73 meeting of the LHCC, 24 November 2004

-CERN-RD50 project –

Development of radiation hard sensors for very high luminosity colliders

STATUS REPORT 2004

Michael Moll
CERN

on behalf of RD50

OUTLINE

- The RD50 collaboration
- Results obtained in 2004
- Summary (Status Nov. 2004)
- Work plan for 2005
- Resources request for 2005

http://www.cern.ch/rd50

RD50

The CERN RD50 Collaboration

http://www.cern.ch/rd50

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

- **Approved as RD50 by CERN in June 2002**
- **Main objective:**

Development of ultra-radiation hard semiconductor detectors for the luminosity upgrade of the LHC to 10^{35} cm^{-2}s^{-1} ("Super-LHC").

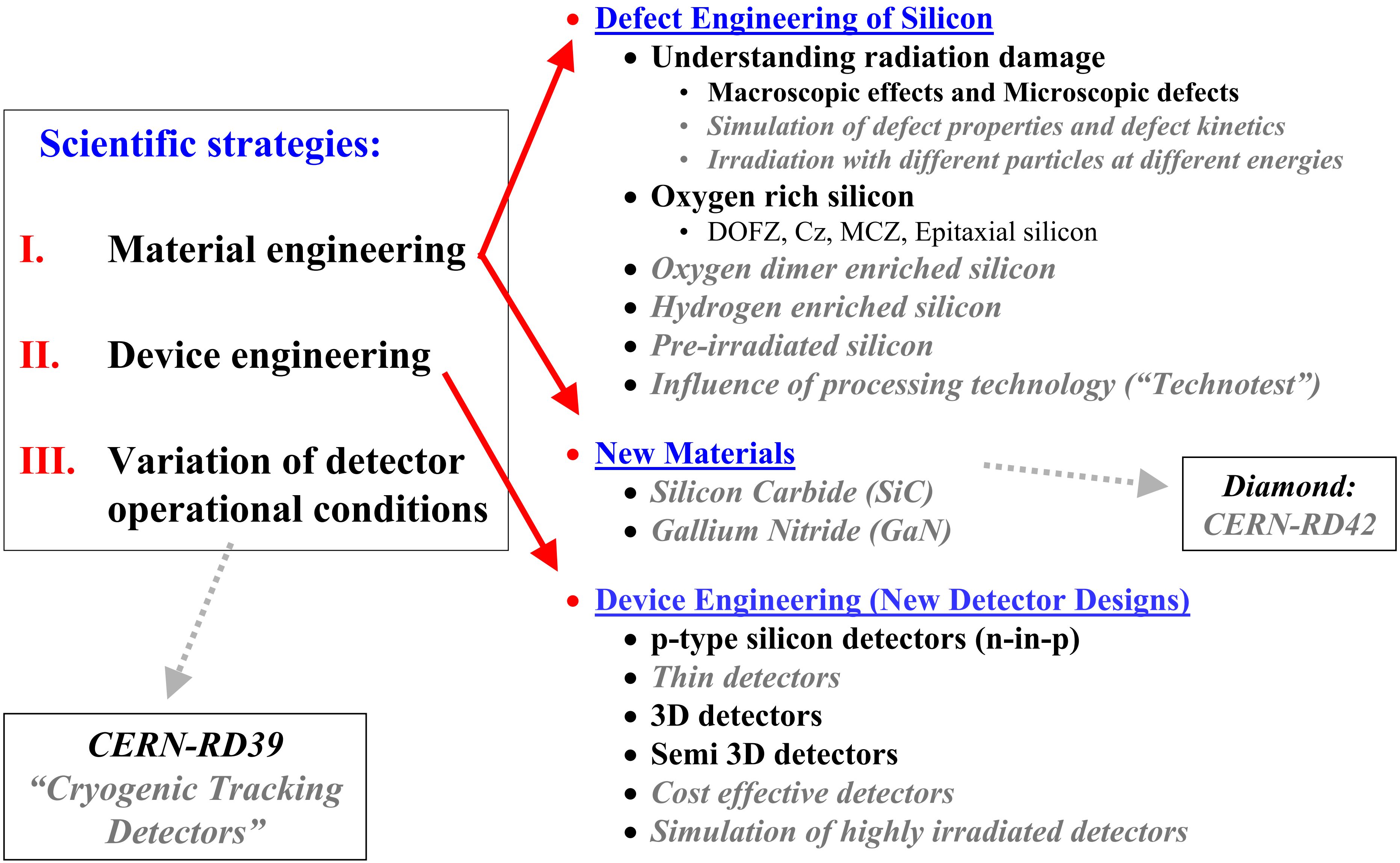
Challenges: - **Radiation hardness up to 10^{16} cm^{-2} required**
- **Fast signal collection** (Going from 25ns to 10 ns bunch crossing ?)
- **Low mass** (reducing multiple scattering close to interaction point)
- **Cost effectiveness** (big surfaces have to be covered with detectors!)

- **Presently 252 Members from 50 Institutes**

Belarus (Minsk), Belgium (Louvain), Canada (Montreal), Czech Republic (Prague (2x)), Finland (Helsinki, Lappeenranta), Germany (Berlin, Dortmund, Erfurt, Hamburg, Karlsruhe), Israel (Tel Aviv), Italy (Bari, Bologna, Florence, Padova, Perugia, Pisa, Trento, Trieste, Turin), Lithuania (Vilnius), Norway (Oslo (2x)), Poland (Warsaw), Romania (Bucharest (2x)), Russia (Moscow), St.Petersburg), Slovenia (Ljubljana), Spain (Barcelona, Valencia), Switzerland (CERN, PSI), Ukraine (Kiev), United Kingdom (Exeter, Glasgow, Lancaster, Liverpool, Sheffield, University of Surrey), USA (Fermilab, Purdue University, Rochester University, Rutgers University, SCIPP Santa Cruz, Syracuse University, BNL, University of New Mexico)

RD50

Approaches of RD50 to develop radiation harder tracking detectors



Scientific strategies:

- **I. Material engineering**
- **II. Device engineering**
- **III. Variation of detector operational conditions**

CERN-RD39
"Cryogenic Tracking Detectors"

- **Defect Engineering of Silicon**
  - **Understanding radiation damage**
    - **Macroscopic effects and Microscopic defects**
    - *Simulation of defect properties and defect kinetics*
    - *Irradiation with different particles at different energies*
  - **Oxygen rich silicon**
    - DOFZ, Cz, MCZ, Epitaxial silicon
  - *Oxygen dimer enriched silicon*
  - *Hydrogen enriched silicon*
  - *Pre-irradiated silicon*
  - *Influence of processing technology ("Technotest")*
- **New Materials**
  - *Silicon Carbide (SiC)*
  - *Gallium Nitride (GaN)*

Diamond:
CERN-RD42

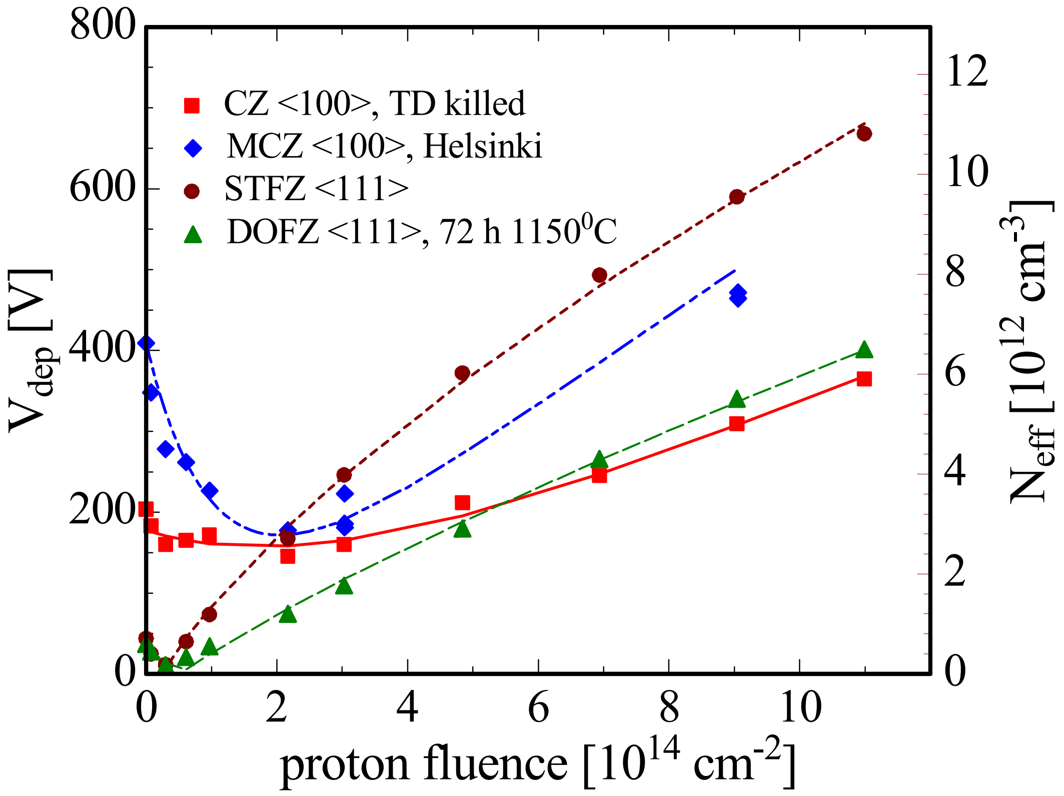
- **Device Engineering (New Detector Designs)**
  - **p-type silicon detectors (n-in-p)**
  - *Thin detectors*
  - **3D detectors**
  - **Semi 3D detectors**
  - *Cost effective detectors*
  - *Simulation of highly irradiated detectors*

RD50 Silicon Materials under Investigation by RD50

Material	Symbol	ρ (Ωcm)	$[O_i]$ (cm^{-3})
Standard n- or p-type FZ	FZ	$1–7\times10^{3}$	$< 5\times10^{16}$
Diffusion oxygenated FZ, n- or p-type	DOFZ	$1–7\times10^{3}$	$\sim 1–2\times10^{17}$
Czochralski Sumitomo, Japan	Cz	$\sim 1\times10^{3}$	$\sim 8-9\times10^{17}$
Magnetic Czochralski Okmetic, Finnland	MCz	$\sim 1\times10^{3}$	$\sim 4-9\times10^{17}$
Epitaxial layers on Cz-substrates, ITME	EPI	50 - 100	$< 1\times10^{17}$

- **CZ and MCZ silicon:**
  - high O_i (oxygen) and O_{2i} (oxygen dimer) concentration (homogeneous)
  - formation of shallow Thermal Donors possible
- **Epi silicon**
  - O_i and O_{2i} content due to out-diffusion from the CZ substrate (inhomogeneous)
  - thin layers: high doping possible (low starting resistivity)

Standard FZ, DOFZ, Cz and MCz Silicon



24 GeV/c proton irradiation

- **Standard FZ silicon**
  - type inversion at ~ 2×10^{13} p/cm^2
  - strong N_{eff} increase at high fluence

- **Oxygenated FZ (DOFZ)**
  - type inversion at ~ 2×10^{13} p/cm^2
  - reduced N_{eff} increase at high fluence

- **CZ silicon and MCZ silicon**
  - no type inversion in the overall fluence range (verified by TCT measurements)
    ⇒ donor generation overcompensates acceptor generation in high fluence range

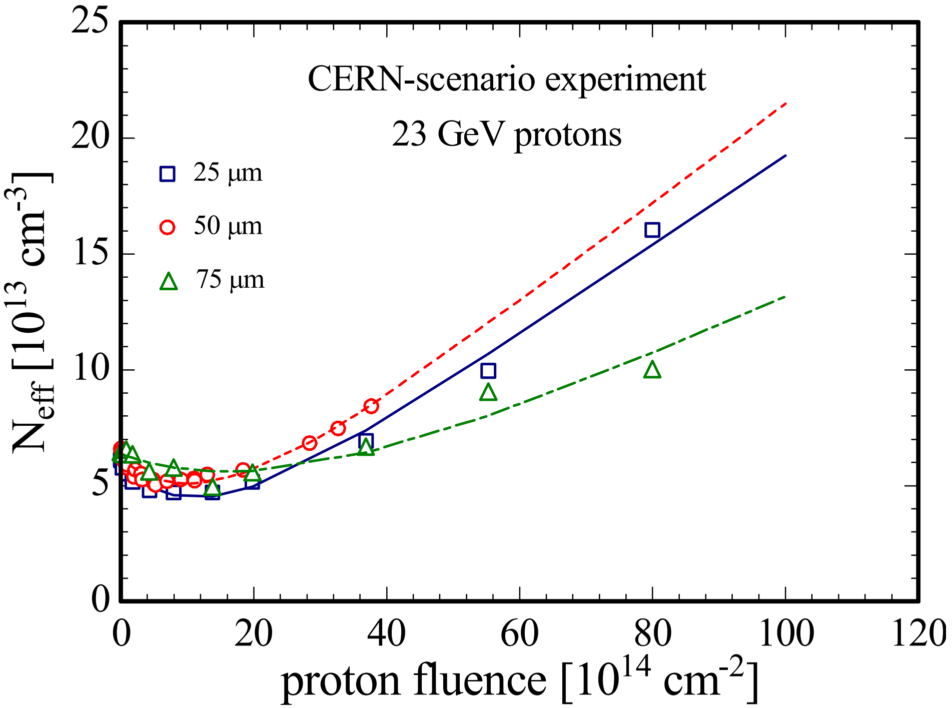
- **Common to all materials:**
  - same reverse current increase
  - same increase of trapping (electrons and holes) within ~ 20%

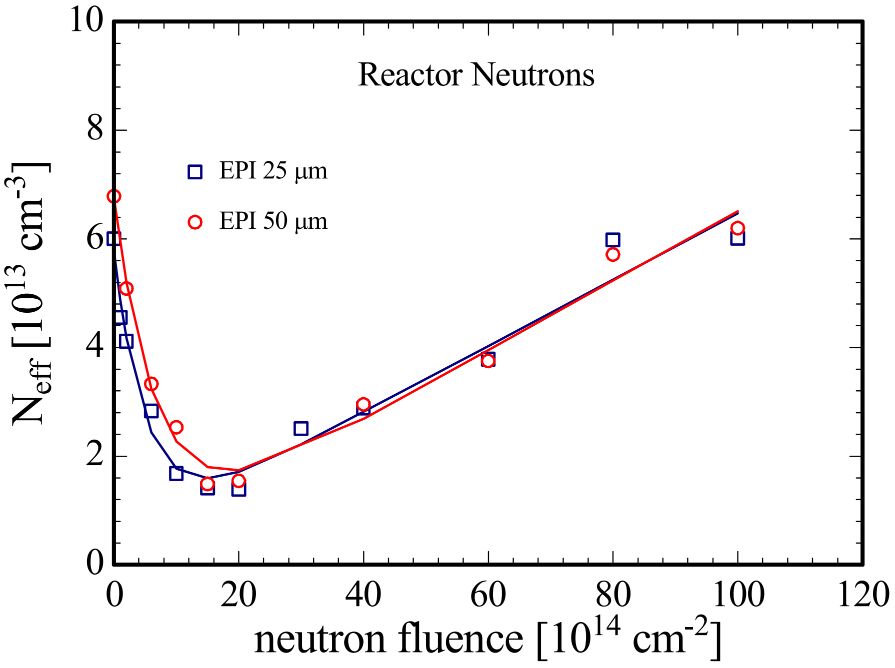
EPI Devices – Irradiation experiments

- ## Epitaxial silicon grown by ITME

E. Fretwurst, Univ. Hamburg, RESMDD04, October 2004

  - **Layer thickness: 25, 50, 75 µm; resistivity: ~ 50 Ωcm**
  - **Oxygen: [O] ≈ 9×10^{16}cm^{-3}; Oxygen dimers (detected via IO$_2$-defect formation)**





- **Development of N$_{eff}$ nearly identical for 25 µm and 50 µm**
- **No type inversion in the full range up to ~ 10^{16} p/cm^2 and ~ 10^{16} n/cm^2**
- **Proposed explanation:**
  introduction of shallow donors bigger than generation of deep acceptors

Characterization of microscopic defects

- γ and proton irradiated silicon detectors -

- **2003: Major breakthrough on γ-irradiated samples**
  - For the first time macroscopic changes of the depletion voltage and leakage current can be explained by electrical properties of measured defects ! [APL, 82, 2169, March 2003]
- **2004: Big step in understanding the improved radiation tolerance of oxygen enriched and epitaxial silicon after proton irradiation**

[I.Pintilie, RESMDD, Oct.2004]

Levels responsible for depletion voltage changes after proton irradiation:

Almost independent of oxygen content:

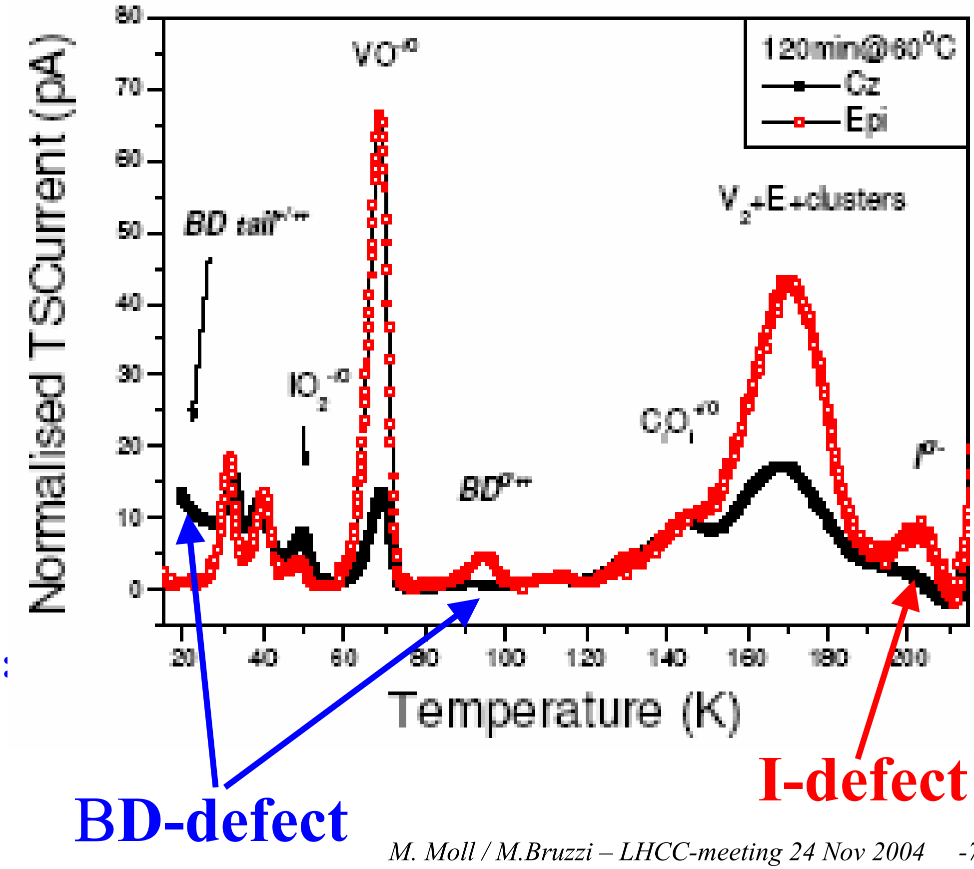
- **Donor removal**
- **"Cluster damage"** ⇒ **negative charge**

Influenced by initial oxygen content:

- **I–defect:** deep acceptor level at E_C-0.54eV (good candidate for the V_2O defect) ⇒ **negative charge**

Influenced by initial oxygen dimer content (?):

- **BD-defect:** bistable shallow thermal donor (formed via oxygen dimers O_{2i}) ⇒ **positive charge**

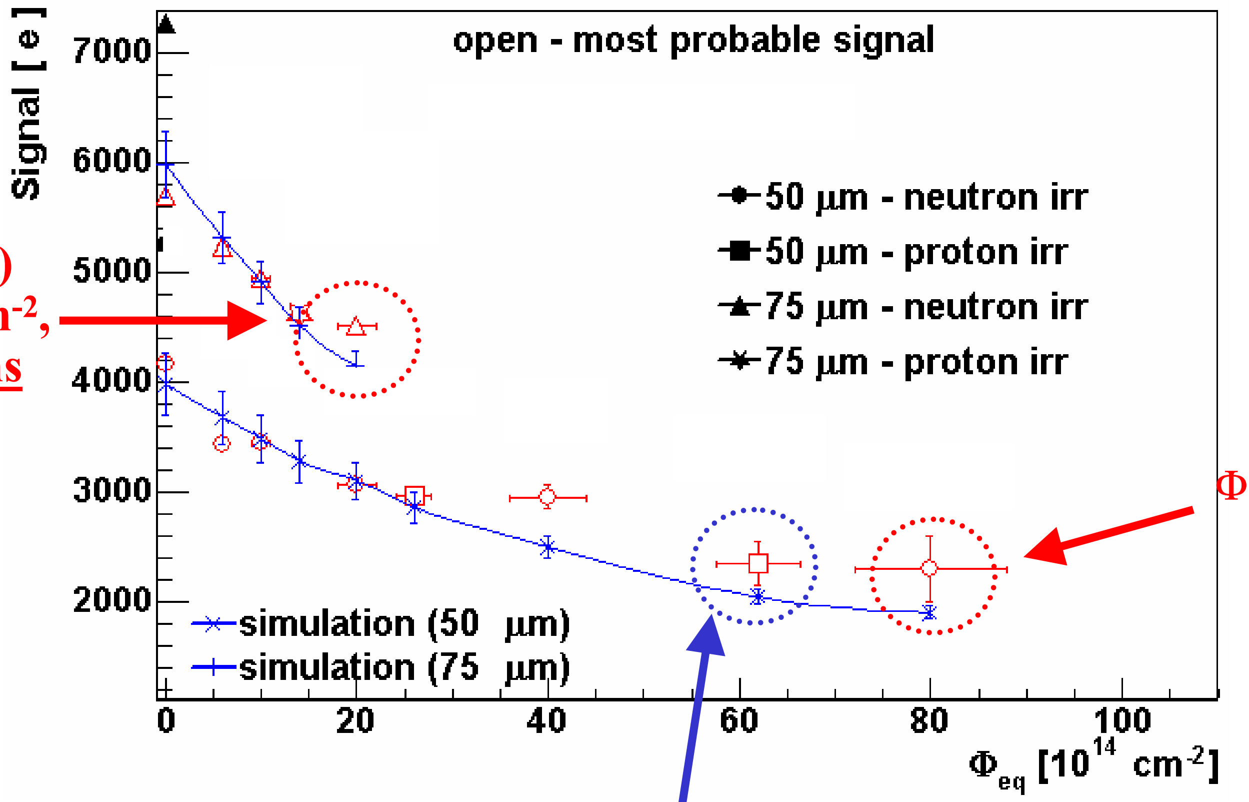


BD-defect

I-defect

Signal from irradiated EPI

- **Epitaxial silicon: CCE measured with beta particles (^{90}Sr)**
  - 25ns shaping time
  - proton and neutron irradiations of 50 µm and 75 µm epi layers



CCE (75 µm)
Φ= 2×10^{15} n/cm^{-2},
<u>4500 electrons</u>

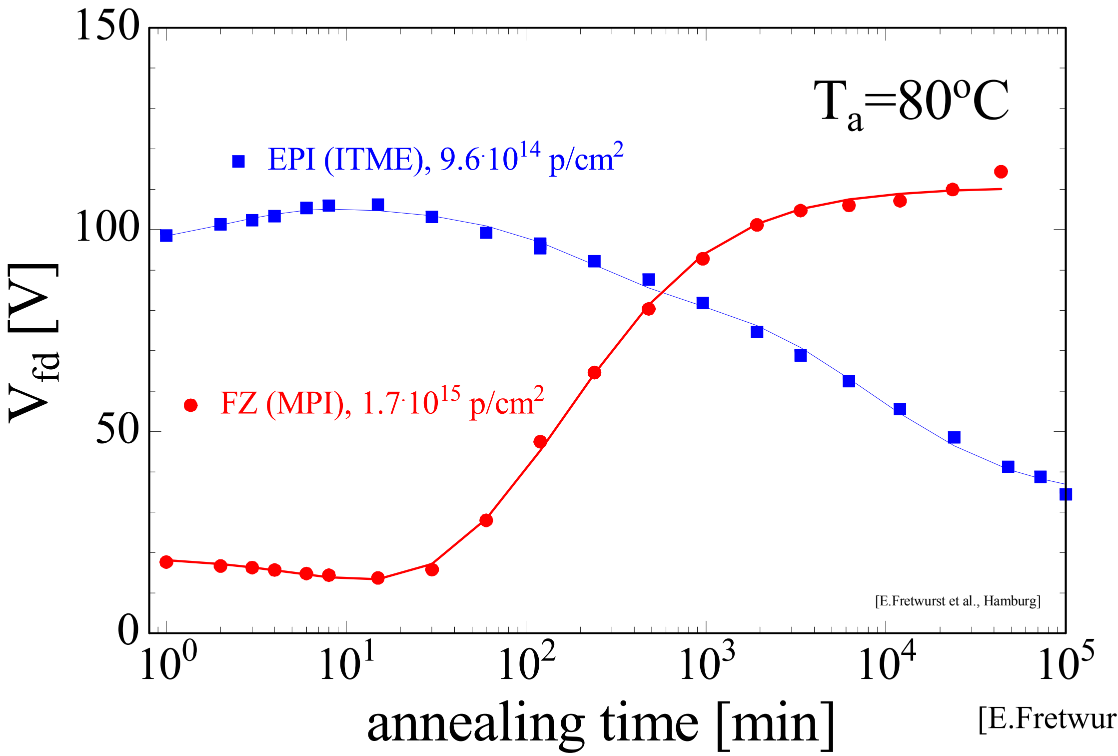
CCE (50 µm)
Φ_{eq}= 8×10^{15} n/cm^{-2},
<u>2300 electrons</u>

CCE (50 µm): Φ= 1×10^{16}cm^{-2} (24GeV/c protons)
<u>2400 electrons</u>

[G.Kramberger et al.,RESMDD - October 2004]

Epitaxial silicon - Annealing

- **50 µm thick silicon detectors:**
  - **Epitaxial silicon (50Ωcm on CZ substrate, ITME & CiS)**
  - **Thin FZ silicon (4KΩcm, MPI Munich, wafer bonding technique)**



[E.Fretwurst et al.,RESMDD - October 2004]

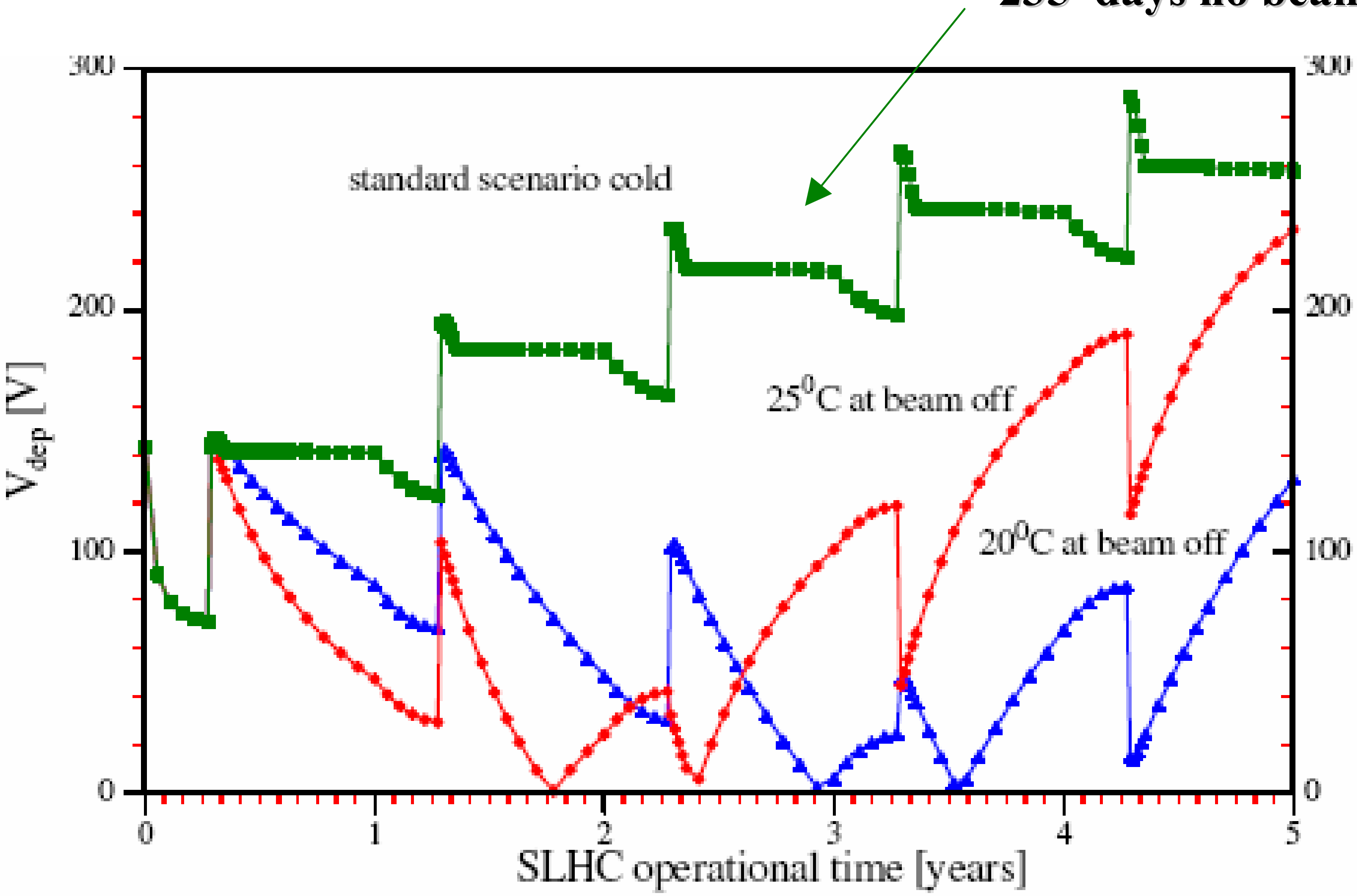
- **Thin FZ silicon: Type inverted, increase of depletion voltage with time**
- **Epitaxial silicon: No type inversion, decrease of depletion voltage with time**

⇒ No need for low temperature during maintenance of SLHC detectors!

Damage Projection – SLHC

- 50 μm EPI silicon: a solution for pixels ?-

- **Radiation level:** ■ $\Phi_{eq}(\text{year}) = 2 \times 10^{15}\ \text{cm}^{-2}$
- **SLHC-scenario:** ■ 1 year = 100 days beam (-7°C)
  30 days maintenance (20°C)
  235 days no beam (-7°C)



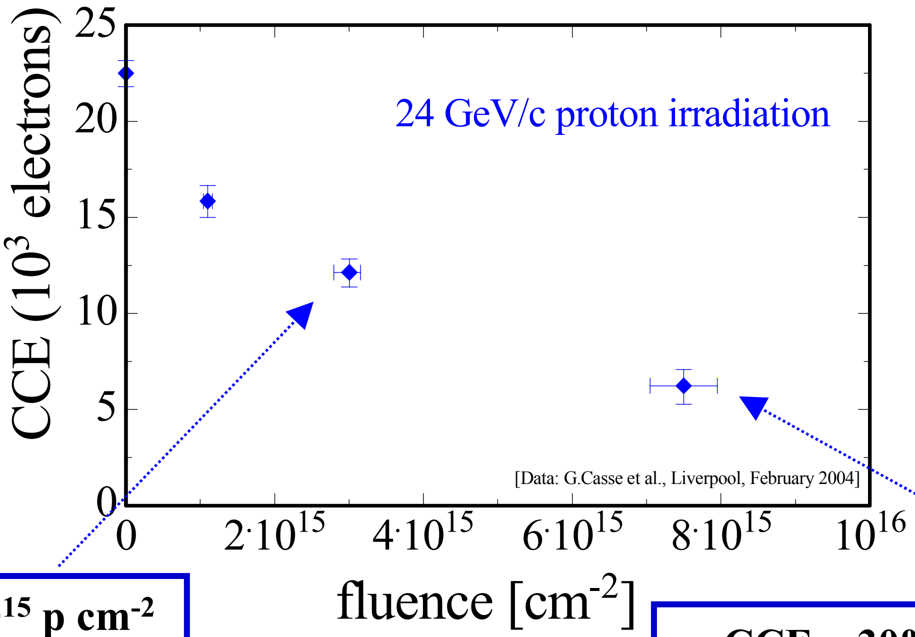
Detector without cooling when not operated (265 days warm):

- 20°C (blue curve)
- 25°C (red curve)

n-in-p microstrip detectors

n-in-p: - no type inversion, high electric field stays on structured side,
- collection of electrons

- Miniature n-in-p microstrip detectors (280μm)
- Detectors read-out with LHC speed (40MHz) chip (SCT128A)
- Material: standard p-type and oxygenated (DOFZ) p-type
- Irradiation:



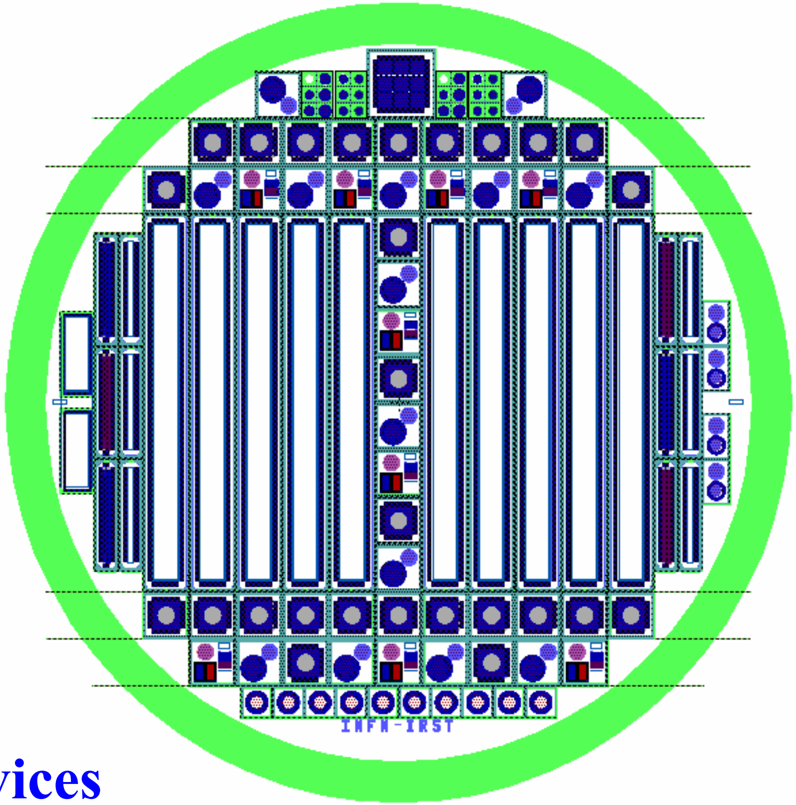
G. Casse et al., Feb 2004

CCE ~ 60% after 3 10^{15} p cm^{-2} at 900V(standard p-type)

CCE ~ 30% after 7.5 10^{15} p cm^{-2} 900V (oxygenated p-type)

At the highest fluence Q~6500e at V_{bias}=900V

RD50 strip/pixel developments



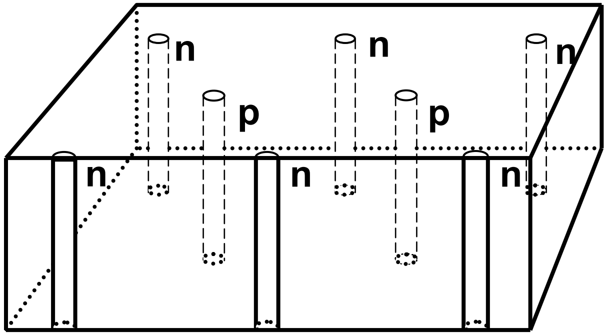
- SMART – mask (Italian RD50 groups)
  - 10 mini-strip (0.6x4.7cm2, 50 and 100 μm pitch, AC coupled)
  - 37 pad diodes and various test structures
  - Wafers processed by IRST, Trento on:
    n-type: MCZ, CZ, FZ, EPI (p-in-n)
    p-type: MCZ, FZ (n-in-p)

- RD50 common mask for segmented devices
  - 26 mini-strip (1x1cm^2, 100 strips, 80μm pitch, AC coupled)
  - 12 pixel detectors, 20 pad diodes and various test structures
  - Mask produced, wafer processing with CNM Barcelona and Micron, U.K. planned for 2005

Device Engineering: 3D detectors

(*Introduced by S.I. Parker et al., NIMA 395 (1997) 328*)

- **Electrodes:**
  - narrow columns along detector thickness-“3D”
  - diameter: **10µm** distance: **50 - 100µm**
- **Lateral depletion:**
  - lower depletion voltage needed
  - thicker detectors possible
  - fast signal
- **Hole processing :**
  - Dry etching, Laser drilling, Photo Electro Chemical
  - Present aspect ratio (RD50) 30:1



3D detector developments within RD50:

1) Glasgow University – pn junction & Schottky contacts

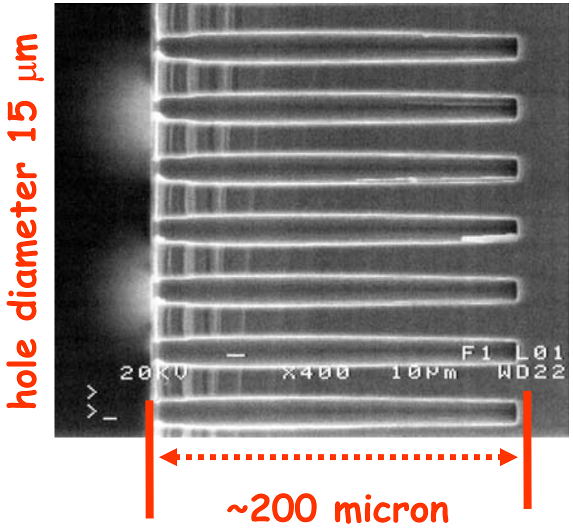
Irradiation tests up to 5×10^{14} p/cm^2 and 5×10^{14} π/cm^2:

V_{fd} = 19V (inverted); CCE drop by 25% (α-particles)

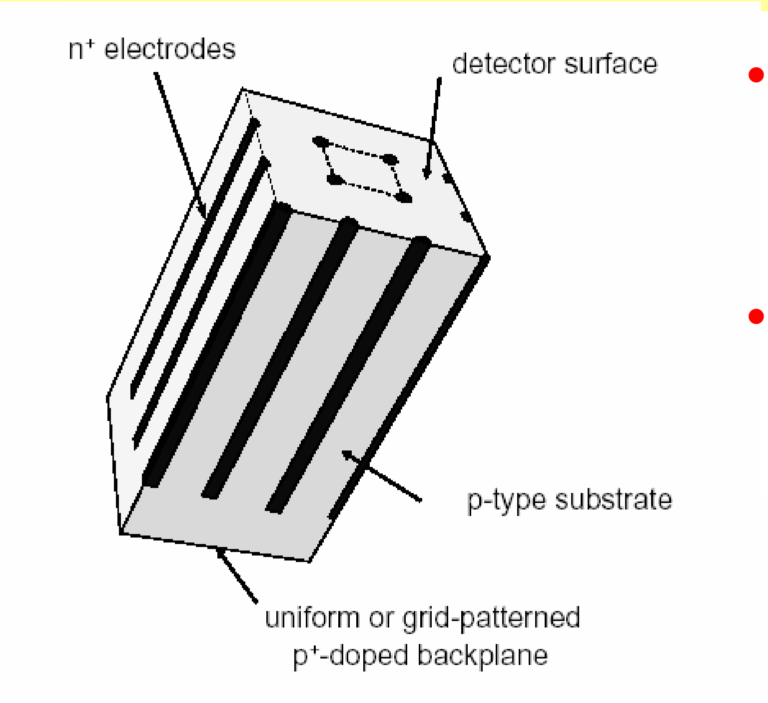
2) IRST-Trento and CNM Barcelona (since 2003)

CNM: Hole etching (DRIE); IRST: all further processing

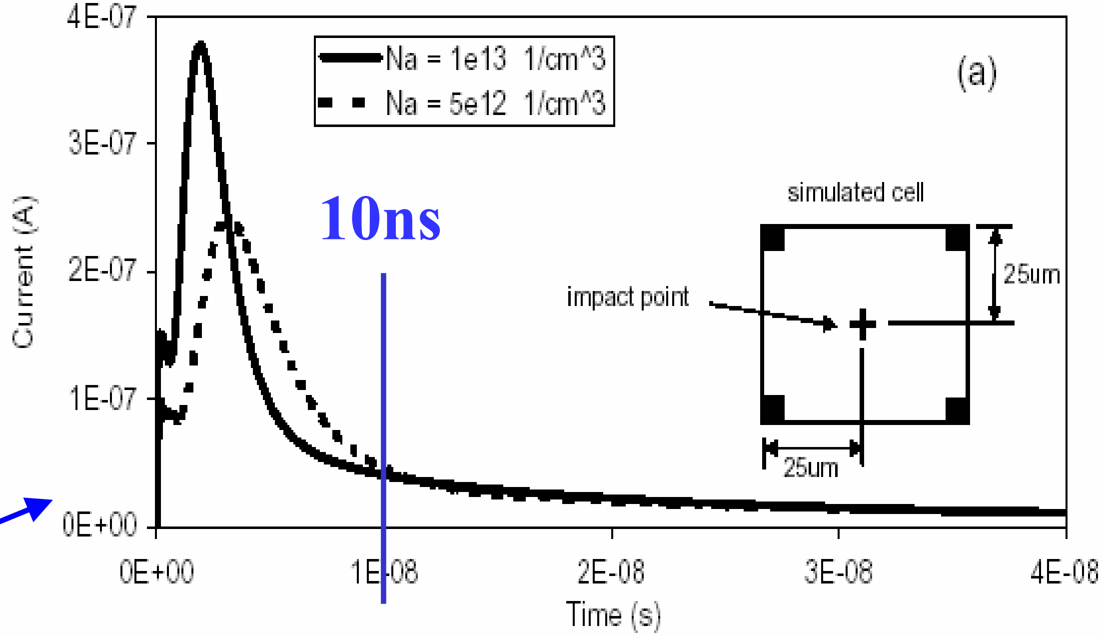
diffused contacts or doped polysilicon deposition



RD50 3D Detectors: New Architecture



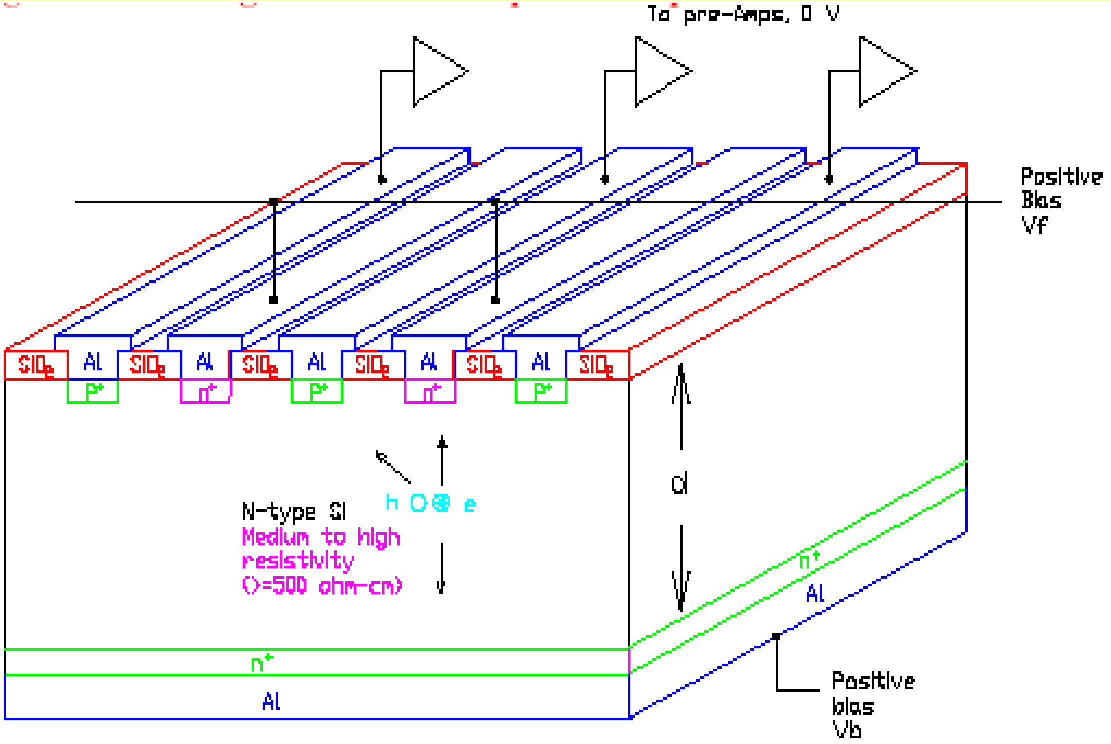
- **Simplified 3D architecture**
  - n^+ columns in p-type substrate, p^+ backplane
  - operation similar to standard 3D detector
- **Simplified process**
  - hole etching and doping only done once
  - no wafer bonding technology needed
- **Fabrication planned for 2005**
  - INFN/Trento funded project: collaboration between IRST, Trento and CNM Barcelona
- **Simulation**
  - **CCE within < 10 ns**
  - worst case shown (hit in middle of cell)



C. Piemonte et al. Presented at STD05, June 04, Hiroshima, in press on Nucl. Instrum. Meth A.

Semi-3D detectors

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



- **Single sided process**
  - **p$^+$ and n$^+$ strips implanted**
  - **n-type substrate**
  - **n$^+$ implanted backside**
- **Processing of first prototypes completed at BNL**
- **First irradiation tests performed**
  - Irradiation 5×10^{14} cm^{-2} (24 GeV/c and 200 MeV protons)
  - **Large reduction of depletion voltage after type inversion observed**

    Standard detector: V_{dep} = ~370 V
    Semi-3D detector: V_{dep} 125-150V
- **Further tests (CCE) are under way**

- Status 2004 -

- 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 silicon detectors **could be a cost-effective radiation hard solution**
    (no type inversion, use p-in-n technology)
  - oxygenated p-type silicon **microstrip detectors show very encouraging results:**
    CCE ≈ 6500 e; $\Phi_{eq}=4\times10^{15}$ cm^{-2}, 300µm

- 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/EPI detectors : drawback: radiation hard electronics for low signals needed
  e.g. 2300e at Φ_{eq} $8x10^{15}cm^{-2}$, 50µm EPI,
  …. thicker layers will be tested in 2005
  3D detectors : drawback: technology has to be optimized
  ….. steady progress within RD50

- New Materials **like SiC and GaN have been characterized (not shown).**
  CCE tests show that these materials are not radiation harder than silicon

Workplan for 2005 (1/2)

Defect and Material Characterization *Convener: B.Svensson, Oslo University*	• **Characterization of irradiated silicon:** ▪ understanding of defect clusters ▪ defects in hydrogenated silicon ▪ **understanding of radiation induced shallow donors** ▪ **influence of oxygen dimers on radiation damage** • SiC: study of dominant radiation-induced defects
Defect Engineering *Convener: E.Fretwurst, Hamburg University*	• Processing of High resistivity n- and p-type MCZ-silicon • **Processing of epitaxial silicon layers of different thickness** • Hydrogenation of silicon detectors • Optimization of oxygen-dimer enriched silicon
Pad Detector Characterization *Convener: J.Harkoenen, HIP Helsinki*	• Characterization (IV, CV, **CCE with** α- and **β-particles**) of test structures produced with the common RD50 masks • Common irradiation program with fluences up to 10^{16}cm^{-2}
New Materials *Convener: J.Vaitkus, Vilnius University*	• **Consolidation of the results regarding the observed limitation in CCE after irradiation**

Workplan for 2005 (2/2)

New Structures	• **Production of 3D detectors made with n^+ columnar electrodes in p-type substrate** • Production of 3D devices with both P and B doping • **Measurement of charge collection before and after irradiation of the processed 3D detectors** • Evaluate charge collection before and after irradiation of semi-3D detectors with LHC like electronics. • Finalize charge collection tests of thinned detectors (50-100μm) up to fast hadron fluences of 10^{16}cm^{-2}
Full Detector Systems *Convener: G.Casse, Liverpool University*	• **Production, irradiation and test of common segmented structures (n- and p-type FZ, DOFZ, MCz and EPI)** • Continue activities linked to LHC experiments • Determination of the SLHC survival scenario of microstrip and pixel detectors when coupled to the available LHC speed electronics

Resources requested for 2005

- **Common Fund:**

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

- **Lab space and technical support at CERN:**

  As a member of the collaboration, the section PH-TA1/SD should provide (as in 2004) 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).

- **CERN Infrastructure:**
  - One collaboration workshop in November 2005 and working group meetings.
  - Keeping the RD50 office in the barrack 591

- Status 2004 -

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    (no type inversion, use p-in-n technology)
  - **oxygenated p-type silicon microstrip detectors show very encouraging results:**
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Further information: http://cern.ch/rd50/