LHCC 2002-003 / P6
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R&D Proposal

Development of Radiation Hard Semiconductor Devices for Very High Luminosity Colliders

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Deputy: **Claude Leroy (Montreal University)**

Contact at CERN: **Michael Moll (CERN EP)**

Outline

1. **Introduction**
2. **Radiation Damage of Si Detectors**
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1. Introduction

LHC $\mathsf{L} = 10^{34}\,\mathrm{cm}^{-2}\mathrm{s}^{-1}$ → $\phi(R=4\,\mathrm{cm}) \sim 3\cdot10^{15}\,\mathrm{cm}^{-2}$ (10 years)

$\phi(R=75\,\mathrm{cm}) \sim 3\cdot10^{13}\,\mathrm{cm}^{-2}$

Technology available, however serious radiation damage will result.

Possible up-grade to

$\mathsf{L} = 10^{35}\,\mathrm{cm}^{-2}\mathrm{s}^{-1}$ $\phi(R=4\,\mathrm{cm}) \sim 1.6\cdot10^{16}\,\mathrm{cm}^{-2}$ (5 years)

A focused and coordinated R&D effort is mandatory to develop reliable and cost-effective radiation hard HEP detector technologies for such radiation levels.

Dedicated radiation hardness studies also beneficial before a luminosity upgrade. Radiation hard technologies now adopted have not been completely characterized:

→ Oxygen-enriched Si in ATLAS pixels

A deep understanding of radiation damage will be fruitful also for the **linear collider** where high doses of e, γ will play a significant role.

The primary goal:

to push the radiation hardness of semiconductor detectors for HEP beyond the limits of the present technologies.

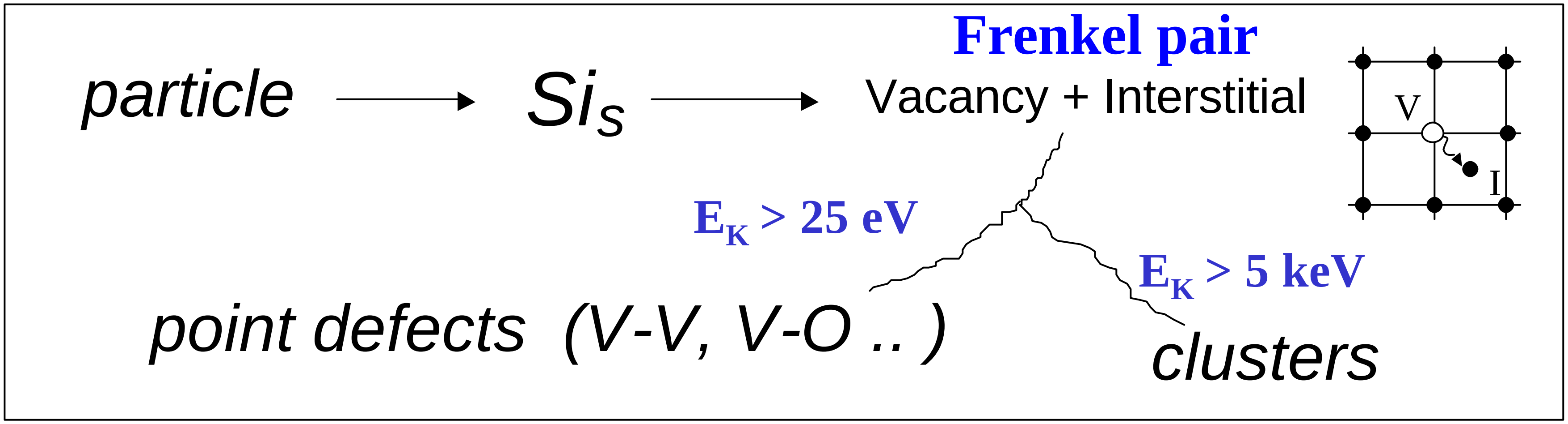
This collaboration builds up on the experience accumulated in previous R&D programs as e.g. RD20 (90-94) and RD48 (ROSE, 95-01)

Knowledge and expertise of this scientific community spans:

- *material and device processing*
- *detector systems design*
- *manufacturing*
- *applied solid state physics*
- *theoretical physics*

Close collaboration with other RDs (RD39, RD42, RD49) **to share resources and scientific results**.

2. Radiation Damage in Si detectors


particle → Si_s → **Frenkel pair** Vacancy + Interstitial

$E_K > 25$ eV point defects (V-V, V-O ..)

$E_K > 5$ keV clusters

Macroscopic Effects:

(a) Change in V_{dep} and N_{eff} . Radiation-induced deep acceptor levels → inversion of the space charge sign: "*type inversion*". After inversion, depletion starts from the n^+ contact.

(b) Increase in the leakage current: Fluence proportional due to the production of radiation-induced generation/recombination centres.

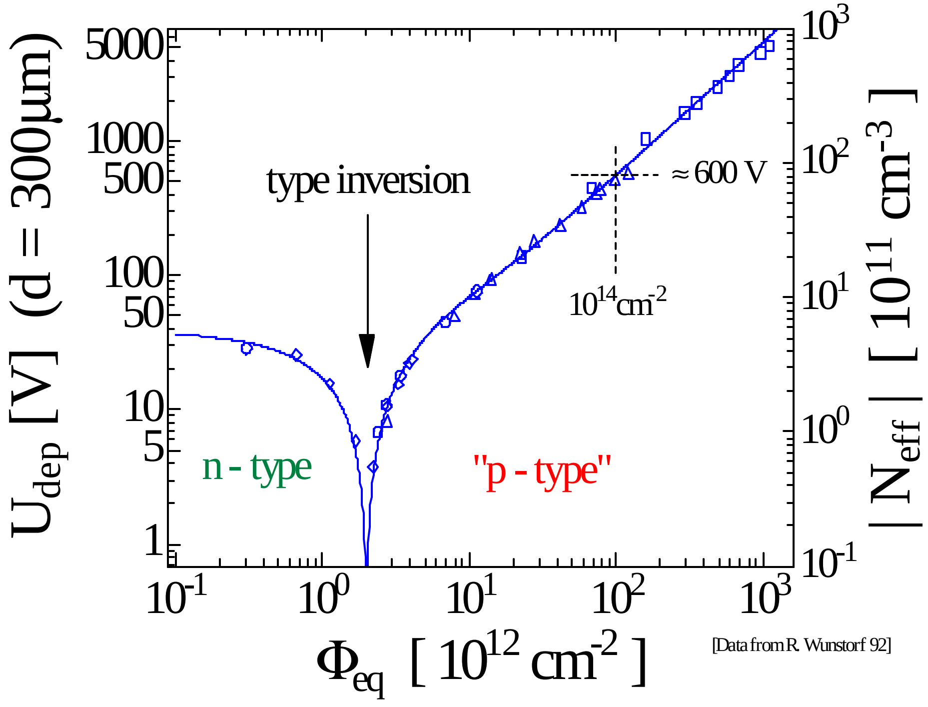
(c) Deterioration of the charge collection efficiency, due to charge carrier trapping mechanisms and partial depletion of the device.

(a) Changes in V_{dep} and N_{eff}

$$V_{dep} = \frac{q \cdot d^2}{2 \cdot e_o \cdot e_r} N_{eff}$$

$$\Delta N_{eff}(f,t,T) = \left| N_{C0}(1-e^{-c \cdot f}) - [g_a \cdot e^{-\frac{t}{t_a(T)}} + g_c + g_y \cdot (1-e^{-\frac{t}{t_y(T)}})] \cdot f \right|$$

$$N_{eff} = \left| N_c(0) \cdot e^{-c f_{eq}} - b \cdot f_{eq} \right|$$



[Data from R. Wunstorf 92]

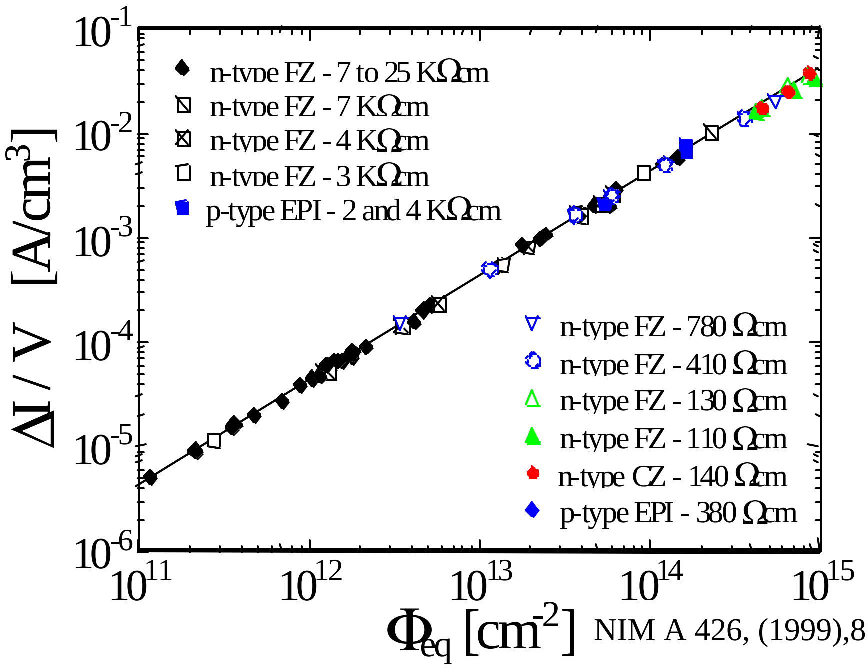
(b) Increase of leakage current

$$\frac{I_{dep}}{Volume} = a \cdot f_{eq}$$

$$a \approx 3 \cdot 10^{-17} \text{ A/cm}$$

RT : I/V ~ 30mA/cm^3 for $\phi = 10^{15}$cm^{-2}

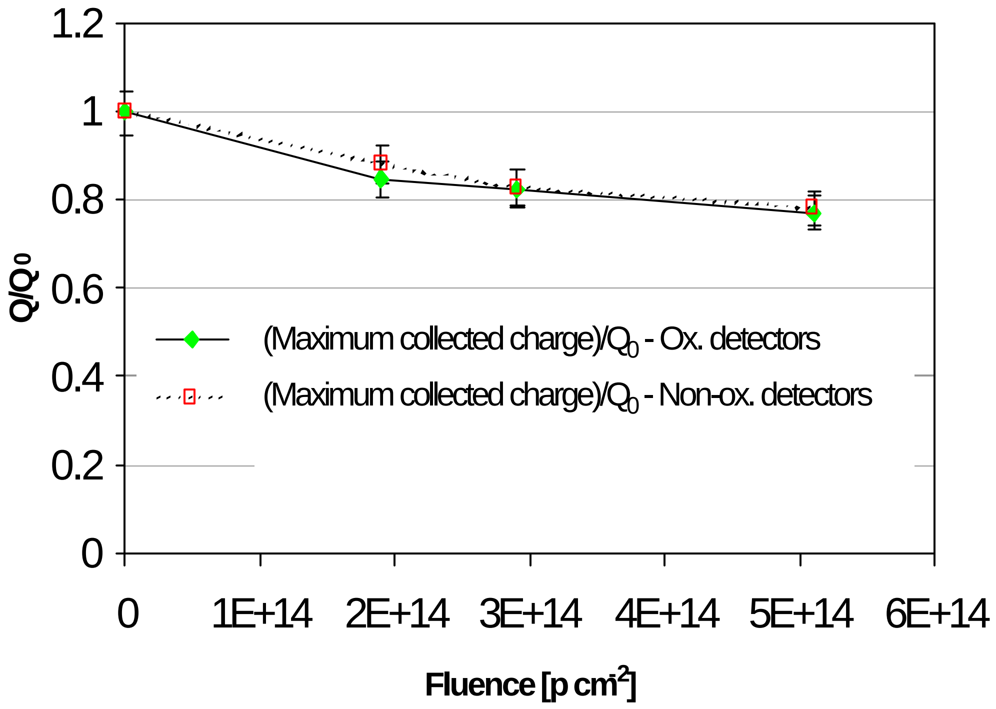
T~ –10°C : I/V reduced by a factor ~20



NIM A 426, (1999),87

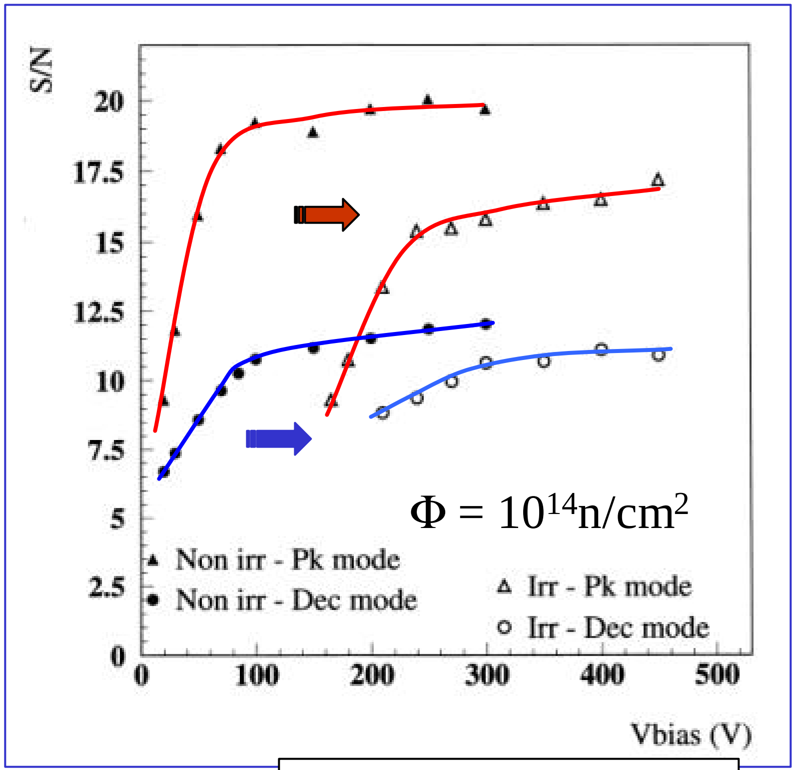
(c) Deterioration of the charge collection efficiency

Trapping mechanisms and incomplete depletion dramatically deteriorate the charge collection efficiency of the device at room temperature for fluences higher than 10^{14}cm^{-2}. At –10°C, a S/N ~ 10 (shaping time 25ns) can be achieved after fluence of ~10^{14} n/cm^2.



ATLAS microstrip + RO electronics

Data: Gianluigi Casse: 1st Workshop on Radiation hard semiconductor devices for high luminosity colliders; CERN; 28-30 November 2002



CMS microstrip + RO electronics

NIM A 476, (2002), 734

3. 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 the recently discussed luminosity upgrade of the LHC to 10^{35} cm^{-2}s^{-1}.

- **Define optimal materials and device structures to ensure best radiation tolerance.**
  - Achieve a deep understanding of radiation damage processes
  - Test and compare simple test structures and segmented devices under realistic operational conditions

- **Develop new low-cost radiation hard detector technologies to instrument the intermediate tracker region (R ~ 20 - 60cm).**

- **Support and collaborate with other HEP detector related research activities on radiation damage.**

Material Engineering: modification of detector bulk material

Defect Engineering of Si → *Oxygen, Oxygen dimers ...*

New Materials → *SiC, ..*

Device Engineering: improvement of present planar detectors

→ *3D detectors, thin detectors*

Change in the operational conditions

→ *Low T (non-cryogenic), forward bias*

Further key tasks:

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

Defect Engineering of Silicon

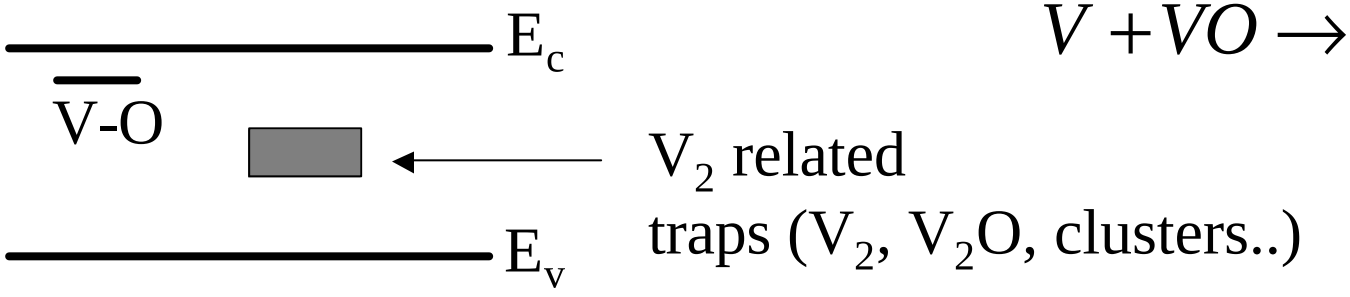
Oxygen is intentionally incorporated into Si to getter radiation-induced vacancies, so preventing the formation of V_2 related deep acceptor levels close to midgap

Competing processes for V →

$$V + O \rightarrow VO$$

$$V + V \rightarrow V_2$$

$$V + VO \rightarrow V_2O$$



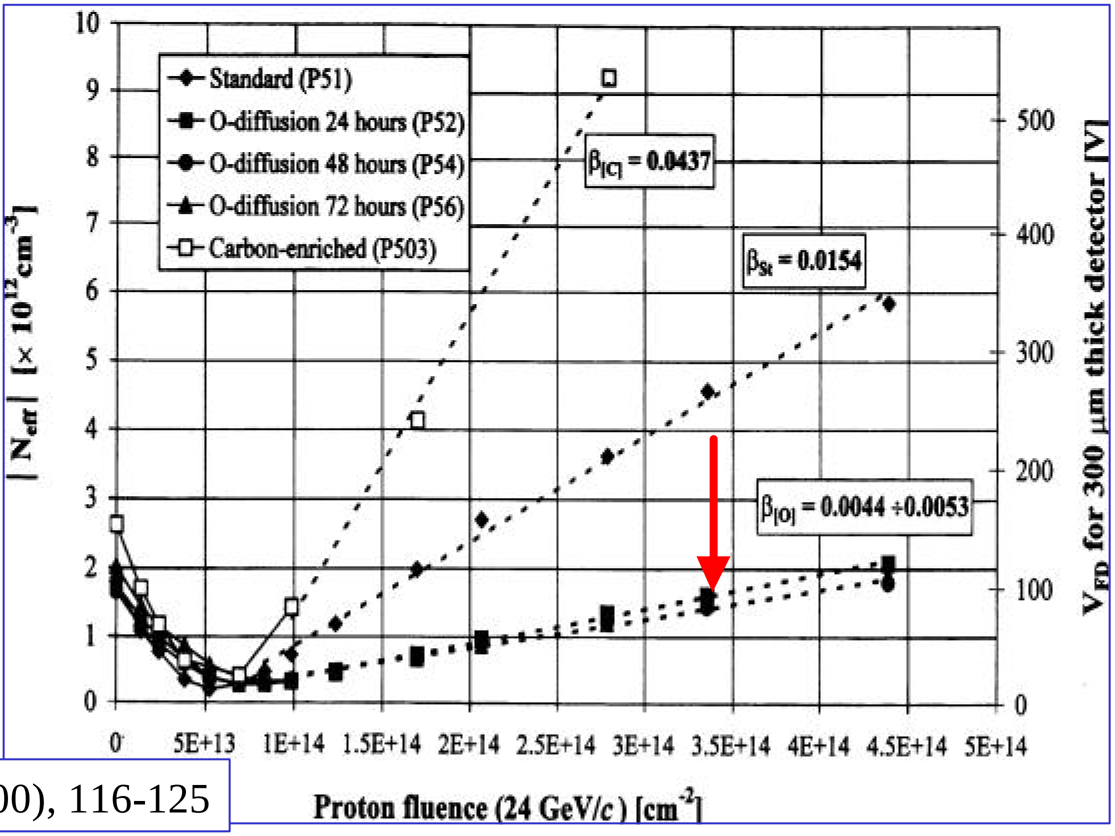
<u>DOFZ</u> : Diffusion Oxygenated Float Zone Si
$[O_i]$ up to $5 \cdot 10^{17}$ cm^{-3}
developed in the framework of RD48

DOFZ Si is significantly radiation harder than standard Si for g, p, p irradiations
Almost no effect for neutron irradiations

$$N_{eff} = \left| N_c(0) \cdot e^{-cf} - b \cdot f \right|$$

$$\beta_{\text{standard Si}} \sim 3\ \beta_{\text{DOFZ}}$$

Reverse annealing significantly reduced



RD48, NIM A 447 (2000), 116-125

ATLAS-Pixel collaboration has now adopted DOFZ Si
CMS-Pixel is considering this option

DOFZ Si : Open Questions

The microscopic defects responsible of the oxygen-effect have not been clearly identified. Direct correlation found between the deep level $E_t = E_c - 0.54eV$ (probablyV_2O) and the macroscopic changes of the detector properties after γ irradiation. **Systematic studies are needed to understand the microscopic mechanisms occurring for proton and neutron irradiation.**

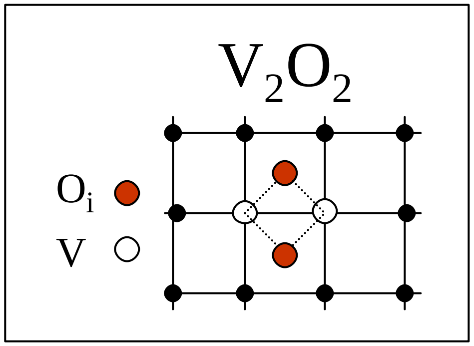
No clear quantitative correlation between oxygen content and radiation hardness, probably due to the impact of individual processes of different manufacturers.

Optimization of the DOFZ process. To determine the optimal process with respect to radiation hardness and cost effectiveness.

Detailed characterization of oxygenated segmented detectors. To compare and quantify the radiation hardness properties of single pad, mini- and full segmented devices made with oxygenated Si.

High resistivity Czochralski Silicon. New developments in Si manufacturing make high resistivity CZ possible. CZ cheaper than DOFZ, same or better radiation tolerance.

Oxygen Dimers in Silicon



Oxygen as O_{2i} (Dimers)

$$V + O \rightarrow VO; \qquad V + VO \rightarrow V_2O$$

$$V + O_2 \rightarrow VO_2; \qquad V + VO_2 \rightarrow \boxed{V_2O_2} \searrow \textit{neutral ?}$$

To create oxygen dimers in the Si bulk: ⟹ Co^{60} γ-irradiation at 350ºC.

First measurements after proton irradiation have shown suppression of V-O and V_2.

[S. Watts et al., presented at Vertex 2001]

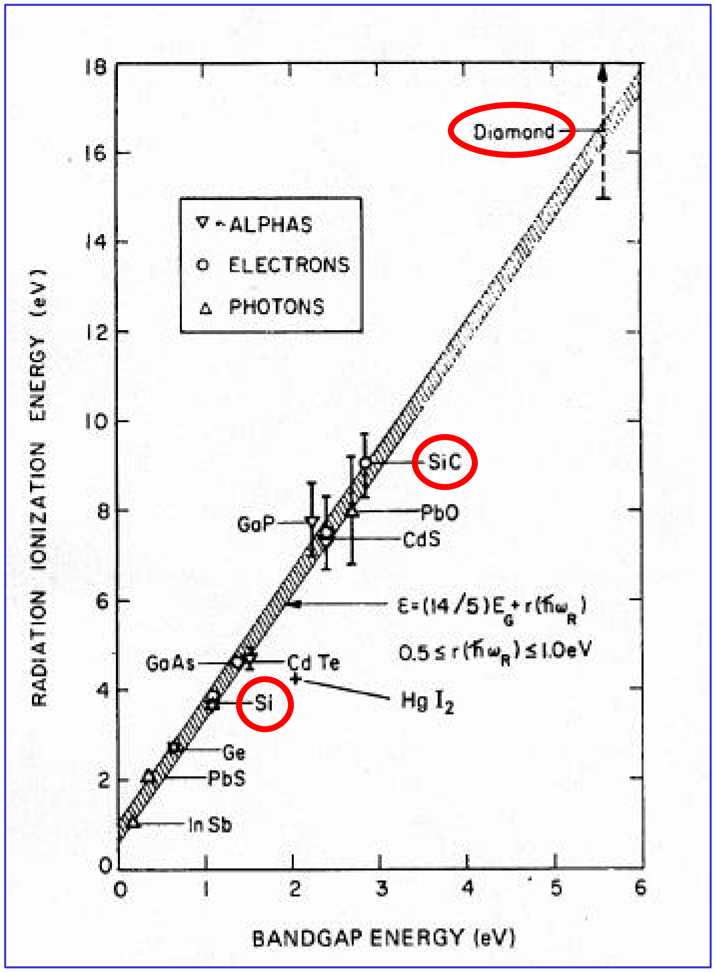
Experimental tests planned to prove the radiation hardness of Oxygen Dimer enriched Si:

- **Inversion of the space charge sign and reverse annealing**
- **Charge collection efficiency**
- **Optimization of dose-rate and exposure time during material processing**

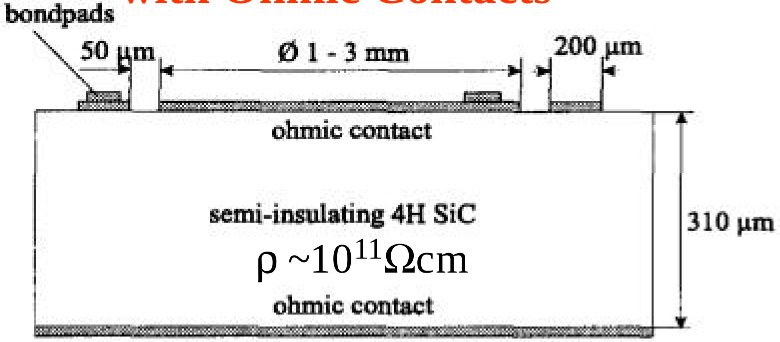
New Materials: Epitaxial SiC

SiC is a most promising material for radiation detection. The 3.3eV gap provides very low leakage currents at room temperature and a mip signal of 5100e per 100μm. Epitaxial SiC Schottky barriers have been successfully tested as alpha detectors and showed a 100% CCE after 24GeV/c proton irradiation up to 10^{14} cm^{-2}.

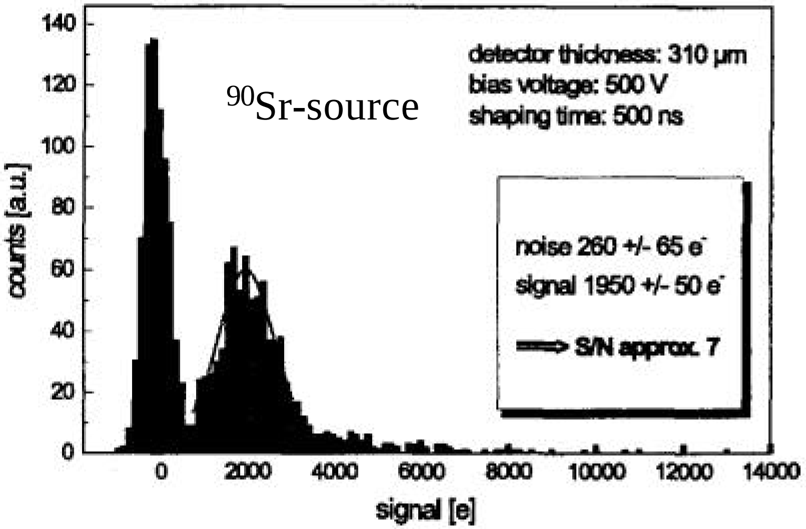
Property	Diamond	4H SiC	Si
E_g [eV]	5.5	3.3	1.12
$E_{breakdown}$ [V/cm]	10^7	$4\cdot10^6$	$3\cdot10^5$
μ_e [cm^2/Vs]	1800	800	1450
μ_h [cm^2/Vs]	1200	115	450
v_{sat} [cm/s]	$2.2\cdot10^7$	$2\cdot10^7$	$0.8\cdot10^7$
Z	6	14/6	14
ε_r	5.7	9.7	11.9
e-h energy [eV]	13	8.4	3.6
τ_h [s]	10^{-9}	$5\cdot10^{-7}$	$2.5\cdot10^{-3}$
Wigner En. [eV]	43	25	13-20



Semi-insulating 4H-SiC with Ohmic Contacts

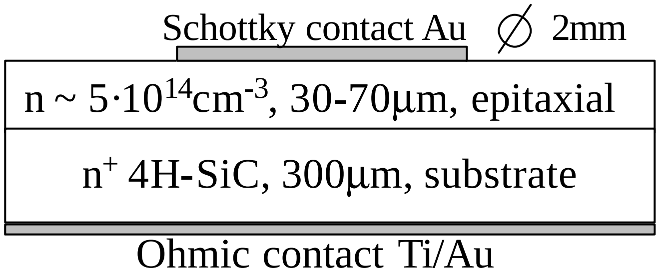


Drawbacks: polarization effects due to deep traps/micropipes deteriorate the CCE



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

Schottky Barrier Epitaxial SiC



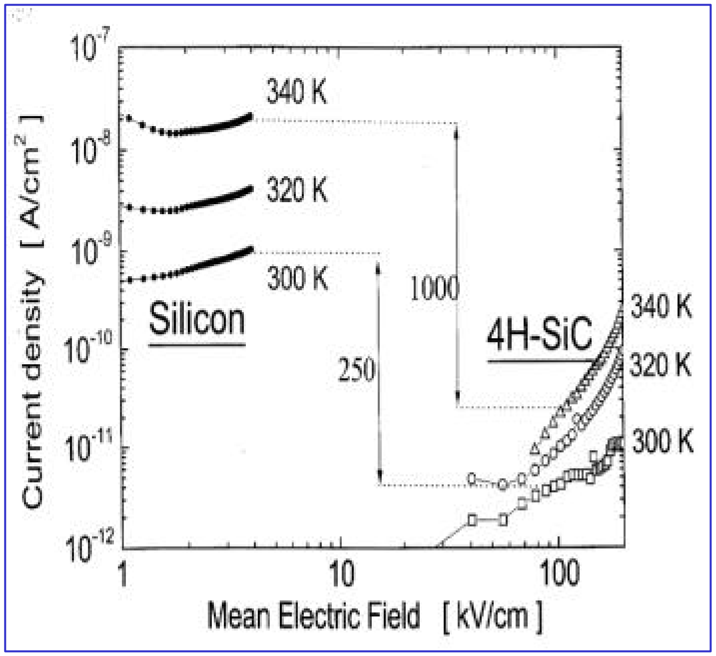
Schottky contact Au ∅ 2mm

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

n^{+} 4H-SiC, 300µm, substrate

Ohmic contact Ti/Au

Low defect density in the epitaxial layer → negligible polarization effects



G. Bertuccio et al., presented at SiCNet II, Parma, March 2002

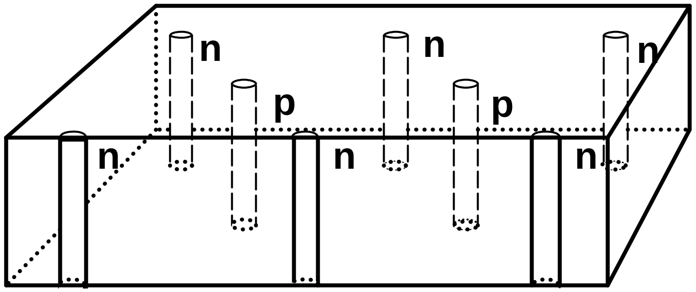
Device Engineering: 3D detectors

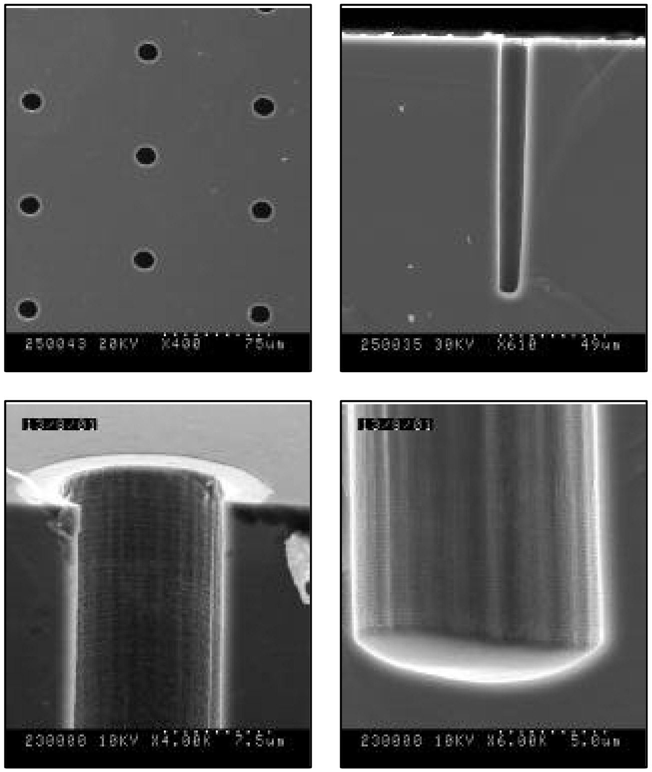
p^+ and n^+ polysilicon electrodes in narrow columns along the detector thickness.

Depletion depth develops laterally - Typical electrode distances: 50-100 μm.

Very fast collection times, low full depletion voltages (~10V), full charge collection over the 300μm detector active thickness

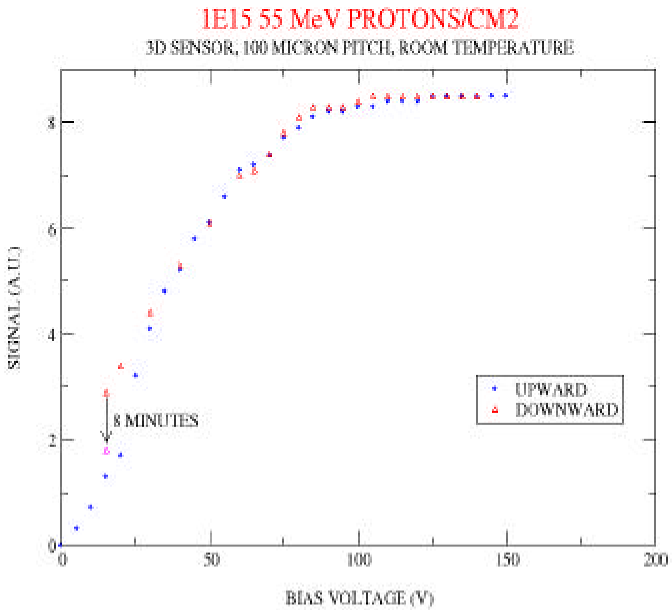
Size up to ~1cm²





R. Bates, 1st Workshop on Radiation hard semiconductor devices for high luminosity colliders, CERN, November 2001.

First radiation hardness tests after 10^{15} cm^{-2} 55MeV protons (measured with IR LED)



Sherwood Parker, IEEE TNS 48 (2001), 1629.

Device Engineering: thin detectors

The basic advantage of thin devices relates to the optimised use of the effective drift length of the carriers while having a low full depletion voltage.

Benefits:

- better tracking precision and momentum resolution
- low operating voltage
- more precise timing
- improved radiation tolerance: 50μm thick, 50Ωcm Si detector (V_{dep} = 200V) undergoes type inversion after 10^{15} cm^{-2}.

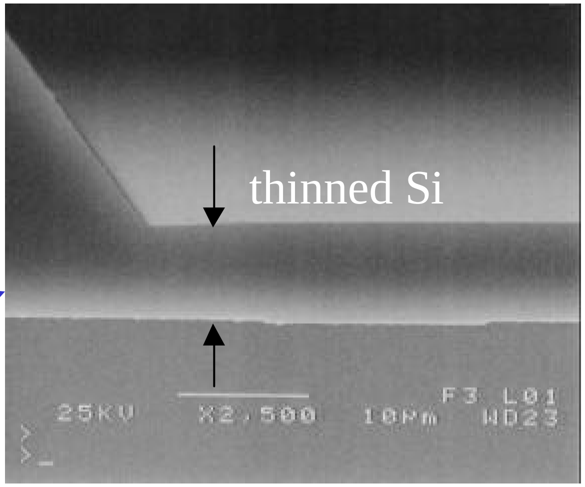
Drawbacks:

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

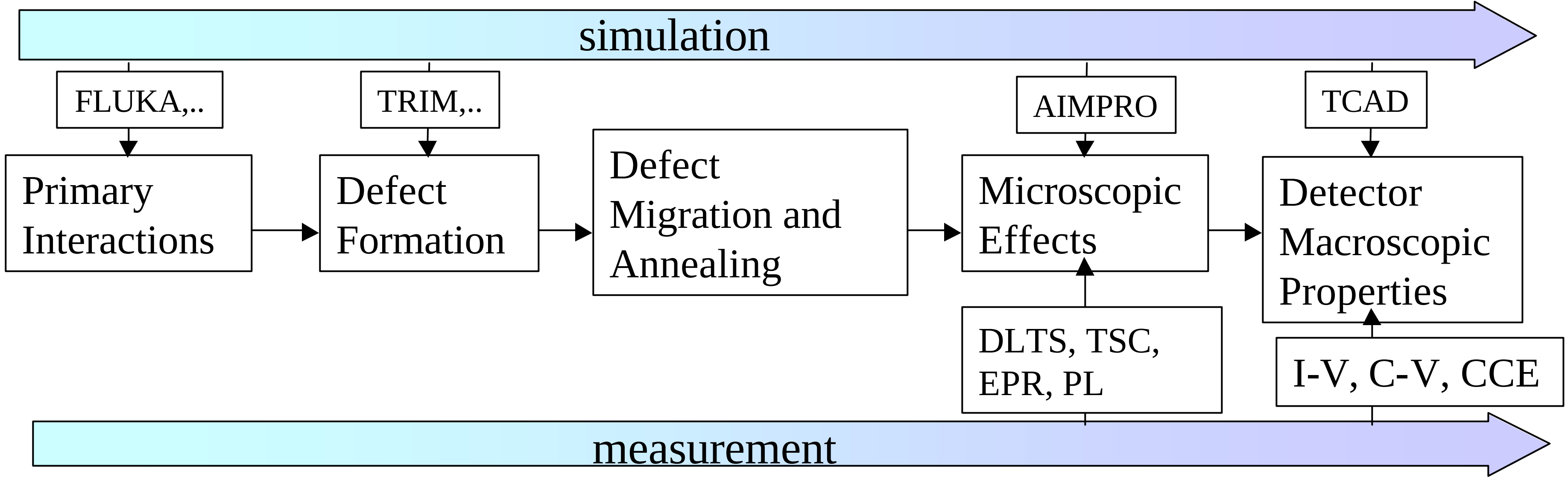
Technical Approach:

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

Thinning Si by chemical attack (IRST – Trento)



Generic studies



simulation

FLUKA,..

TRIM,..

AIMPRO

TCAD

Primary Interactions

Defect Formation

Defect Migration and Annealing

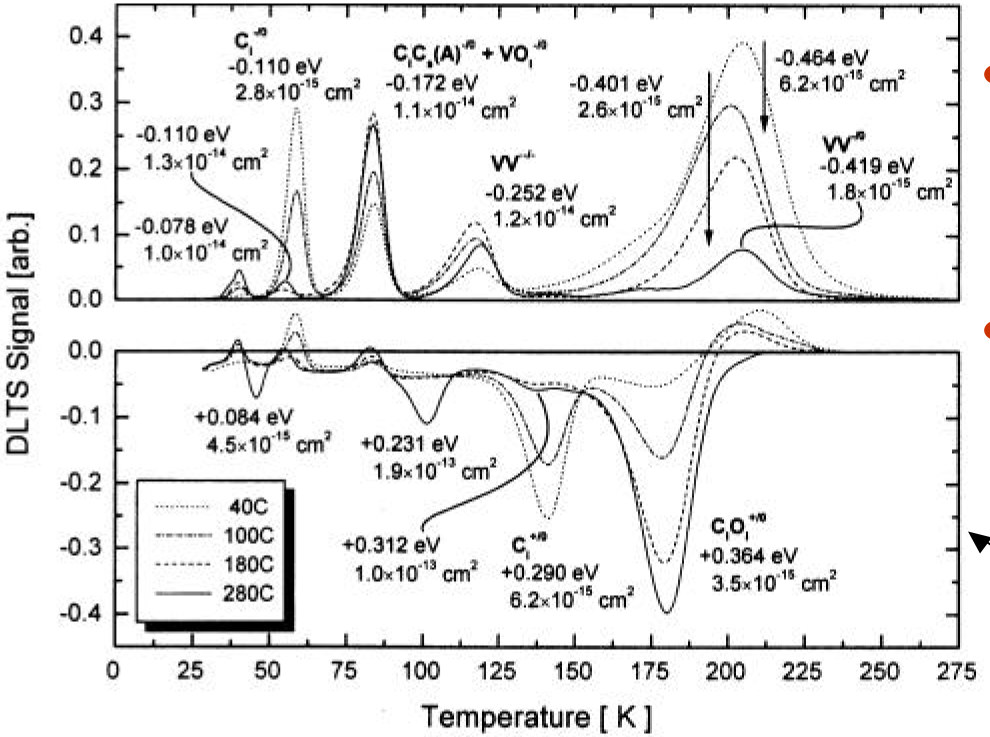
Microscopic Effects

Detector Macroscopic Properties

DLTS, TSC, EPR, PL

I-V, C-V, CCE

measurement



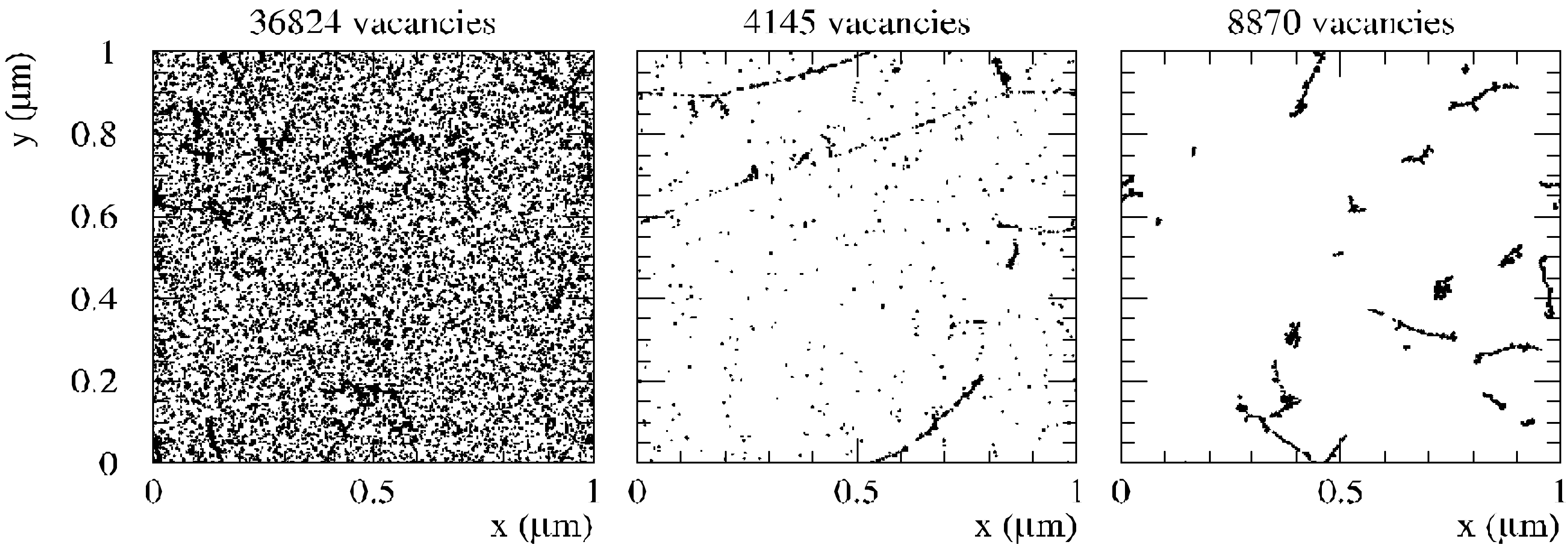
- **Characterisation of microscopic defects in close link with Solid State Physics experts.**

- **Investigations on irradiated detectors** **Comparison between simple test structures, mini and full size segmented devices**

DLTS - ϕ =3.5x10^{11} cm^{-2} , 5.3MeV n
RD48, NIM A 466 (2001) 308

- **Modeling and simulation of defect formation:** indispensable for understanding radiation damage process and for development of new defect-engineered materials.

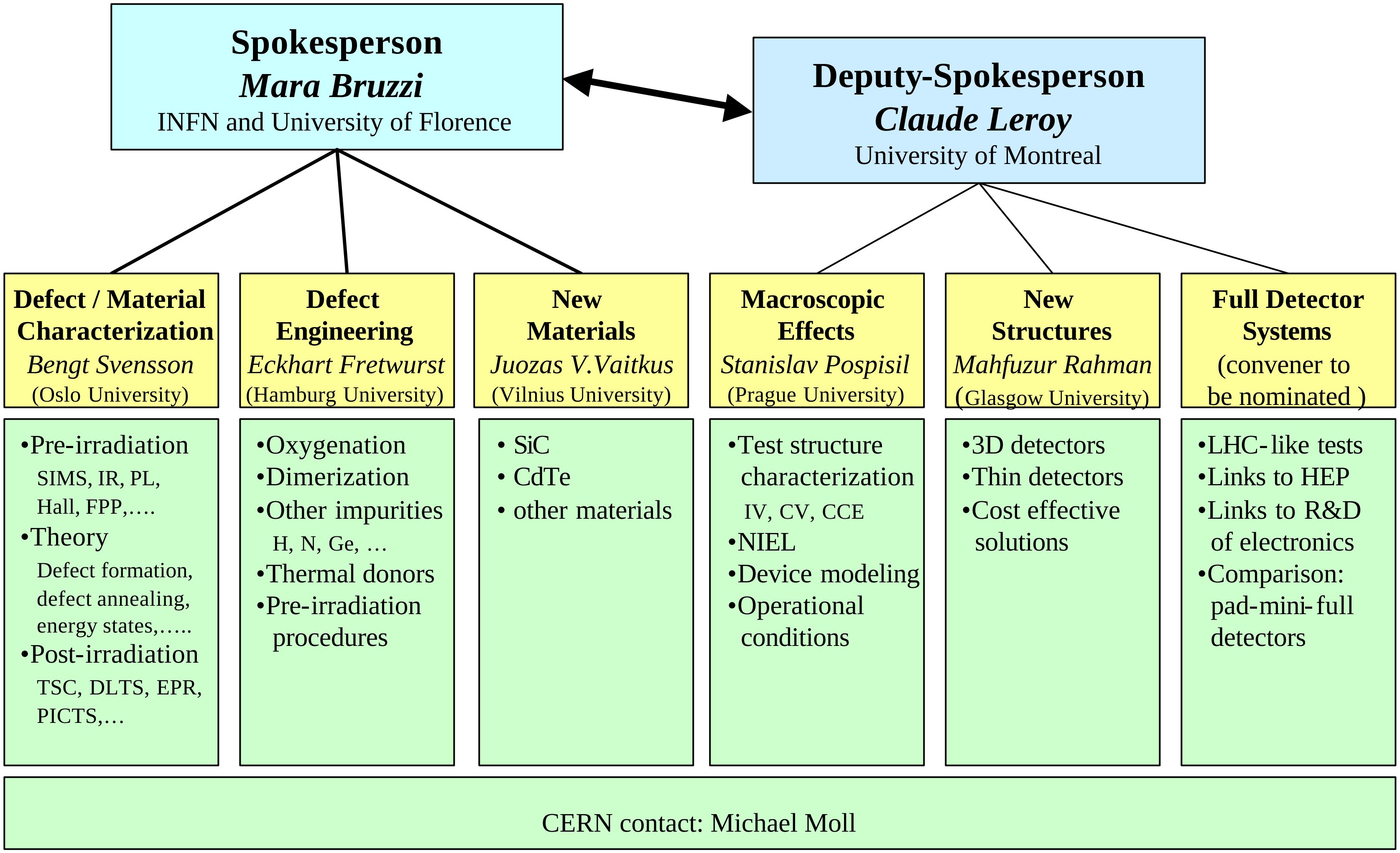
Mika Huhtinen -
ROSE/Techn.Note/2001-02



10 MeV protons **24 GeV/c protons** **1 MeV neutrons**

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

4. Scientific Organization



Spokesperson
Mara Bruzzi
INFN and University of Florence

Deputy-Spokesperson
Claude Leroy
University of Montreal

Defect / Material Characterization
Bengt Svensson
(Oslo University)

- Pre-irradiation
  SIMS, IR, PL, Hall, FPP,….
- Theory
  Defect formation, defect annealing, energy states,…..
- Post-irradiation
  TSC, DLTS, EPR, PICTS,…

Defect Engineering
Eckhart Fretwurst
(Hamburg University)

- Oxygenation
- Dimerization
- Other impurities
  H, N, Ge, …
- Thermal donors
- Pre-irradiation procedures

New Materials
Juozas V.Vaitkus
(Vilnius University)

- SiC
- CdTe
- other materials

Macroscopic Effects
Stanislav Pospisil
(Prague University)

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

New Structures
Mahfuzur Rahman
(Glasgow University)

- 3D detectors
- Thin detectors
- Cost effective solutions

Full Detector Systems
(convener to be nominated)

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

CERN contact: Michael Moll

5. Links with Industry

Manufacturers directly involved in the project:

- CiS Institut fur Mikrosensorik, Erfurt, Germany
- SINTEF, Oslo, Norway
- Centro National Microelectronica, Barcelona, Spain
- ITC-IRST , Microsystems Division, Trento, Italy
- ITME, Warsaw, Poland
- Institute of Microelectronics and Microsystems, CNR, Italy

Wafer Processing:	DOFZ Si , epitaxial Si, CZ high res., SiC
Device processing:	single pad, baby, microstrip and pixel detectors, micromachining processes

6. Irradiation Facilities

BNL	Co^{60} g-source, 10^{3}-10^{5} rad/hour
Brunel	Co^{60} g-source
CERN	23 GeV protons: 1-3x10^{13}p/cm^{2}/h; neutron field 3-10x10^{12}n/cm^{2}/hour
Demokritos	reactor, gamma, protons
Helsinki (HIP)	15 MeV protons
Karlsruhe	25 MeV protons
Kurchatov	35 MeV p, n, ions
Kiev	reactor, 14MeVn, 7MeV p, 50-200MeV p
Louvain	ion, p, neutrons (<20MeV>) 2x10^{14}n/cm^{2}/hour
Ljubljana	TRIGA reactor; fast neutron flux: 4x10^{12} to 7x10^{15} n/cm^{2}/ hour
Lund	e 3-7 MeV, gamma
Montreal	12 MeV protons
Oslo	1-10 MeV , charged ions, pA-mA
Padova	up to 28MeV p, heavy ions
Prague	p 0.3-2 MeV, n 14 MeV
PSI	p^{+}, 10^{14} /cm^{2}/day
St.Petersburg	protons
Surrey	gamma
Trieste	e, 1 GeV

7. Work plan for the first year

1. Design and fabrication of common test structure from oxygenated and standard Si: (single pad, baby microstrips, gated biased diodes for surface studies, macro pixels)

- Determination of a common design and process
- Get Si wafers (p- and n-type) from different producers with different resistivity and orientation (<100> and <111>)
- Perform the oxygenation process at ITME, IRST, CiS, CNM, SINTEF, Helsinki
- Material characterization (SIMS, IR, resistivity profile) of the oxygenated wafers (ITME)
- Processing at ITME, IRST, CiS, CNM, SINTEF, Helsinki with common test structures, oxygen. and standard
- Material characterization (SIMS, IR, resistivity profile) of few processed structures

2. Tests on New structures

- First tests on micromachining technology and epitaxial Si-layers for thin detectors
- First charge collection measurements with mips on epitaxial SiC detectors (existing devices)
- First tests of irradiated 3D detectors with readout electronics

3. Irradiation of existing (ROSE, CMS, ATLAS,..) test structures beyond 5×10^{14} cm^{-2}

- Agreement on post-irradiation procedures and samples handling

4. First tests on heavily irradiated single pad and full detectors structures

- Macroscopic studies on irradiated standard and DOFZ Si devices and on oxygen-dimer enriched silicon diodes

5. Defect Characterisation

- Cross calibration of defect characterisation systems by means of twin irradiated single pad diodes
- Defect characterisation in oxygen-dimer enriched Si
- Characterisation of shallow levels in oxygen enriched Si

8. Milestones for the first year

1. **Establish the operational limits of single pad and full detectors beyond $5\times10^{14}\,\mathrm{cm}^{-2}$.**
2. **Common test structures: Ready for distribution to the collaboration**
3. **Improved understanding of the defect distribution in irradiated oxygen enriched Si (shallow + deep)**
4. **Establish the radiation hardness potential of oxygen-dimer enriched Si**
5. **First set of thinned detectors produced**

Second and third year :

As given in the proposal and more detailed in the first status report