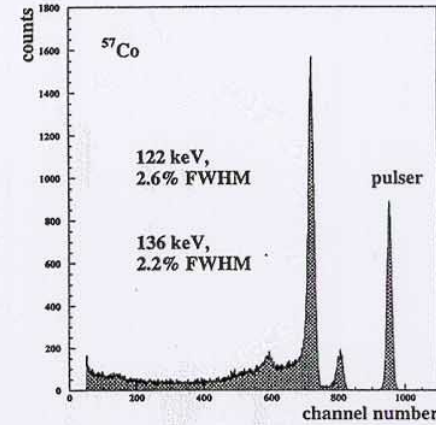
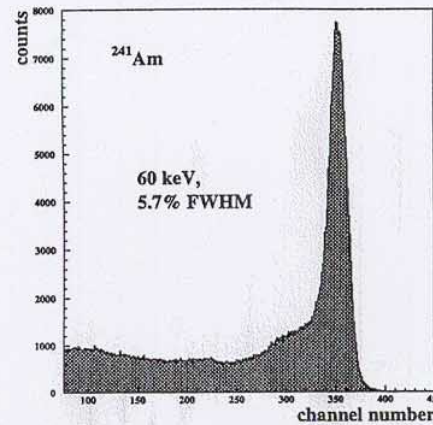
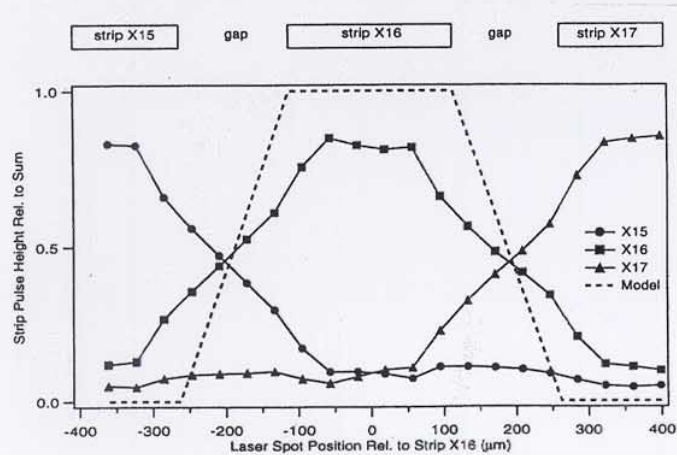
Reason: nuclear σ larger
 more reaction channels
 → lower energies of residuals

Development of CdZnTe strip detectors - Example

(taken from O. Tousignant et al., University of Montreal and University of New Hampshire, Space Science Center)



Small segment of the prototype strip detector.



Silicon in comparison:

$\tau \approx 1 \mu s$
 $\mu \cdot \tau \approx 1$
 $E \approx 10^4 \text{ V/cm}$
 $t_{drift} / \tau \approx 3 \cdot 10^{-6}$
 for $d = 300 \mu m$

TRAPPING

$\mu \cdot \tau$ - problems

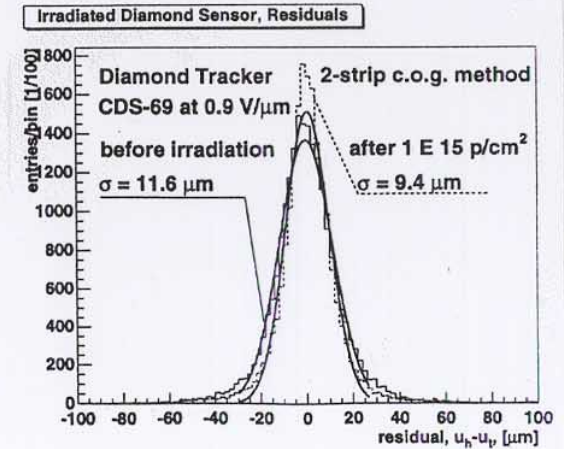
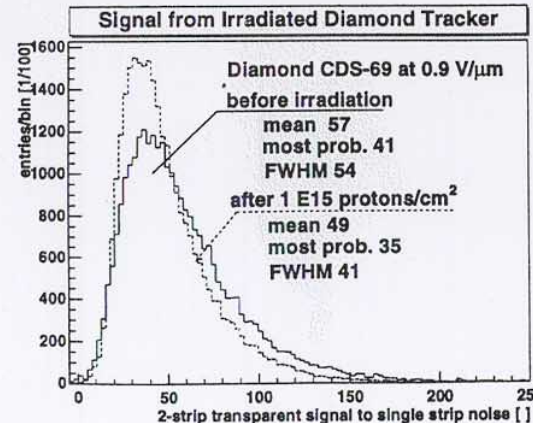
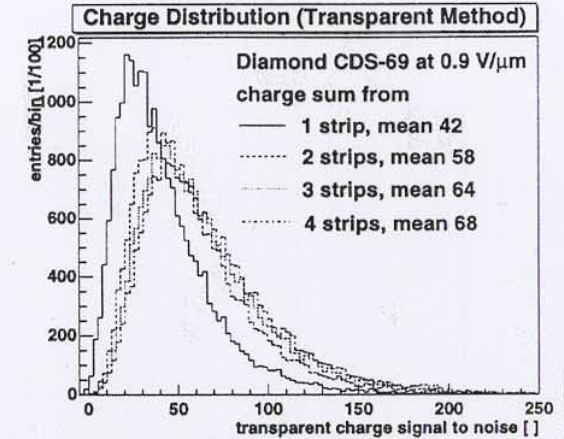
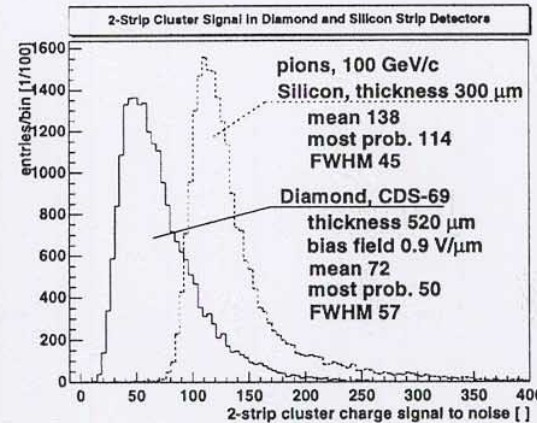
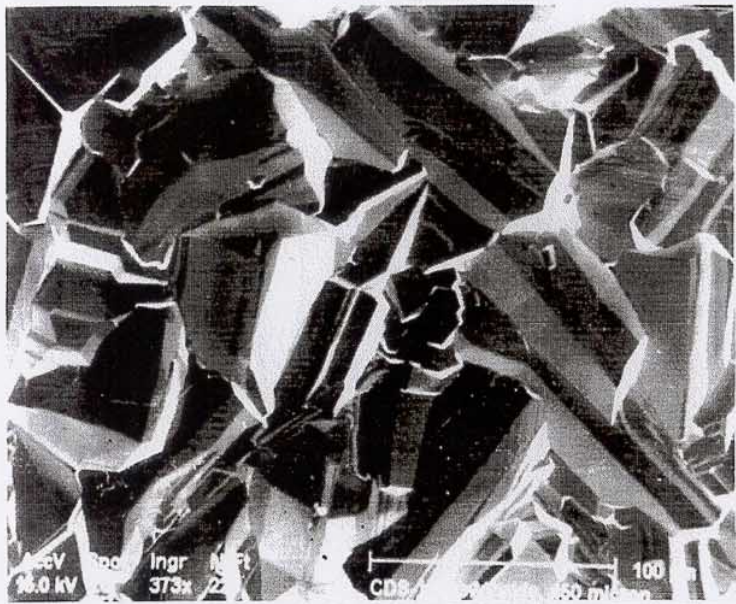
$\mu_e \tau_e = 55 \cdot 10^{-6}$
 $\mu_h \tau_h = 48 \cdot 10^{-6}$
 $E \approx 10^3 \text{ V/cm}$
 $t_{drift} / \tau \approx 1$ for $d = 300 \mu m$

*However:
 promising material
 for limited applications*

| | Mobility $\text{cm}^2 \text{V}^{-1} \text{s}^{-1}$ | Trapping Time | Detrapping Time |
|-----------|---|---------------|-----------------|
| Electrons | 1000 | 55 ns | 28 ns |
| Holes | 15 | 3.2 μs | > 50 μs |

CVD Diamond as material for strip and pixel detectors

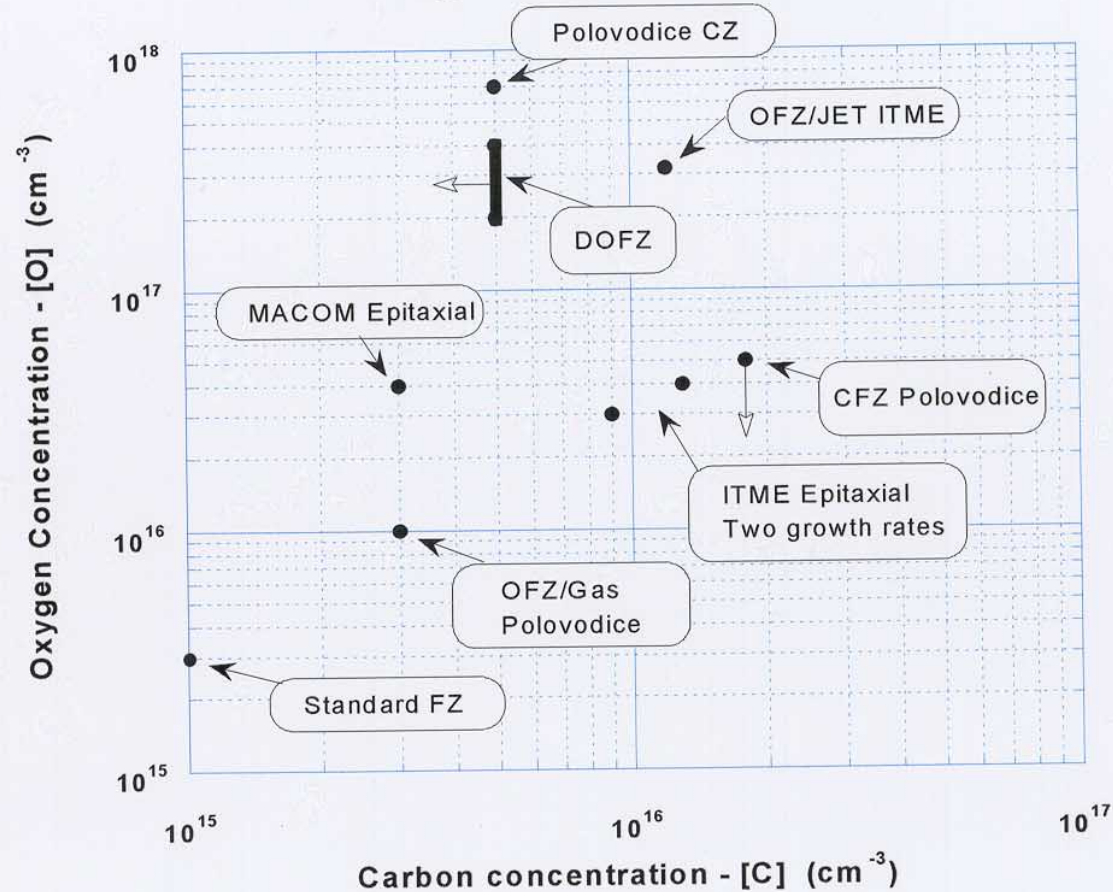
(example: CERN-RD42 Collaboration)



Virtues: "fastest" semiconductor
 large X_0 , low ϵ
 large bandgap, usable @ RT
 high radiation tolerance

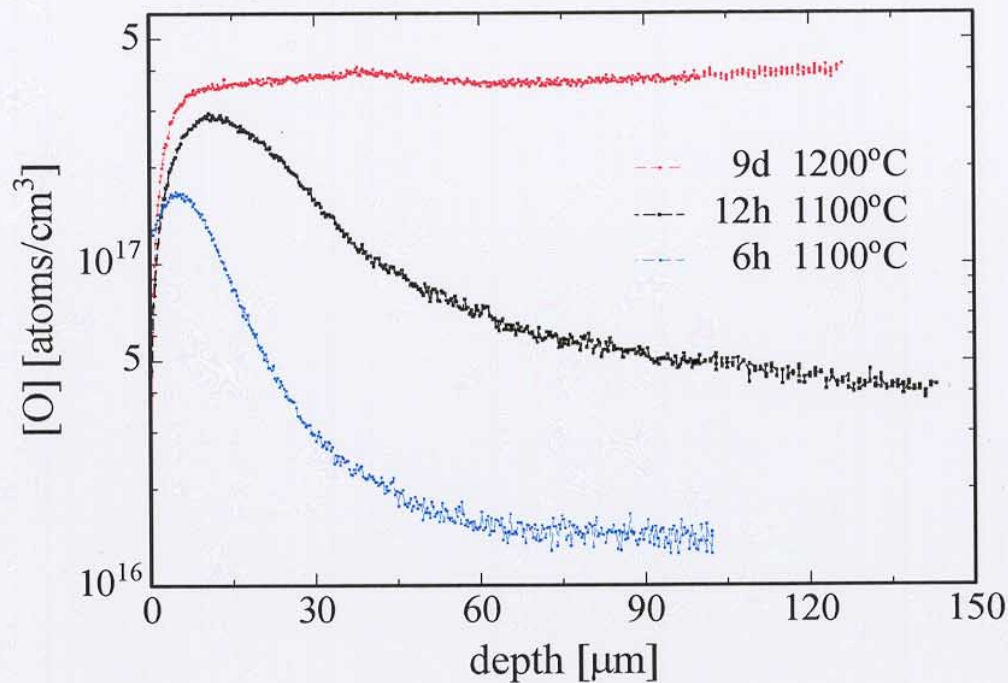
Problems: polycrystalline → trapping
 limited charge collection eff.
 polarization effects
 cost ?

Oxygen and Carbon - the key ingredients -



- ◆ **DOFZ – Diffusion oxygenated Float Zone**
Controlled introduction of oxygen,
easily included in manufacturing process, low cost

Oxygen diffusion



◆ DOFZ – Diffusion oxygenated Float Zone

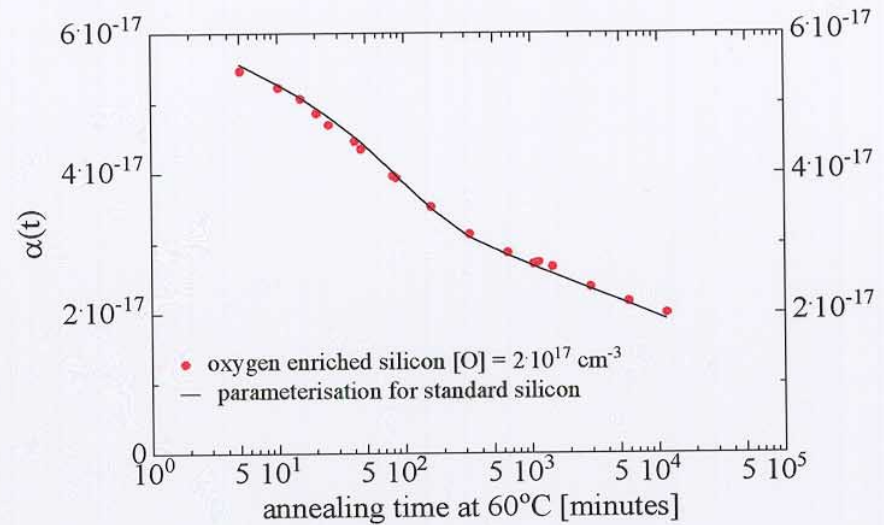
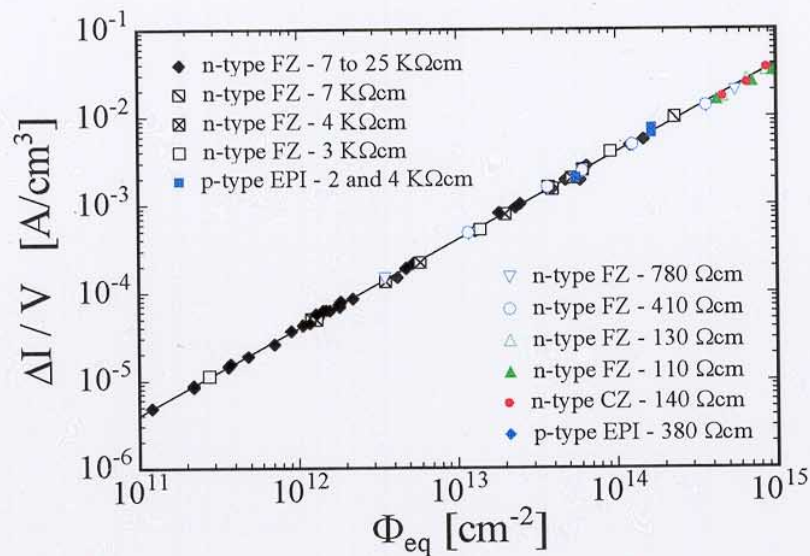
Open question:

Diffusion time/oxygen concentration needed to get the beneficial effect?

For the moment:

16 h diffusion at 1150°C ([O] = 1.5 × 10¹⁷ cm⁻³) seems to be sufficient

Leakage Current – Annealing



◆ Oxygenated and Standard Silicon show same annealing

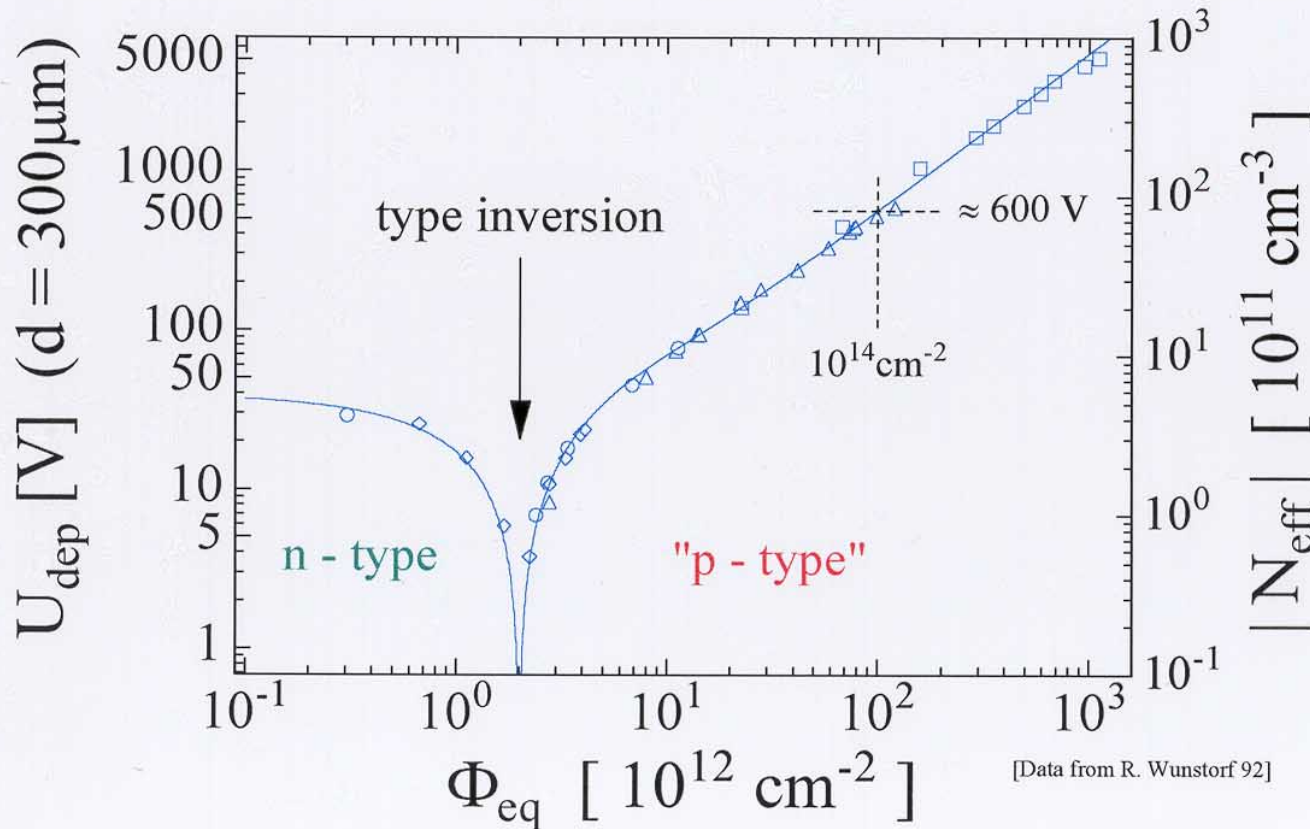
◆ Damage parameter α : $\alpha = \frac{\Delta I}{V \cdot \Phi_{eq}}$ independent of Φ_{eq}

used for fluence (NIEL) calibration !

N_{eff} - effective doping concentration

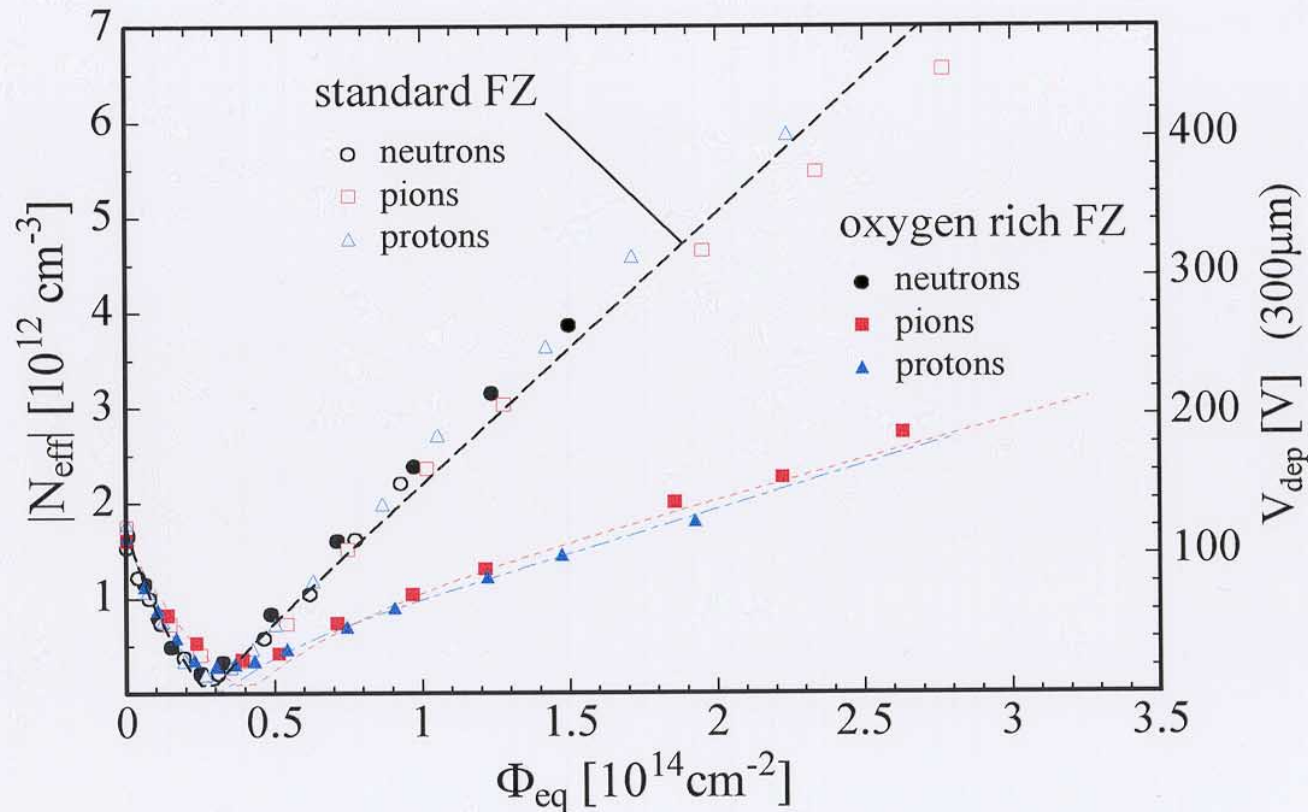
$$|N_{\text{eff}}| \propto \frac{V_{\text{dep}}}{d^2}$$

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



Oxygen and standard silicon - Particle dependence -

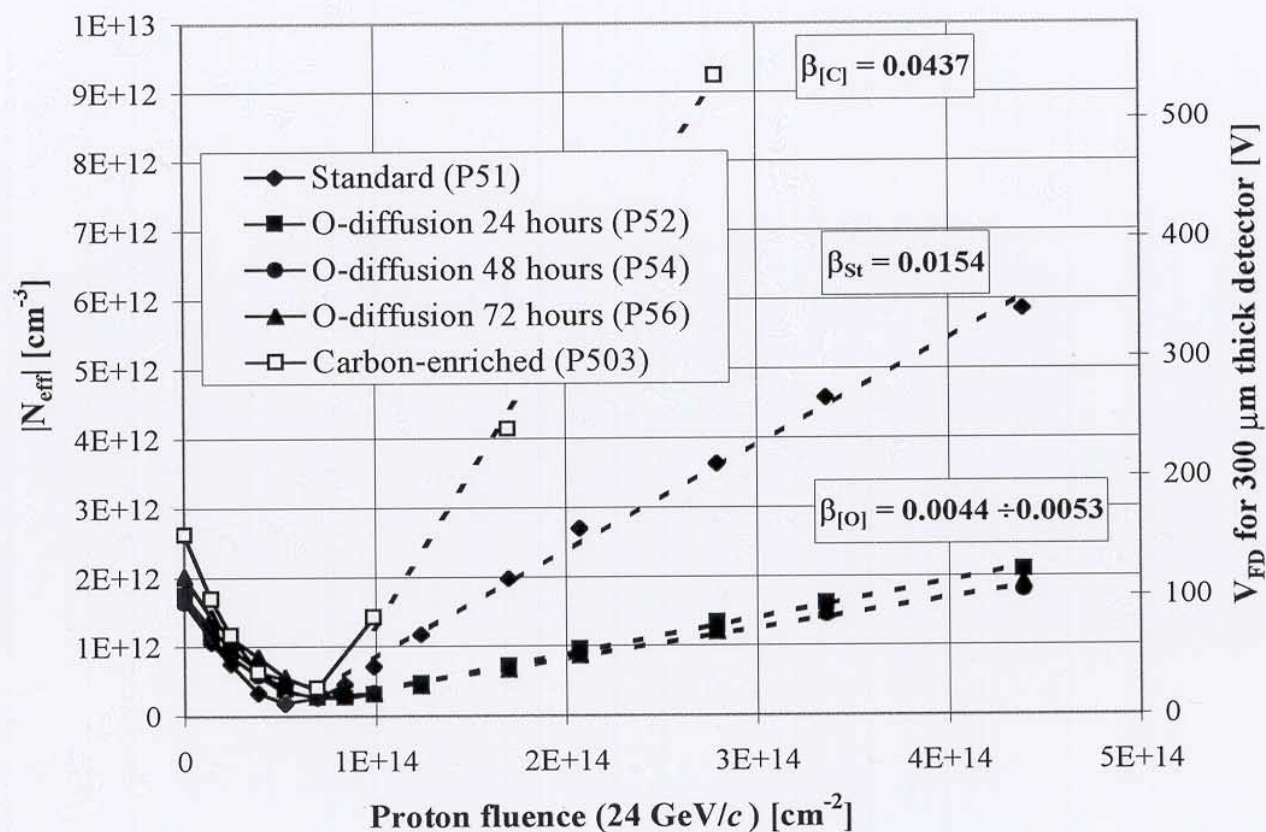
24 GeV/c protons - 192 MeV pions - reactor neutrons



- ◆ Strong improvement for pions and protons
- ◆ No improvement for neutrons

Influence of Carbon and Oxygen concentration

24 GeV/c proton irradiation

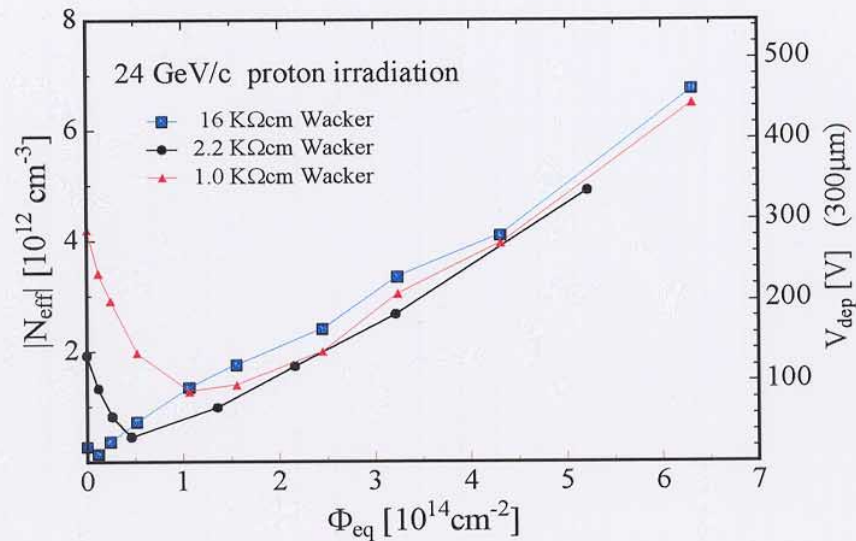


Compared to standard silicon:

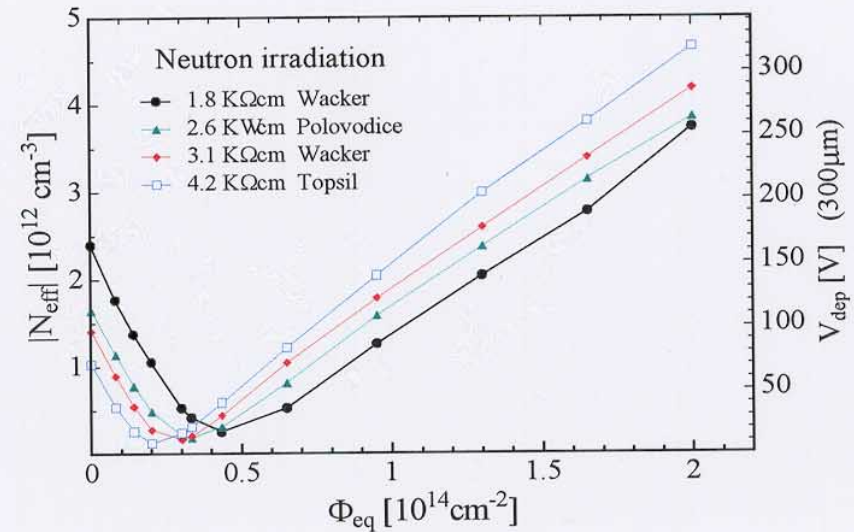
- ◆ High Carbon \Rightarrow less radiation hard
- ◆ High Oxygen \Rightarrow radiation harder

Influence of initial resistivity on oxygen rich material

24 GeV/c proton irradiation



Reactor neutron irradiation



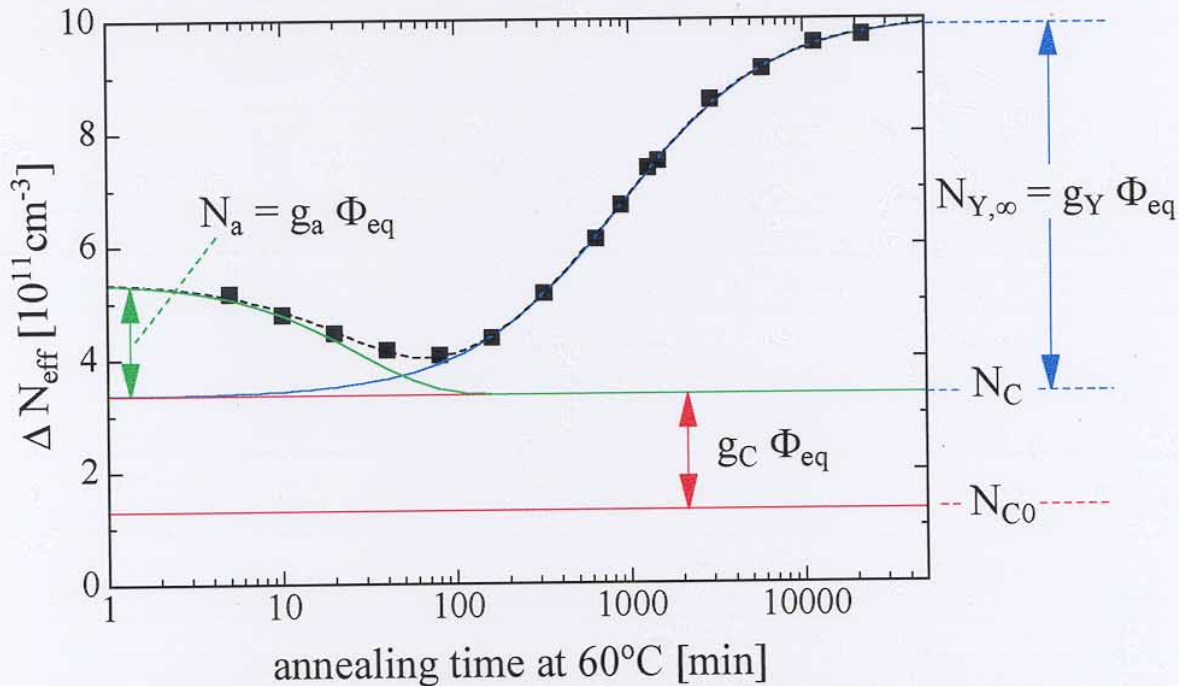
- ◆ Measured after annealing equivalent to 10 days at room temperature
- ◆ Low resistivity material beneficial for neutron irradiation

Annealing behavior: N_{eff}

- Hamburg Model -

$$\Delta N_{eff}(\Phi_{eq}, t) = N_{eff0} - N_{eff}(\Phi_{eq}, t)$$

Change of N_{eff} with respect to N_{eff0} (value before irradiation):



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

short term annealing:

$$N_a = \Phi_{eq} \times \sum_i g_{ai} \times \exp\left(-\frac{t}{\tau_i}\right)$$

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

stable damage:

$$N_C = N_{C0} \cdot \left(1 - \exp(-c \cdot \Phi_{eq})\right) + g_C \cdot \Phi_{eq}$$

incomplete „donor removal“
+ introduction of stable acceptors

long term reverse annealing:

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

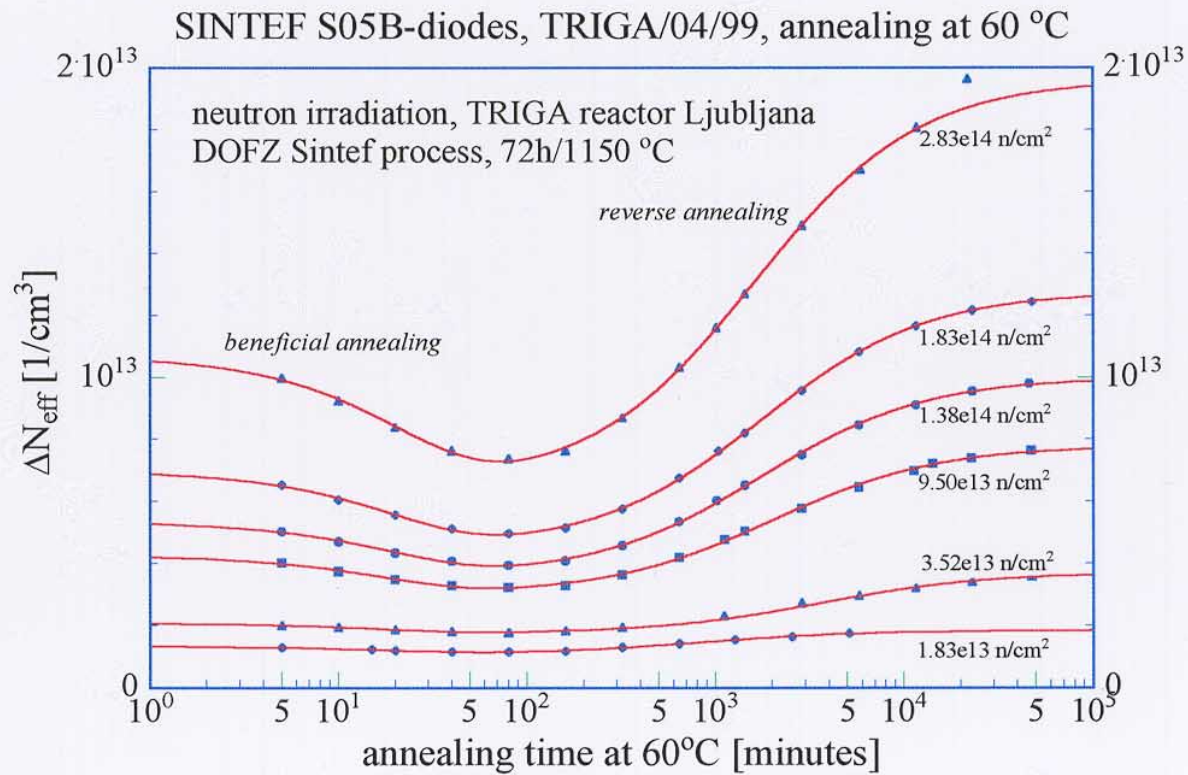
second order parameterization (with $N_{Y,\infty} = g_Y \cdot \Phi_{eq}$). gives best fit

But:

τ_y independent of Φ_{eq}
 \Rightarrow underlying defect reaction based on **first order** process!

Systematic analysis of annealing data

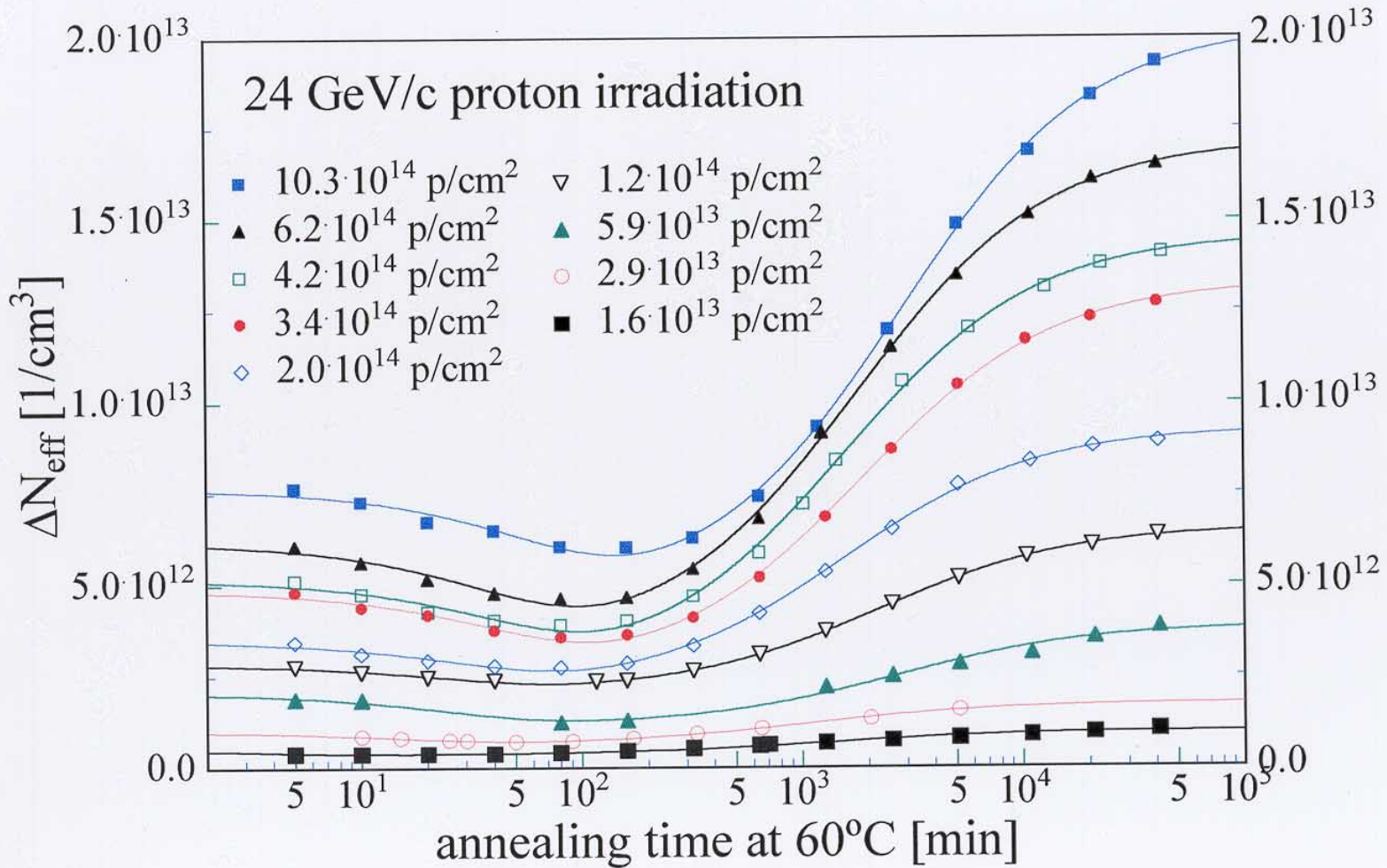
Example: oxygen enriched silicon after neutron irradiation



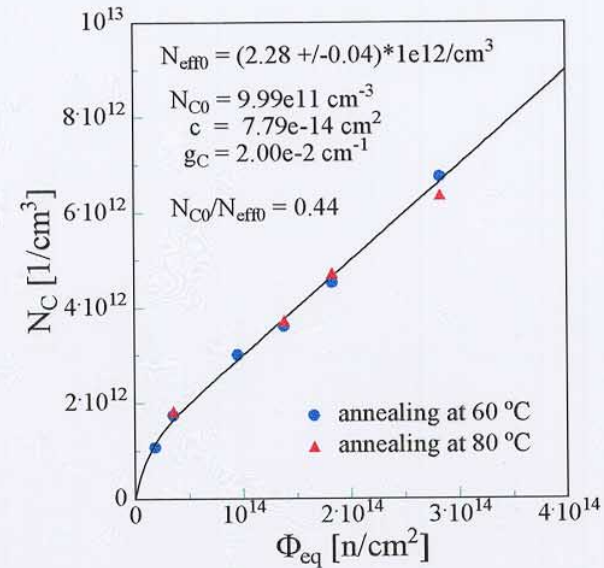
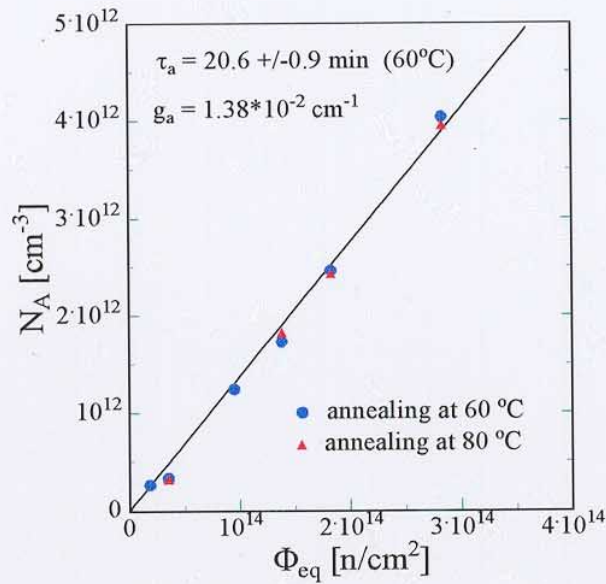
S05B-ANNEAL-P | 19.3.2000

Systematic analysis of annealing data

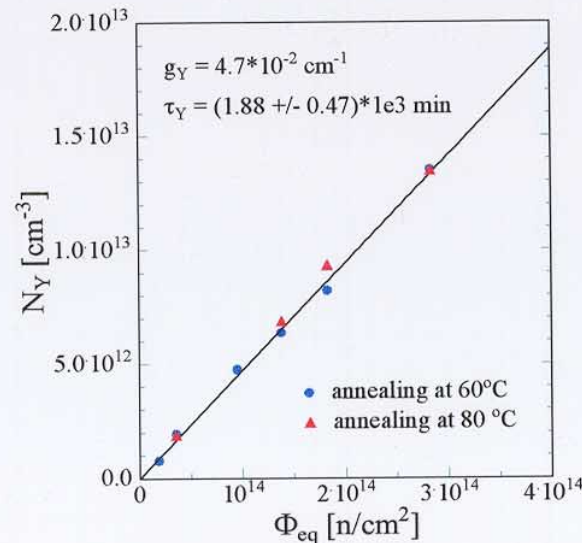
Example: oxygen enriched silicon after proton irradiation



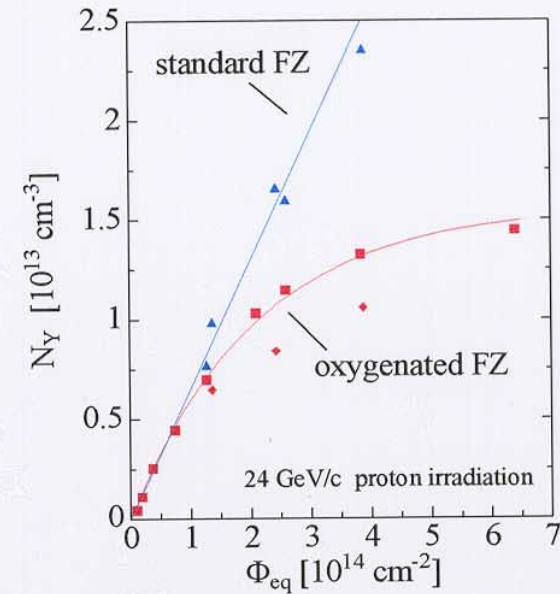
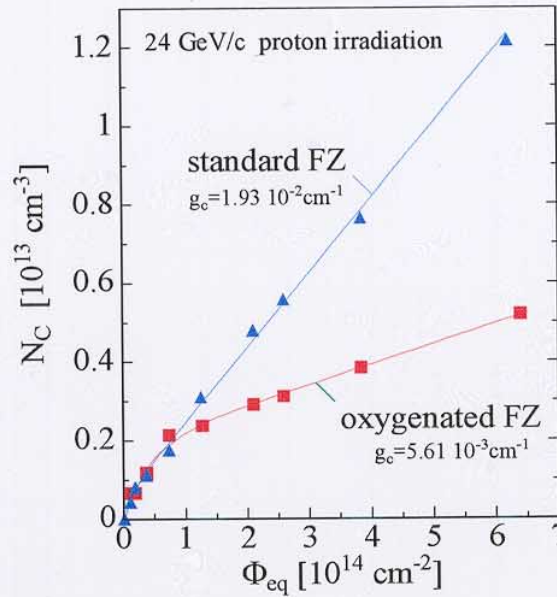
Extraction of damage parameters



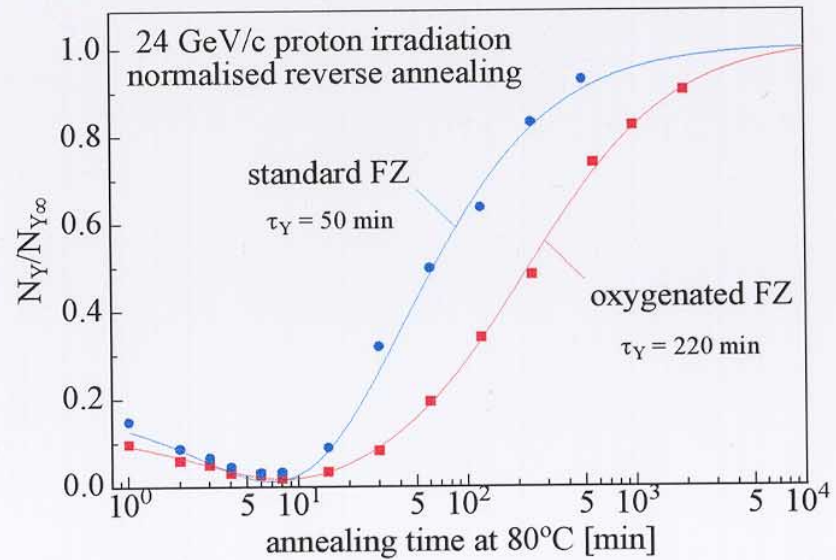
- ◆ neutron irradiated
O-rich diodes
- ◆ Extracted parameters independent of annealing temperature (60°C, 80°C)



Extraction of damage parameters



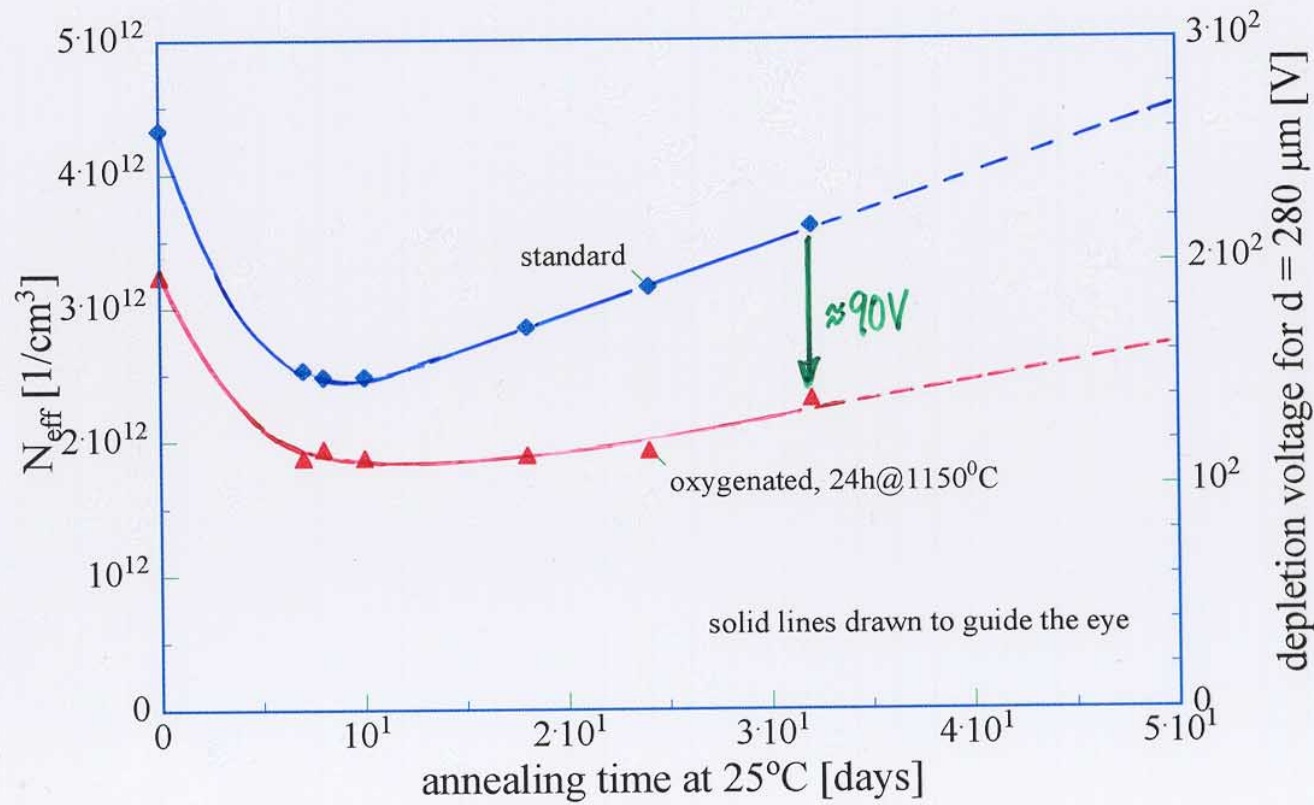
- ◆ proton irradiated
O-rich diodes
- ◆ g_c improved by a factor of 3
- ◆ saturation of reverse annealing
- ◆ delayed reverse annealing



Suppression of Reverse Annealing in O-enriched Si-strip detectors

An important result from MPI Munich confirming the ROSE predictions

CiS-detectors, 2-5 k Ω cm, irradi. by 3×10^{14} p/cm 2 at -10°C , 100V bias
(data from L. Andricek and G. Lutz, MPI Munich)



MPI-DATA | 1.6.2000

Comparison: C_s/V and CCE/V

- proton irradiated oxygenated silicon -

CCE measurement:

TCT - 830nm,
front illumination

$t_{\text{ann}} = 8 \text{ min at } 80^\circ\text{C}$

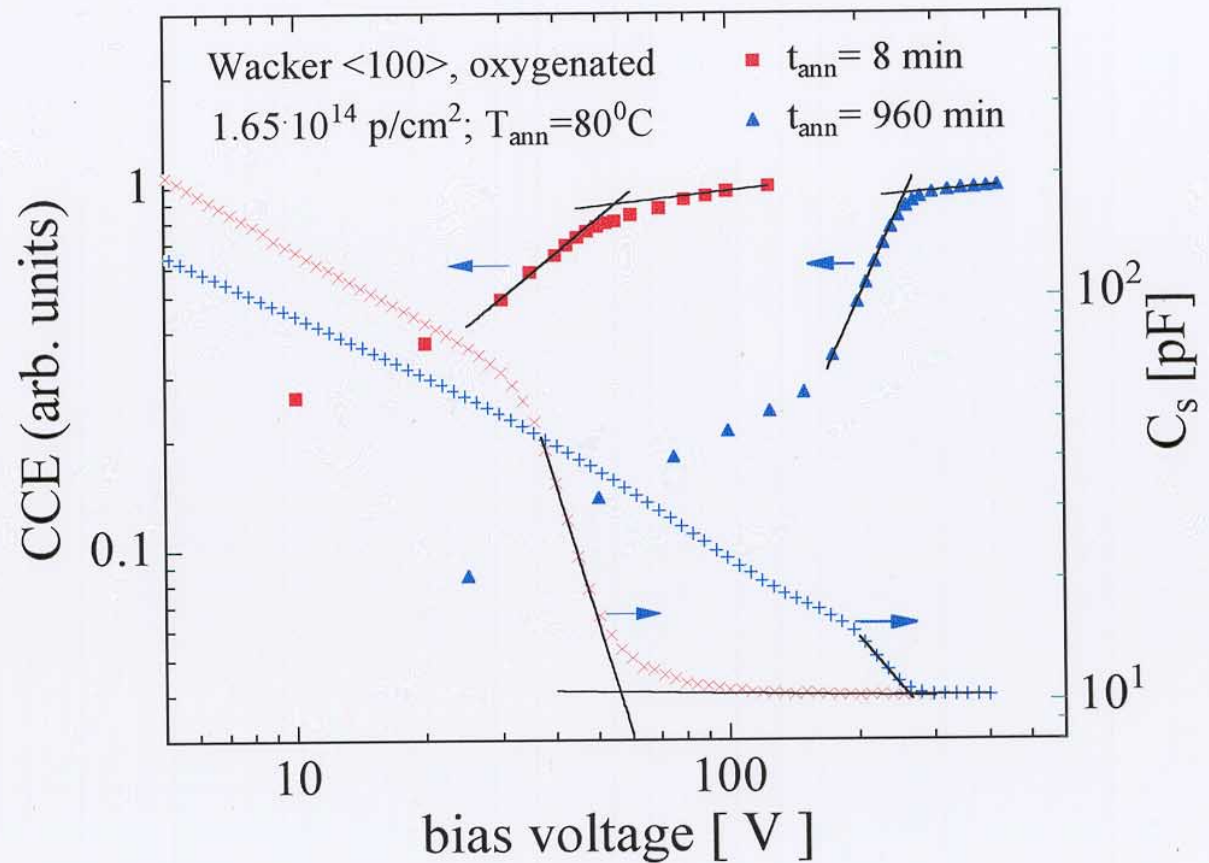
$V_{\text{dep}}(C/V) = 56 \text{ V}$

$V_{\text{dep}}(CCE/V) = 55 \text{ V}$

$t_{\text{ann}} = 960 \text{ min at } 80^\circ\text{C}$

$V_{\text{dep}}(C/V) = 260 \text{ V}$

$V_{\text{dep}}(CCE/V) = 258 \text{ V}$



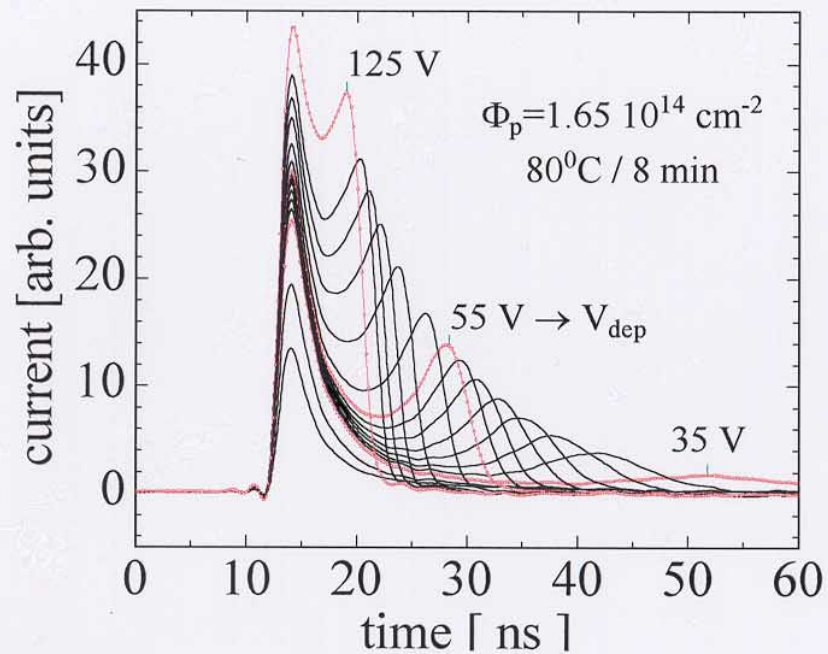
◆ V_{dep} : Coincidence between CV and CCE

◆ However: $CCE(V)$ depends on both: V_{dep} and trapping !

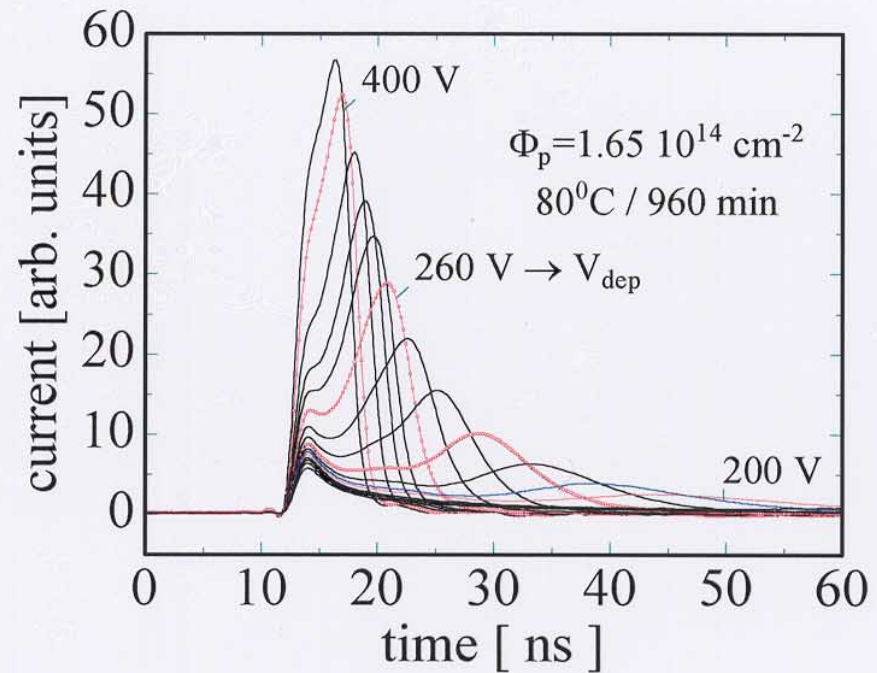
CCE/V measurements

- proton irradiated oxygenated silicon -
- TCT with 835nm laser (front illumination) -

8 min at 80°C



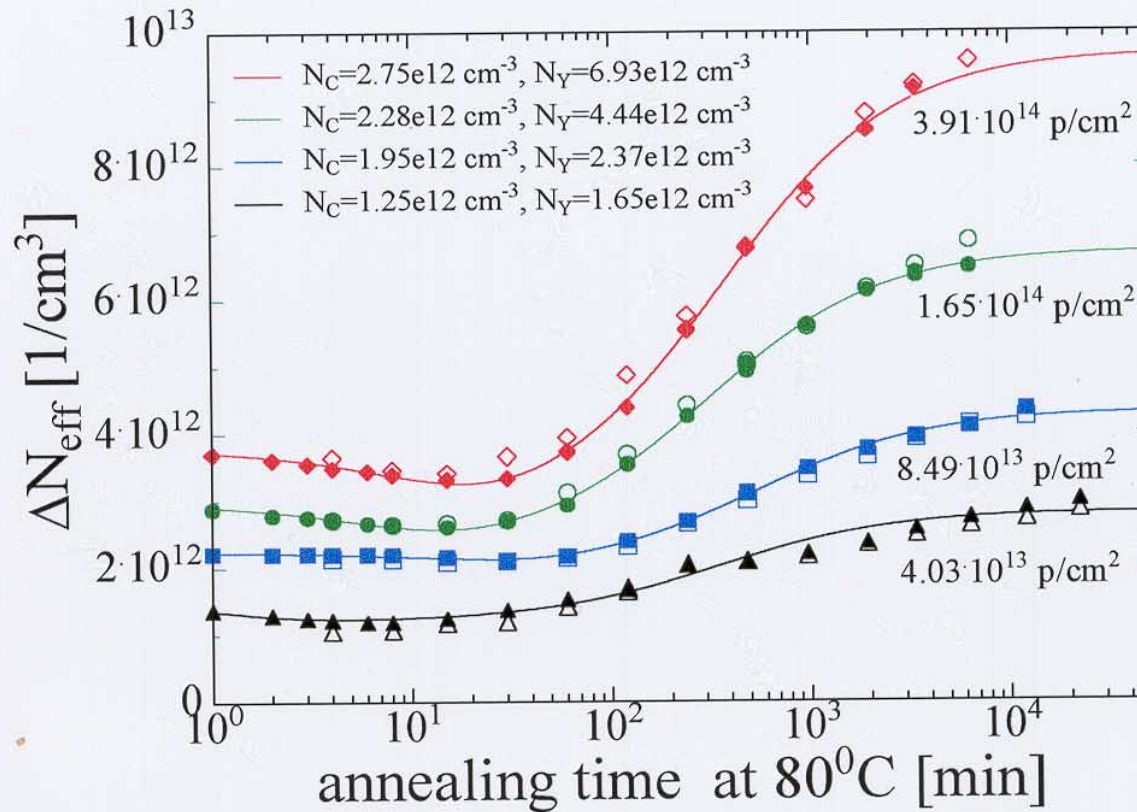
960 min at 80°C



- ◆ Double junction clearly visible after 8 min at 80°C
- ◆ After 960 min at 80°C "clear" type inversion

ΔN_{eff} from CCE-V (TCT) and C_s -V measurements

- proton irradiated oxygenated silicon -



- ◆ Open symbols: CCE-V values
- ◆ Filled symbols: C_s -V
- ◆ ΔN_{eff} (resp. V_{dep}): Coincidence between C_s -V and CCE (TCT)

Damage Parameters for standard and oxygen-enriched silicon

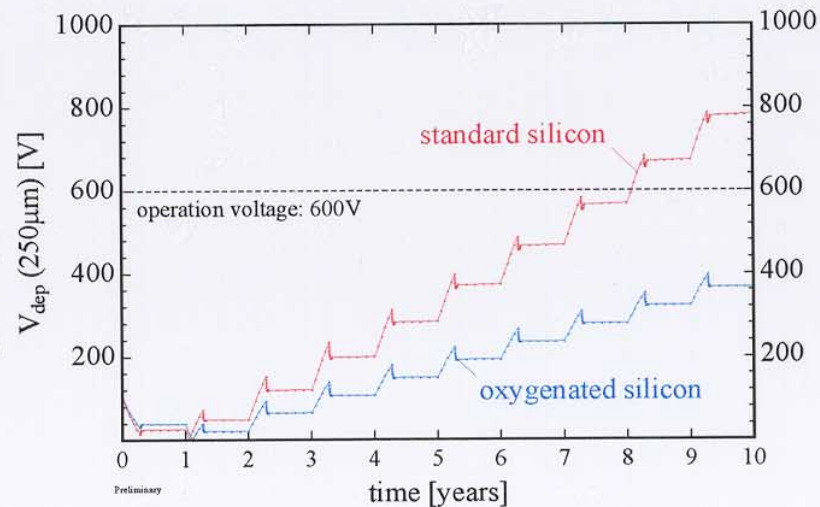
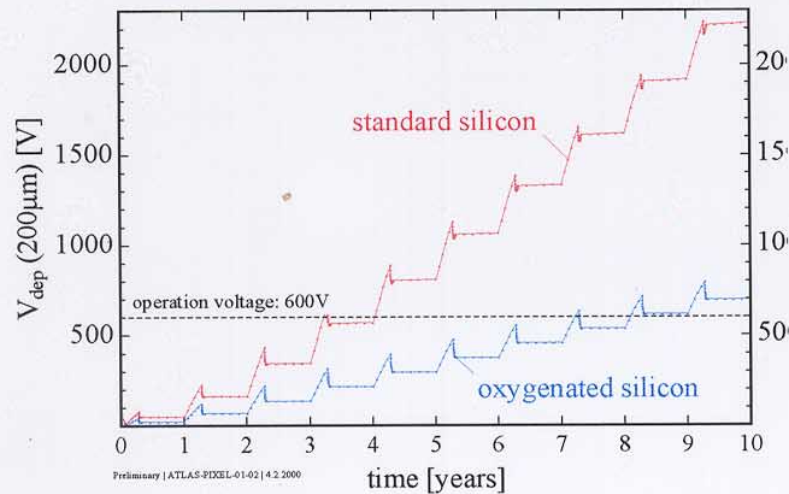
| | Standard Silicon | | Oxygen-enriched Silicon | |
|----------------------------|--------------------------------------|--------------------------------------|--------------------------------------|--|
| | Neutrons | Protons | Neutrons | Protons |
| g_a | $1.8 \times 10^{-2} \text{ cm}^{-1}$ | - | $1.4 \times 10^{-2} \text{ cm}^{-1}$ | - |
| $\tau_a(20^\circ\text{C})$ | 55 h | - | 70 h | - |
| g_C | $1.5 \times 10^{-2} \text{ cm}^{-1}$ | $1.9 \times 10^{-2} \text{ cm}^{-1}$ | $2.0 \times 10^{-2} \text{ cm}^{-1}$ | $5.3 \times 10^{-3} \text{ cm}^{-1}$ |
| N_{C0}/N_{eff0} | 0.70 | - | 0.45 | 1.0 |
| g_Y | $5.2 \times 10^{-2} \text{ cm}^{-1}$ | $6.6 \times 10^{-2} \text{ cm}^{-1}$ | $4.8 \times 10^{-2} \text{ cm}^{-1}$ | $2.3 \times 10^{-2} \text{ cm}^{-1} (*)$ |
| $\tau_Y(20^\circ\text{C})$ | 480 d | - | 800 d | 950 d |

(*) saturation value measured for $\Phi_{\text{eq}} = 6 \cdot 10^{14} \text{ cm}^{-2}$

⇒ Simulation of LHC scenarios; Example: ATLAS Pixel layers

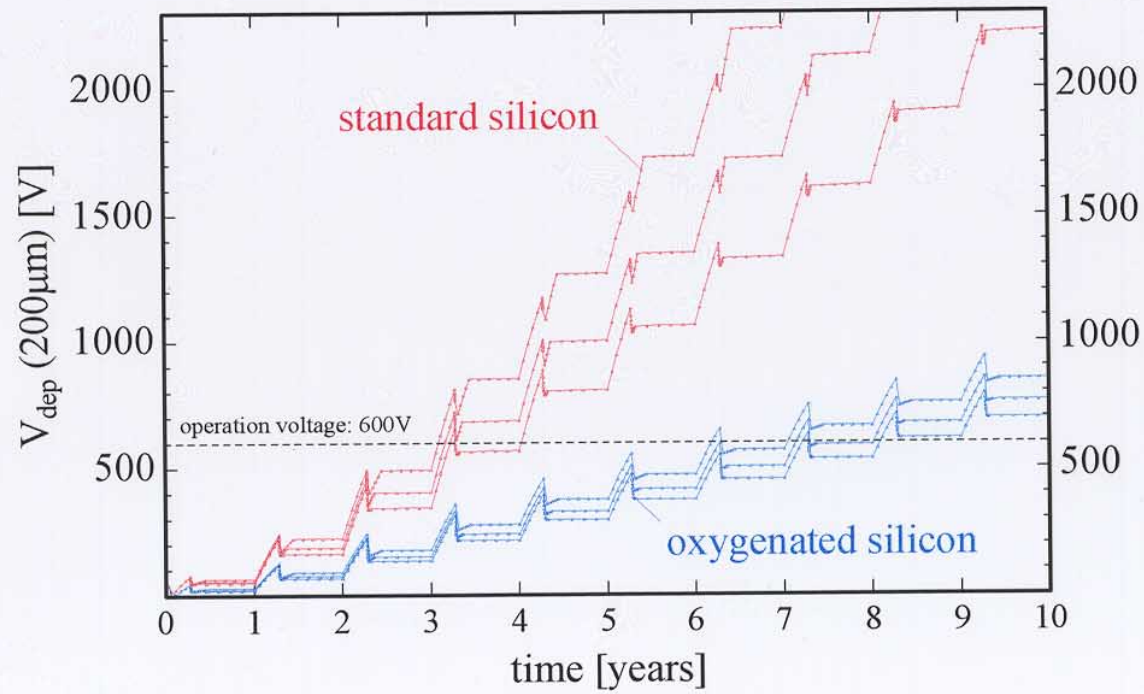
B-Layer (4cm)

1st Layer (10cm)



Damage Projection – ATLAS Pixel Detector – B-Layer

- ◆ **Radiation level for B-Layer :**
 - $\Phi_{\text{eq}}(\text{year}) = 3.5 \times 10^{14} \text{ cm}^{-2}$ (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)



Summary

- For mass application Silicon is and will remain the prime detector grade semiconductor
 - + Si: material & process technology based on large scale, commercial
 - + Rad. Hardness problem improved considerably by defect engineering
 - + LHC-ATLAS-B-layer shown to withstand 10 y operation
 - + with even long maintenance periods
 - however: cooling necessary
- Other material of interest for specific applications

Diamond as the only non-Si monatomic semiconductor

- + Rad. hard, ultra fast, small ϵ , usable @ RT
- Polycrystalline non ideal CCE, polarisation

Compound semiconductors

becoming interesting but except GaAs not beyond experimental stage

Rad hardness usually less than for monatomic semicond. (Anti-site eff.)

The ROSE collaboration

35 member groups from HEP and Semiconductor Physics
+ associated major manufacturing companies

Visit our web-site for...

... more information
... status reports
.....references,
.... preprints, etc....

<http://cern.ch/rd48>

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