LHCC – meeting, CERN, 26.11.2003

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

Status Report 2002/2003

LHCC-2003-058/LHCC-RD-002

Mara Bruzzi

INFN - University of Florence, Italy

On behalf of the CERN RD50 Collaboration

Complete author list at http://www.cern.ch/rd50

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

280 Members from 55 Institutes

Main Objective

Development of ultra-radiation hard semiconductor detectors, able to withstand fast hadron fluences and doses as expected for luminosity upgrade of the LHC to 10^{35} cm^{-2}s^{-1}.

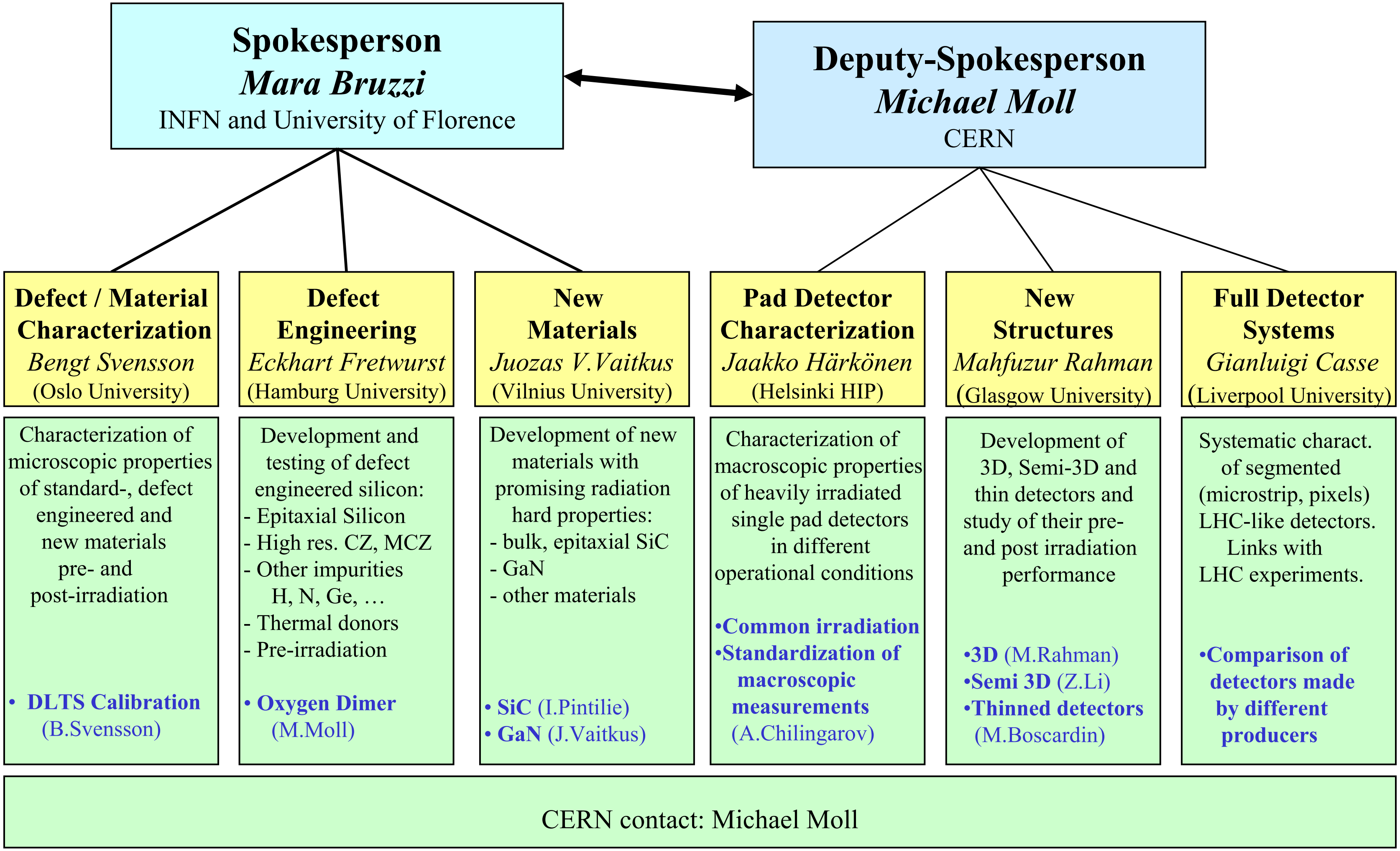
47 European and Asian institutes (34 west, 11 east)
Belgium (Louvain), Czech Republic (Prague (2x)), Finland (Helsinki (2x), Oulu), Germany (Berlin, Dortmund, Erfurt, Halle, Hamburg, Karlsruhe), Greece (Athens), Italy (Bari, Bologna, Florence, Milano, Modena, Padova, Perugia, Pisa, Trento, Trieste, Turin), 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)

7 North-American institutes
Canada (Montreal), USA (Fermilab, Purdue University, Rutgers University, Syracuse University, BNL, University of New Mexico)

1 Middle East institute
Israel (Tel Aviv)

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

Scientific Organization of RD50



Spokesperson
Mara Bruzzi
INFN and University of Florence

Deputy-Spokesperson
Michael Moll
CERN

Defect / Material Characterization
Bengt Svensson
(Oslo University)

Characterization of microscopic properties of standard-, defect engineered and new materials pre- and post-irradiation

- **DLTS Calibration** (B.Svensson)

Defect Engineering
Eckhart Fretwurst
(Hamburg University)

Development and testing of defect engineered silicon:
- Epitaxial Silicon
- High res. CZ, MCZ
- Other impurities H, N, Ge, …
- Thermal donors
- Pre-irradiation

- **Oxygen Dimer** (M.Moll)

New Materials
Juozas V.Vaitkus
(Vilnius University)

Development of new materials with promising radiation hard properties:
- bulk, epitaxial SiC
- GaN
- other materials

- **SiC** (I.Pintilie)
- **GaN** (J.Vaitkus)

Pad Detector Characterization
Jaakko Härkönen
(Helsinki HIP)

Characterization of macroscopic properties of heavily irradiated single pad detectors in different operational conditions

- **Common irradiation**
- **Standardization of macroscopic measurements** (A.Chilingarov)

New Structures
Mahfuzur Rahman
(Glasgow University)

Development of 3D, Semi-3D and thin detectors and study of their pre- and post irradiation performance

- **3D** (M.Rahman)
- **Semi 3D** (Z.Li)
- **Thinned detectors** (M.Boscardin)

Full Detector Systems
Gianluigi Casse
(Liverpool University)

Systematic charact. of segmented (microstrip, pixels) LHC-like detectors. Links with LHC experiments.

- **Comparison of detectors made by different producers**

CERN contact: Michael Moll

Characterization of microscopic defects

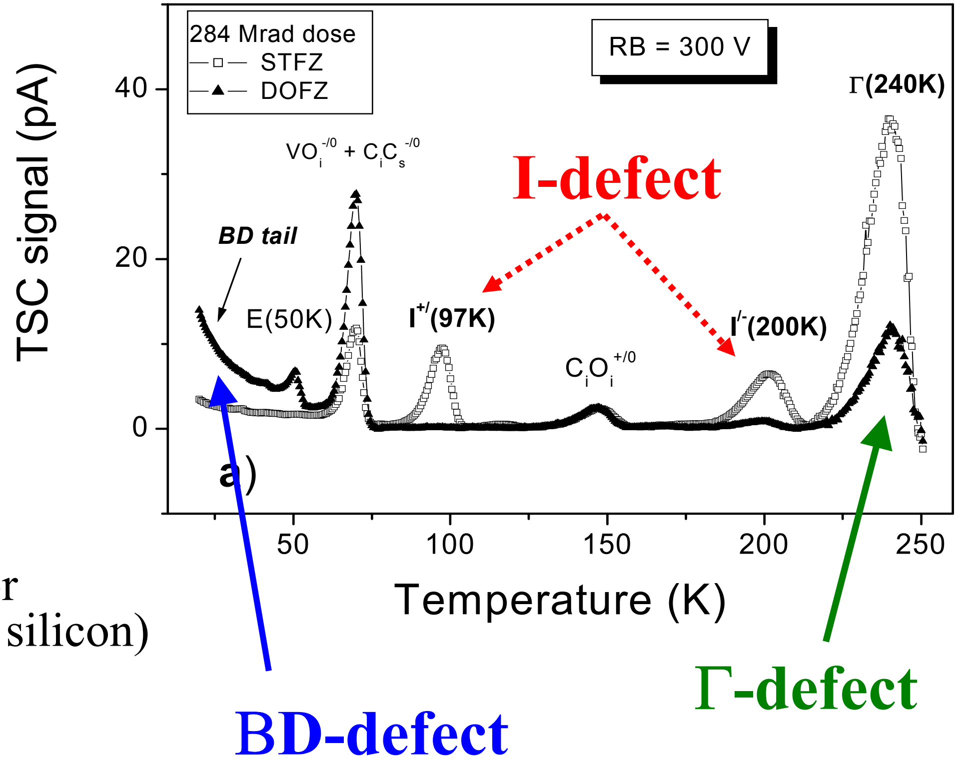
- Example: γ-irradiated silicon detectors -

- For the first time macroscopic changes of the depletion voltage and leakage current can be explained by electrical properties of measured defects → Major breakthrough!

(published in Applied Physics Letters)

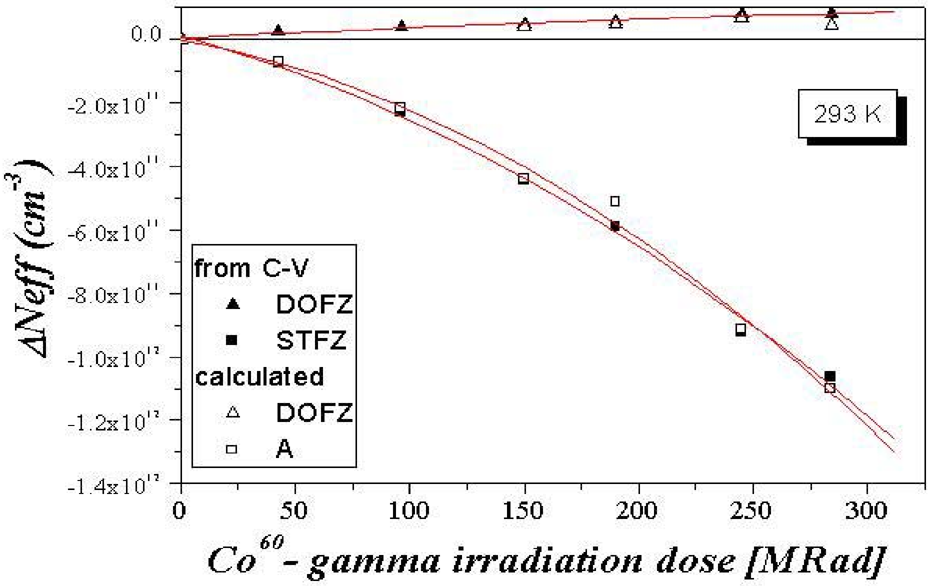
Levels responsible for macroscopic changes after γ-irradiation:

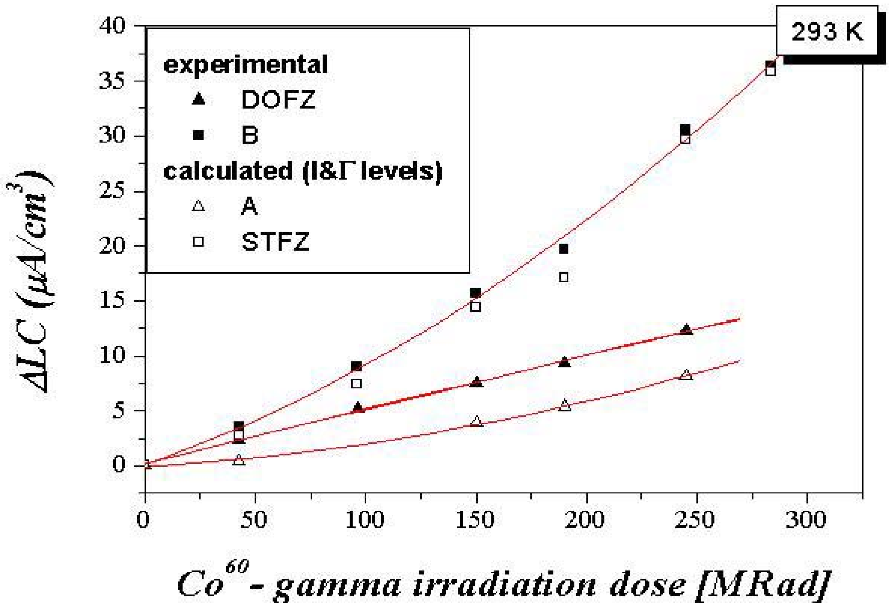
- **I–defect:** acceptor level at E_C-0.54eV (coming up for approx. 85% of damage)
  peculiarity: quadratic dose dependence
- **Γ-defect:** acceptor level at E_V+0.68eV (coming up for approx. 10% of damage)
- **BD-defect:** bistable shallow thermal donor (important in oxygen enriched silicon)



Microscopic defects ⇔ Macroscopic properties

- Example: γ-irradiated silicon detectors -





- ♦ **Comparison for effective doping concentration (left) and leakage current (right)**
  - as predicted by the microscopic measurements and
  - as deduced from CV/IV characteristics

RD50 – Common Irradiations / Common Detectors

RD50 - Irradiations in 2002/2003

Gammas

- ^{60}Co – γ BNL, USA

Electrons

- 6, 15 MeV e - Stockholm KTH, Sweden
- 900 MeV e – Trieste, Italy

Protons

- 10, 20,30 and 50 MeV p Jyväskylä, Finland
- 27 MeV p, Legnaro, Italy
- 34 MeV p, Karlsruhe, Germany
- 20, 24 GeV/c p PS CERN, Switzerland

Pions

- 200 MeV π PSI, Switzerland

Neutrons

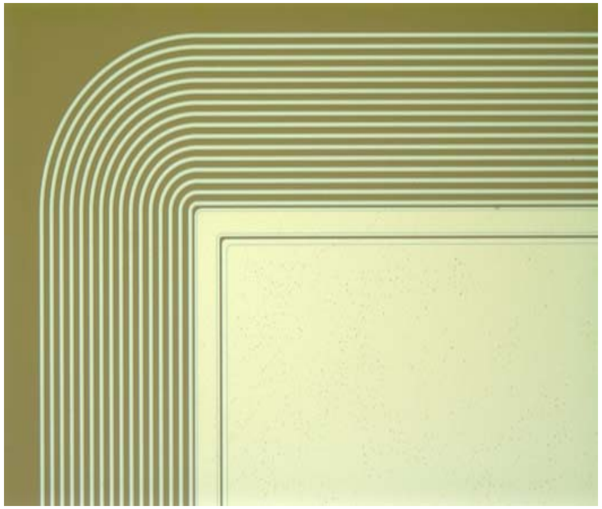
- reactor nTRIGA, JSI, Ljubljana, Slovenia
- 30-60 MeV n Louvain, Belgium

Ions

- 58 MeV Li-ions Legnaro, Italy

RD50 – Common Pad Detector Mask

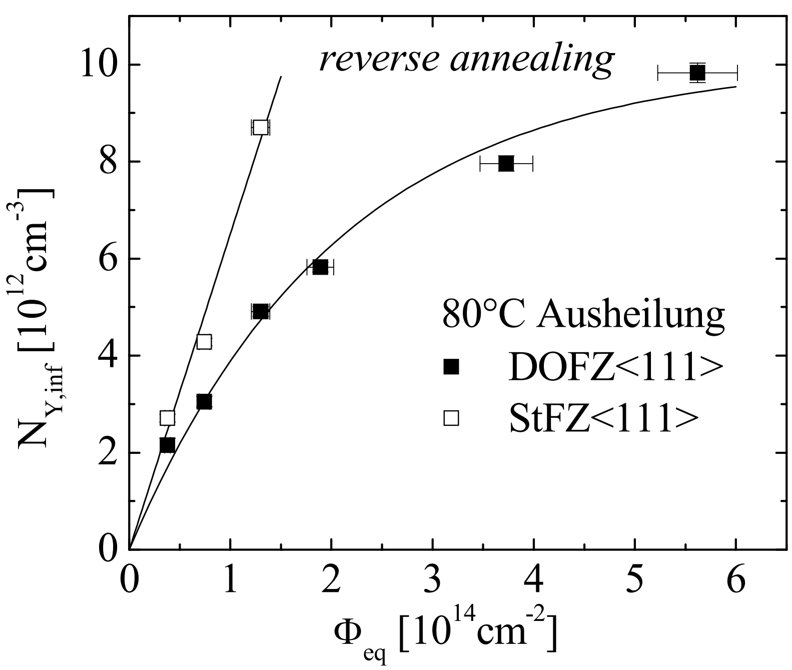
- **common pad detector mask was designed**
  Multi-guard ring structure (16µm); Wide guard ring (100µm);
  Distance between active area implant and first guard is 10µm;
  100 diodes on 4” wafer
- **first wafers have been processed with this mask**
- **in 2004 further detectors on new materials will be processed**

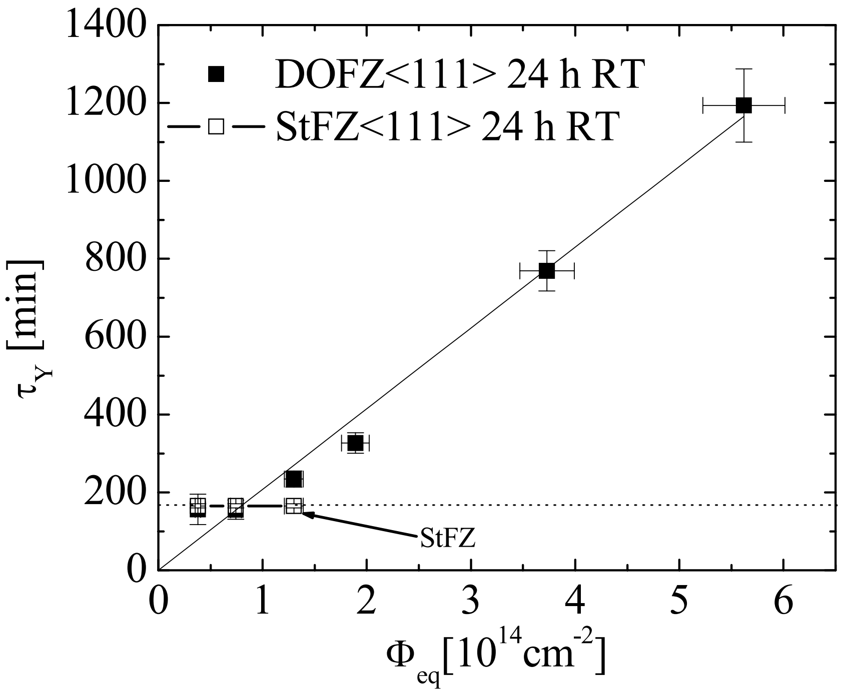


Defect engineered silicon

- DOFZ – Diffusion Oxygenated FZ Silicon -

- **Improved radiation hardness of oxygen enriched silicon substantiated by numerous studies** (gammas, protons of different energy, pions, neutrons, Lithium ions) **on detectors produced by different manufacturers.**

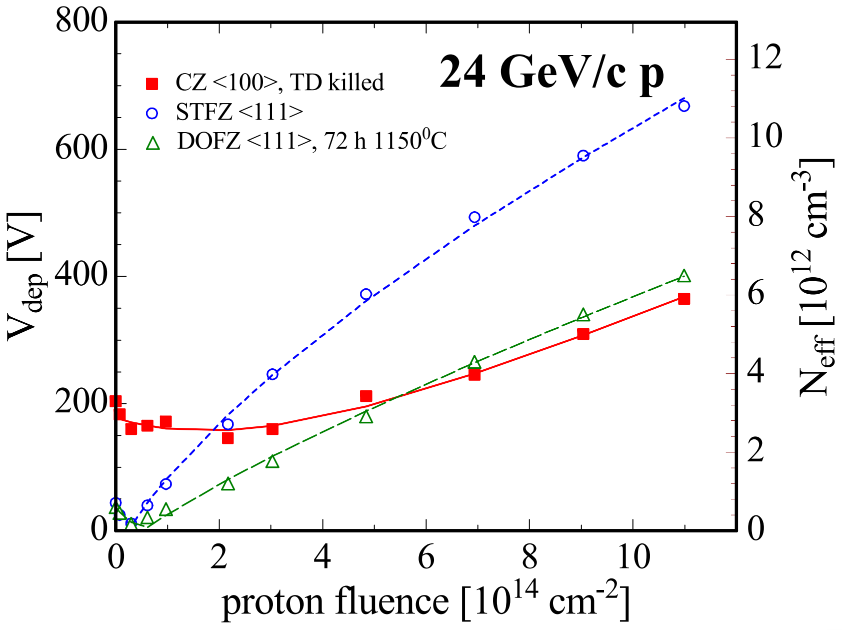




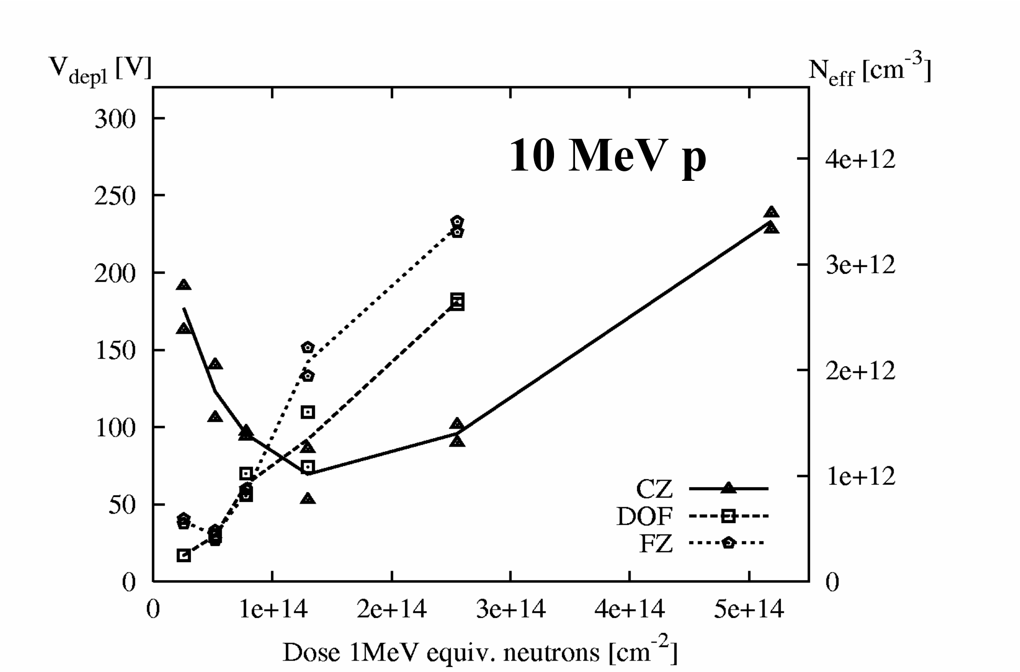
- **Reverse annealing:**
  - saturation of the reverse annealing amplitude
  - time constant is depending on fluence (increasing with increasing fluence)

Czochralski Silicon (CZ)

- **Detectors fabricated on high resistivity MCZ (Okmetic) and CZ (Sumitomo-Sitix) silicon and irradiated in several irradiation campaigns.**
- **Considerably smaller changes of V_{dep} with respect to standard FZ silicon shown**
- **Formation of thermal donors by irradiation play a major role in the macroscopic behavior of CZ-devices.**
- **Processing of CZ silicon under control now**
- **Low cost material**



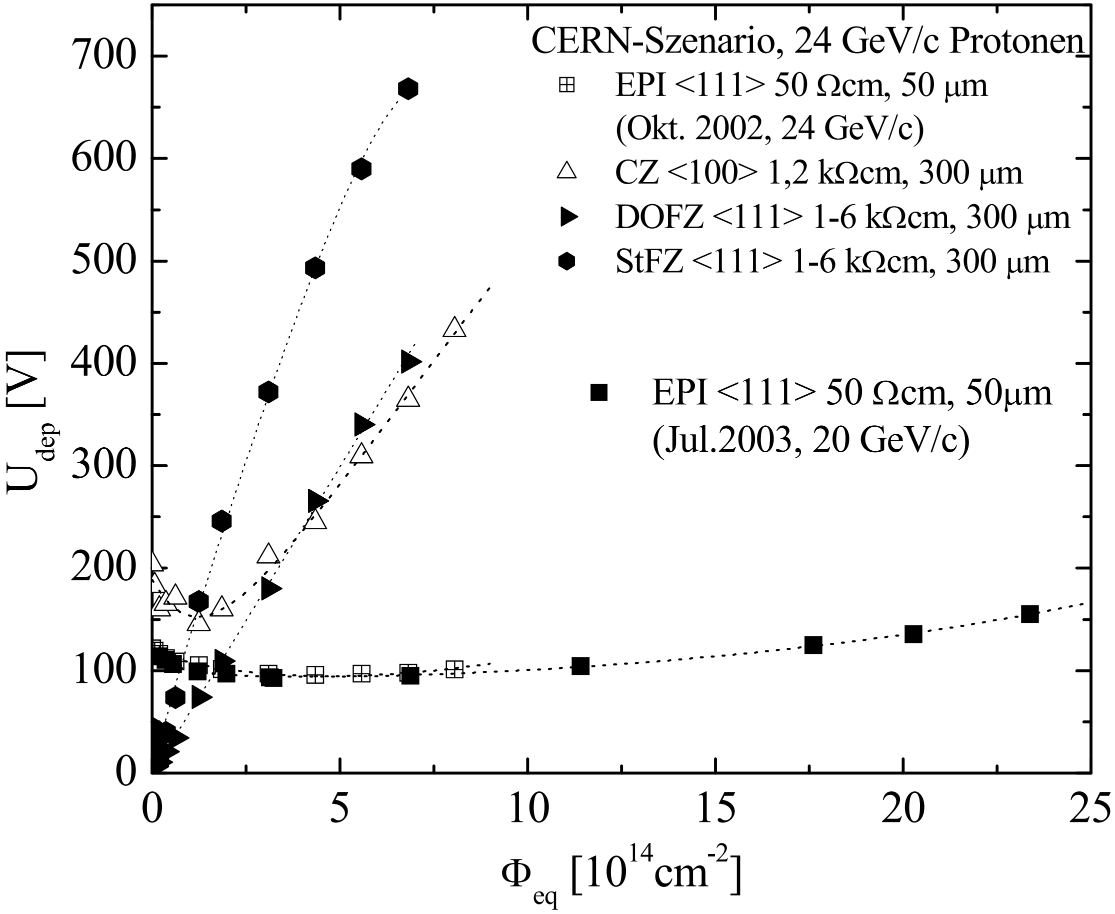
CZ - Sumitomo

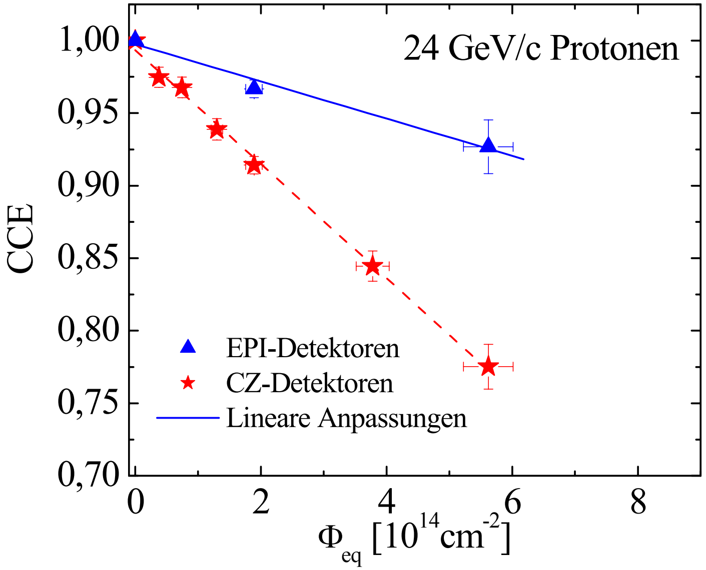


MCZ - Okmetic

Epitaxial silicon

- **First production of detectors performed by CiS** (50µm, 50Ωcm layer on CZ-substrate)
- **Irradiation tests performed** with 24 GeV/c protons, 58 MeV Li and reactor neutrons (up to $1\cdot10^{16}$cm^{-2}); no type inversion observed for proton irradiation





- **CCE measured with α-particles**
- **After fluence of $5\cdot10^{14}$ cm^{-2}**
  EPI : 7% charge loss
  CZ and DOFZ :20% charge loss

New Materials

- Wide bandgap semiconductors ⟹ lower leakage current than in Si
- radiation harder than silicon ? (to be proven)
- More charge than from diamond detectors with same thickness (51e/µm for mips)

Semi-Insulating SiC

$\rho > 10^{11}\,\Omega$cm due to vanadium compensation

CCE 60% in as-grown, ~55% after irradiation with 10^{13}cm^{-2} 300 MeV/c π

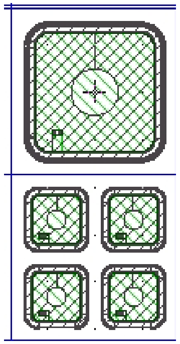
Vanadium is responsible of incomplete charge collection

Epitaxial SiC

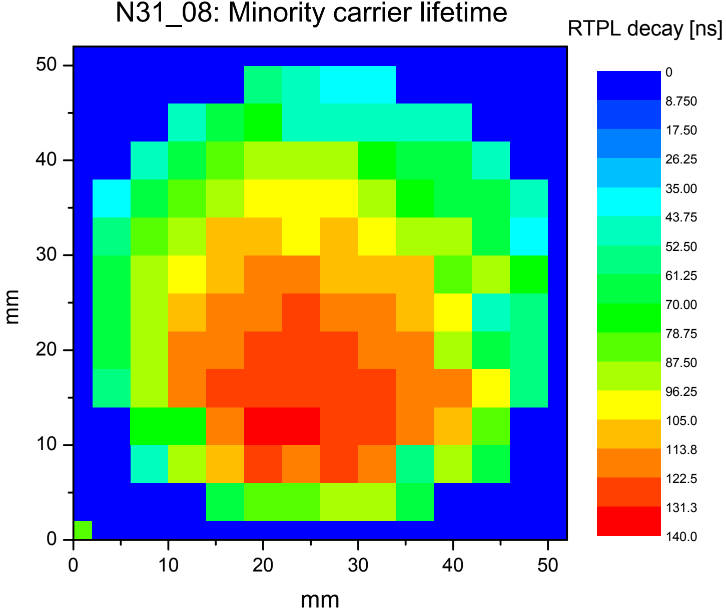
-6 new 2” wafers W~50µm, $N_{eff} \geq 5 \cdot 10^{13}$cm^{-3} produced by IKZ

-Common RD50 test structures produced and irradiated

-Several research activities already in action on previously produced SiC detectors



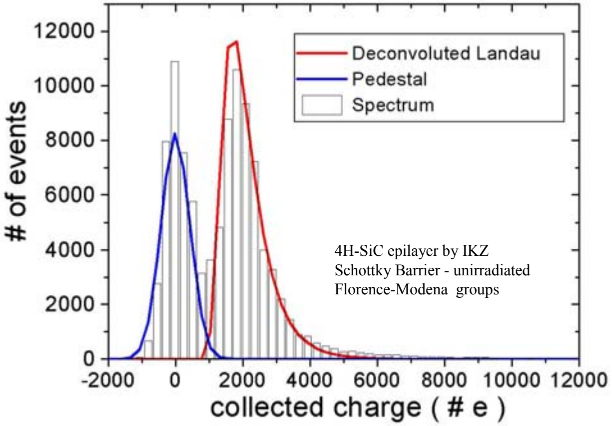
RD50 Ni Schottky barrier common test structures



Minority Carrier Lifetime distribution on a 4H-SiC epilayer grown by IKZ, Berlin

RD50 Research activities on previously produced epitaxial SiC detectors

Epilayer from IKZ Berlin, W~40µm, N_{eff} =5x10^{13}cm^{-3}
-100% CCE for V_{fd}~60V with β from ^{90}Sr
- No priming/polarization effects

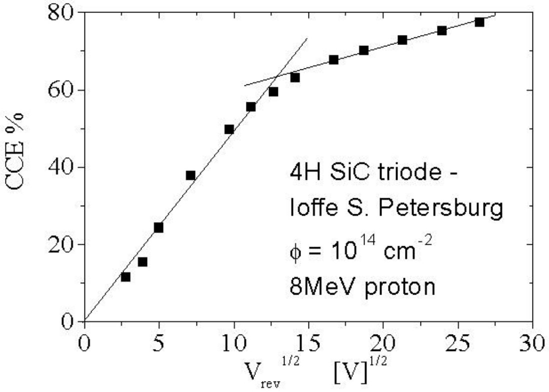


4H-SiC epilayer by IKZ
Schottky Barrier - unirradiated
Florence-Modena groups

Preliminary Irradiation of SiC epilayers with different particles, energy and fluences:

- Generation of deep levels with energy 0.18-1.22eV
- Reduction of N_{eff}
- CCE tested with α-particles from ^{241}Am

100% CCE after 8.2MeV e^- up to 9.5x10^{15}cm^{-2}
80% CCE after 8MeV p up to 10^{14}cm^{-2}



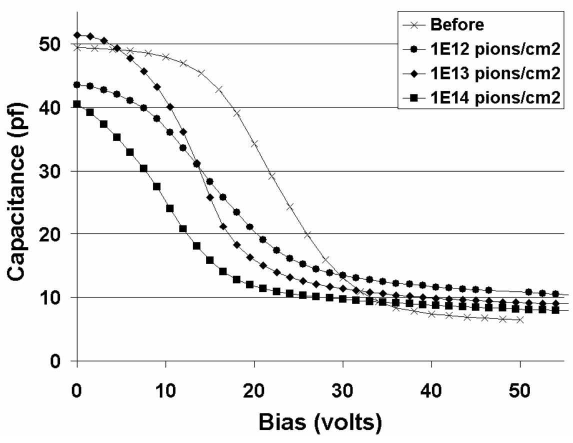
4H SiC triode -
Ioffe S. Petersburg
$\phi = 10^{14}$ cm^{-2}
8MeV proton

Semi-Insulating GaN detectors

-SI-GaN thin epitaxial layer (University of Tokushima, Japan). CCE tested with α-particles ^{241}Am after irradiation with neutrons (Ljubljana) up to 5x10^{14}cm^{-2} : CCE ~77%

-Thicker (500µm) high resistivity GaN by Lumilog now available to our collaboration.

New Structures



3-D devices proposed by S. Parker. Columnar electrodes to collect charge through detector total thickness.

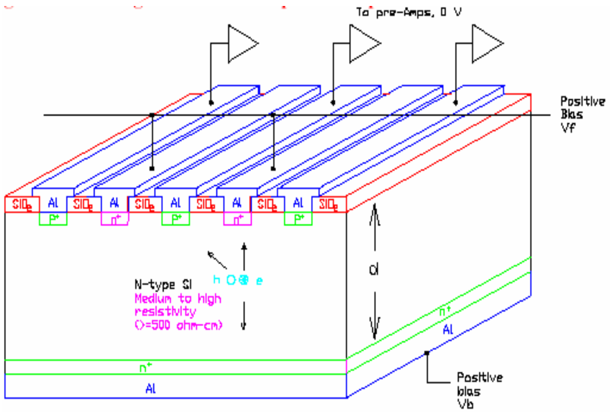
- 3D detectors produced at Glasgow by plasma etching: 85μm pore spacing, diameter 10μm, pore length 130μm, V_{fd}~30V.

- Irradiated with 300 MeV/c π at PSI. V_{fd}~20V and CCE drops from ~60% to ~45% after 10^{14} π/cm^2.

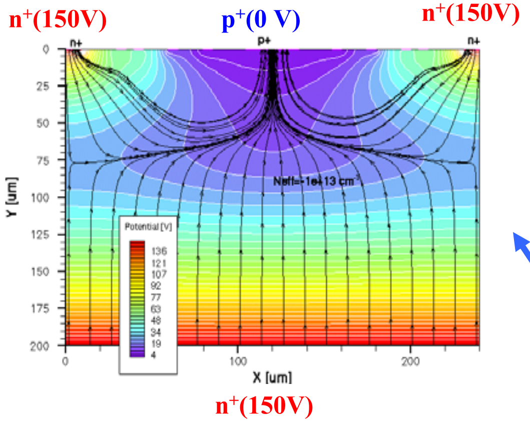
- Process should be optimized.

Semi 3-D devices proposed by Z. Li, BNL.

- Planar technology easier to process than 3D sensors
- Single-sided processing
- Large reduction in detector full depletion voltage after SCSI
- Processing of first prototype almost completed.



Z. Li et al. NIMA478, (2002), 303-310



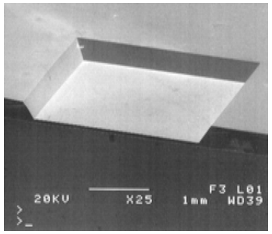
Simulation of electric profile in semi 3D after irradiation to $5x10^{14}$ n/cm^2.

Thin Si detectors

After 10^{16}cm^{-2} active thickness is mainly limited by the reduced effective carrier drift lengths. Thin detectors control V_{fd} and leakage current, allows to use low resistivity material to shift the SCSI in the high fluence range and reduce material budget.

-Epitaxial Si detectors : 50µm thick produced by ITME, processed by CiS, irradiated up to 9x10^{15} 24GeV p/cm².

-Thinned Si detectors: IRST-Trento produced a set of thinned single pad detectors (99-57µm) by chemical attack from 300µm-thick wafers.



IRST-Trento: SEM of a silicon wafer thinned by TMAH

Cross section of a thinned silicon detector by IRST-Trento

Thickness [µm]	Leakage Current [nA/cm^3]	V_{dep} [V]
300	80	12
99	30	~1
57	55	<1

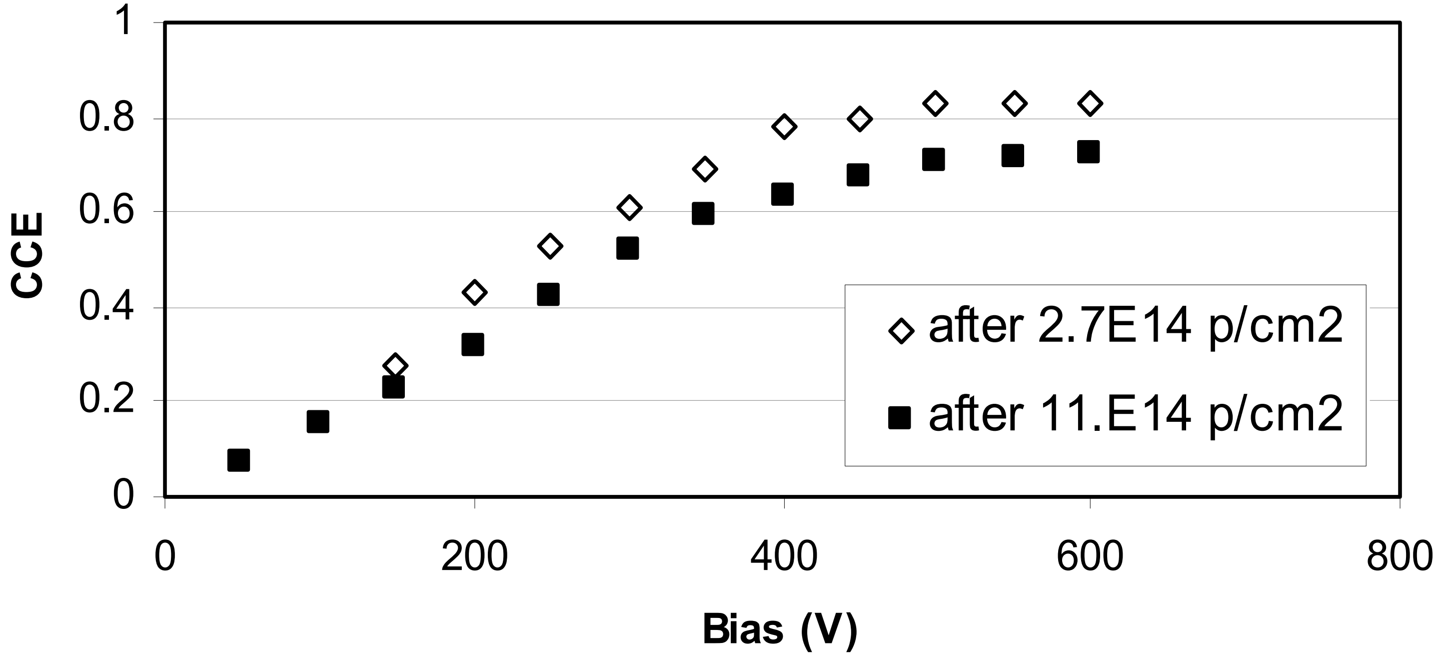
Irradiation, tests and comparison between thinned and epitaxial Si detectors will be carried out next year.

Characterisation of microstrip detectors with defect engineered Si

Manufactured first miniature microstrip detectors:

- Epitaxial Si, MCZ Si and CZ Si detectors (p-in-n)
- p-type oxygenated detectors (n-in-p)

Some detectors irradiated up to 10^{16} cm^{-2} 24GeV protons, tests in progress

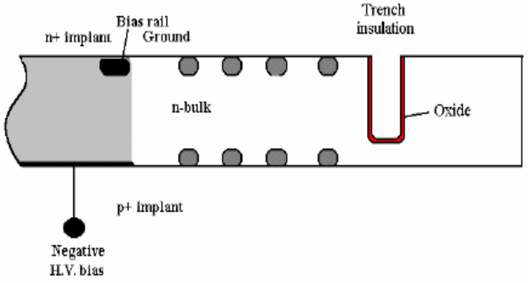


CCE of oxygen enriched n-in-p microstrip detectors after 24GeV p irradiation (diode configuration). Measurements with LHC-like electronics are in progress.

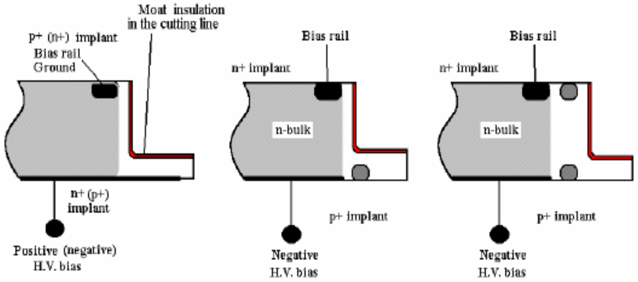
Design and process of common tests structures

- Provide common tests structures to the collaboration.
- Compare devices produced by different manufacturers.
- Trench etched outside the guard rings to reduce distance of active volume from cut edge

Proposed geometries to control the edge field. Trench etched outside the guard-rings.

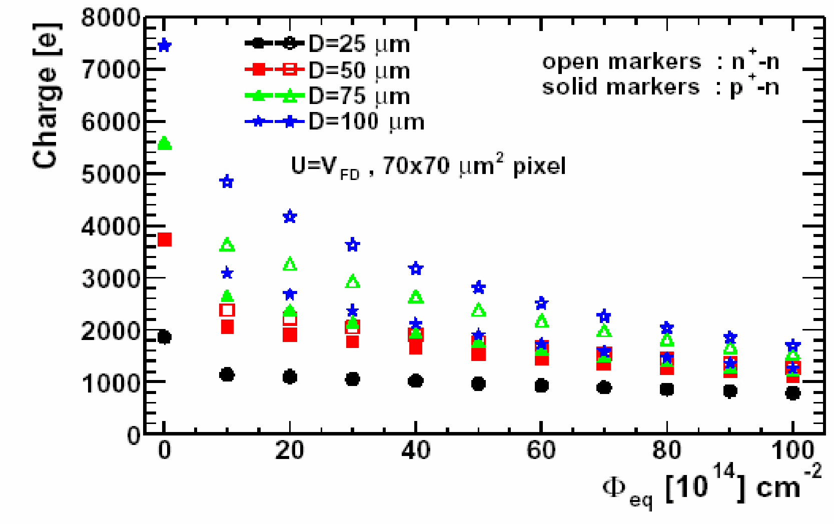


More extreme solutions with or without backside guard-rings.



Simulation at very high fluences

n$^+$-n and p$^+$-n $70\text{x}70\mu m^2$ pixels: at 10^{16}cm^{-2} only 1000-2000e are collected, with small differences between different material thicknesses



Links with LHC Experiments

- Test beam on Cz Si microstrip detector with LHCb VeLo;
- manufacturing of CMS pixels with Cz Si;
- Trench etched outside the guard rings for e.g. TOTEM, LHCb VELO.
- Simulation of ATLAS pixels efficiency carried out up to 10^{16}cm^{-2}.

Conclusion

– Status End of 2003 -

- **At the fluence of 10^{16}cm^{-2} (Innermost layer of a SLHC detector) the active thickness of any silicon material is significantly reduced due to trapping.**

  The two most promising options so far are:

  Thin detectors : drawback: radiation hard electronics for low signals needed
  3D detectors : drawback: technology has to be optimized

- **At fluences up to 10^{15}cm^{-2} (Outer layers of a SLHC detector) the change of the depletion voltage and the large area to be covered by detectors is the major problem.**

  CZ detectors could be a cost-effective radiation hard solution

- **New Materials like SiC and GaN have been characterized. However, thicker samples and more radiation studies are needed to assess if these materials could be an alternative to Silicon.**

Workplan for 2004

Defect and Material Characterization

- Multivacancy-oxygen centers in irradiated silicon
- Irradiation-induced defect clusters in silicon
- Irradiated silicon carbide samples
- Hydrogenated silicon detectors
- Dimerized silicon and silicon detectors

Defect Engineering

- Processing of Oxygen enriched FZ-silicon,
  High resistivity n- and p-type MCZ-silicon,
  Epitaxial silicon layers, Pre-irradiated silicon
- Hydrogenation of silicon detectors in hydrogen plasma
- Optimization of epi-layer thickness
- Optimization of oxygen-dimer enriched silicon

Pad Detector Characterization

- Electrical characterization (IV, CV, CCE with α- and β-particles) of the test structures produced with the common RD50 mask
- Common irradiation program with fluences up to 10^{16}cm^{-2}.

Workplan for 2004

New Materials

- Irradiation and test of common SiC Schottky structures.
- Acquisition of thicker SiC epilayers and assessment of their CCE
- Study of semi-insulating SiC detectors without vanadium doping
- Study of thick high resistivity GaN Schottky barrier detectors

New Structures

- Improvement of 3D detector fabrication method, going to junction doping technique. Measurement of CCE with β-particles
- Semi-3D device fabrication and testing before and after irradiation.
- Testing of thinned detectors and comparison with epitaxial detectors

Full Detector Systems

- Production, irradiation and test of common segmented structures
- Cross check of results obtained by segmented and pad detectors
- Continue activities linked to LHC experiments
- Determination of the survival scenario of microstrip detectors when coupled to the available LHC speed electronics
- Use of simulation tools for improving the design of segmented devices
- Charge trapping studies on segmented detectors

Resources requested for 2004

Common Fund:

RD50 has a Common Fund and **does not request any financial support.** ☺

Lab space at CERN:

As a member of the collaboration, the section EP-TA1/SD should provide (as in 2003) access to available **lab space in building 14** (characterization of irradiated detectors), **in building 28** (lab space for general work) and in the **Silicon Facility** (hall 186, clean space).

Technical support at CERN:

The collaboration intends to use the existing **test beams (PS / SPS)** and the **irradiation facility in the CERN PS** complex in 2004.

The above mentioned infrastructure is under the responsibility of the section EP-TA1/SD. RD50 relies on an appropriate support of these facilities by CERN. A low level of support from EP-MIC, EP-ED and EP-ESS may be profitable.