Development of Radiation Hard Sensors for Very High Luminosity Colliders - CERN-RD50 project -

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On behalf of CERN RD50 Collaboration

http://www.cern.ch/rd50

Panja Luukka, 6th International Conference on Large Scale Applications and Radiation Hardness of Semiconductor Detectors, September 29-October 1, 2003, Firenze, Italy

Outline

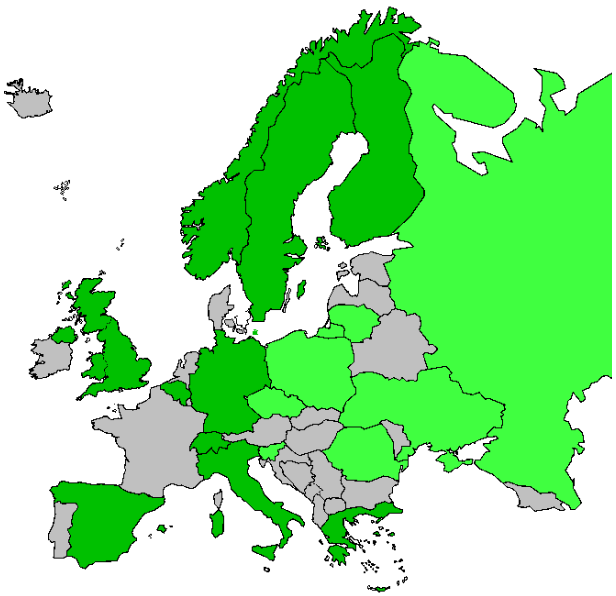
- Motivation and Introduction of RD50
- Radiation Damage
- RD50 - Approaches to obtain radiation hard sensors
- Latest results of defect engineering
  - Cz-Si detectors and epi-Si detectors
  - Results of irradiations with
    - Low and high energy protons
    - γ irradiation
    - Neutron irradiation
- RD50 – future work plan
- Summary

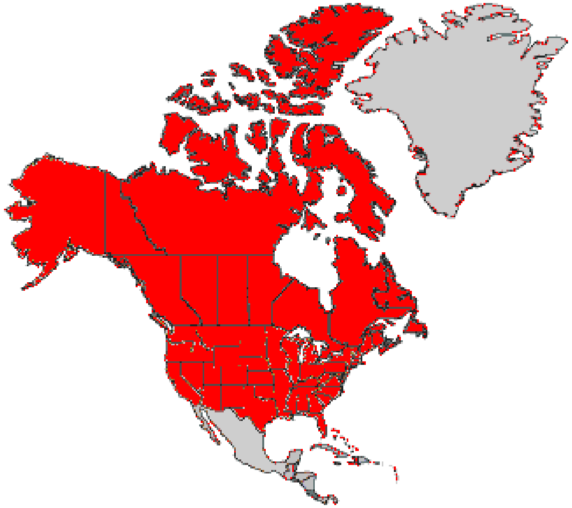
RD50 - Development of Radiation Hard Semiconductor Devices for High Luminosity Colliders

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: $L = 10^{34} cm^{-2}s^{-1}$ —10 years→ ϕ(R=4cm) $\sim 3\cdot10^{15}cm^{-2}$
ϕ(R=75cm) $\sim 3\cdot10^{13}cm^{-2}$

⇨ Technology available ⇨ However, serious radiation damage!

× 5

S-LHC: $L = 10^{35} cm^{-2}s^{-1}$ —5 years→ ϕ(R=4cm) $\sim 1.6\cdot10^{16}cm^{-2}$

⇨ 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, g 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:

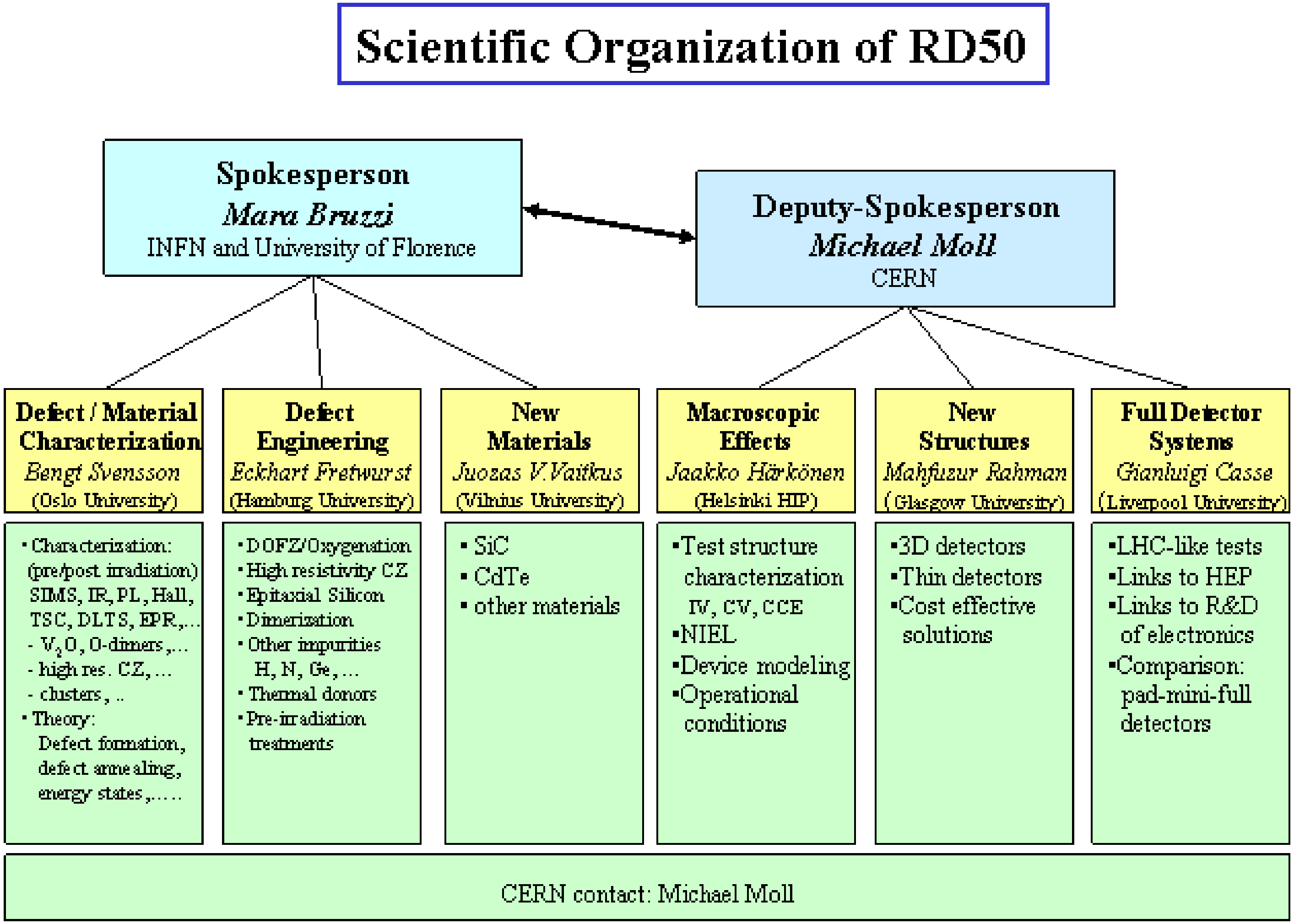
- **Material engineering**
  - Defect engineering of silicon (Cz-Si, oxygenation, dimers, …)
  - New detector materials (SiC, …)
- **Device engineering**
  - Improvement of present planar detectors (3D detectors, thin detectors, cost effective detectors,…)

In order to meet the goal:

- **Basic studies (Device and defect modeling, simulations)**

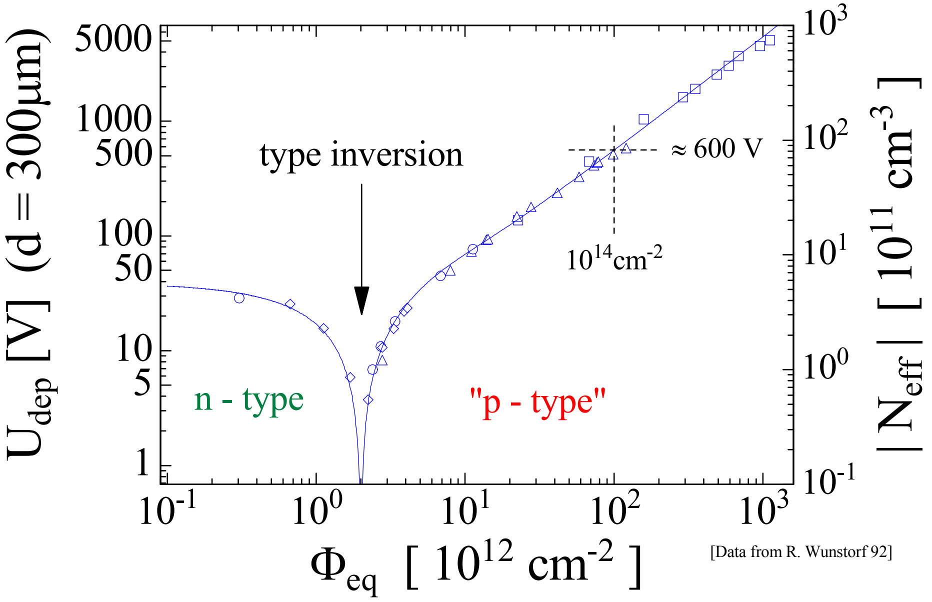
Scientific Organization of RD50

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

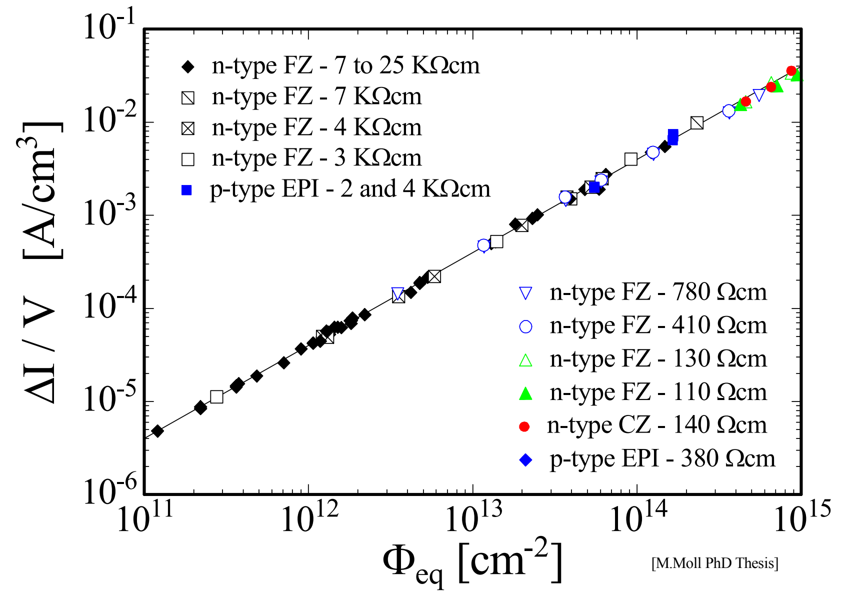


Radiation Damage - Macroscopic Effects

- Evolution of the full depletion voltage
- Increase of the leakage current
  - Can be helped with cooling



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



2. Increase of leakage current

Defect Engineering of Silicon

- **Defect engineering is deliberate incorporation of impurities into the detector bulk material**
- **Best example: <u>Oxygen</u>**

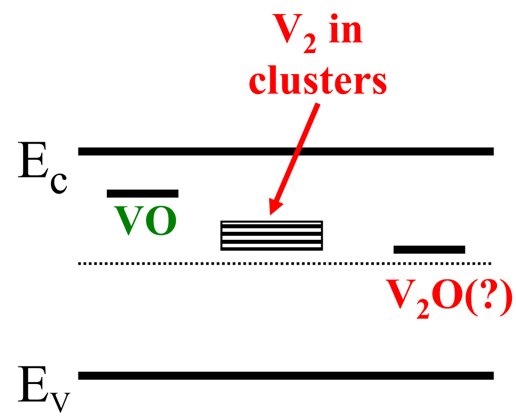
  Idea: Incorporate Oxygen to getter radiation-induced vacancies
  ⇒ prevent formation of Di-vacancy (V_2) related deep acceptor levels

Observation: Higher oxygen content ⇒ 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)**

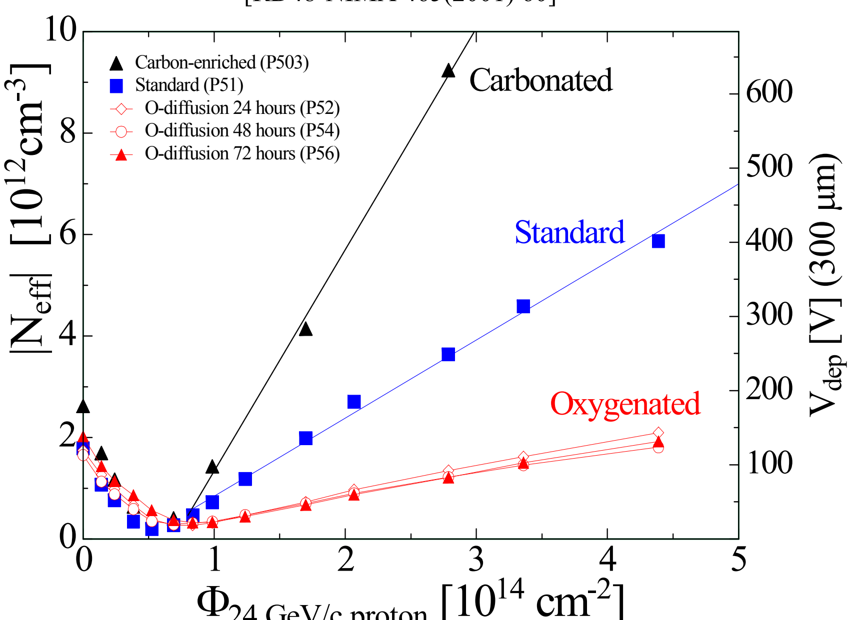
ROSE
RD48
http://cern.ch/rd48

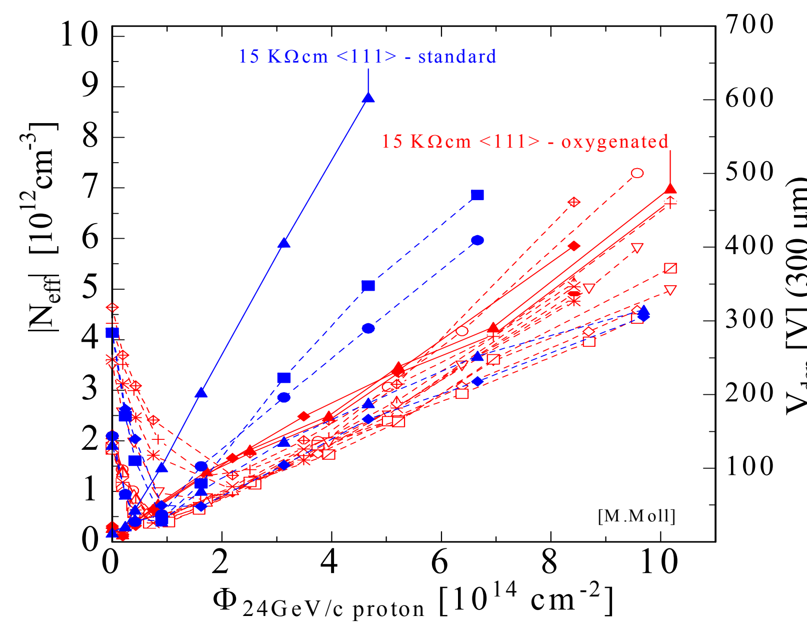
- 1982 First oxygen diffusion tests on FZ
  [Brotherton et al. J.Appl.Phys.,Vol.53, No.8.,5720]
- 1995 First tests on detector grade silicon
  [Z.Li et al. IEEE TNS Vol.42,No.4,219]
- **1999 Introduced to the HEP community by RD48 (ROSE)**

First tests show clear advantage of oxygenation

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

[RD48-NIMA 465(2001) 60]

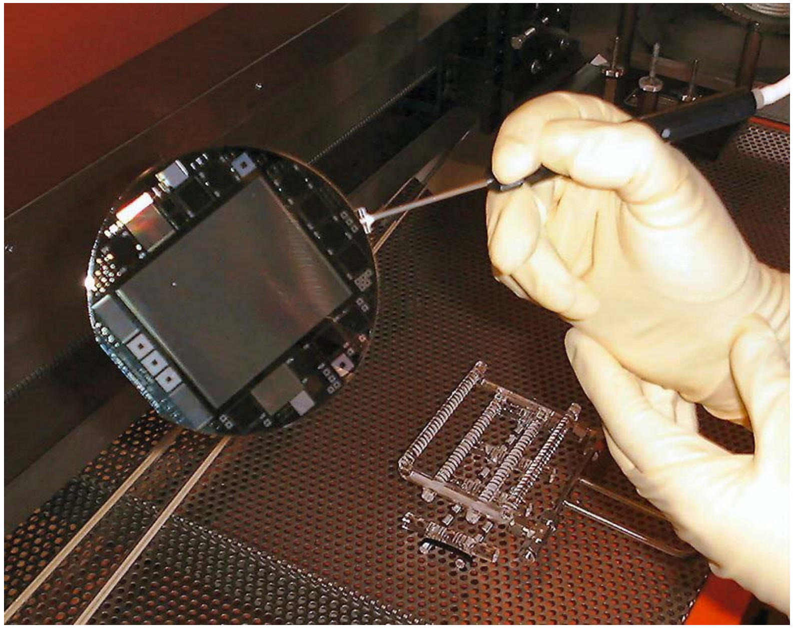




High Resistivity Czochralski Silicon

Oxygen increases the radiation hardness of silicon detectors

* Cz-Si intrinsically contains oxygen, 10^{17}-10^{18} cm^{-3}



High resistivity Cz-Si available from several manufacturers (Okmetic Ltd. Finland, Sumitomo Sitix Ltd. Japan)

* Earlier not available because of no commercial interest
* RF-IC industry interest on high res Cz-Si

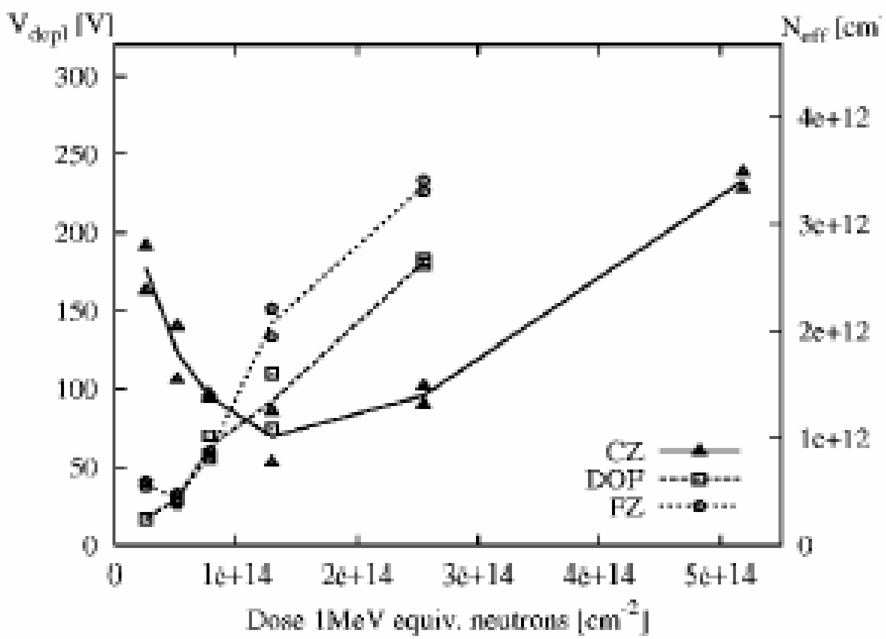
There are reports of Cz-Si of resistivity ≥5kΩcm, "***High resistivity CZ silicon for RF applications substituting GaAs***", T.Abe and W.Qu, Electrochem. Society Proc. Vol. 2000-17

Low energy proton irradiation

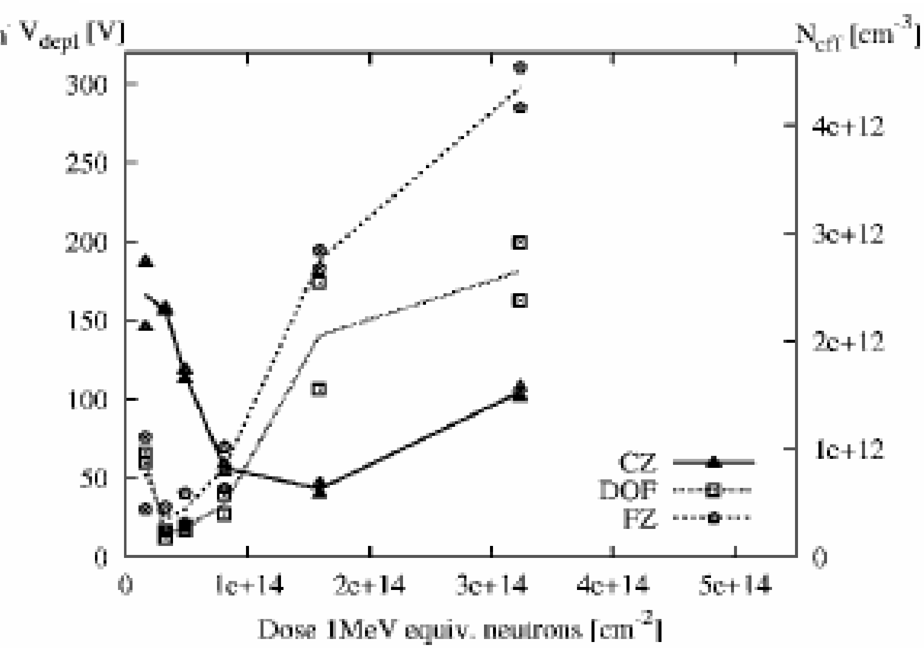
- The full depletion voltage of Cz-Si devices reaches its minimum after about $1{,}5 \cdot 10^{14}$ cm^{-2} irradiation
- V_{fd} of Cz-Si is less after $5 \cdot 10^{14}$ cm^{-2} irradiation than its initial pre-irradiation value 260V

[E. Tuominen et al., Radiation hardness of Cz-Si studied by 10 and 20 MeV protons, IEEE Trans. Nucl. Sci., in press.]

Irradiation performed at the Accelerator Laboratory of Univ. Jyväskylä.
Cz-Si from Okmetic.
Fz-Si wafers from Topsil AS.
Processing at Microelectronics Centre of Helsinki Univ.of Technology



10 MeV



20 MeV

High energy proton irradiation

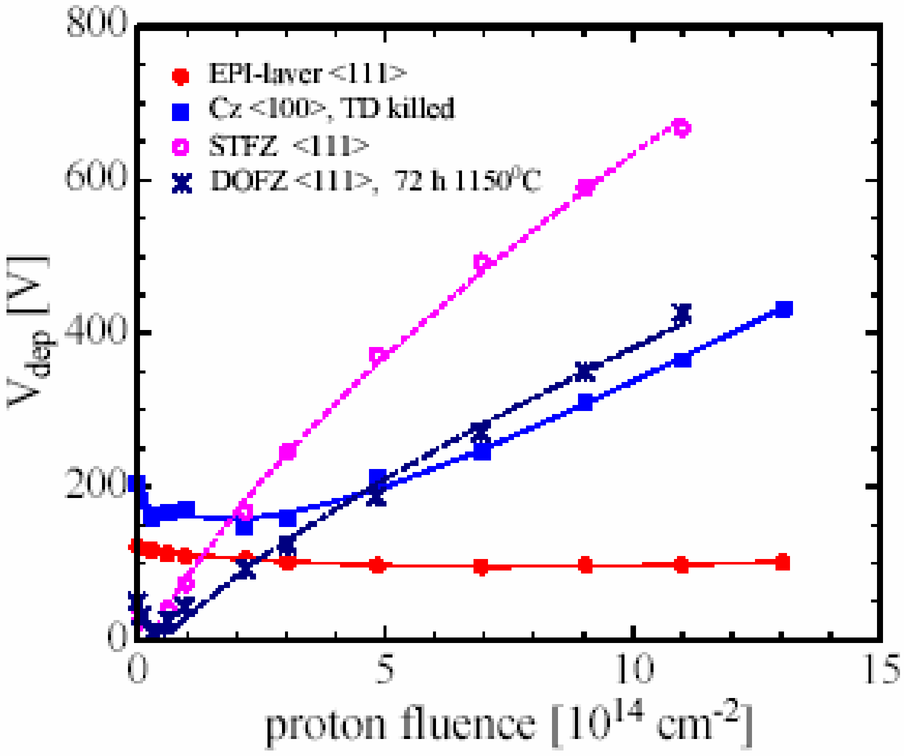
Cz-Si no essential improvement with respect DOFZ

EPI-silicon:

- **No type inversion**
- **Small change in depletion voltage**

[G. Kramenberger et al., Superior radiation tolerance of thin epitaxial silicon detectors, Nucl. Instr. & Meth. A, in press.]

[E. Fretwurst et al., 2nd RD50 Workshop, May 2003]



Irradiation performed at the CERN PS
Cz-Si from Sitix. Fz-Si wafers from Wacker.
Processing at CiS, Erfurt, Germany.

24 GeV/c

γ irradiation

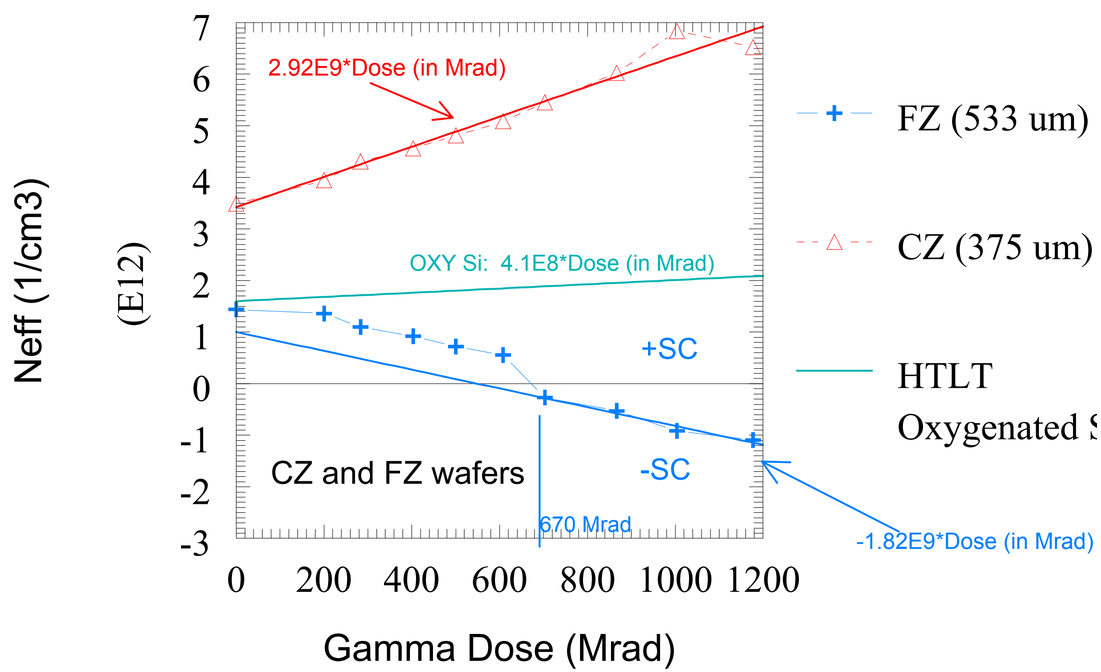
DOF

- No type inversion for oxygen enriched silicon!
- Slight increase of positive space charge

Irradiation performed at the Brookhaven National Laboratory
Cz-Si from Okmetic. Fz-Si wafers from Wacker.
Processing at BNL & Helsinki MEC.

Cz-Si

- Introduction of positive space charge!
- Does it compensate hadron induced acceptors ?



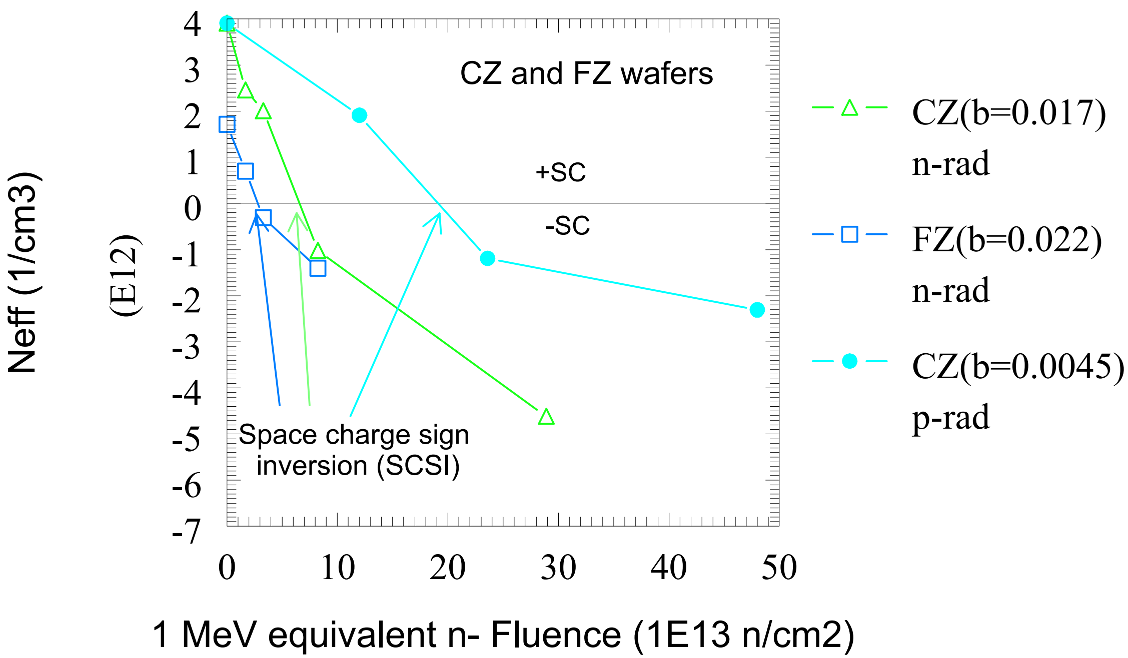
[Z.Li et al., Radiation hardness of high resistivity Cz-Si detectors after gamma, neutron and proton radiations, IEEE Trans. Nucl. Sci., in press.]

Neutron irradiation

Cz-Si and DOF

- No essential difference
- As reported earlier (ROSE) oxygen does not improve radiation hardness against the neutrons.

Irradiation performed at the University of Massachusetts
Cz-Si from Okmetic.
Fz-Si wafers from Wacker.
Processing at BNL& Helsinki MEC.



RD50 – Work plan – What is happening right now?

All RD50 institutes:

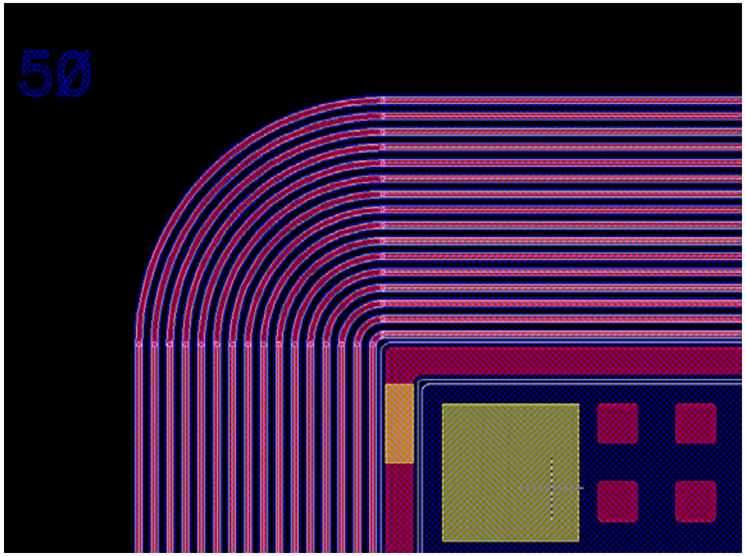
Common order of high resistivity Cz-Si wafers.

- 5 institutes
- N and p-type wafers

Design of common masks for test structures and strip detectors

Common RD50 subprojects.
Funded by the collaboration common fund

- SiC
- Oxygen dimer
- Semi 3D detectors
- Pre-irradiated silicon



Corner of RD50 test diode and multi guard ring structure

Summary

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

- **Defect engineering is successful and effective strategy to improve radiation hardness**

- **Cz-Si detectors have been irradiated with**
  - Low energy protons > clear improvement in radiation hardness.
  - High energy protons > slightly better than DOFZ, clearly better than STFZ
  - Gammas > positive space charge generation, negative SC generation and type inversion in STFZ
  - Neutrons > no clear improvement in Cz-Si and DOFZ materials

- **Detectors with 50μm epitaxial active layer show great radiation hardness**
  - Almost insensitive to V_{fd} increase
  - No type inversion

Further information: http://cern.ch/rd50/
e.g.: Proposal and all transparencies of RD50 Workshops at CERN