Development of semiconductor detectors for very harsh radiation environments in high energy physics applications

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On behalf of the RD50 collaboration – http://www.cern.ch/rd50/

OUTLINE:

•Introduction to RD50

•Radiation damage in silicon

•Detector radiation hardening strategies

•Silicon activities: status, recent results and plans

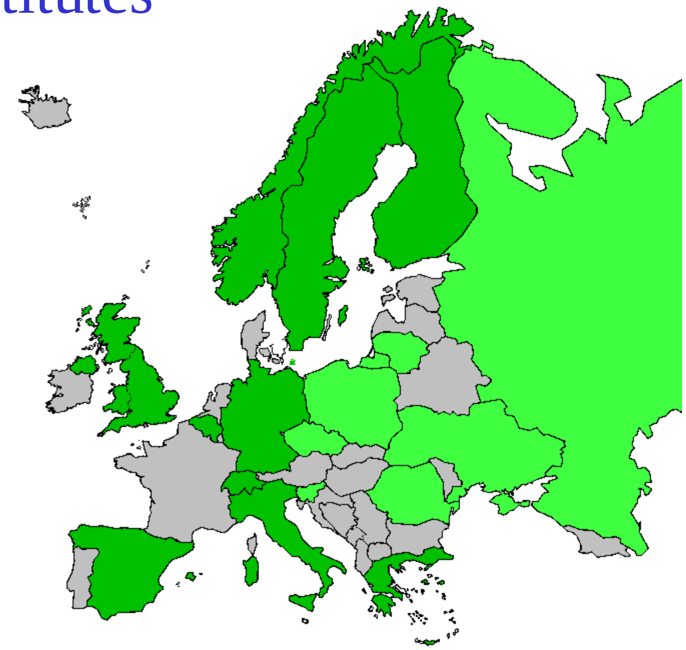
•Non-silicon activities

•Summary

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

280 Members from 55 Institutes

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



Belgium (Louvain), **Czech Republic** (Prague (2x)), **Finland** (Helsinki (2x), Laappeenranta), **Germany** (Berlin, Dortmund, Erfurt, Halle, Hamburg, Karlsruhe), **Greece** (Athens), **Italy** (Bari, Bologna, Florence, Milano, Modena, Padova, Perugia, Pisa, Torino, 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, New Mexico University, Purdue University, Rutgers University, Syracuse University, BNL)

1 Middle East institute

Israel (Tel Aviv)

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

M.Moll 8/2003

Our challenge …

LHC: $L = 10^{34}\ cm^{-2}s^{-1}$

10 years scientific program.

Hadron ϕ (R=4cm) ~ **$3 \cdot 10^{15}$** cm^{-2}

Hadron ϕ (R = 75cm) ~ **$3 \cdot 10^{13}$** cm^{-2}

Detectors designed for this environment, highest fluences still critical. For radii < 4 cm (LHCb VELO) detector replacement foreseen after ~ 3 y.

Super LHC: $L = 10^{35}\ cm^{-2}s^{-1}$

5 years scientific program.

Hadron ϕ (R=4cm) ~ **$1.6 \cdot 10^{16}\ cm^{-2}$**

Specific R&D on radiation hardening is necessary. Cost for detector replacements can be a big issue. Harder detectors ⇒ affordable experiments

Objectives:

- Detector operation up to 10^{16} cm^{-2}
- Fast signal collection (bunch crossing interval ~ 10ns)
- Low mass (reducing multiple scattering close to the interaction region).

Strategies:

Three fundamental strategies have been identified in order to achieve radiation harder tracking detectors.

- **Material engineering -** deliberate modification of the detector bulk material (impurities in silicon or semiconductor materials other than silicon).
- **Device engineering -** improvement of present planar detector structures (modification of the electrode configuration, new detector geometries,…)
- **Variation of detector operational conditions -** low temperatures, forward bias...

Ultimate radiation hardening can be achieved through the understanding of the physics underlying the radiation-induced degradation of detector properties and the charge collection capabilities of different detector types. To this purpose RD50 plans to promote extensive:

- **Basic studies**

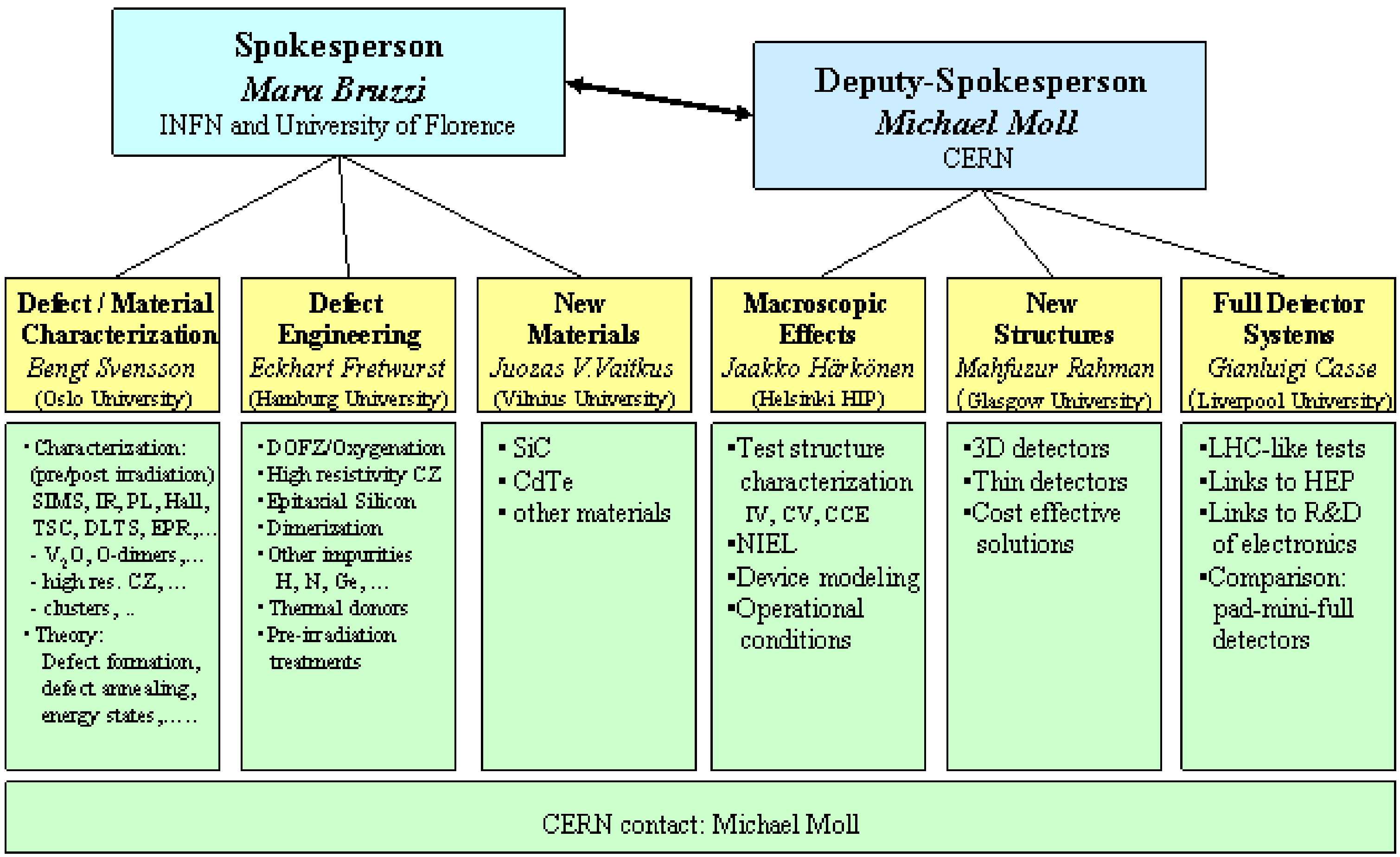
  characterization of microscopic defects as well as the parameterization of macroscopic detector properties under different irradiation and annealing conditions.

- **Defect modeling and device simulation**

  computer simulations covering the whole process of radiation damage: particle-lattice interaction, formation of defects, their structural and electrical properties, impact of these defects on the macroscopic properties of the detectors and simulations of the macroscopic device in the presence of defects.

- **Test of segmented devices and detector systems**

Scientific Organization of RD50



RADIATION DAMAGE IN SILICON: microscopic effects.

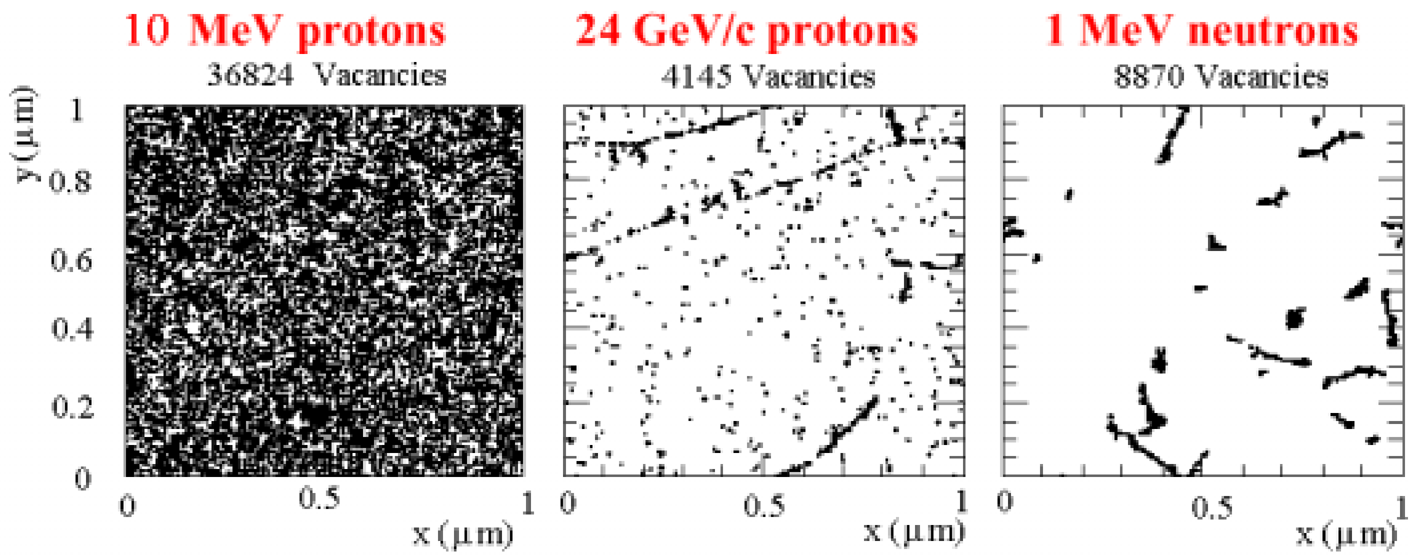
Impinging particle

→ **Point defects** (E > 25eV)

→ **Cluster defects** (E > 5keV)

Initial distribution of vacancies (10^{14} cm^{-2})

M. Hutinen (ROSE TN 2001/02)



Ratio point/cluster defects depend on particle/energy

60Co-γ , E_γ ~ 1MeV
Displacement
no clusters

Electrons:
E_e > 255 keV displacement
E_e > 8 MeV clusters

Neutrons:
E_n > 185 keV displacement
E_n > 35 keV clusters

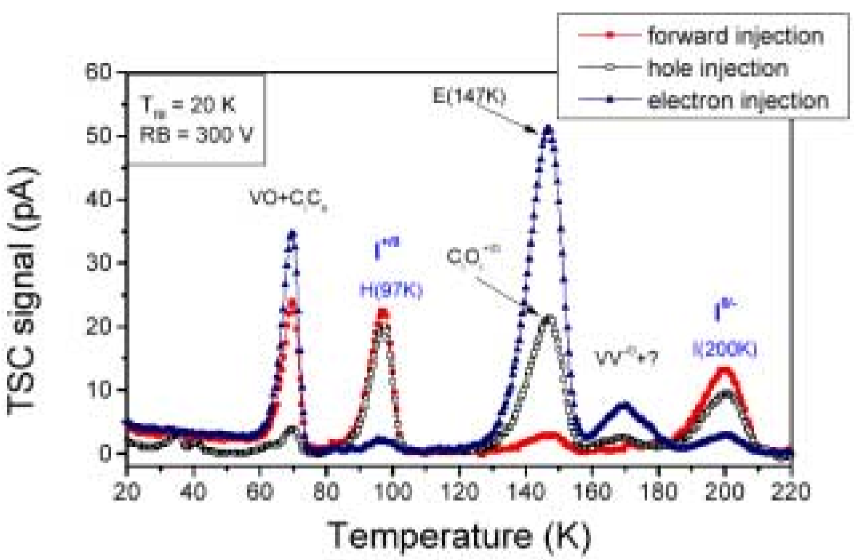
Investigations of radiation induced defects: the techniques, the challenge

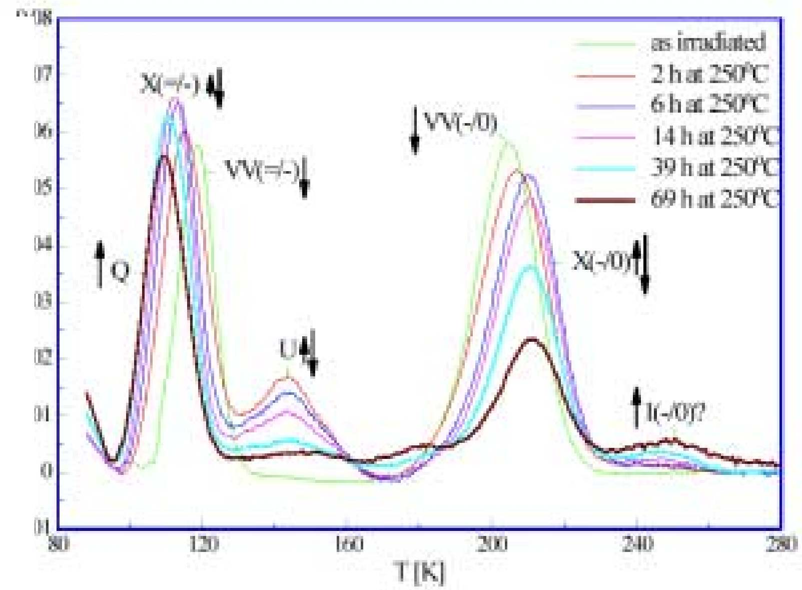
Radiation induced defects introduce energy levels in the silicon band-gap (deep levels). They are responsible for the degradation of the electrical properties of the detectors. The knowledge of all the radiation induced defects and of their evolution with time accounts for the radiation damage. The main players are the displacement in the silicon lattice (vacancies) and the impurities in the crystal. Theoretical calculations (energy levels and charge state of defects) and experimental studies at a microscopic levels are necessary to build a complete model of the radiation damage. These studies should give guidance on the material engineering of the silicon detector material.

Investigations of radiation induced defects: the techniques, the challenge

Experimental methods are available to study the radiation induced deep levels in silicon. Theoretical calculations and comparison with well known defect help the identification of the charge state and chemical composition of the measured levels.

Identification of defects: DLTS, TSC to study deep levels

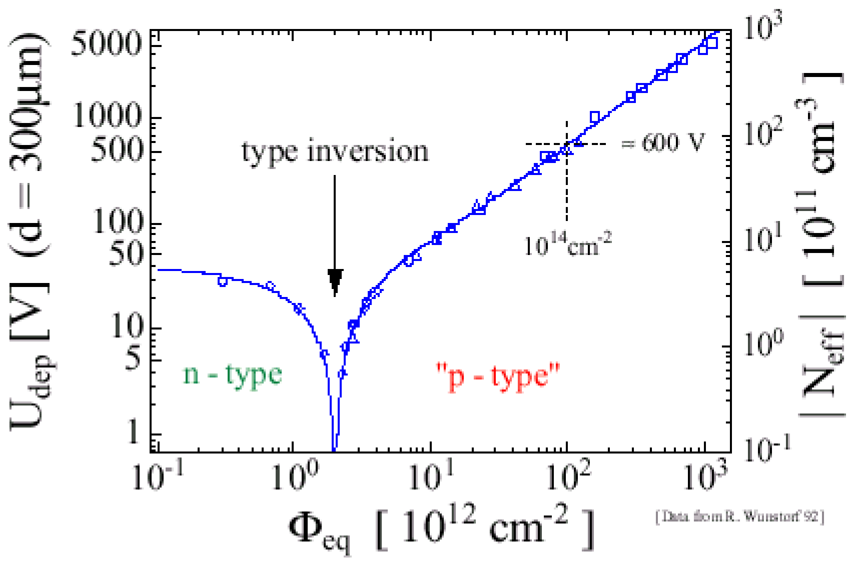


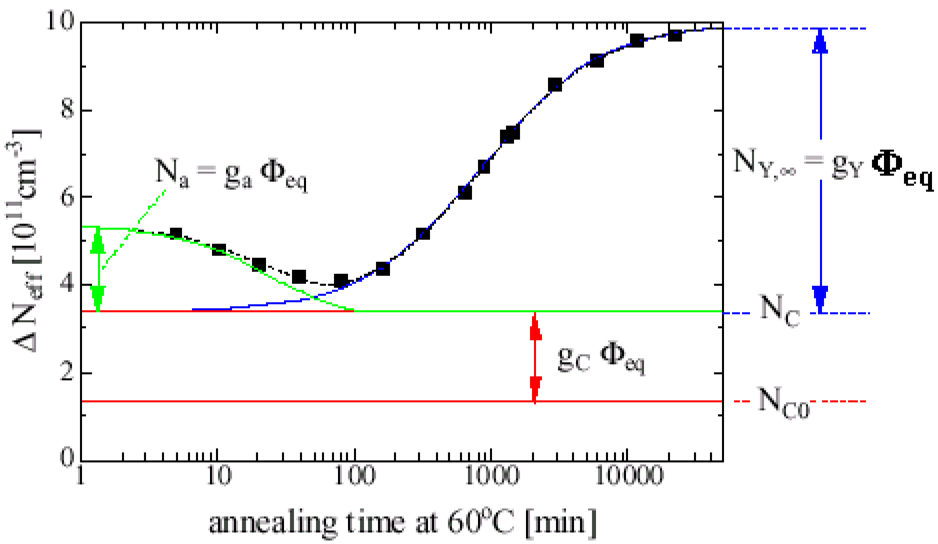


Examples from I.Pintilie, 2nd RD50 workshop, CERN 18-20 May 2002

Radiation induced changes in the electrical properties of silicon detectors

Effective space charge ($N_{eff} \Rightarrow V_{fd}$) with fluence and time

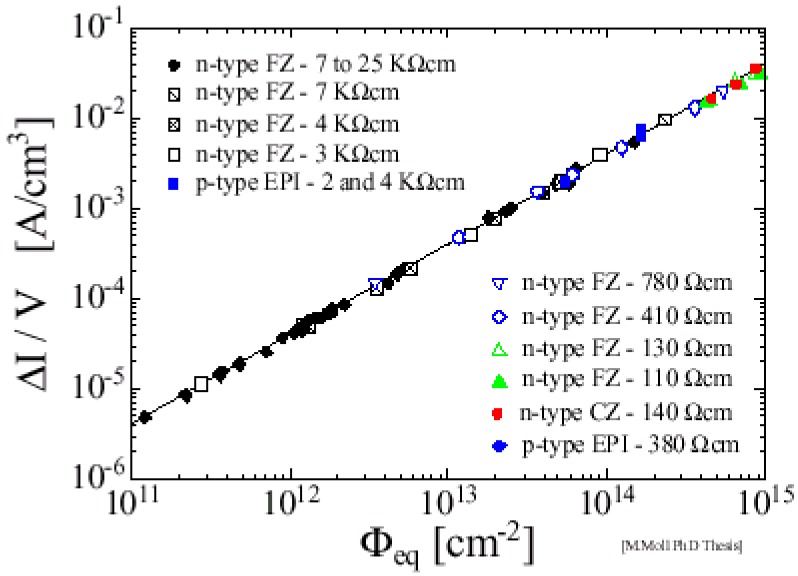


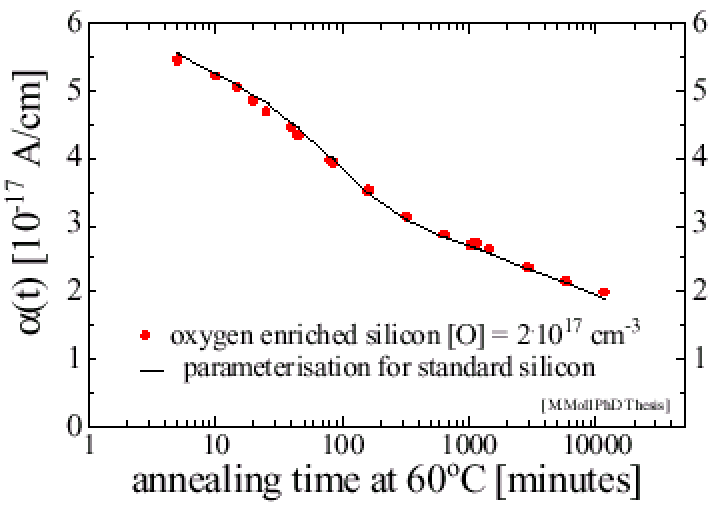


Parameters: β, g_c, g_y

Radiation induced changes in the electrical properties of silicon detectors

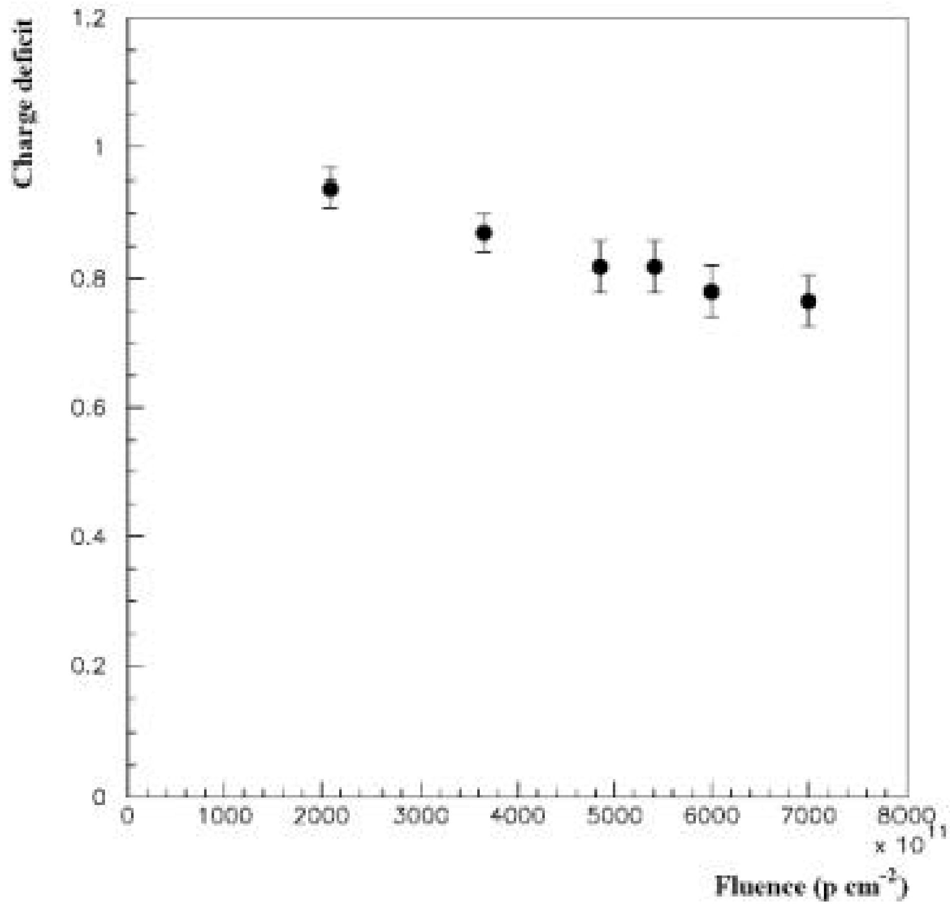
Reverse current with fluence and time





Parameters: α

Radiation induced changes in the electrical properties of silicon detectors



Signal (^{106}Ru ß–source) degradation as a function of fluence in a non-homogeneous irradiated detector (n-in-n). Data G. Casse

Controlling the degradation of the detector properties → **Defect engineering of the silicon crystal: influence the defect kinetics with intentional introduction of selected impurities**

Successful example: Oxygen

A model for the radiation damage

$$V + O \rightarrow VO$$

$$VO + V \rightarrow V_2O$$

Electrically active, introduces negative space charge, contributes to the degradation of the electrical properties of silicon detectors

$$V + O \rightarrow VO$$

$$VO + O \rightarrow VO_2$$

Competing reaction, less favourable.

Increasing the O concentration can decrease the formation rate of V_2O

$VO \uparrow$ $VO_2 \downarrow$

Available O rich and standard silicon materials

Standard N-type FZ : [O] < 5 10^{16} cm^{-2}

High temperature diffused N-type from SiO_2 layer, ρ =6-7 k Ωcm : [O] ~ 1-2 10^{17} cm^{-2} (material developed within the RD48 collaboration)

Epi-layer: 50 µm, n-type, ρ = 50 Ωcm, on CZ-substrate, n-type ρ = 0.01 Ωcm, [O] 1. 10^{18} cm^{-3}

High resistivity CZ N-type, ρ =1.2 k Ωcm : [O] ~ 8-9 10^{17} cm^{-2}

High resistivity MCZ (Magnetic CZ) N-type, ρ =1.2 k Ωcm : [O] ~ 5-9 10^{17} cm^{-2} ?

Standard P-type FZ, ρ =6-7 k Ωcm : [O] < 5 10^{16} cm^{-2}

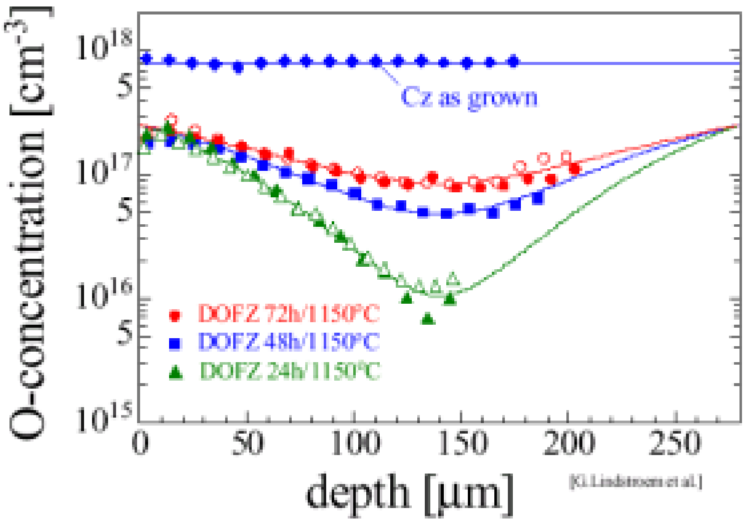
High temperature diffused P-type from SiO_2 layer : [O] ~ 1-2 10^{17} cm^{-2}

High resistivity CZ P-type : [O]~ 8-9 10^{17} cm^{-2} ?

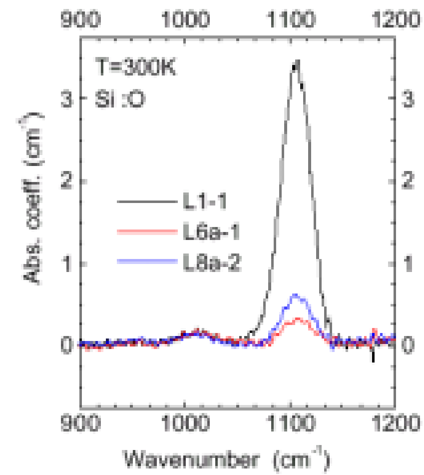
Macroscopic changes in oxygen rich silicon

Measurement of [O]

Profile (SIMS)

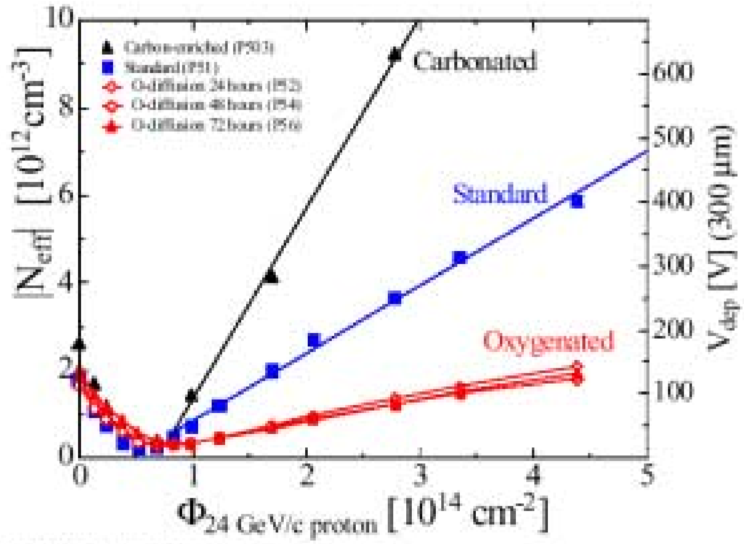


Infrared absorption (average)



Diffusion time @ 1150 °C	24h	48h	72h
Average [O] (cm^{-3})	6.8 10^{16}	1.0 10^{17}	1.4 10^{17}

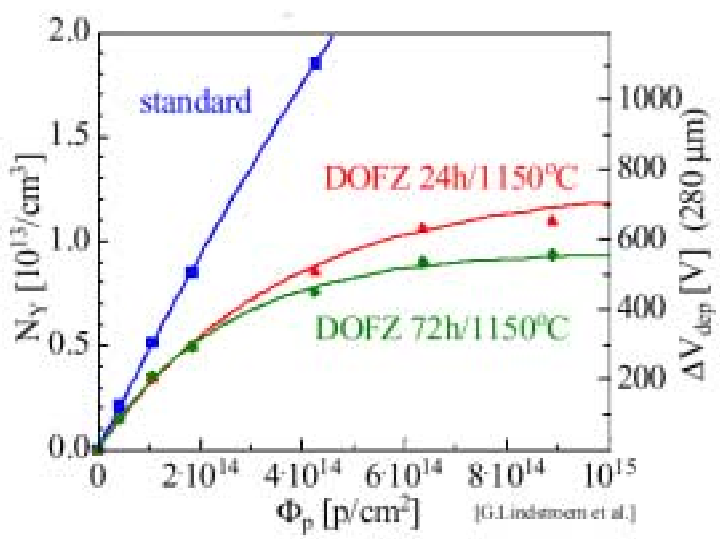
Macroscopic changes in oxygen rich silicon

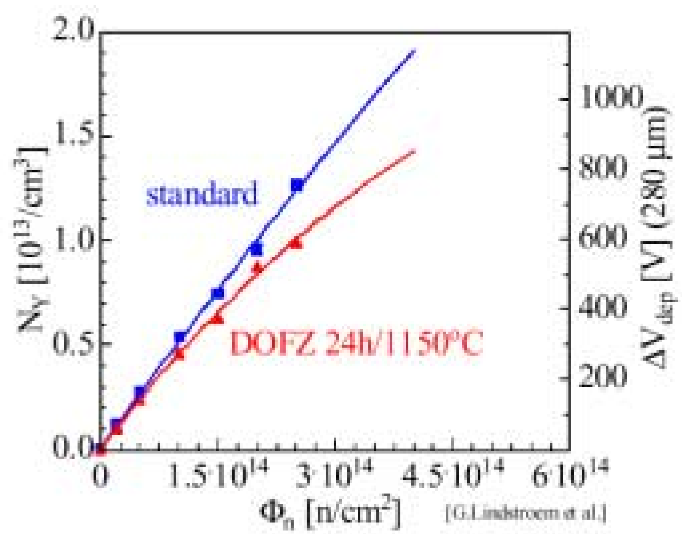


[RD48-NIMA 465(2001) 60]

Benefit with 24 GeV/c protons in term of β. No benefit with neutrons.

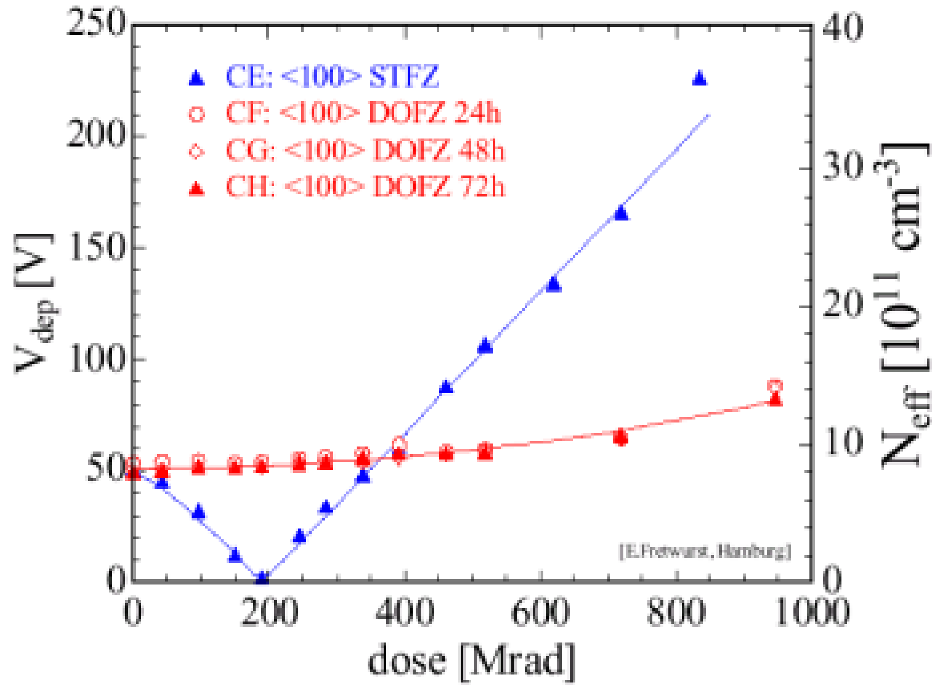
Benefit in term of N_y with 24 GeV/c protons (more pronounced) and neutrons.

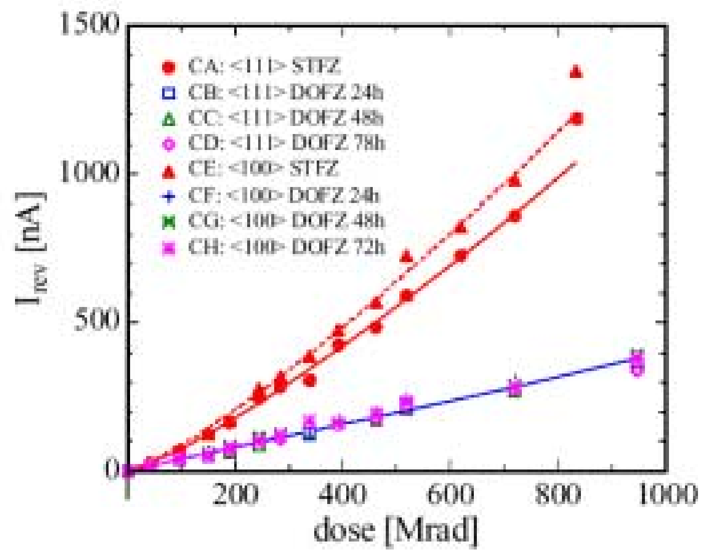




Macroscopic changes in oxygen rich silicon

Spectacular effect with Co-60 γ irradiation. Suppression of type inversion and of the degradation of N_{eff} (slight increase of N_{eff} maybe explained by thermal door activation), reduction of the increase of reverse current, small dependence on [O]>5.10^{16} cm^{-3}.





Macroscopic changes in oxygen rich (up to 2. 10^{17} cm^{-3} FZ-silicon

Oxygen enriched silicon has evidenced the difference between cluster damage and point damage. Oxygen is very effective in enhancing the radiation hardness of silicon when point defects are dominant.

γ irradiation: spectacular effect in suppressing the changes in N_{eff} and reverse current with irradiations and time.

Fast charged hadron irradiation: improvement in β (not dependent on [O], with [O] $\geq 7.10^{16}$ cm^{-3}), some improvement in N_y ([O] $> 1.10^{17}$ cm^{-3}, with some possible small dependence on [O])

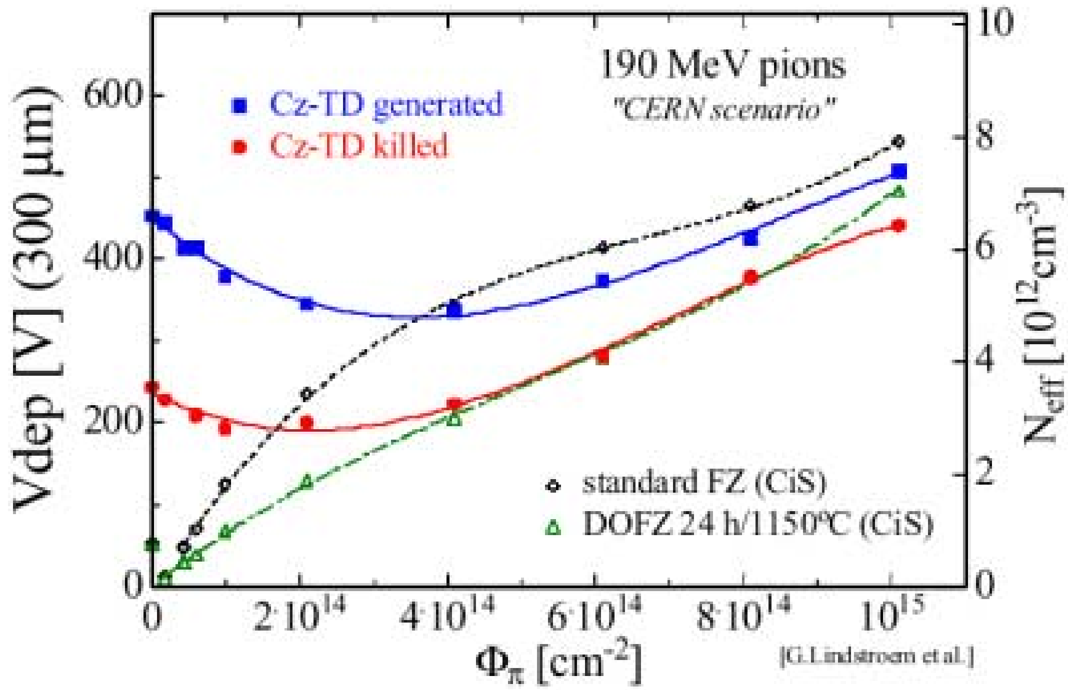
Neutron (1 MeV) irradiation: no improvement in β, some improvement in N_y ([O] $> 1.10^{17}$ cm^{-3}, with some possible small dependence [O]).

Oxygen in Silicon: RD50 activities

CZ silicon, 190 MeV π irradiation

Comparison between standard FZ-, DOFZ- and Cz- silicon diodes

Expected behaviour of initial resistivity with activation of thermal donor, without suitable thermal cycling during manufacturing



No type inversion for the CZ-silicon

Reverse current and charge trapping comparable to FZ silicon

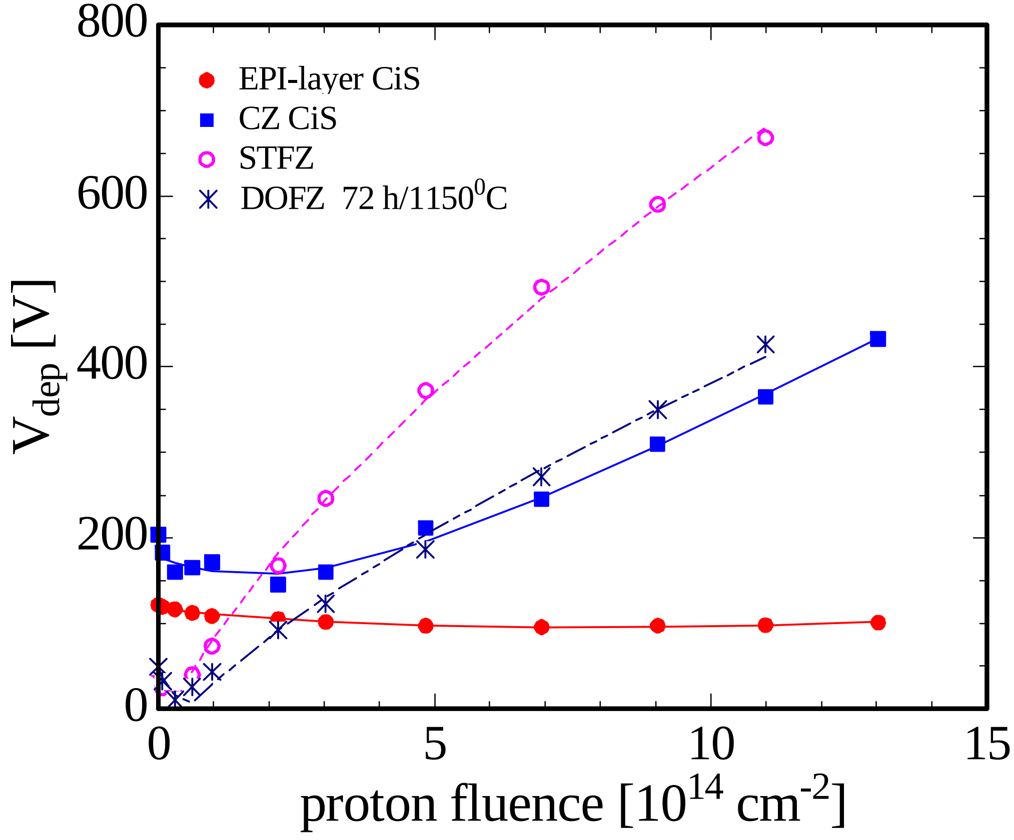
Oxygen in Silicon: RD50 activities

Cz and EPI silicon, 24 GeV/c p irradiation

Comparison between standard FZ-, DOFZ-, Cz- and EPI-silicon diodes

No type inversion for the CZ-and EPI silicon. Strong decrease of β with EPI silicon.

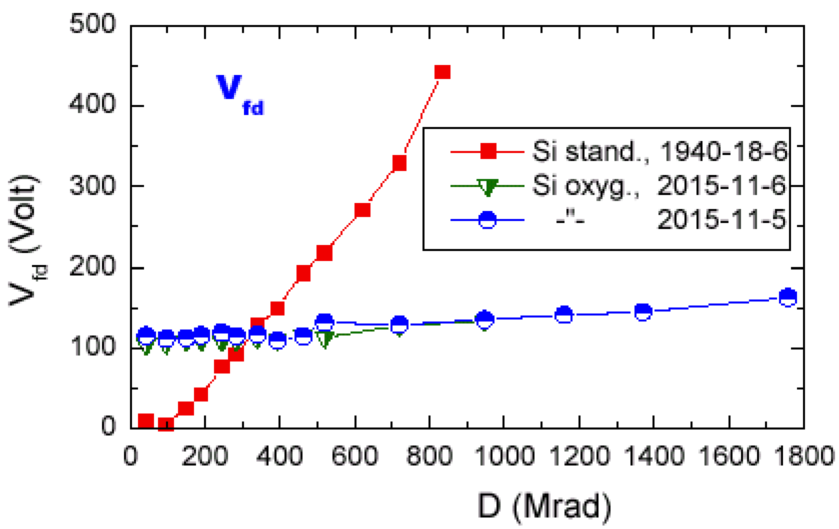
Reverse current and charge trapping comparable to FZ silicon



Oxygen in Silicon: RD50 activities

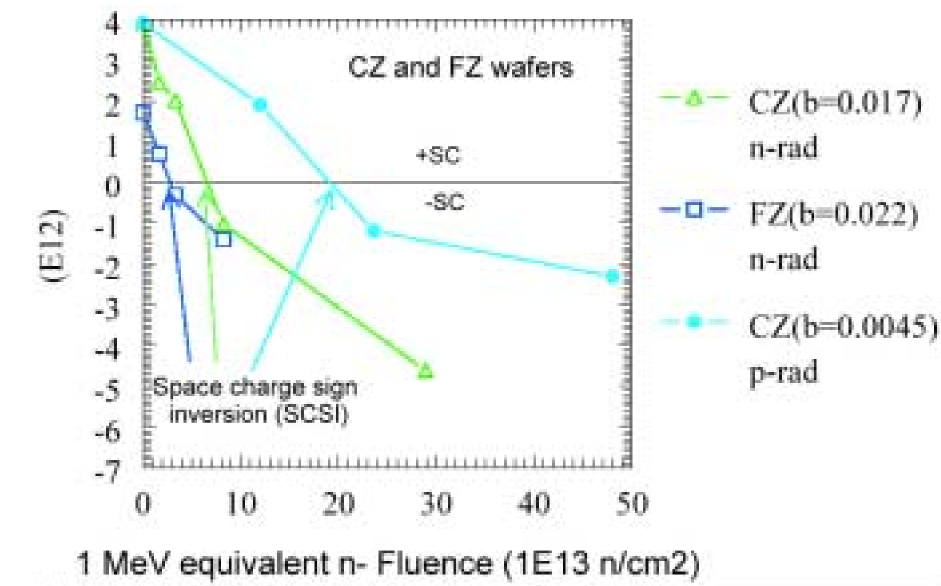
MCZ silicon, γ, n and p irradiation

^{60}Co g : No type inversion for the MCZ silicon. Slight increase of N_{eff} **with dose (**due to activation of thermal donors?)



Data from Z. Li, 2nd RD50 workshop

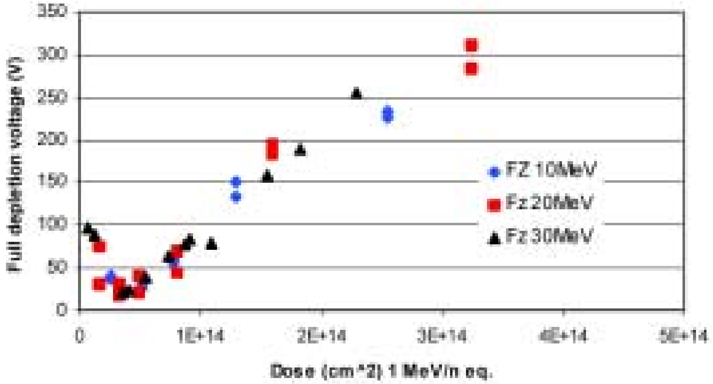
N and p : type inversion for the MCZ silicon. Improvement compared to standard FZ silicon

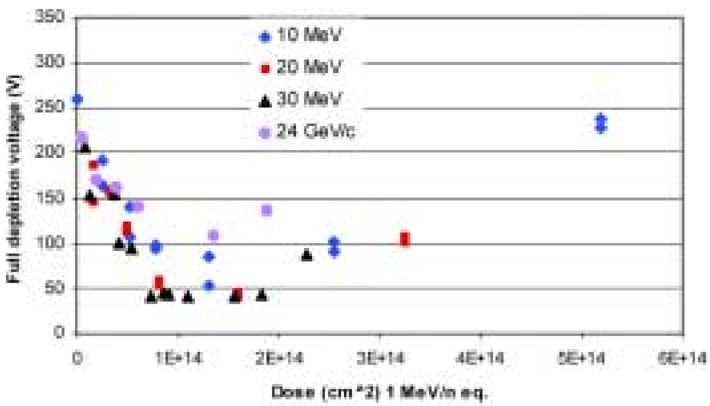


Oxygen in Silicon: RD50 activities

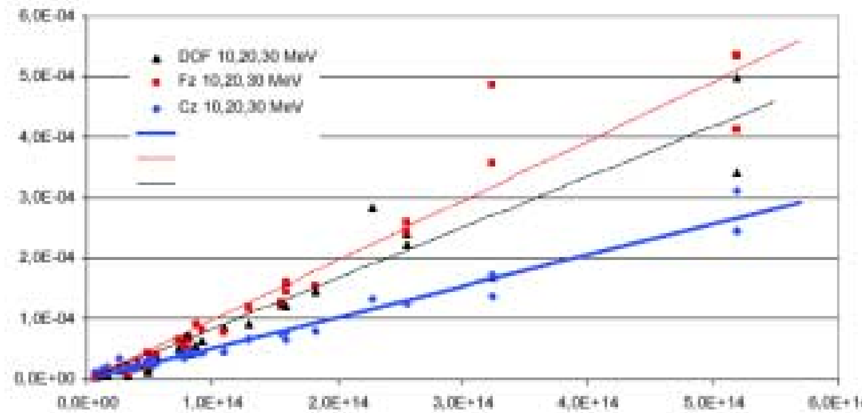
MCZ silicon, low energy p irradiation

Improvement in V_{fd}





Reduction of reverse current?

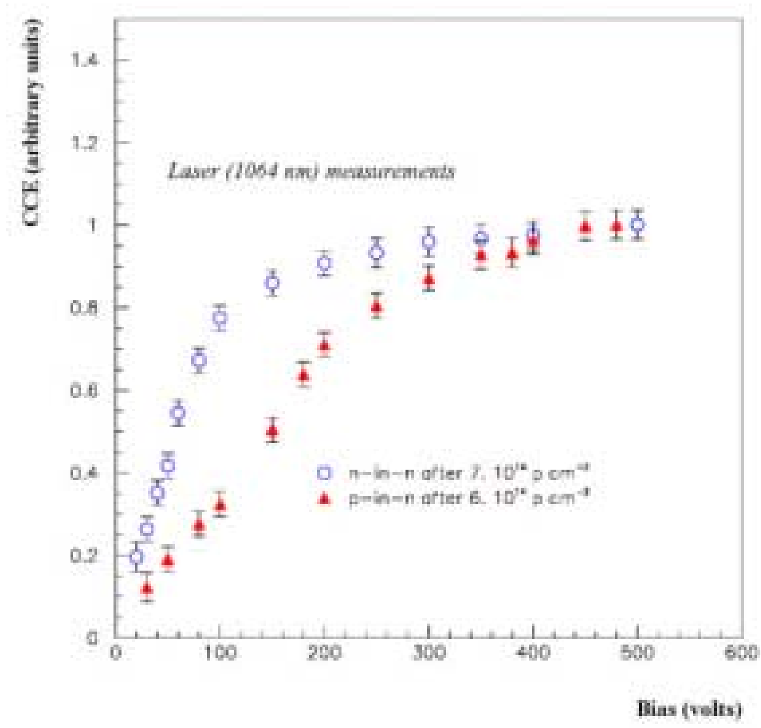


Why it is important to avoid type inversion?

Keeping the high electric field on the read out side: significant benefit in charge collection at low bias voltages with segmented detectors.

Example: comparison between a traditional p-in-n geometry (with high electric field on the backplane after type inversion) and n-in-n geometry (high electric field on the read-out side after type inversion)

n-side read-out detector after 7.10^{14} p cm^{-2}, p-side detector after 6.10^{14} p cm^{-2}.



Data from G. Casse

Avoiding type inversion in p-in-n detectors will similarly improve the Charge collection at low voltages for the traditional p-in-n diode geometry.

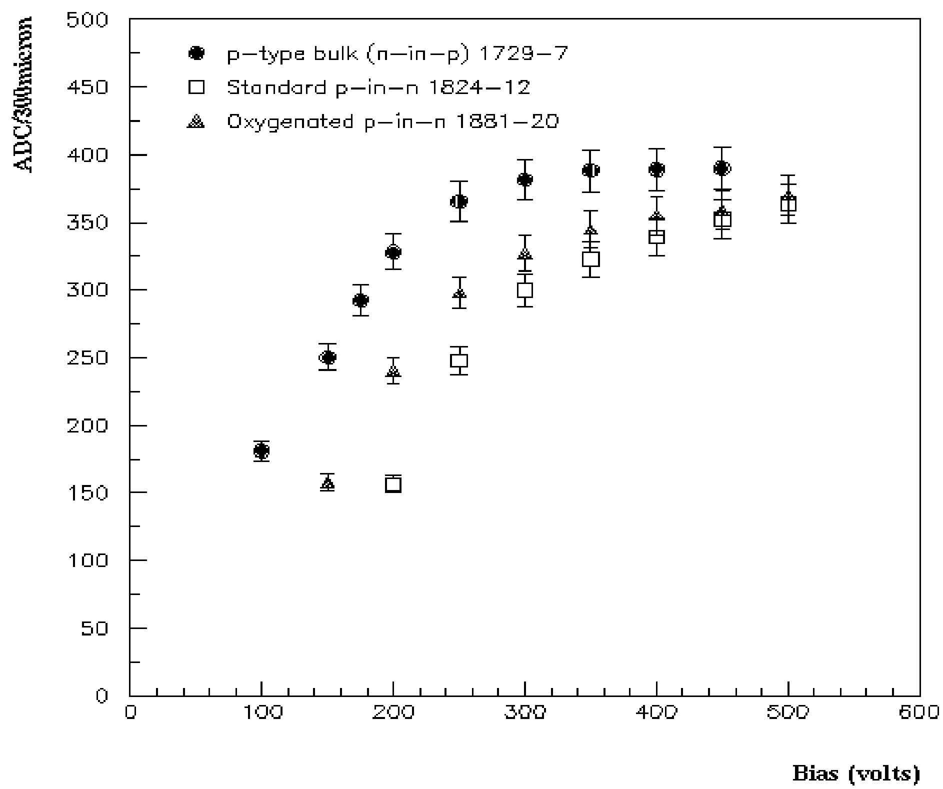
Keeping the high field on the read-out side of single side segmented devices:

1. N-in-n diode geometry (now used for the highest radiation hard performances): double sided process is mandatory
2. N-in-p diode geometry (full size segmented detector have been manufactured on p-type substrates): double sided process is not required
3. P-in-n geometry with non-inverting n-type silicon

What's the best solution?

1. Is the best proven technology, very good radiation hardness results with oxygen enriched silicon, the mandatory double sided process is more expensive. Fast signal formation (e^- read out).
2. This can be cheaper, but high resistivity p-type wafers are less common. Oxygen enrichment available. Fast signal formation (e^- read out).
3. Cheap processing. Slower signal formation (h read out).

N-in-p full size segmented (microstrip) detectors have been made and successfully tested on standard p-type substrate

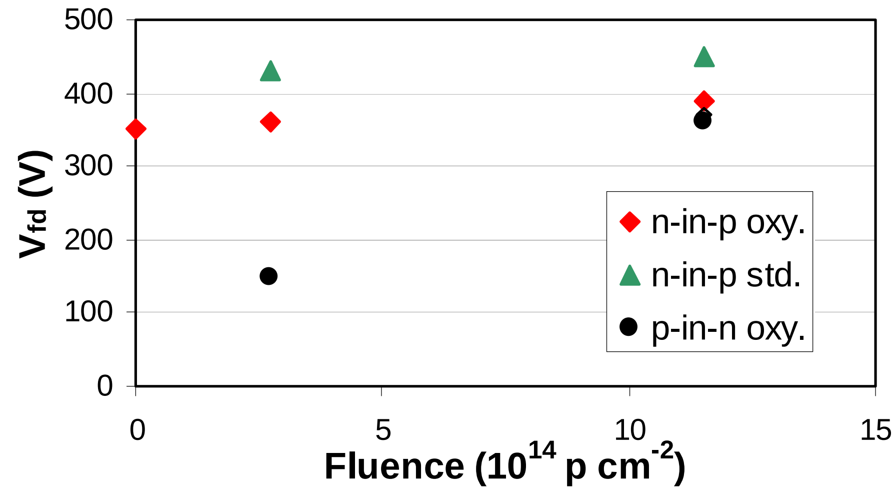


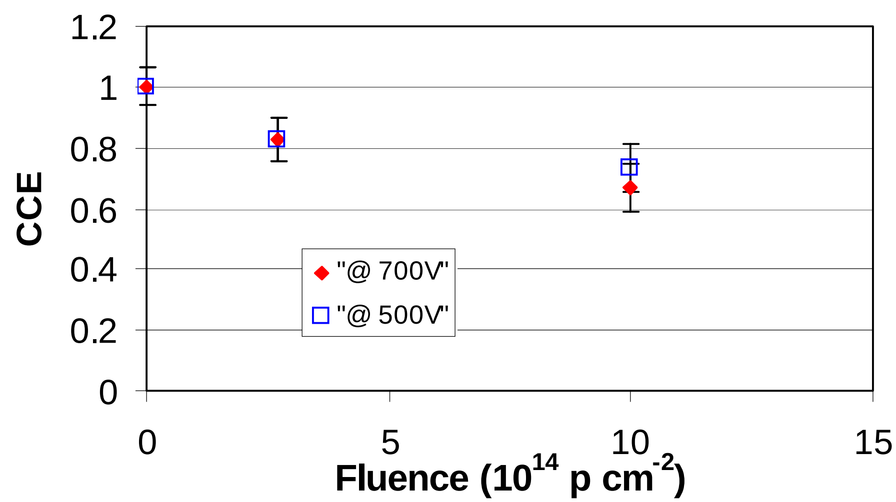
First results with oxygenated p-type silicon detectors

The oxygenated p-type detectors show less dependence of the full depletion voltage on dose.

⇒ This may be due to the lower resistivity (High V_{fd}) starting material

Further studies with initial higher resistivity of the p-type substrate are needed. Also interesting to test the high res. CZ p-type





Data from G. Casse

Defect engineering: future investigations

Interstitial oxygen kinetics is the most studied. A model is available, and efforts are performed towards the identification of the key defects (V_2O) (see ,…….). Still not able to account for all the macroscopic effects. Further studies are necessary. Possible clues for O kinetics will be given by the study of **oxygen interstitial dimer (O_{2i})** enriched silicon. **A task force is operating in RD50 to study this issue (see RD50 web pages).**

→

O_2: beneficial to rad-hardness?

VO_2 neutral (but V_2O_2: charged) vs

V_2, VO, V_2O (charged)

Creating O_2 with pre-irradiation

$V+O \rightarrow VO$, $VO+O \rightarrow VO_2$,
$I+VO_2 \rightarrow O_2$

HEP irradiation

$V+O_2 \rightarrow VO_2$, $V+VO_2 \rightarrow V_2O_2$

Is it possible to use **impurities other than oxygen** to dope the silicon crystal? Oxygen is armless during the industrial processing. A different doping must be beneficial in term of radiation hardness and usable in industrial processing lines. Indications from theory and dedicated processing lines from collaborating manufacturers are necessary to investigate different impurities.

New materials

RD50 is investigating also material alternative to silicon, namely SiC, GaN (III nitrides), CaZnTe.

SiC

Property	Diamond	4H SiC	Si
E_g [eV]	**5.5**	3.3	**1.12**
$E_{breakdown}$ [V/cm]	10^7	$4\cdot10^6$	$3\cdot10$[illegible]
μ_e [cm^2/Vs]	1800	800	1450
μ_h [cm^2/Vs]	1200	115	450
v_{sat} [cm/s]	$2.2\cdot10^7$	$2\cdot10^7$	$0.8\cdot10^7$
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}	$5\cdot10^{-7}$	$2.5\cdot10^{-3}$
Wigner En.[eV]	**43**	**25**	**13-20**

Bandgap higher than silicon: low leakage current

Signal:

Si ⇒ 89 e/µm

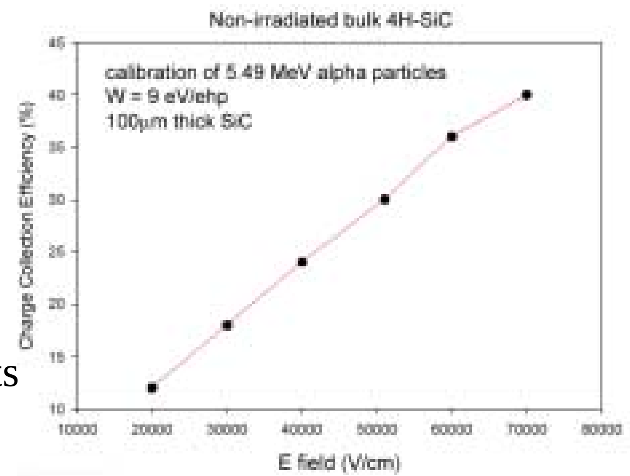
SiC ⇒ 51 e/µm

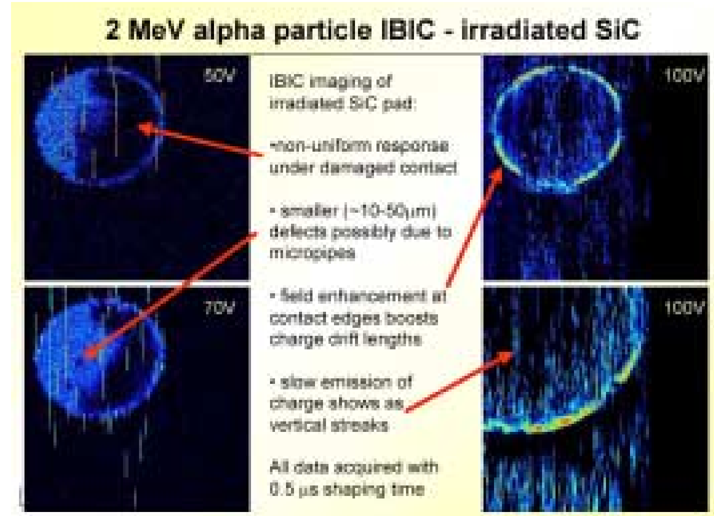
Diamond ⇒ 36 e/µm

Displacement threshold Higher than Si ⇒ better Radiation tolerance?

SiC

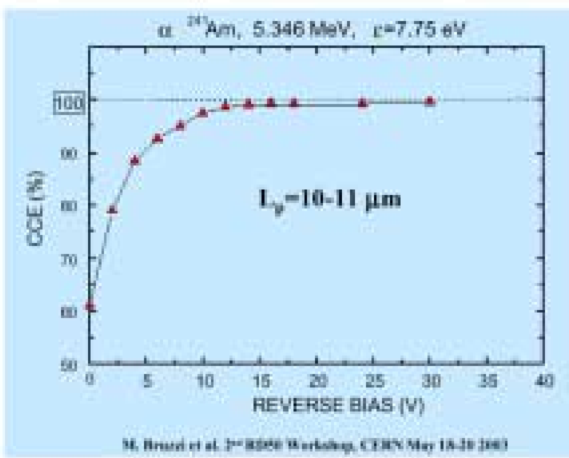
Bulk SiC has incomplete charge collection (no e transport) and suffers for polarisation effects (traps/micropipes)

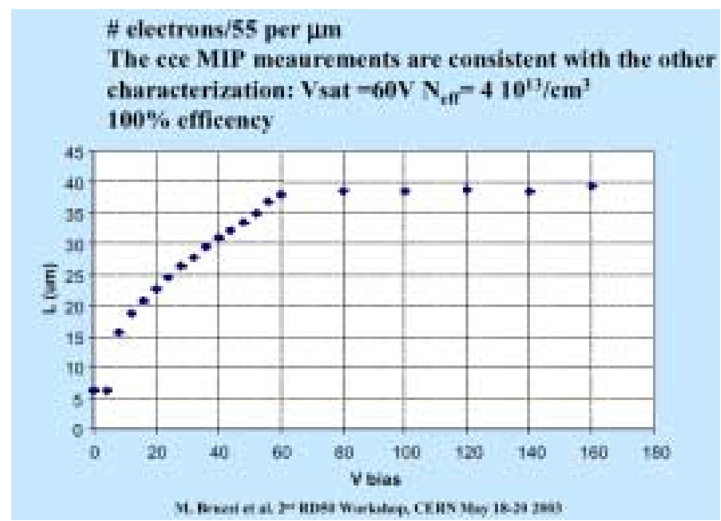




Data: P. Sellin

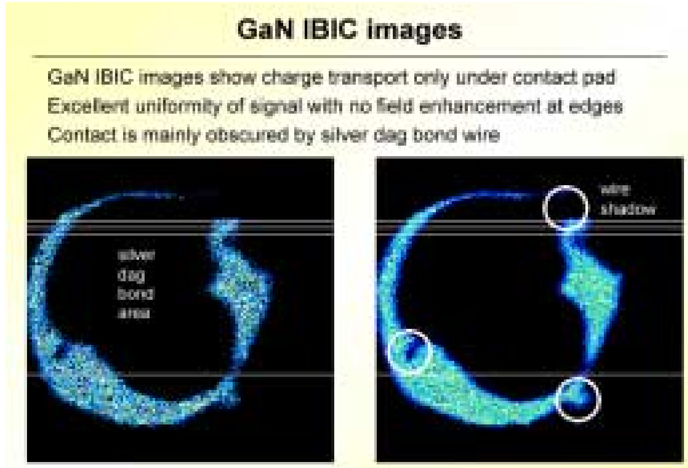
Epitaxial SiC: good homogeneity and charge collection, negligible polarisation – Thin layers (up to 50µm), very high cost: 9000 $ for 2" wafers





GaN

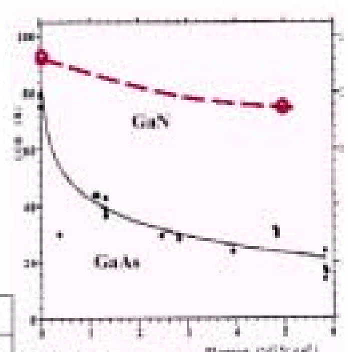
See P. Sellin and J. Vaitkus talks at 2nd RD50 workshop



Conclusions for GaN

1.

SI- GaN	Energy /fluence	c.c.e.
nonirradiated		92 %
Irradiated by X-rays	10 keV / 600 Mrad	100 %
Irradiated by neutrons	> 100 keV / $5 \cdot 10^{14}$ cm^{-2}	77 %



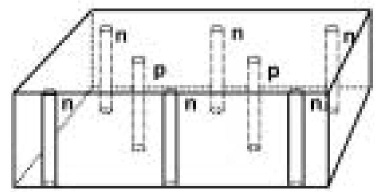
Irradiation by neutrons

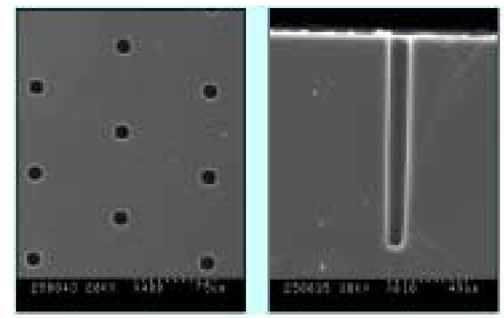
2. A main actuality: to grow a thick SI-GaN !!!

New structures

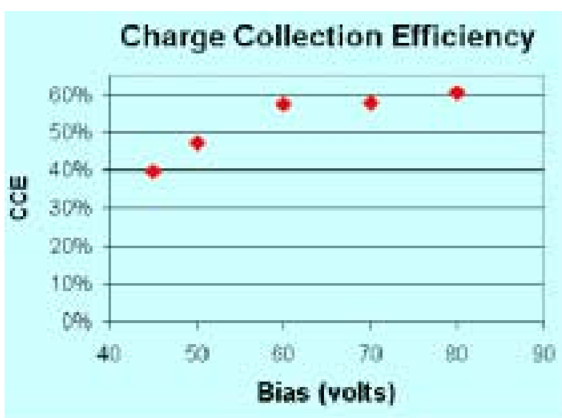
3-d devices, proposed by S. Parker.

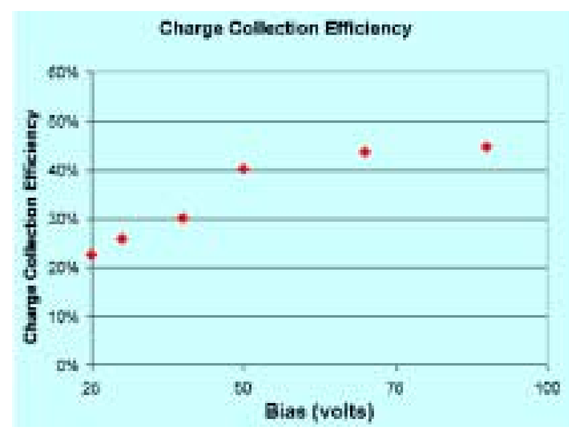
Holes processing: dry etching, Laser drilling, Photo electrochemical. Present aspect ratio (within RD50) 13:1, target > 30:1





Some result (α spectroscopy) before and after 10^{14} 300 MeV/c π cm^{-2}



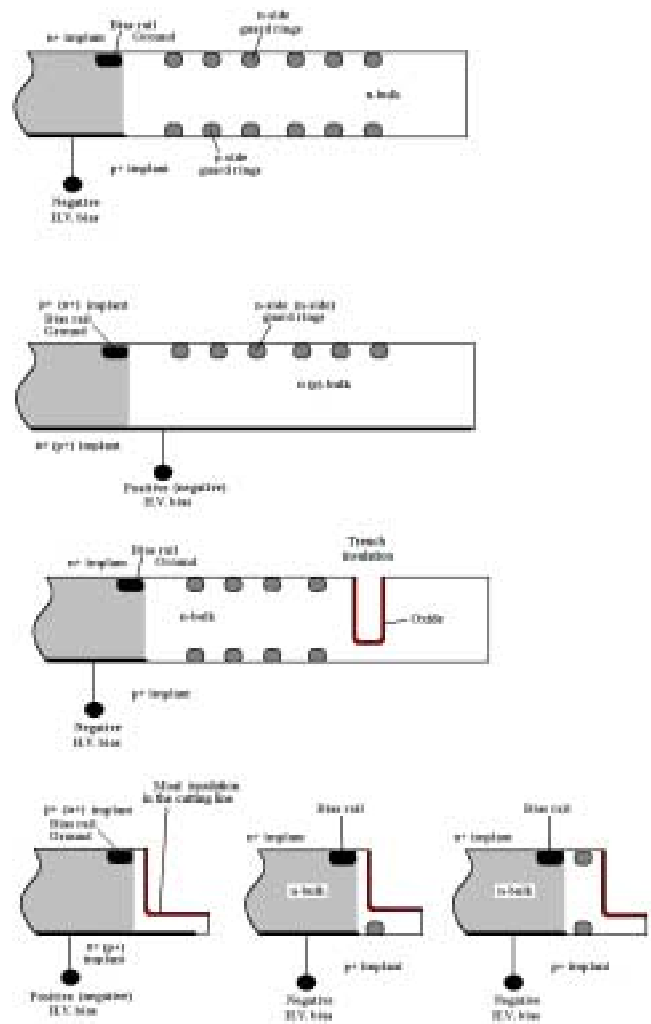


Data from P. Roy, 2nd RD50 workshop

Very promising silicon devices for speed and radiation hardness.

Trenched insulation

Proposed method for reducing the edge field:



Applications: experiments where the safe space between active area and cut edge of silicon detectors is harmful (e.g. TOTEM, ATLAS luminosity monitor, LHCb VELO…). Is it a matter of radiation hardness: yes, in the sense that high doses imply the ability of the detector to withstand high bias voltages.

No Conclusions, work in progress

ON:

•Further understanding of O in silicon (model, experimental results on MCZ and CZ, O in p-type, thermal donors, epi Si, influence of H…)

•Irradiations of samples to very high doses

•Pre-irradiation of samples: a radiation hardening technique?

•Further studies on SiC and GaN

•3-d: improvement of aspect ratio, electrodes, contacts

•thinned detectors, edge-less detectors, semi-3d

•Comparison and feedback simulation/results

•………..

More news at the 3rd RD50 workshop 3-5 November 2003 in CERN