11th International Workshop on Vertex Detectors, VERTEX 2002, Hawaii, November 3-8, 2002

Development of Radiation Hard Sensors for Very High Luminosity Colliders

- CERN-RD50 project -

Michael Moll

CERN - Geneva - Switzerland

On behalf of CERN RD50 Collaboration

http://www.cern.ch/rd50

Outline

- Motivation and Introduction to RD50
- Radiation Damage
  - Microscopic defects (changes in bulk material)
  - Macroscopic damage (changes in detector properties)
- RD50 - Approaches to obtain radiation hard sensors
  - Material Engineering
  - Device Engineering
- RD50 – future work plan
- Summary

RD50 – A very young collaboration!

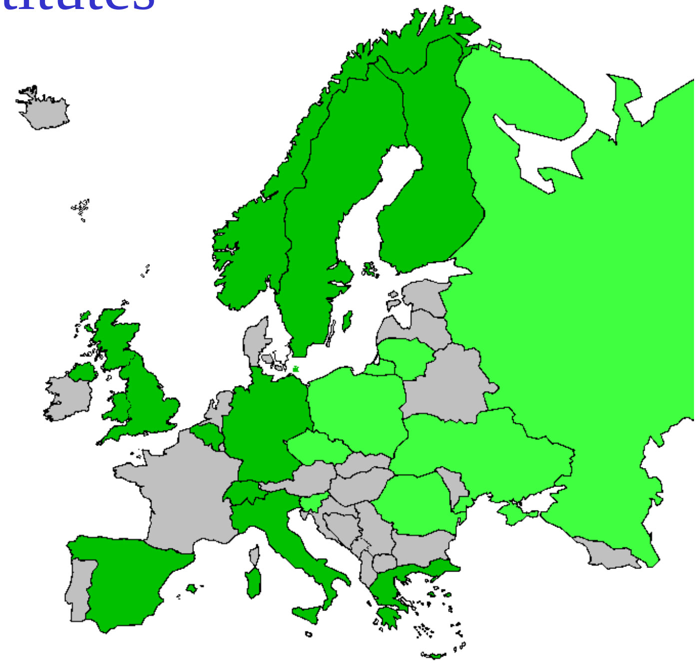
11/2001 – Workshop on rad-hard devices
02/2002 - R&D Proposal
06/2002 - Approved as CERN-RD50
10/2002 - 1st RD50 Workshop
now: startup of specialized working groups

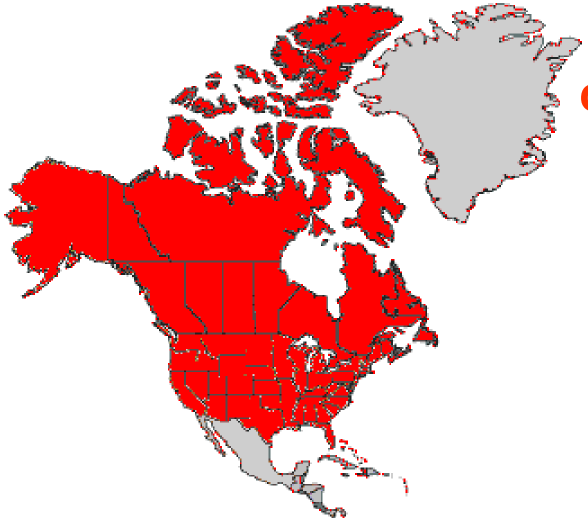
RD50 - Development of Radiation Hard Semiconductor Devices for High Luminosity Colliders

274 Members from 52 Institutes

45 European and Asian institutes (34 west, 11 east)

Belgium (Louvain), **Czech Republic** (Prague (2x)), **Finland** (Helsinki (2x), Oulu), **Germany** (Berlin, Dortmund, Erfurt, Halle, Hamburg, Karlsruhe), **Greece** (Athens), **Italy** (Bari, Florence, Milano, Modena, Padova, Perugia, Pisa, Trento, Triest), **Lithuania** (Vilnius), **Norway** (Oslo (2x)), **Poland** (Warsaw), **Romania** (Bucharest (2x)), **Russia** (Moscow (2x), St.Petersburg), **Slovenia** (Ljubljana), **Spain** (Barcelona, Valencia), **Sweden** (Lund) **Switzerland** (CERN, PSI), **Ukraine** (Kiev), **United Kingdom** (Exeter, Glasgow, Lancaster, Liverpool, London, Sheffield, University of Surrey)





6 North-American institutes

Canada (Montreal), **USA** (Fermilab, Purdue University, Rutgers University, Syracuse University, BNL)

1 Middle East institute

Israel (Tel Aviv)

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

Motivation to form a new R&D Collaboration

- **LHC upgrade** ("Super-LHC" … later than 2010)

LHC: $L = 10^{34}\text{cm}^{-2}\text{s}^{-1}$ $\xrightarrow{\text{10 years}}$ $f(\mathbf{R=4cm}) \sim \mathbf{3\cdot10^{15}cm^{-2}}$

$f(\mathbf{R=75cm}) \sim \mathbf{3\cdot10^{13}cm^{-2}}$

⇨ Technology available ⇨ However, serious radiation damage!

´ 5

S-LHC: $L = 10^{35}\text{cm}^{-2}\text{s}^{-1}$ $\xrightarrow{\text{5 years}}$ $f(\mathbf{R=4cm}) \sim \mathbf{1.6\cdot10^{16}cm^{-2}}$

⇨Focused and coordinated R&D mandatory

⇨ develop radiation hard and cost-effective detectors

- **LHC experiments** (…starting 2007)

Radiation hardness studies also beneficial before a luminosity upgrade.

⇨ Radiation hard technologies now adopted have not been completely characterized: Oxygen-enriched Si in ATLAS/CMS pixels

- **Linear collider experiments**

Deep understanding of radiation damage will be fruitful for linear collider experiments where high doses of e, γ will play a significant role.

RD50 - Scientific objectives and strategies

Main Objective:

To develop radiation hard semiconductor detectors that can operate beyond the limits of present devices. These devices should withstand fast hadron fluences of the order of 10^{16} cm^{-2}, as expected for example for a recently discussed luminosity upgrade of the LHC to 10^{35} cm^{-2}s^{-1}.

Three R&D strategies:

- **Material engineering**
  - Defect engineering of silicon (oxygenation, dimers, …)
  - New detector materials (SiC, …)
- **Device engineering**
  - Improvement of present planar detectors (3D detectors, thin detectors, cost effective detectors,…)
- **Variation of detector operational conditions**
  - Low temperature operation
  - Forward bias operation

}

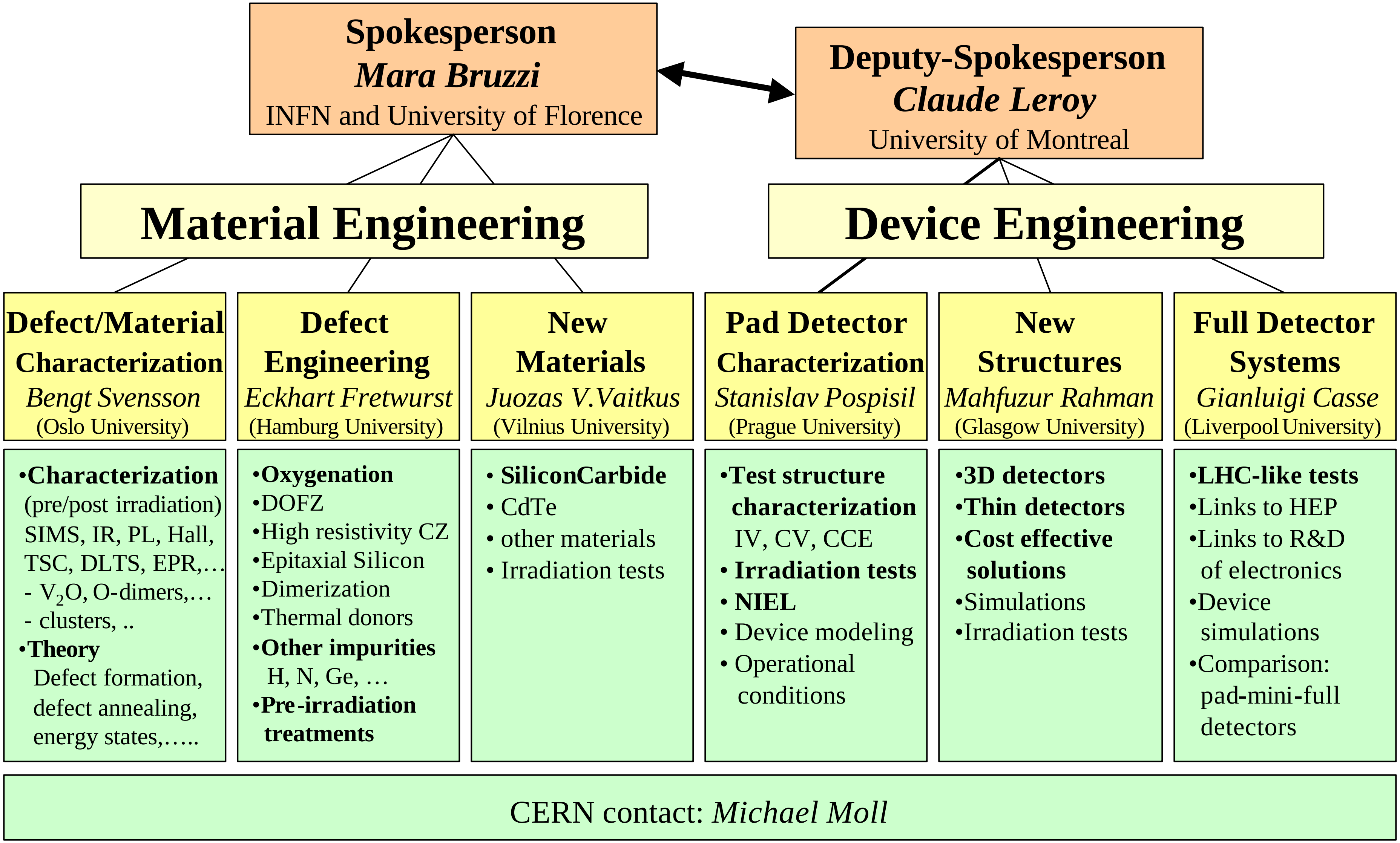
RD50
Center of gravity

Further key tasks:

- **Basic studies**
- **Defect modeling and device simulation**

Scientific Organization of RD50

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



Spokesperson
Mara Bruzzi
INFN and University of Florence

Deputy-Spokesperson
Claude Leroy
University of Montreal

Material Engineering

Defect/Material Characterization
Bengt Svensson
(Oslo University)

- **Characterization**
  (pre/post irradiation)
  SIMS, IR, PL, Hall, TSC, DLTS, EPR,…
  - V_2O, O-dimers,…
  - clusters, ..
- **Theory**
  Defect formation, defect annealing, energy states,…..

Defect Engineering
Eckhart Fretwurst
(Hamburg University)

- **Oxygenation**
- DOFZ
- High resistivity CZ
- Epitaxial Silicon
- Dimerization
- Thermal donors
- **Other impurities**
  H, N, Ge, …
- **Pre-irradiation treatments**

New Materials
Juozas V.Vaitkus
(Vilnius University)

- **SiliconCarbide**
- CdTe
- other materials
- Irradiation tests

Device Engineering

Pad Detector Characterization
Stanislav Pospisil
(Prague University)

- **Test structure characterization**
  IV, CV, CCE
- **Irradiation tests**
- **NIEL**
- Device modeling
- Operational conditions

New Structures
Mahfuzur Rahman
(Glasgow University)

- **3D detectors**
- **Thin detectors**
- **Cost effective solutions**
- Simulations
- Irradiation tests

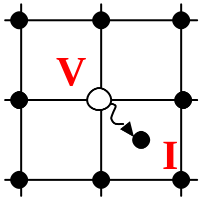
Full Detector Systems
Gianluigi Casse
(Liverpool University)

- **LHC-like tests**
- Links to HEP
- Links to R&D of electronics
- Device simulations
- Comparison: pad-mini-full detectors

CERN contact: *Michael Moll*

Radiation Damage – Microscopic Effects

particle → Si_S → E_K>25 eV



Vacancy + **I**nterstitial → *point defects (V-O, C-O, ..)*

→ E_K > 5 keV *point defects and clusters of defects*

♦ ^{60}Co-gammas
- Compton Electrons with max. E_g »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

More point defects ⟷ More clusters

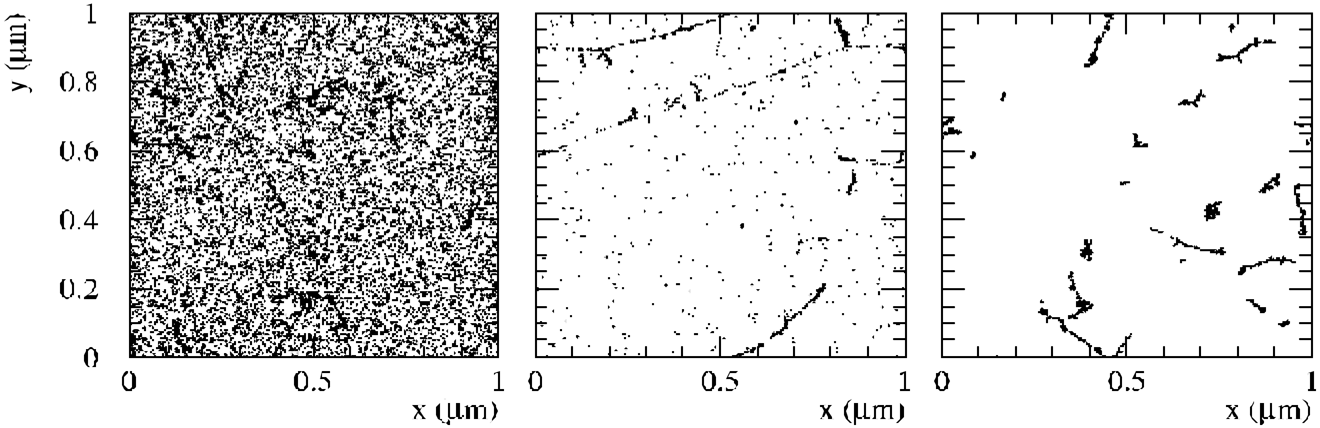
Initial distribution of vacancies in (1mm)^3 after 10^{14} particles/cm^2

[Mika Huhtinen ROSE TN/2001-02]

10 MeV protons 36824 vacancies

24 GeV/c protons 4145 vacancies

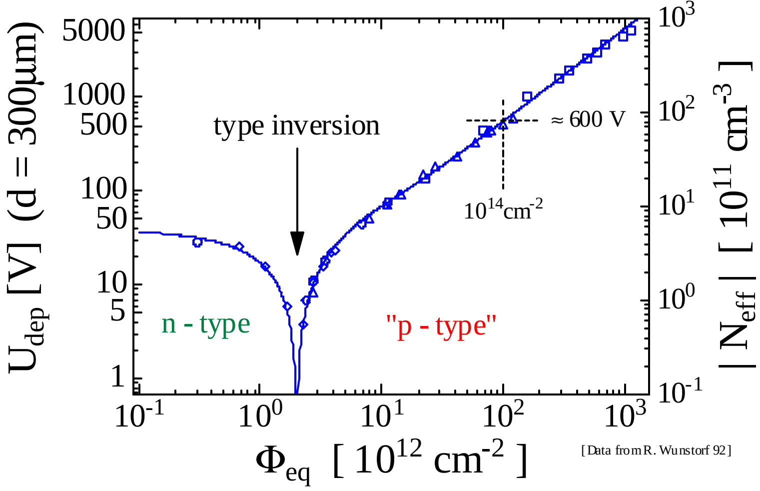
1 MeV neutrons 8870 vacancies



Radiation Damage – 3 Macroscopic Effects

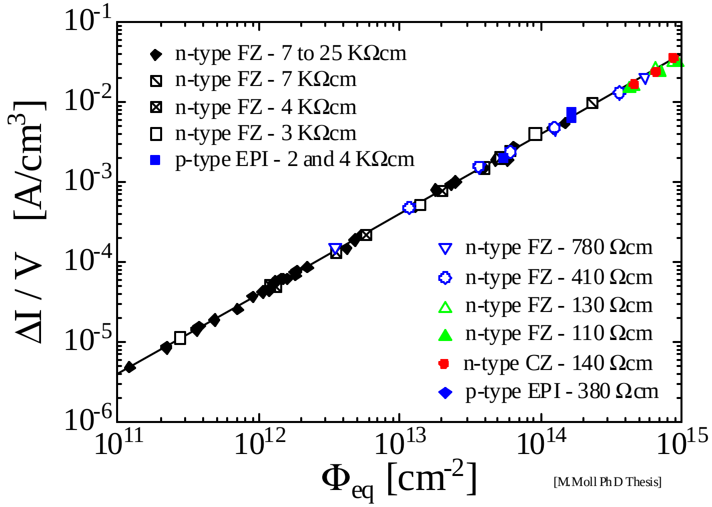
Irradiation

1. Change of V_{dep} (N_{eff})



[Data from R. Wunstorf 92]

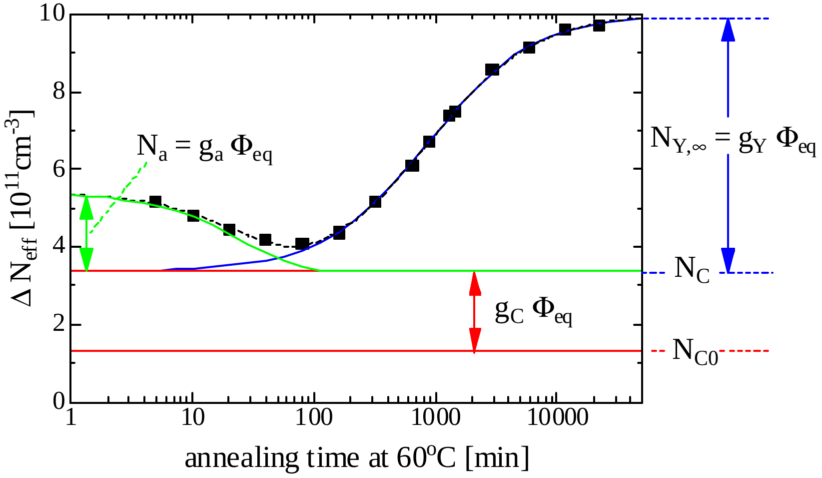
2. Increase of leakage current

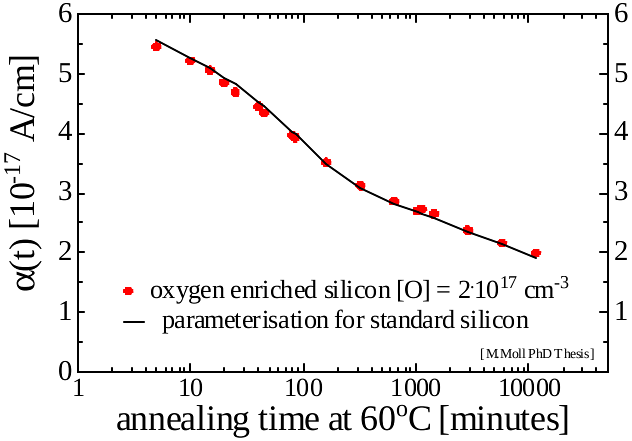


[M.Moll PhD Thesis]

Annealing

(e.g. at 60°C)





[M.Moll PhD Thesis]

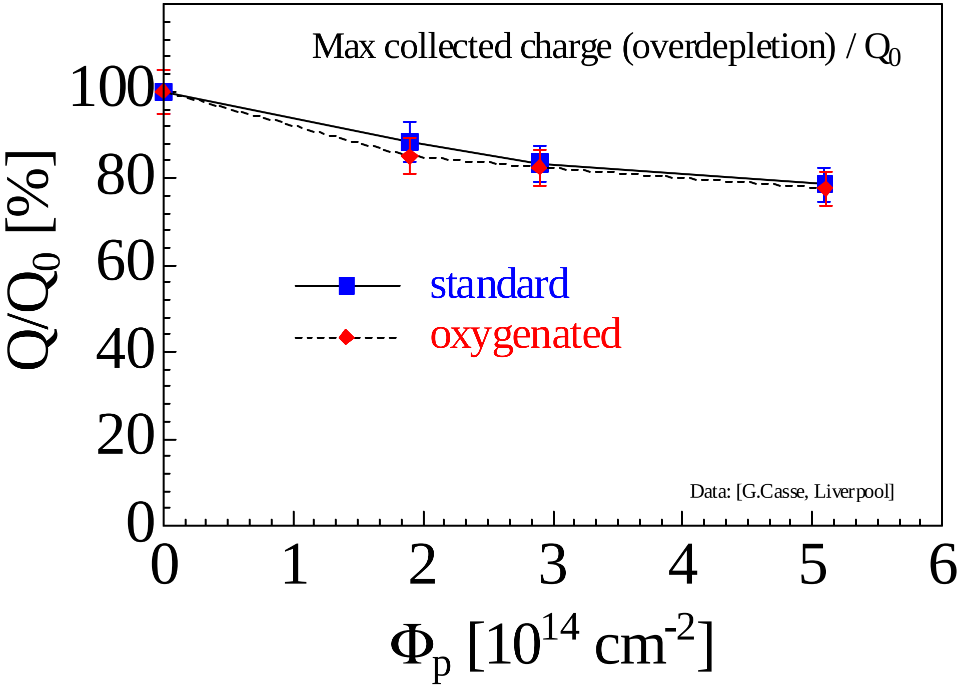
Gamma irradiation: type inversion and increase of leakage current, but: no annealing !

Michael Moll – VERTEX 2002,Hawaii, November 3-8, 2002

3. Deterioration of the charge collection efficiency

◆ **Two mechanisms reduce collectable charge:**
- Trapping (electrons and holes)
- Underdepletion (detector design and geometry)

ATLAS microstrip + RO electronics



Data: Gianluigi Casse; 1st Workshop on Radiation Hard Semiconductor Devices for High Luminosity Colliders; CERN; 28-30 November 2002

◆ **Oxygenation has no influence on trapping.**

◆ **After $5 \cdot 10^{14}$ p/cm^2 (24GeV/c)**
- 80% of charge collected (25ns)
- overdepletion needed !

More details in later talk:
"Charge collection in silicon"
Gianluigi Casse, Liverpool

Defect Engineering of Silicon

- **Influence the defect kinetics by incorporation of impurities**

- **Best example: <u>Oxygen</u>**

  Idea: Incorporate Oxygen to getter radiation-induced vacancies

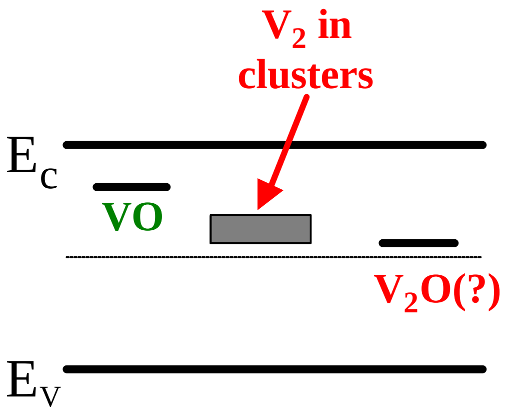
  Þ prevent formation of Di-vacancy (V_2) related deep acceptor levels

Observation: **Higher oxygen content Þ less negative space charge**
(less charged acceptors)

- **One possible mechanism: V_2O is a deep acceptor**

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

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



- **Experimental evidence for V_2O? Yes!**

  - Acceptor at E_c- 0.545 eV [I.Pintilie: 1st RD50 Workshop, APL 81(2002)165]

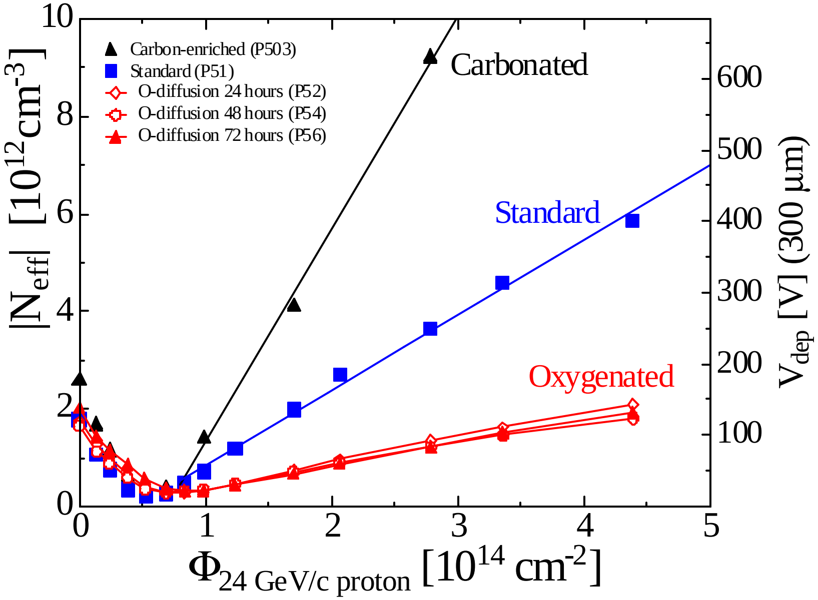
  - Double-acceptor at E_c- 0.43eV(-/0) and E_c- 0.23eV (--/-)
  [E.Monakhov 1st RD50 Workshop, PRB 65(2002)233207]

Oxygen enriched silicon

- **DOFZ (Diffusion Oxygenated Float Zone Silicon)**
  - 1982 First oxygen diffusion tests on FZ [Brotherton et al. J.Appl.Phys.,Vol.53, No.8.,5720]
  - 1995 First tests on detector grade silicon [Z.Li et al. IEEE TNS Vol.42,No.4,219]
  - **1999 Introduced to the HEP community by RD48 (ROSE)**

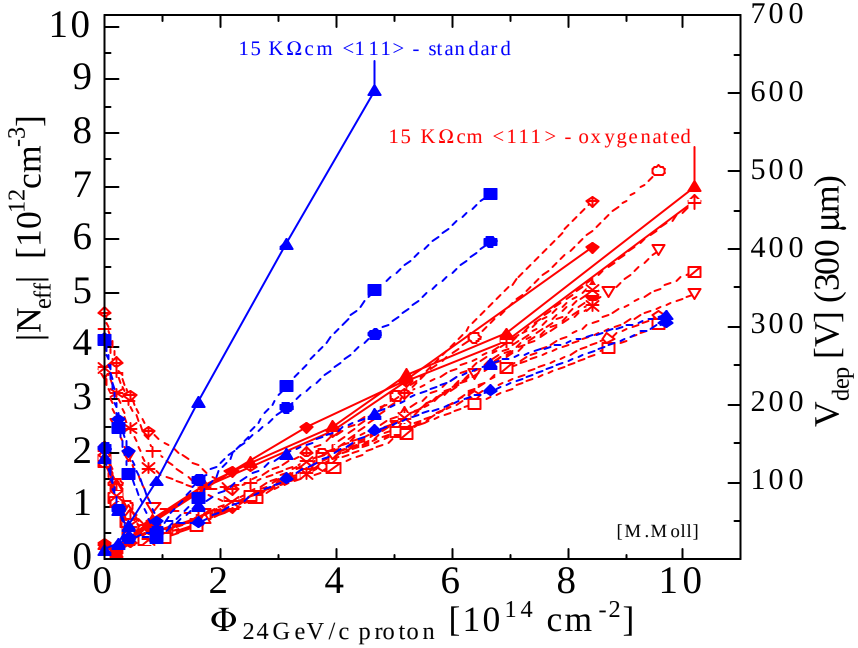
ROSE
RD48
http://cern.ch/rd48

First tests show clear advantage of oxygenation



[RD48-NIMA 465(2001) 60]

Later systematic tests reveal strong variations with no clear dependence on oxygen content



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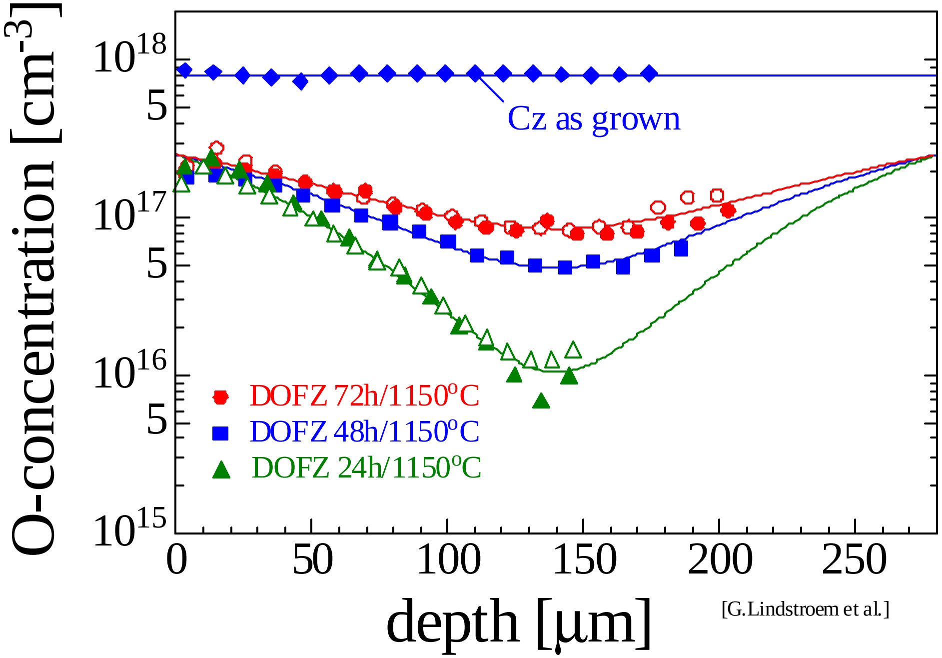
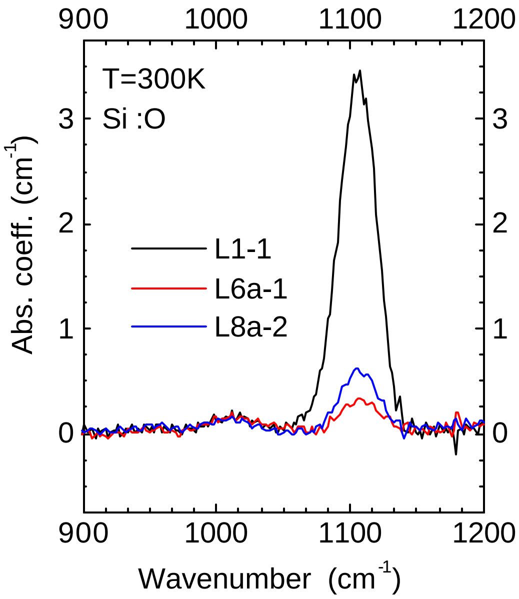
Characterization of Oxygen concentration in DOFZ

SIMS – [O] depth profile



[G.Lindstroem et al.]

IR-absorption: average [O]



Sample	CZ	DOFZ 24h/1150C	DOFZ 48h/1150C	DOFZ 72h/1150C
SIMS [O/cm^3]	8.1e17	5.7e16	9.9e16	1.2e17
IR [O/cm3]	8.5e17	6.8e16	1.0e17	1.4e17

- **Average: $[O]_{IR}/[O]_{SIMS}$ = 1.1 ± 10%**

Details: [G.Lindstroem et al. 1st RD50-Workshop]

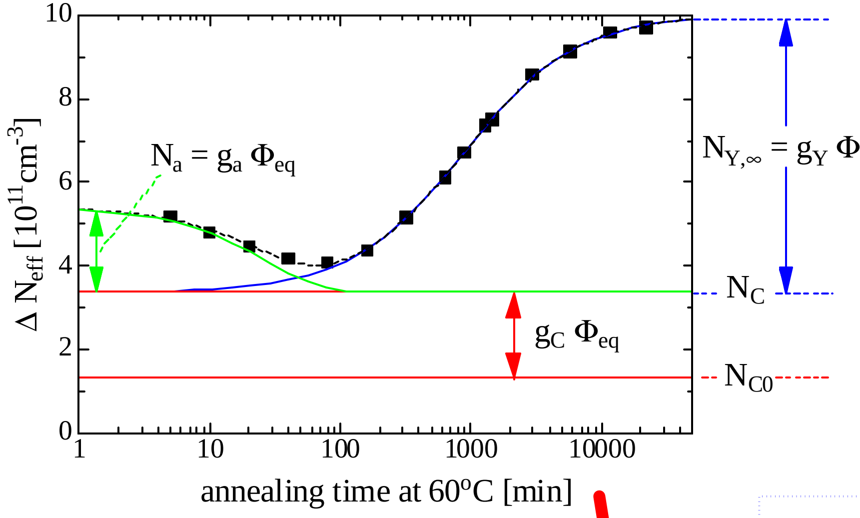
⇒ **Oxygen in DOFZ is mono-atomic (no clustering)**

Annealing after 24 GeV/c proton irradiation

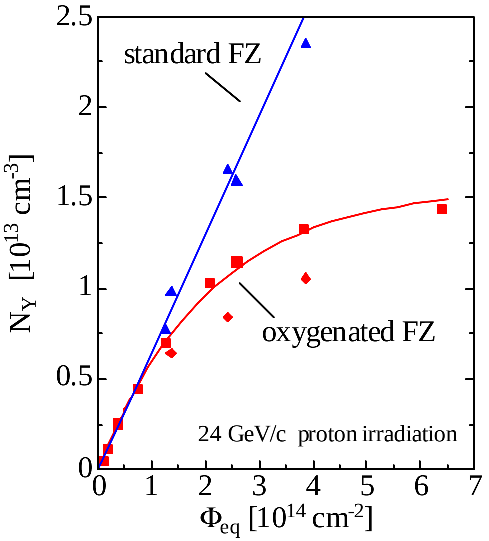
ROSE
RD48
http://cern.ch/rd48

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

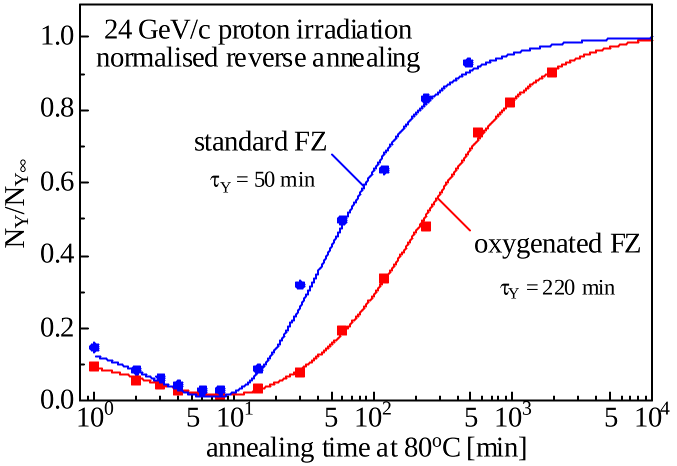
= **beneficial annealing** + **stable damage** + **reverse annealing**

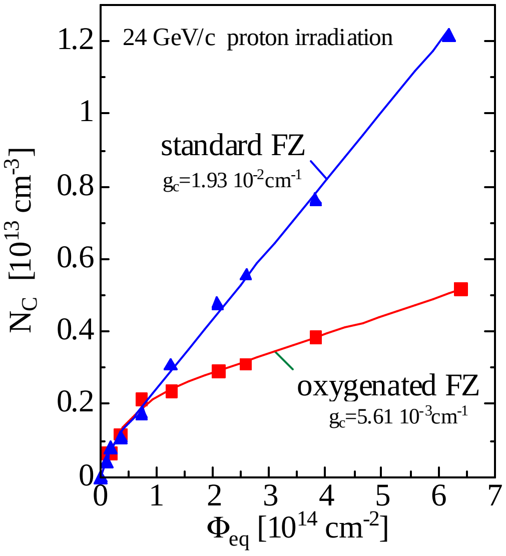


Saturation of reverse annealing



delayed reverse annealing





Stable damage reduced by a factor of 3

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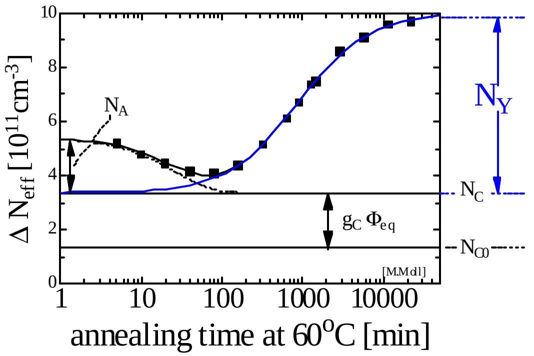
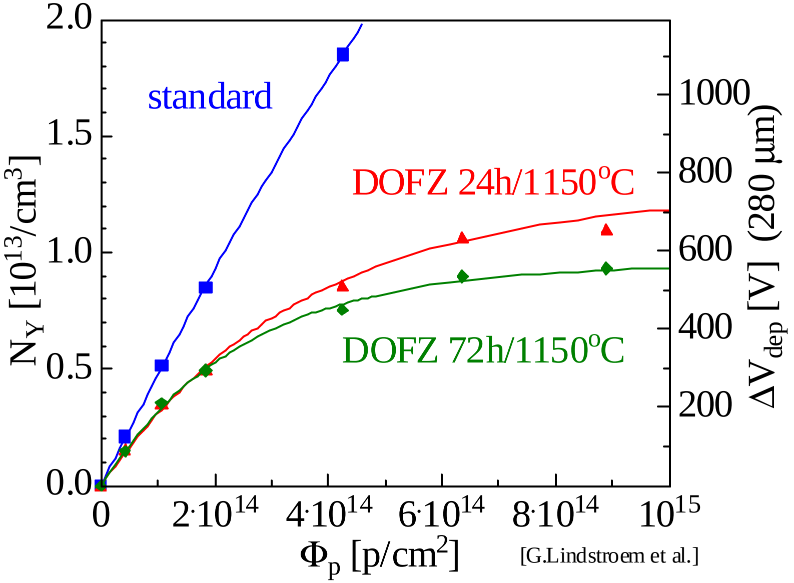
How much [O] is enough?

- **Reverse annealing amplitude N_Y after proton and neutron irradiation**

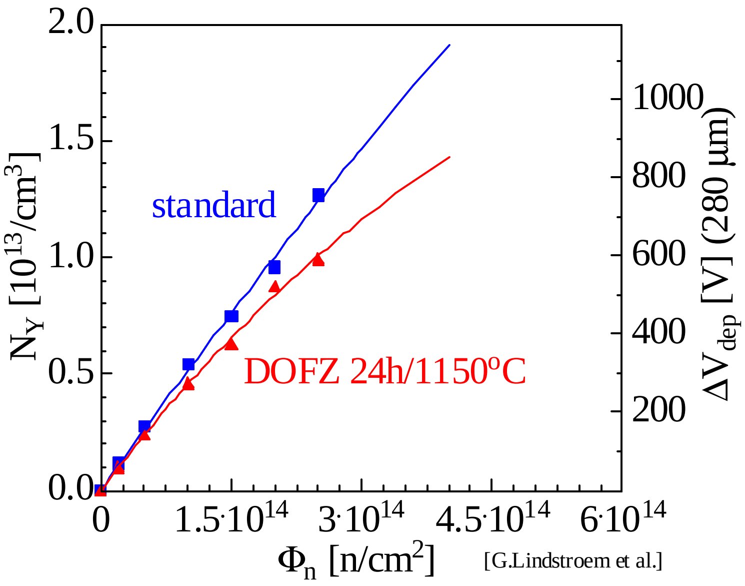


20 GeV/c proton irradiation



[G.Lindstroem et al.]

neutron-irradiation



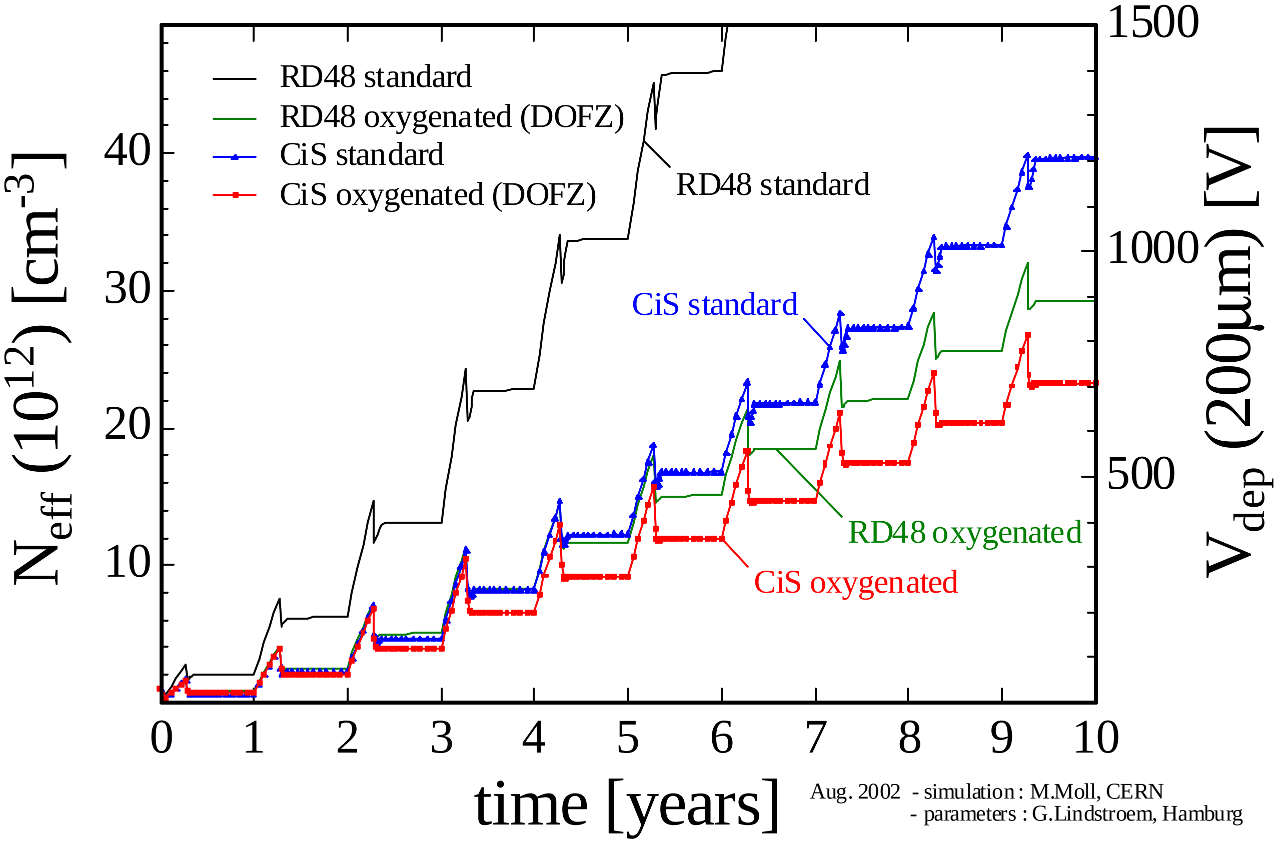
[G.Lindstroem et al.]

- **Saturation of reverse annealing for protons and neutrons**
- **Higher beneficial effect for protons**
- **No big difference between 24h and 72h oxidation at 1150°C**

Details: [G.Lindstroem et al. 1st RD50-Workshop]

Updated Damage Projection - ATLAS Pixel B-layer

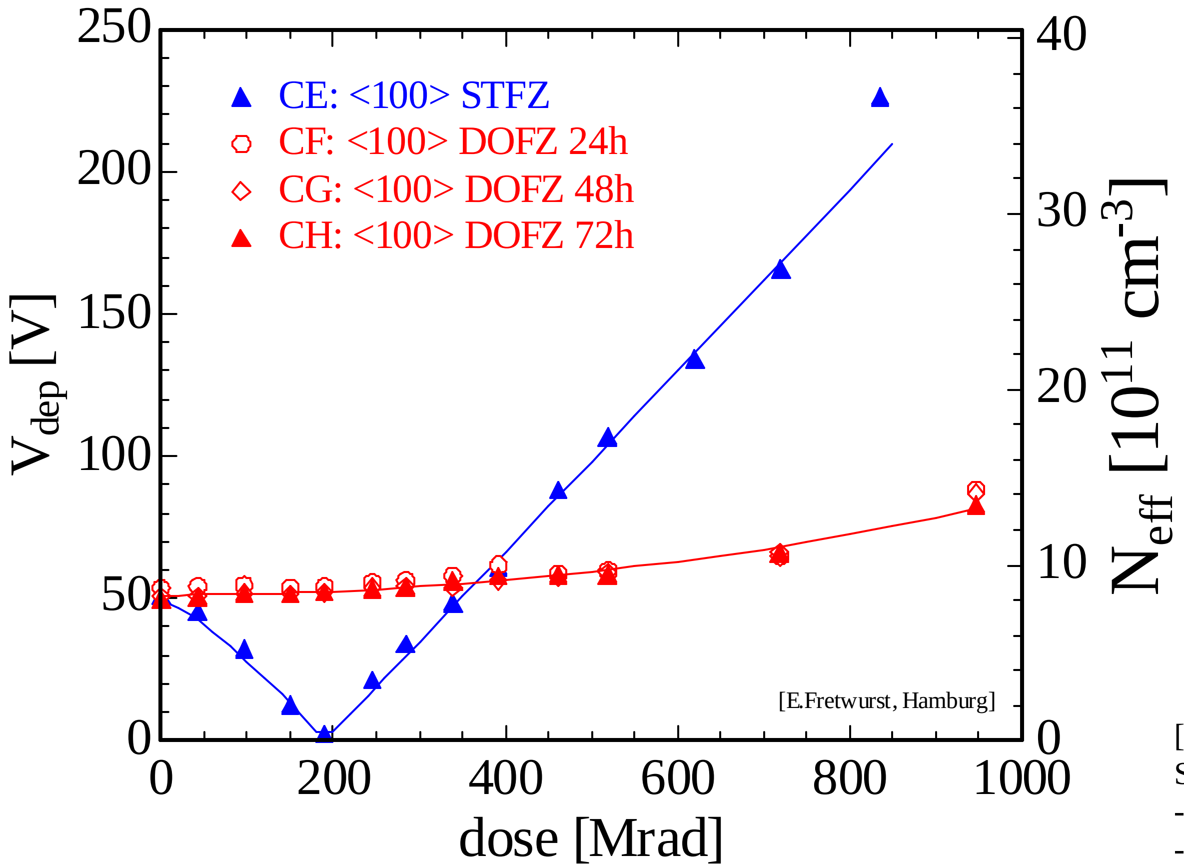
- **Radiation level:**
  - **F$_{eq}$(year) = 3.5 ´ 10^{14} cm^{-2}** (full luminosity)
    > 85% charged hadrons
- **LHC-scenario:**
  - **1 year = 100 days beam (-7°C)**
    30 days maintenance (20°C)
    235 days no beam (-7°C)



Aug. 2002 - simulation : M.Moll, CERN
- parameters : G.Lindstroem, Hamburg

- **New:**
  - **Std. Silicon:**
    rad.harder than predicted by RD48
  - **DOFZ:**
    reverse annealing delayed and saturating with high fluences

DOFZ : Spectacular Improvement of g-irradiation tolerance

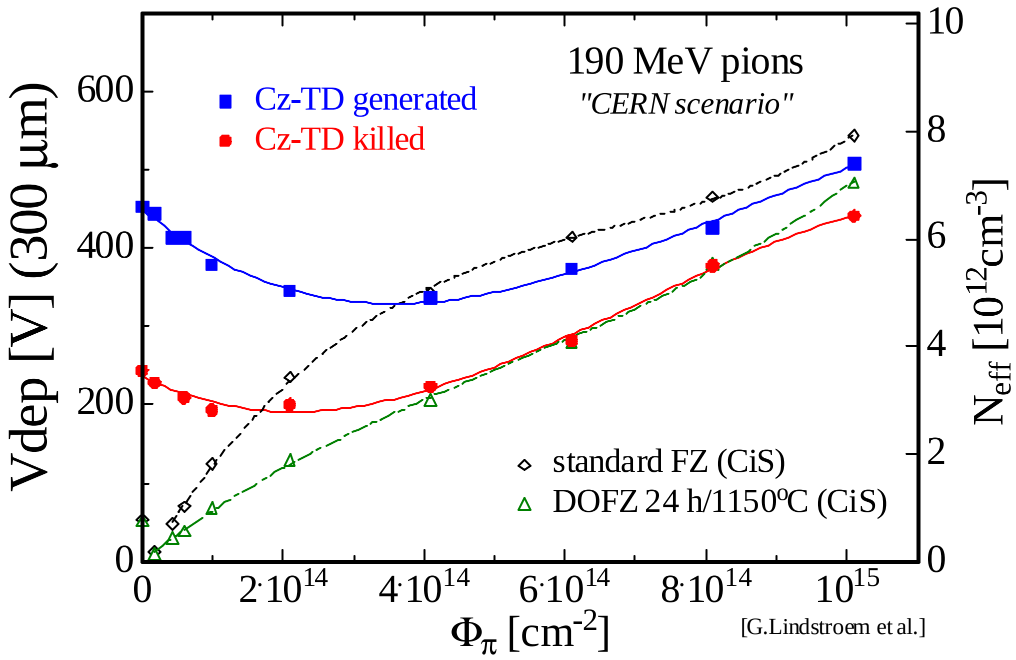


[E.Fretwurst et al. 1st RD50 Workshop]
See also:
- Z.Li et al. [NIMA461(2001)126]
- Z.Li et al. [1st RD50 Workshop]

- ♦ **No type inversion for oxygen enriched silicon!**
- ♦ **Slight increase of positive space charge**
  (due to Thermal Donor generation?)

Material Engineering: Czochralski silicon (CZ)

- **Very high Oxygen content 10^{17}-10^{18}cm^{-3}** (Grown in quartz (SiO_2)crucible)
- **High resistivity (>1KWcm) available only recently** (Magnetic CZ technology)
- **CZ wafers cheaper than FZ** (RF-IC industry got interested)



[G.Lindstroem et al.]

Irradiation of test-structures:

- **Only small change in V_{dep} up to $1\cdot10^{15}$ p/cm^2**
- **No type inversion**
- **Leakage current and charge trapping as for FZ silicon**
- **Very high oxygen content: Beware of thermal donors !**

Details: [G.Lindstroem, 1st RD50 Workshop]
[Z.Li, 1st RD50 Workshop]

- **First full size detectors produced:** MCZ, 900 Ωcm, 32.5 cm^2, strip 10µm, pitch 50µm
  - **Electrical performance:** 3µA@900V Details: [E.Tuominen, 1st RD50 Workshop]
  - **Test beam:** Signal/Noise ≈ 10 ; Efficiency ≥ 95% ; Resolution of 10µm
  - **Radiation tests:** under way

Defect Engineering: Oxygen Dimers in Silicon

- **Idea: Transform Oxygen into Oxygen dimers (O_2)**

Standard Si : **$V+O \rightarrow VO$; $V+VO \rightarrow V_2O$** → deep acceptor (neg. charged)

Dimered Si : **$V+O_2 \rightarrow VO_2$; $V+VO_2 \rightarrow V_2O_2$** → Simulations: deep acceptor (but shallower than V_2O) →neutral in SCR ?

- **How to produce silicon containing dimers ?**
  - Co^{60}-γ or electron irradiation at 350°C
    $V+O \rightarrow VO$; $VO+O \rightarrow VO_2$; $I+VO_2 \rightarrow O_2$

- **Does it work ?**

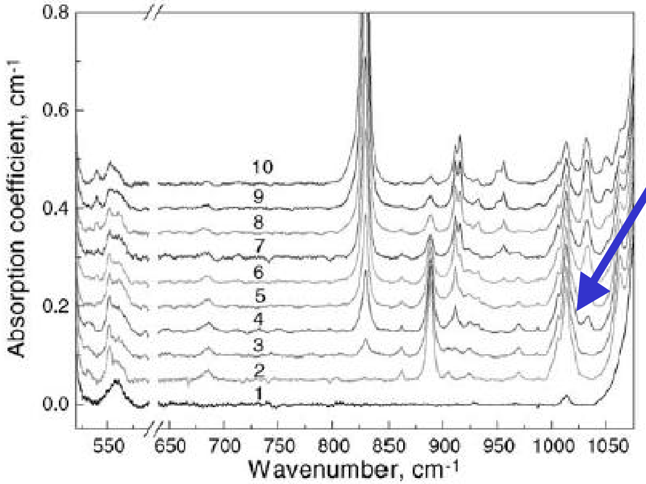


Fig. 1. Room temperature absorption spectra for C-lean n-Cz–Si ($\rho = 50\,\Omega$ cm): (1) as-grown; (2) after electron irradiation at 350°C, $F = 8 \times 10^{17}$ cm^{-2}; (3–10) after RT irradiation. F(cm^{-2}): (3) 1×10^{16}, (4) 5×10^{16}, (5) 10^{17}, (6) 2×10^{17}, (7) 4×10^{17}, (8) 7×10^{17}, (9) 1.1×10^{18}, (10) 6×10^{18}.

- **2001 – L.Lindstroem et al.: IR measurements show dimer line after 350°C electron – irrad. of CZ silicon.** [Lindstr.om et al. PhysicaB 308 (2001) 284]

- **2002 – S.Watts et al.: First test on FZ detectors performed. No clear evidence for dimers.**
  [Watts et al NIM A485 (2002) 153]

- **2003 - Systematic tests under way**
  (RD50 - Dimer Task Force)

Epitaxial SiC
“A material between Silicon and Diamond”

Property	**Diamond**	**4H SiC**	**Si**
E_g [eV]	**5.5**	**3.3**	**1.12**
$E_{breakdown}$ [V/cm]	10^7	$4 \cdot 10^6$	$3 \cdot 10^5$
μ_e [cm^2/Vs]	1800	800	1450
μ_h [cm^2/Vs]	1200	115	450
v_{sat} [cm/s]	$2.2 \cdot 10^7$	$2 \cdot 10^7$	$0.8 \cdot 10^7$
Z	6	14/6	14
ε_r	5.7	9.7	11.9
e-h energy [eV]	**13**	**8.4**	**3.6**
τ_h [s]	10^{-9}	$5 \cdot 10^{-7}$	$2.5 \cdot 10^{-3}$
Wigner En.[eV]	**43**	**25**	**13-20**

- **Wide bandgap (3.3eV)**

⇒ **lower leakage current than silicon**

- **Signal:**

Diamond	**36 e/μm**
SiC	**51 e/μm**
Si	**89 e/μm**

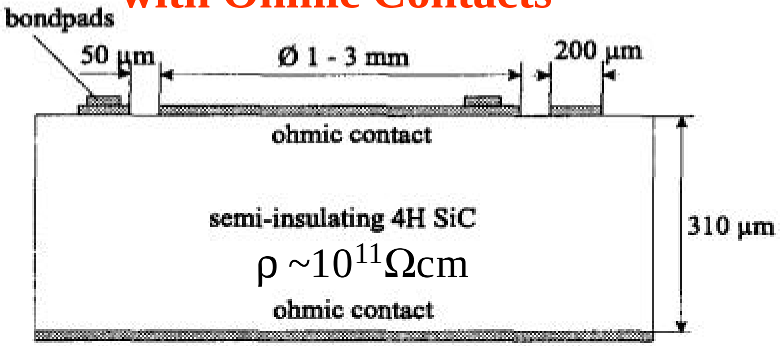
⇒ **more charge than diamond**

- **Higher displacement threshold than silicon**

⇒ **radiation harder than silicon (?)**

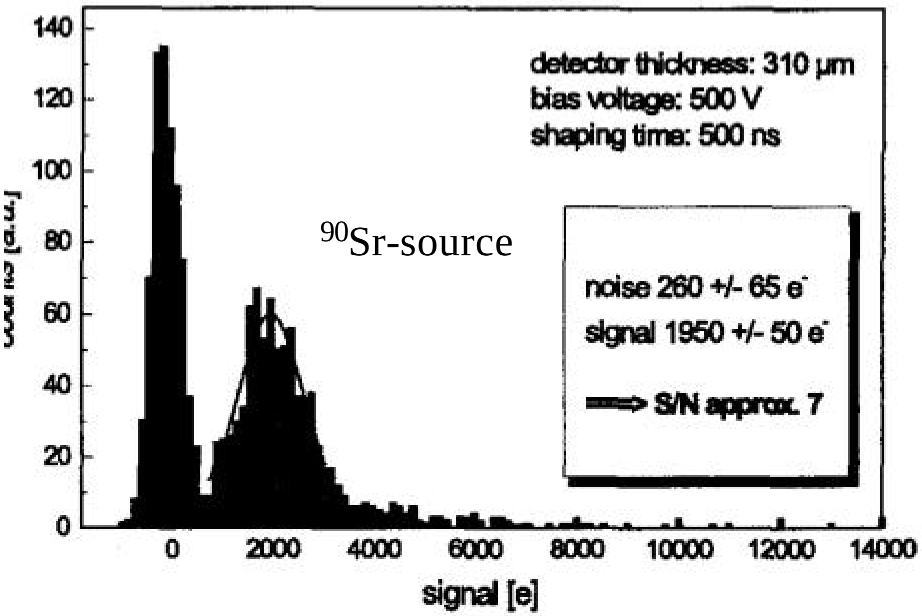
About Diamond:
See later talk“Diamond”
by *Mara Bruzzi*

Semi-insulating 4H-SiC with Ohmic Contacts



$\rho \sim 10^{11} \Omega\text{cm}$

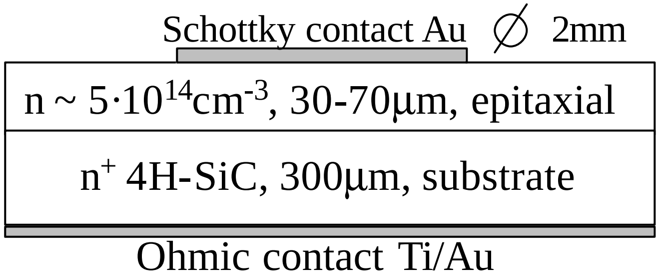
polarization effects due to deep traps/micropipes ® CCE deterioration



^{90}Sr-source

Nucl.Phys.B Proc. Suppl.78 (1999), 516

Schottky Barrier Epitaxial SiC



Schottky contact Au ∅ 2mm

n ~ $5 \cdot 10^{14}$cm^{-3}, 30-70µm, epitaxial

n^{+} 4H-SiC, 300µm, substrate

Ohmic contact Ti/Au

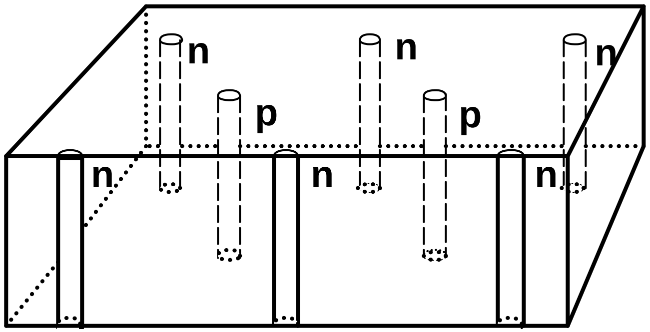
low defect density in epi layer

® negligible polarization effects

Present status: e.g. CREE (USA)

- 20-50 µm epitaxial 4H-SiC
- ≈ 9.000$ - 2”wafer

Device Engineering: 3D detectors



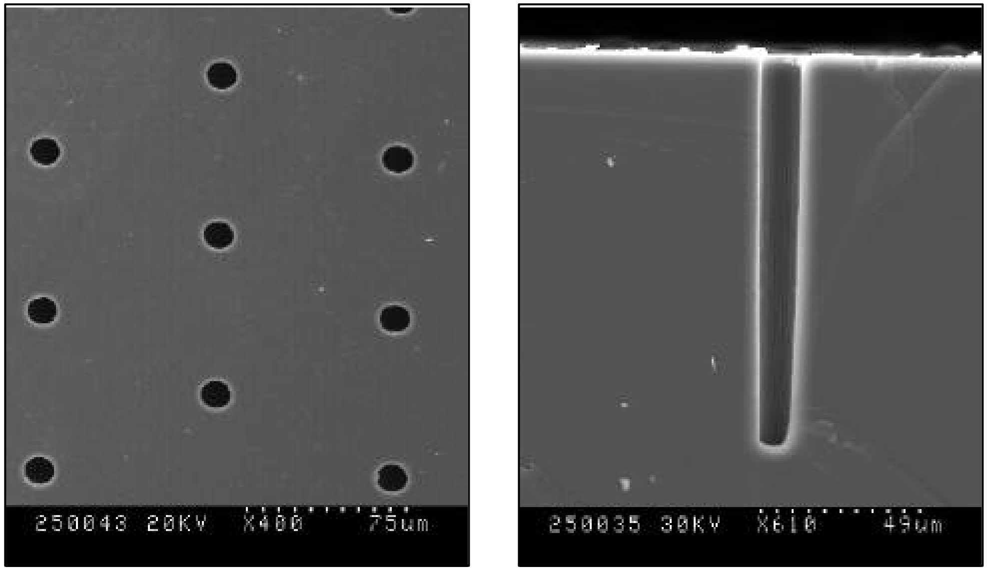
Present size up to ~1cm^2

♦ Electrodes:

- **narrow columns along detector thickness-“3D”**
- **diameter:** 10µm **distance:** 50 - 100µm

♦ Lateral depletion:

- **lower depletion voltage needed**
- **thicker detectors possible**
- **fast signal**



[P. Roy, Glasgow, 1st RD50 Workshop]

♦ Hole processing :

- **Dry etching**
- **Laser drilling**
- **Photo Electro Chemical**

♦ Electrode material

- **Doped Polysilicon (Si)**
- **Schottky (GaAs)**

♦ Irradiation tests

- **$1\cdot10^{15}$ p/cm^2 (55 MeV, 23GeV)**
- **$2\cdot10^{14}$ p/cm^2 (190 MeV)**

More details on Friday:
“Molecular Biology”
Sherwood Parker, Hawaii

Device Engineering: thin detectors

Benefits:

- better tracking precision and momentum resolution
- low operating voltage
- more precise timing
- improved radiation tolerance:

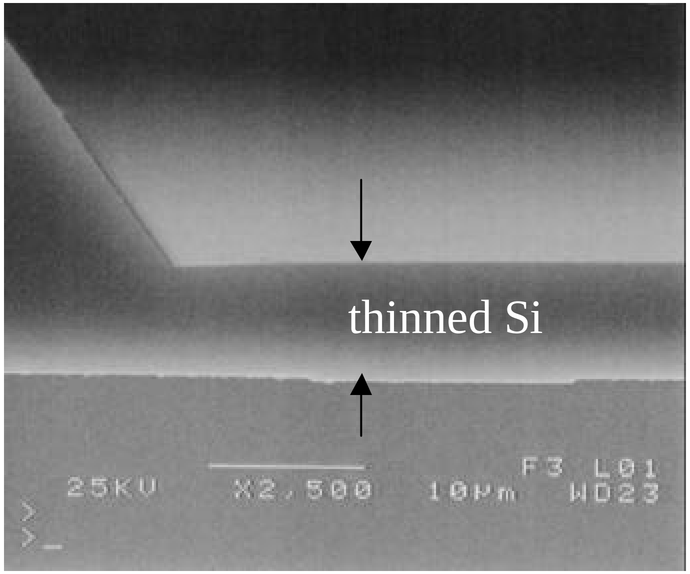
50µm thick, 50Ωcm Si detector ($V_{dep} = 200V$): type inversion after 10^{15} cm^{-2}

Drawbacks:

- mip signal ~ 3500e-h pairs
- relatively broad Landau distribution at higher values

Technical Approach:

- Epitaxial Si device
- Thinning with chemical attacks and micro-machining



Thinning Si by chemical attack (IRST – Trento)

RD50 – Work plan – What is happening right now?

All RD50 institutes:

- **Inter-calibration of microscopic/macroscopic measurement equipment/procedures**
- **Exchange of already produced samples and on-stock material**
- **Design of common masks for test structures**
- **Evaluation of irradiation facilities, common irradiation runs**

RD50 subgroups already working on:

- DOFZ (influence of process, particle dependence of damage)
- Epitaxial silicon, Hydrogen and Thermal donors in silicon
- High resisitivity CZ detector characterization/production
- V_xO_x defect identification and simulation, Oxygen dimer production
- Irradiation of samples up to very high fluences > $5{\cdot}10^{15}$ cm^{-2}, CV – CCE comparison
- Evaluation of semiconductors other than silicon, production of 4H-SiC wafers
- 3D and thin detectors – optimal processing technique?
- Cross check of detector simulation tools within RD50
- … much more

Summary

- **Future detectors for - LHC upgrade will face fluences up to** $1.6\cdot10^{16}\mathrm{cm}^{-2}$
  - Linear Collider will face high flux of e-m-radiation

- **Newly formed CERN-RD50 collaboration following three strategies:**
  - **Material Engineering**
    Silicon: Oxygenation, CZ, dimers, other impurities, …
    New Materials: SiC and others
  - **Device Engineering**
    Geometries with short carrier drift length: 3D and thin detectors
    Device modeling, cost effective solutions, n-in-p, n-in-n, …
  - **Modification of Operational Conditions**
    Forward Bias operation, charge injection, …

- **Different particles cause different displacement damage**
  - **Increase of leakage current**
  - **Change of** V_{dep} **: Increase of negative space charge (not for CZ silicon)**
  - **Charge loss: Trapping and loss of active volume**

⇒ **To obtain ultra radiation hard sensors a combination of the above mentioned approaches depending on radiation environment, application and available readout electronics will be best solution.**

Further information: http://cern.ch/rd50/

e.g.: Proposal and all transparencies of 1st RD50 Workshop (CERN, 2-4 Oct 2002)