Workshop on ATLAS Upgrades for High Luminosity, CERN, 13 February 2005

RD50: Radiation hard sensors for Super - LHC

Michael Moll
CERN
on behalf of RD50

OUTLINE

- RD50 collaboration (Organization & links to ATLAS experiment)
- Material engineering - Radiation tolerant sensor materials
  - Silicon – FZ, DOFZ, CZ, MCZ, Epitaxial (new materials for SLHC)
  - Other semiconductors (SiC, GaN) (not an option for SLHC?!)
- Device engineering - Radiation tolerant detector concepts
- Conclusion

http://www.cern.ch/rd50

The CERN RD50 Collaboration

http://www.cern.ch/rd50

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

- Collaboration formed in November 2001
- Experiment 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)

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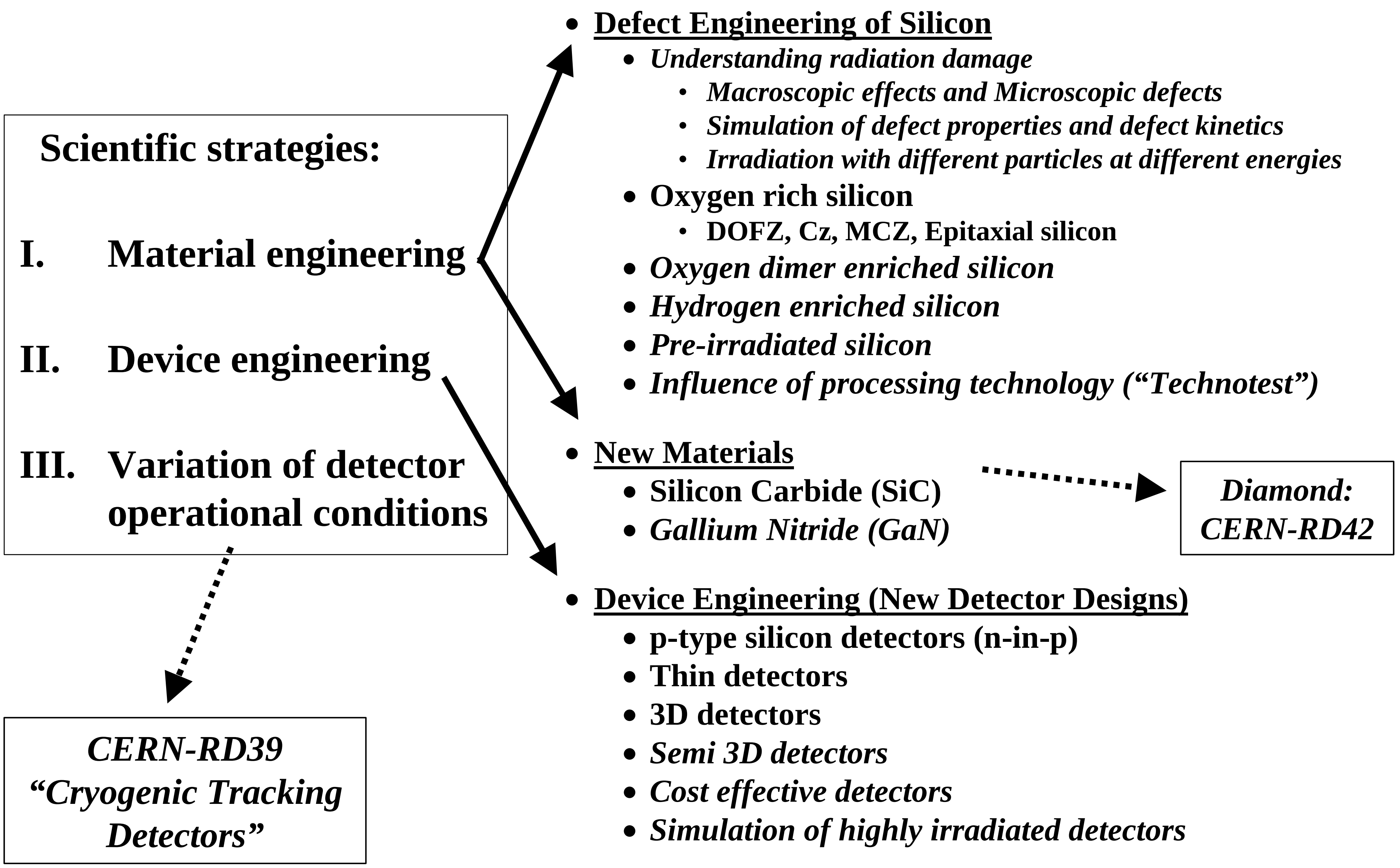
Approaches of RD50 to develop radiation harder tracking detectors



Scientific strategies:

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

- **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

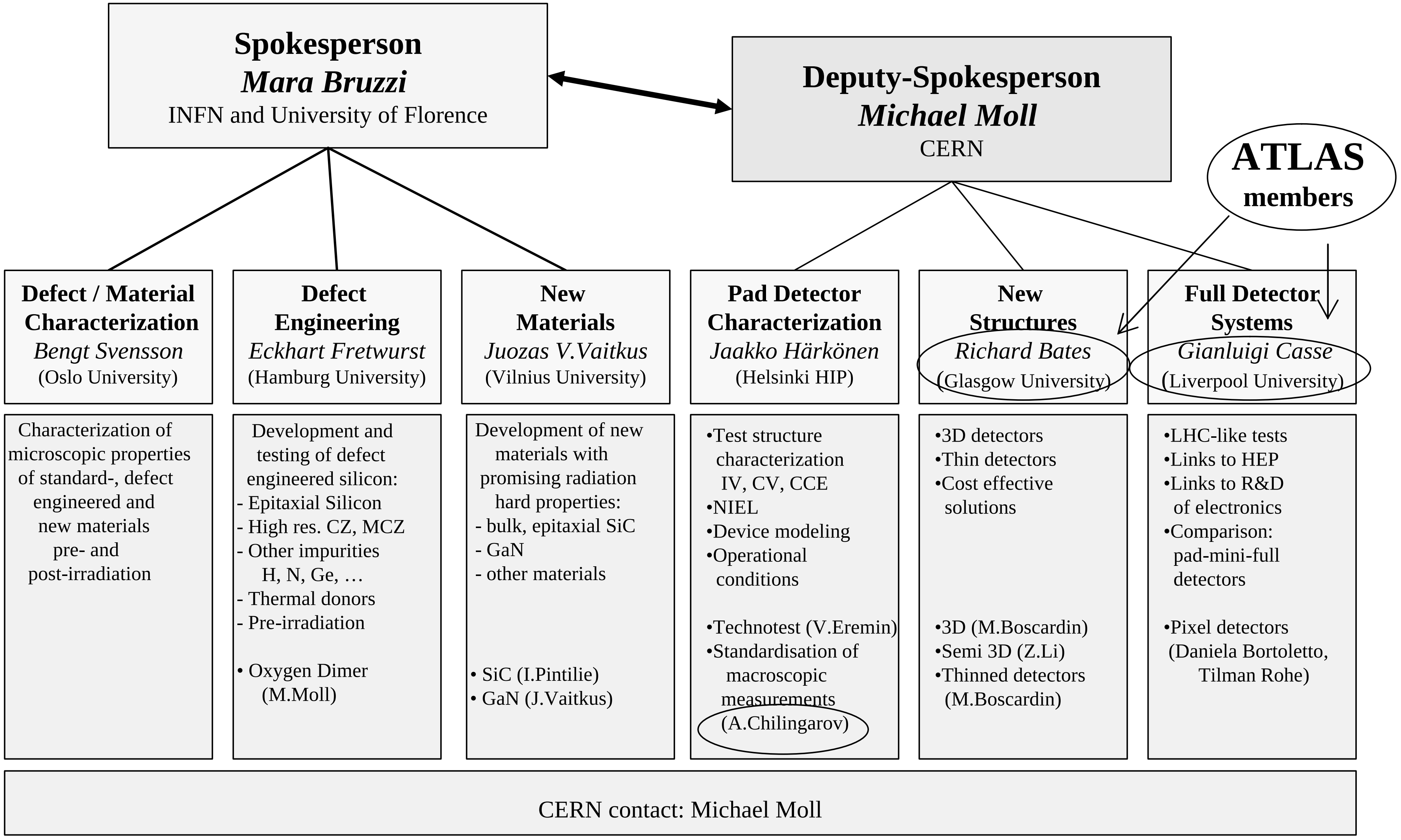
- **Device Engineering (New Detector Designs)**
  - **p-type silicon detectors (n-in-p)**
  - **Thin detectors**
  - **3D detectors**
  - ***Semi 3D detectors***
  - ***Cost effective detectors***
  - ***Simulation of highly irradiated detectors***

CERN-RD39 "Cryogenic Tracking Detectors"

RD50

Scientific Organization of RD50

Development of Radiation Hard Semiconductor Devices for High Luminosity Colliders



Spokesperson
Mara Bruzzi
INFN and University of Florence

Deputy-Spokesperson
Michael Moll
CERN

ATLAS members

Defect / Material Characterization *Bengt Svensson* (Oslo University)	**Defect Engineering** *Eckhart Fretwurst* (Hamburg University)	**New Materials** *Juozas V.Vaitkus* (Vilnius University)	**Pad Detector Characterization** *Jaakko Härkönen* (Helsinki HIP)	**New Structures** *Richard Bates* (Glasgow University)	**Full Detector Systems** *Gianluigi Casse* (Liverpool University)
Characterization of microscopic properties of standard-, defect engineered and new materials pre- and post-irradiation	Development and testing of defect engineered silicon: - Epitaxial Silicon - High res. CZ, MCZ - Other impurities H, N, Ge, … - Thermal donors - Pre-irradiation	Development of new materials with promising radiation hard properties: - bulk, epitaxial SiC - GaN - other materials	•Test structure characterization IV, CV, CCE •NIEL •Device modeling •Operational conditions	•3D detectors •Thin detectors •Cost effective solutions	•LHC-like tests •Links to HEP •Links to R&D of electronics •Comparison: pad-mini-full detectors
	• Oxygen Dimer (M.Moll)	• SiC (I.Pintilie) • GaN (J.Vaitkus)	•Technotest (V.Eremin) •Standardisation of macroscopic measurements (A.Chilingarov)	•3D (M.Boscardin) •Semi 3D (Z.Li) •Thinned detectors (M.Boscardin)	•Pixel detectors (Daniela Bortoletto, Tilman Rohe)

CERN contact: Michael Moll

Silicon Materials under Investigation by RD50

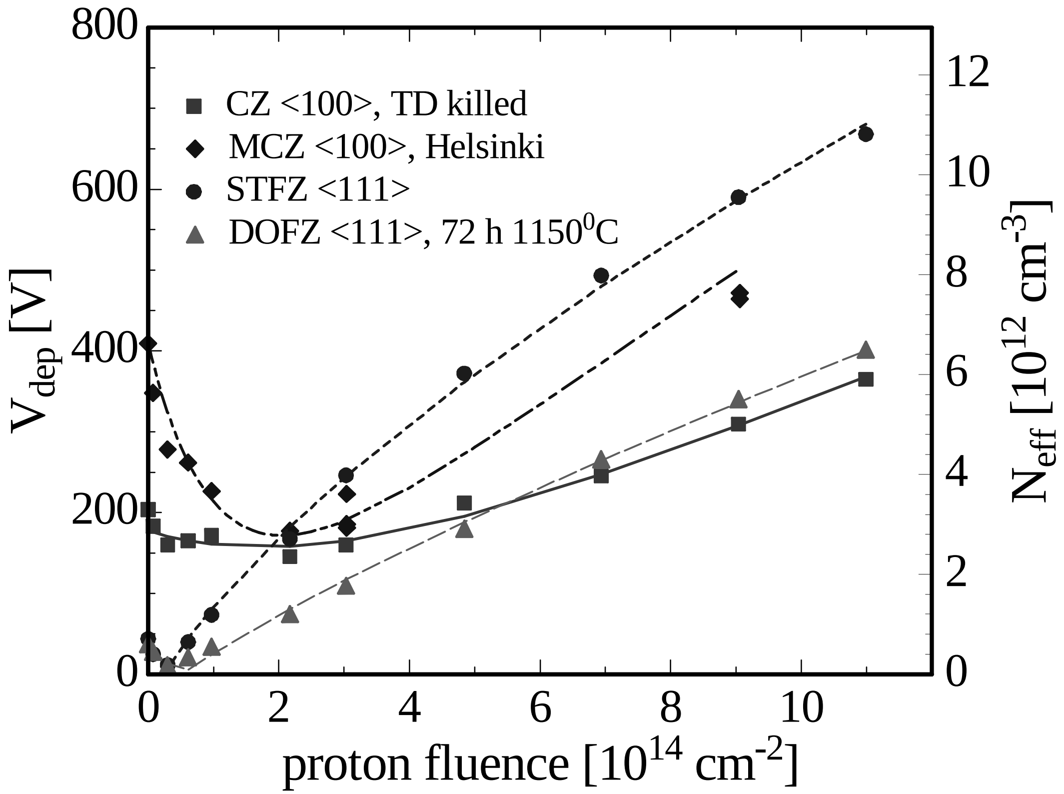
Material	Symbol	r (Wcm)	$[O_i]$ (cm^{-3})
Standard n- or p-type FZ	FZ	1–7´10^{3}	< 5´10^{16}
Diffusion oxygenated FZ, n- or p-type	DOFZ	1–7´10^{3}	~ 1–2´10^{17}
Czochralski Sumitomo, Japan	Cz	~ 1´10^{3}	~ 8-9´10^{17}
Magnetic Czochralski Okmetic, Finnland	MCz	~ 1´10^{3}	~ 4-9´10^{17}
Epitaxial layers on Cz-substrates, ITME	EPI	50 - 100	< 1´10^{17}

- **CZ silicon:**
  - very high O_i (oxygen) and O_{2i} (oxygen dimer) concentration (homogeneous)
  - formation of shallow Thermal Donors possible

- **Epi silicon**
  - high O_i , O_{2i} content on substrate side due to out-diffusion from CZ substrate, low O_i , O_{2i} content on surface side (inhomogeneous distribution)
  - thin layers: high doping possible (low starting resistivity)

Standard FZ, DOFZ, Cz and MCz Silicon

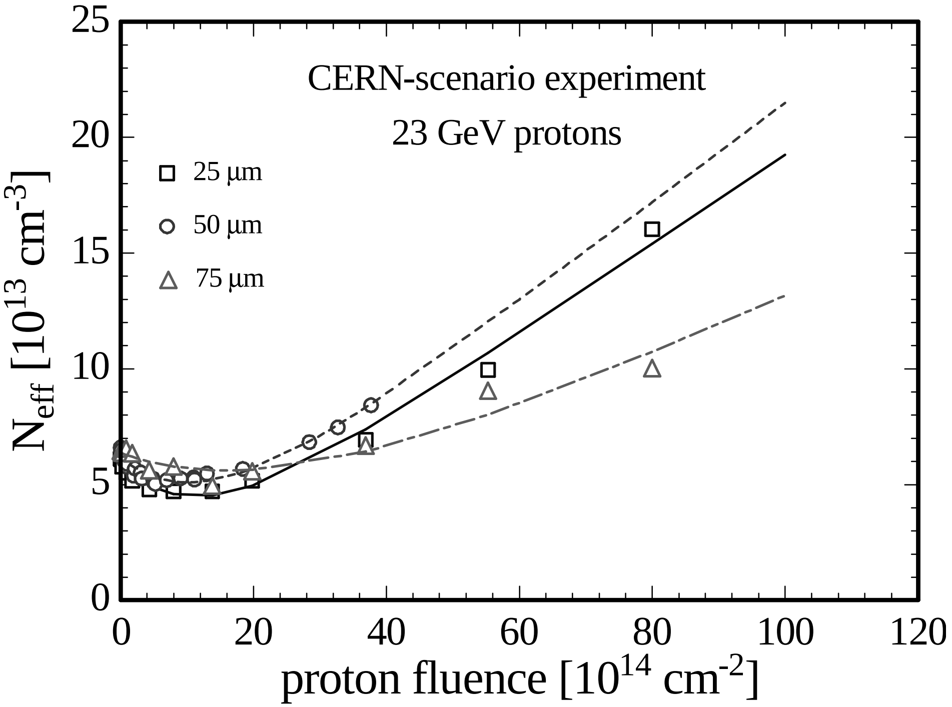
24 GeV/c proton irradiation

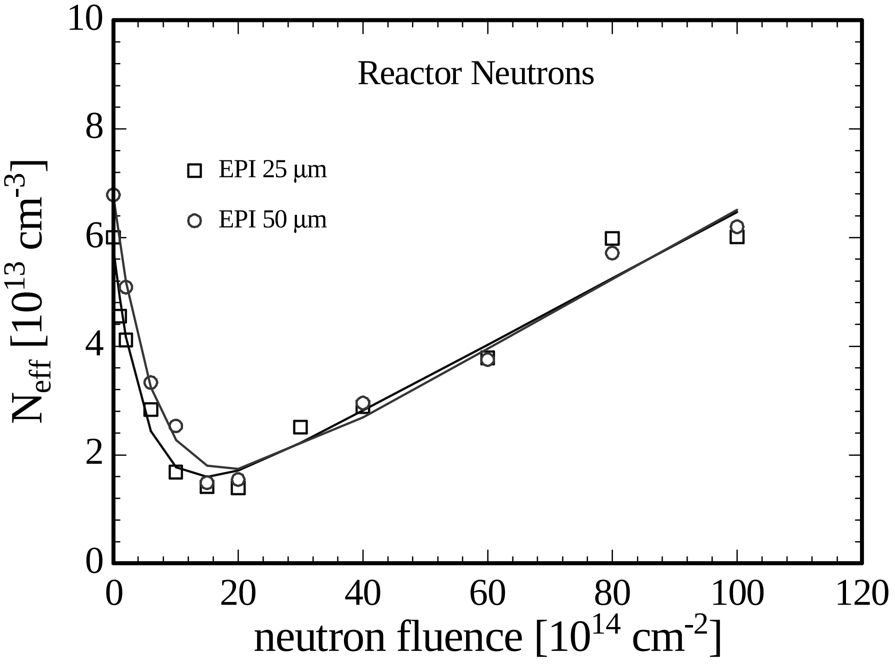


- **Standard FZ silicon**
  - **type inversion at ~ 2´10^{13} p/cm2**
  - **strong N_{eff} increase at high fluence**
- **Oxygenated FZ (DOFZ)**
  - **type inversion at ~ 2´10^{13} p/cm2**
  - **reduced Neff increase at high fluence**
- **CZ silicon and MCZ silicon**
  - **<u>no type inversion</u> for charged hadron irradiation in the overall fluence range**
    (verified for CZ silicon by TCT measurements, preliminary result for MCZ silicon)
    - Þ **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 mm; resistivity: ~ 50 Wcm**
  - **Oxygen: [O] » 9´10^{16}cm^{-3} (Oxygen dimers detected via IO_2-defect formation)**





- **Development of N_{eff} nearly identical for 25 mm and 50 mm**
- **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

- g and proton irradiated silicon detectors -

- **2003: Major breakthrough on g-irradiated samples**
  - <u>For the first time</u> macroscopic changes of the <u>depletion voltage and leakage current</u> 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 <u>independent of oxygen</u> content:

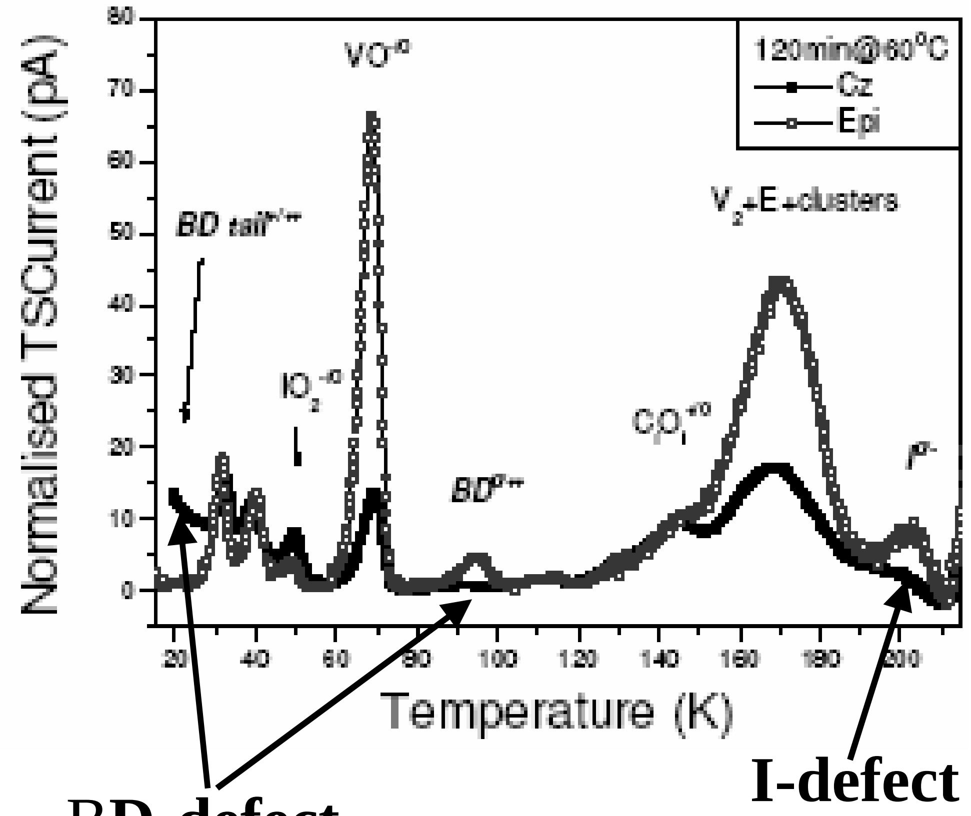
- **Donor removal**
- **“Cluster damage”   Þ negative charge**

Influenced by <u>initial oxygen</u> content:

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

Influenced by <u>initial oxygen dimer</u> content (?):

- **BD-defect:** bistable shallow thermal <u>donor</u>
  (formed via oxygen dimers O_{2i})
  Þ **positive charge**

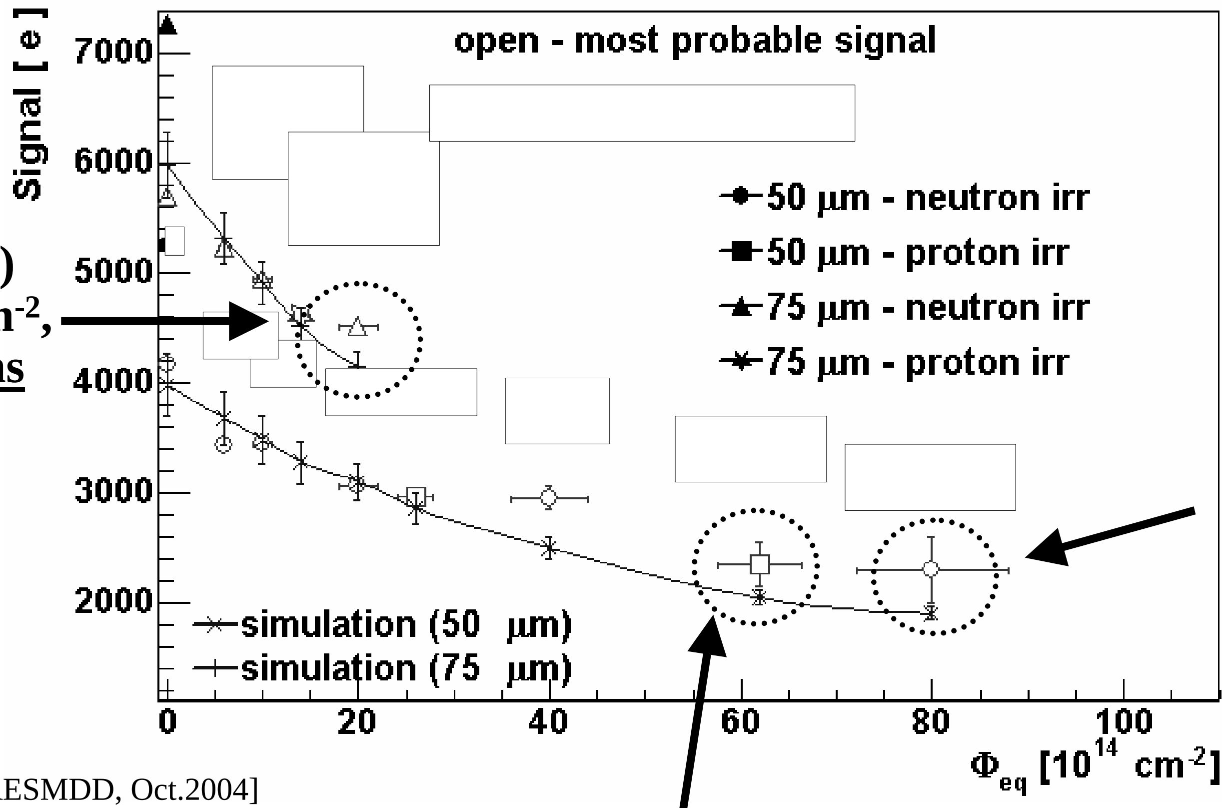


BD-defect

I-defect

Signal from irradiated EPI

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



CCE (75 mm)
F = $2x10^{15}$ n/cm^{-2},
<u>4500 electrons</u>

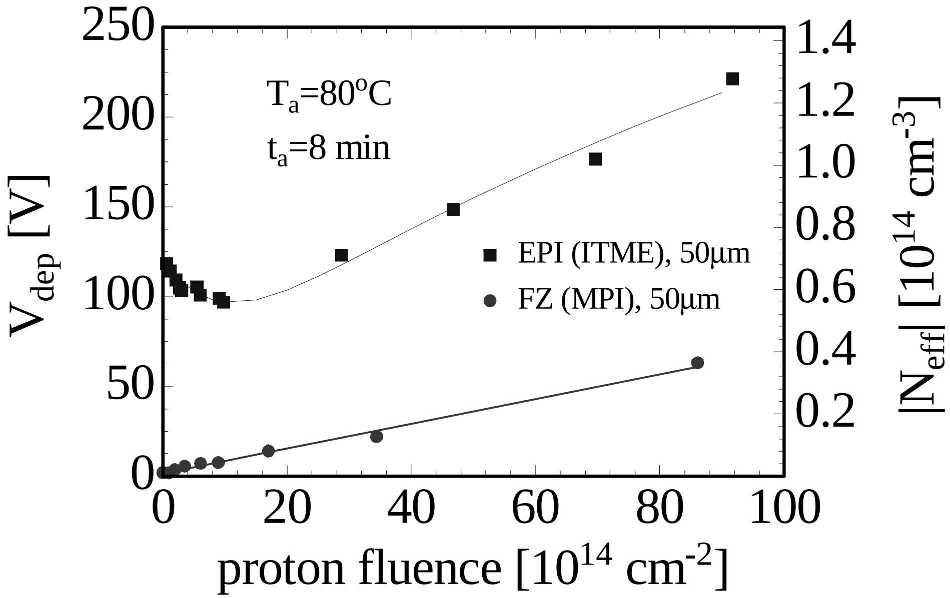
CCE (50 mm)
F $_{eq}$ = $8x10^{15}$ n/cm^{-2},
<u>2300 electrons</u>

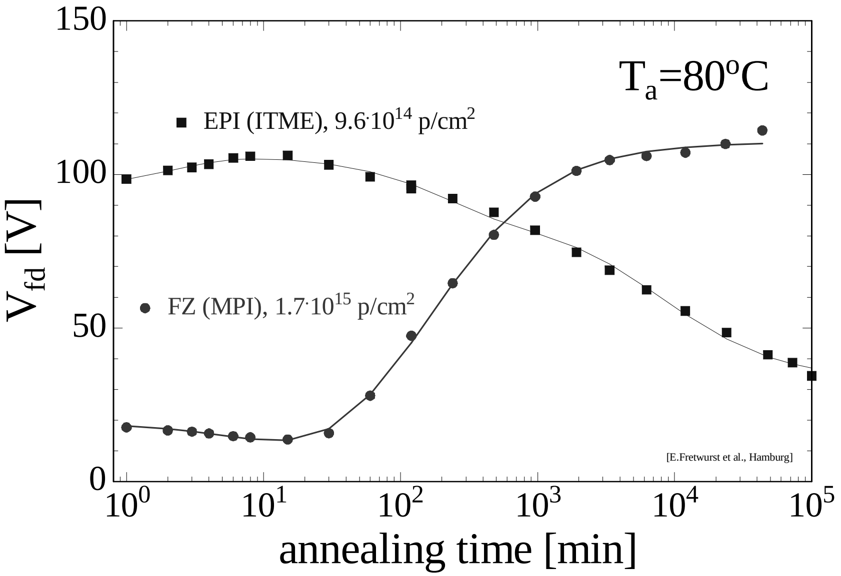
[G.Kramberger, RESMDD, Oct.2004]

CCE (50 mm): F = $1x10^{16}$cm^{-2} (24GeV/c protons)
<u>2400 electrons</u>

Epitaxial silicon - Annealing

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





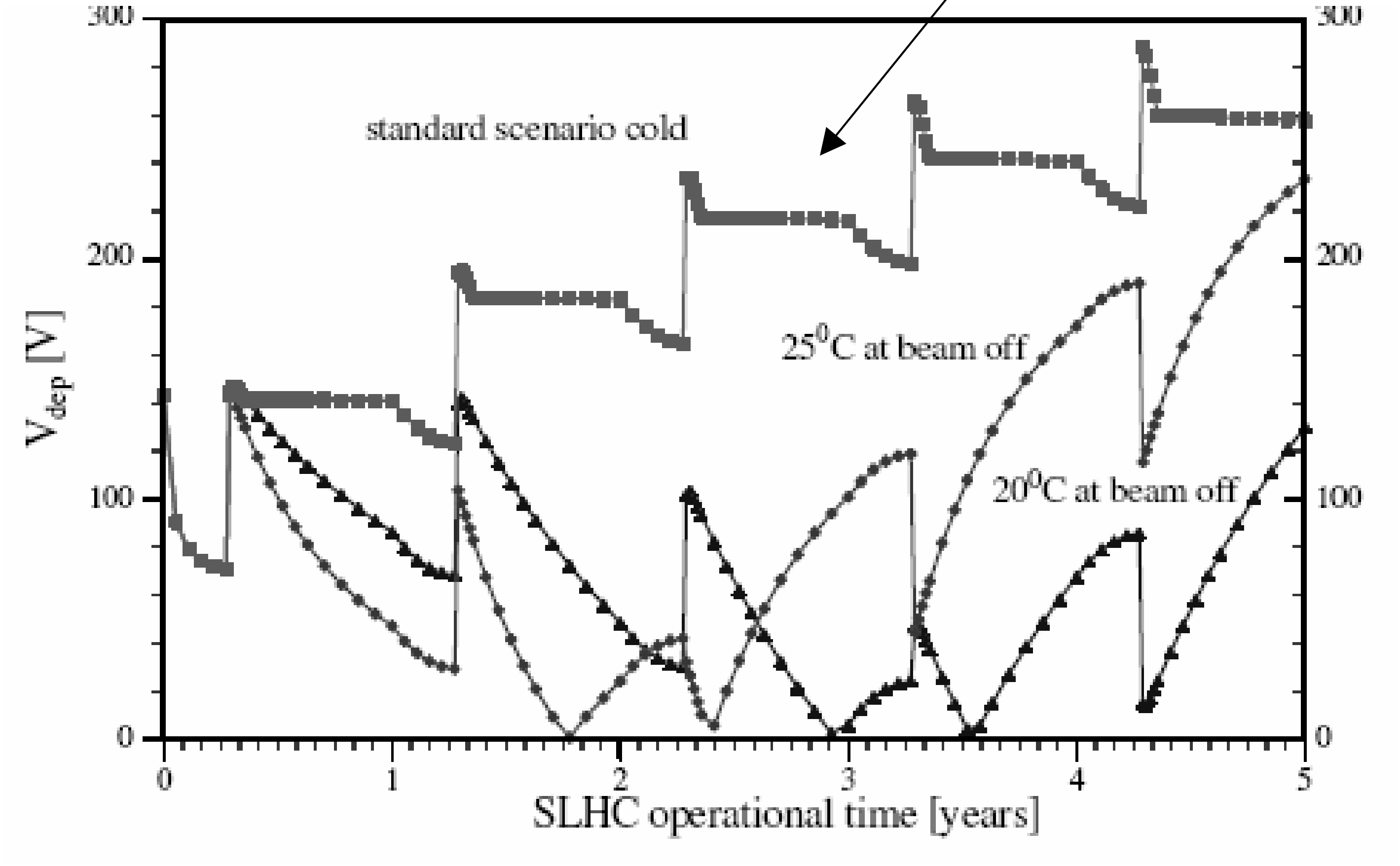
[E.Fretwurst et al.,RESMDD - October 2004]

- **Thin FZ silicon: Type inverted, increase of depletion voltage with time**
- **Epitaxial silicon: No type inversion, decrease of depletion voltage with time**
  Þ No need for low temperature during maintenance of SLHC detectors!

Damage Projection – SLHC

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

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



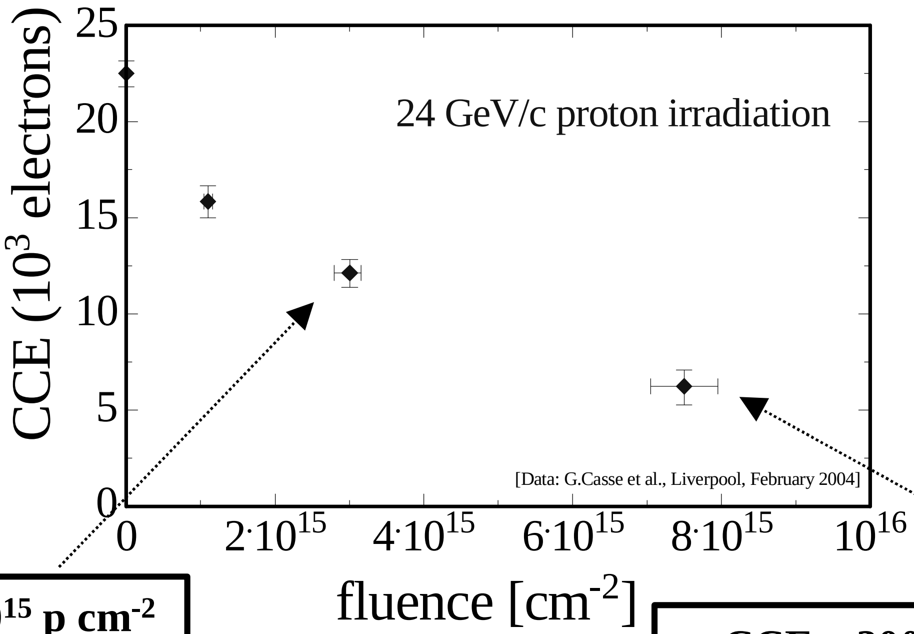
Detector without cooling when not operated (265 days warm):

- **20ºC (blue curve)**
- **25ºC (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 (280mm)**
- **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

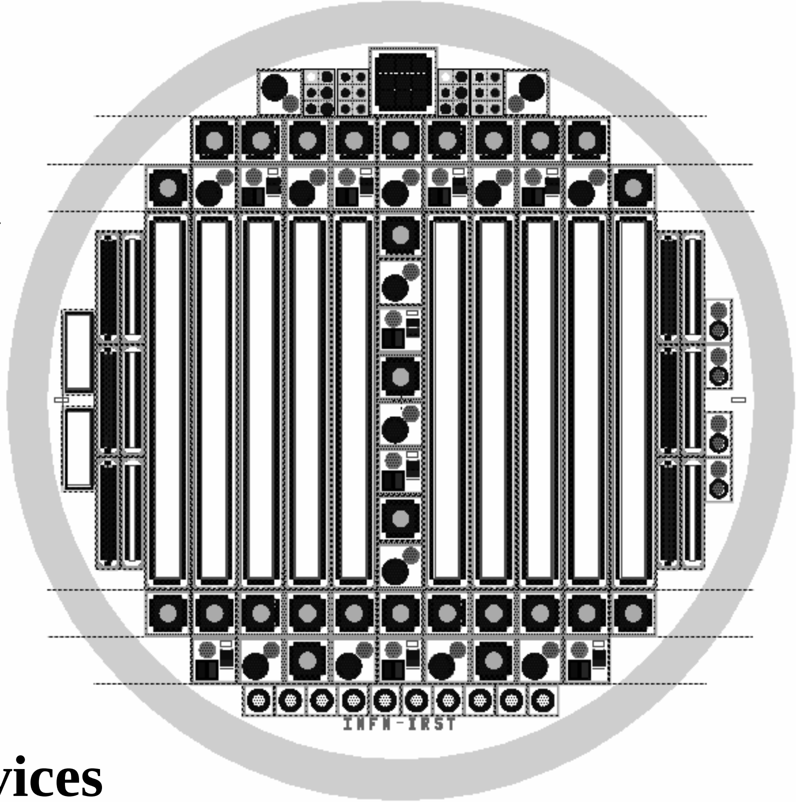
CCE ~ 60% after 3 10^{15} p cm^{-2}
at 900V(standard p-type)

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)

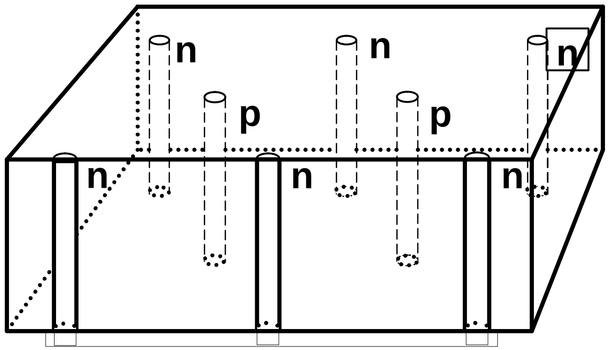


- **RD50 common mask for segmented devices**
  (coordinated by G.Casse, Liverpool)
  - **26 mini-strip (1x1cm^2, 100 strips, 80μm pitch, AC coupled)**
  - **12 pixel detectors, 20 pad diodes and various test structures**
  - **Mask produced, wafer processing with CNM Barcelona and Micron, U.K. planned for 2005 (n/p-type MCZ; n/p-type DOFZ; n/p-type epi (150 μm)**

RD50 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

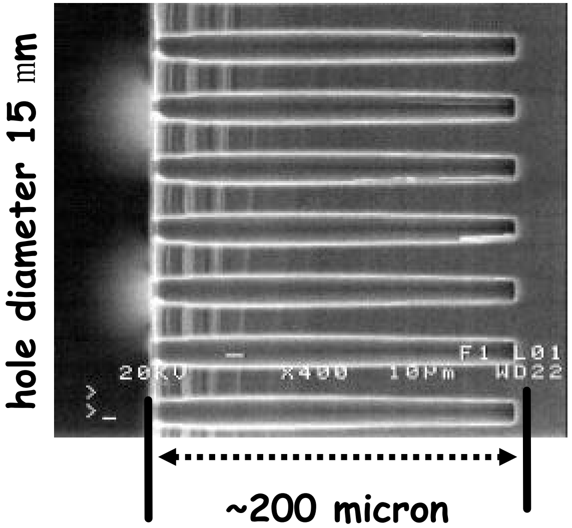
Irradiation tests up to 5x10^{14} p/cm^2 and 5x10^{14} π/cm^2:

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

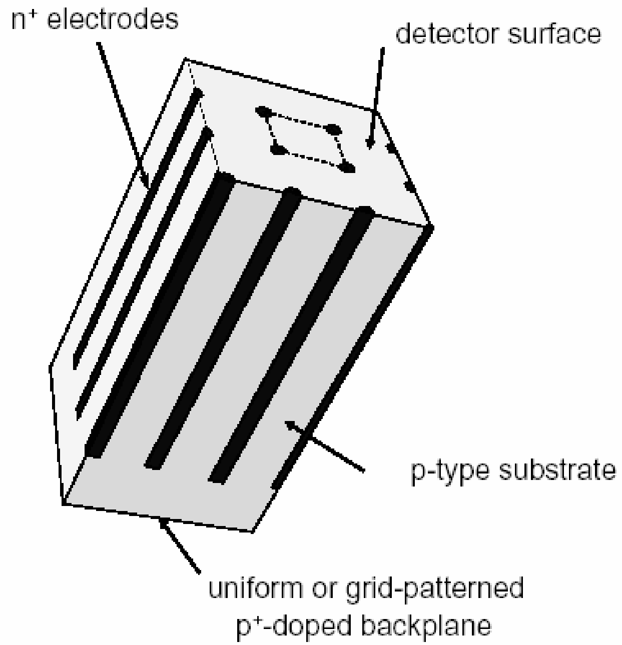
2) IRST-Trento and CNM Barcelona (since 2003)

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

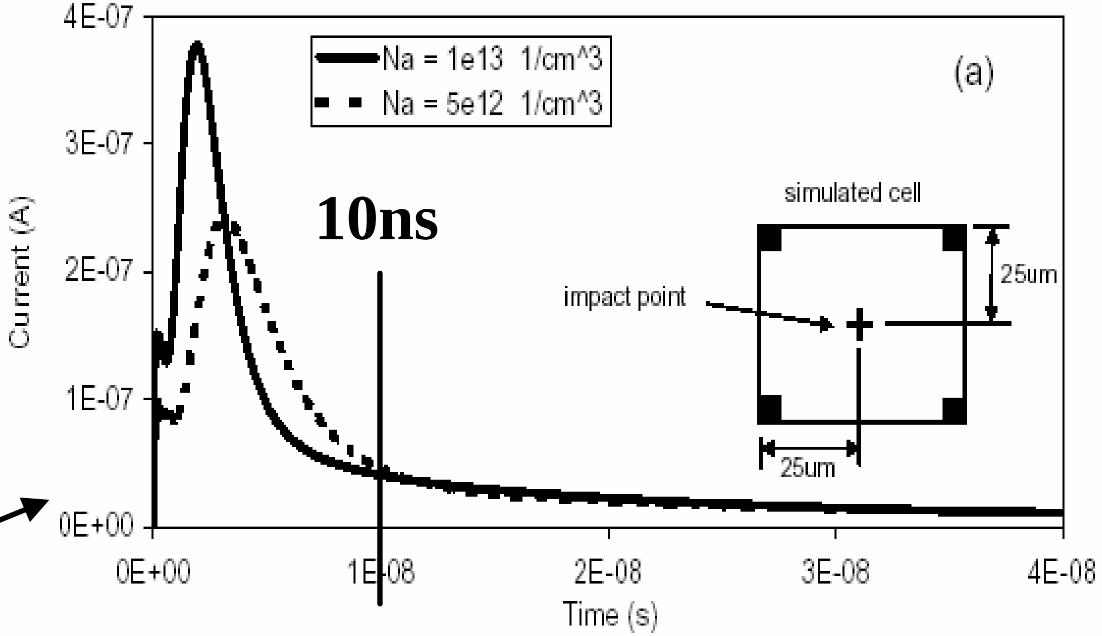
diffused contacts or doped polysilicon deposition



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.

Summary

- **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, collection of electrons

- **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

What next ?

Where should RD50
and the ATLAS experiment
start to collaborate now?

RD50 Workplan for 2005 (1/2)

Defect and Material Characterization	• **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 **produce structured prototype devices (pixel, strip) from new materials**	• 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	• Characterization (IV, CV, **CCE with** α- and b**-particles**) of test structures produced with the common RD50 masks • Common irradiation program with fluences up to 10^{16}cm^{-2}
New Materials	• **Systematic studies up to 10^{16}cm^{-2} to verify the observed radiation damage**

RD50 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	• **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**

test structured devices with your fast readout electronic

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Further information: http://cern.ch/rd50/