PIXEL 2005 international workshop, September 5-8, Bonn, Germany

Radiation Tolerant Sensors for Pixel Detectors

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CERN - Geneva - Switzerland

on behalf of the

- CERN-RD50 project –

http://www.cern.ch/rd50

Outline

- Motivation to develop radiation harder detectors: Super-LHC
- Introduction to the RD50 collaboration
- Radiation Damage in Silicon Detectors (A review in 5 slides)
  - Macroscopic damage (changes in detector properties)
- Approaches to obtain radiation hard sensors
  - Material Engineering
  - Device Engineering
- Summary

Main motivations for R&D on Radiation Tolerant Detectors: Super - LHC

- **LHC upgrade**

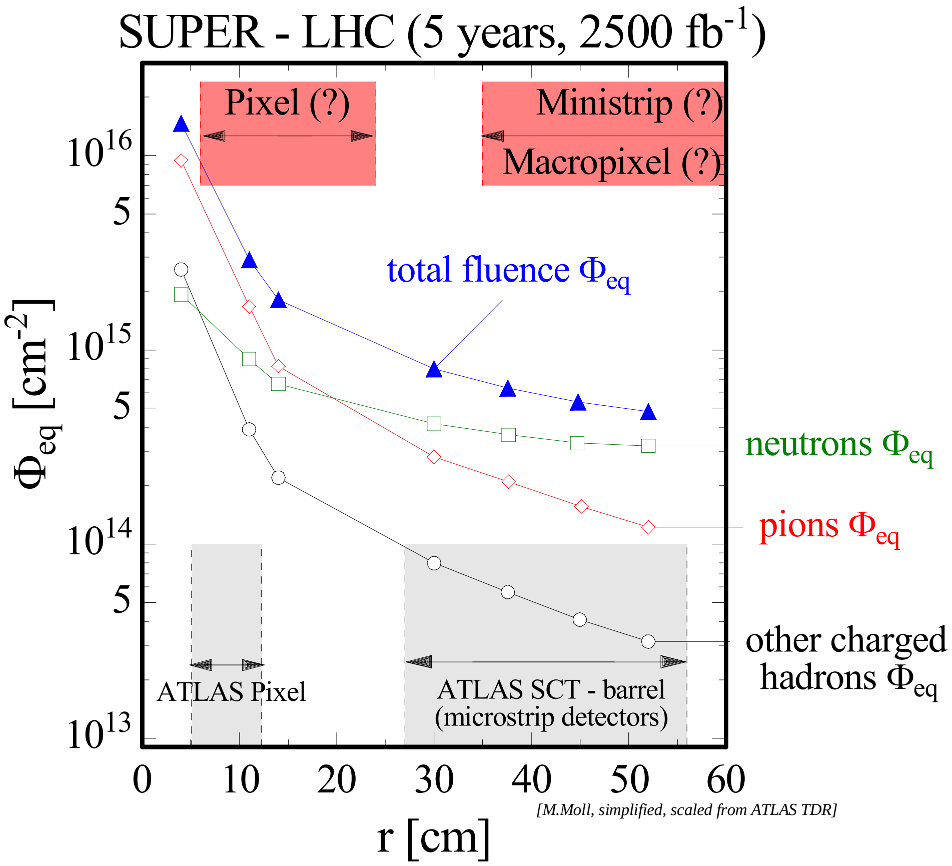
⇨**LHC (2007), L = 10^{34}cm^{-2}s^{-1}**

10 years → **500 fb^{-1}** $\phi(r=4\text{cm}) \sim 3\cdot10^{15}\text{cm}^{-2}$

× 5

⇨**Super-LHC (2015 ?), L = 10^{35}cm^{-2}s^{-1}**

5 years → **2500 fb^{-1}** $\phi(r=4\text{cm}) \sim 1.6\cdot10^{16}\text{cm}^{-2}$



[M.Moll, simplified, scaled from ATLAS TDR]

- **LHC (Replacement of components)**

e.g. - LHCb Velo detectors (~2010)
- ATLAS Pixel B-layer (~2012)

- Linear collider experiments (generic R&D)

Deep understanding of radiation damage will be fruitful for linear collider experiments where high doses of e, γ will play a significant role.

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 251 members from 51 institutes

Belarus (Minsk), Belgium (Louvain), Canada (Montreal), Czech Republic (Prague (3x)), Finland (Helsinki, Lappeenranta), Germany (Berlin, Dortmund, Erfurt, Freiburg, Hamburg, Karlsruhe), Israel (Tel Aviv), Italy (Bari, Bologna, Florence, Padova, Perugia, Pisa, Trento, Turin), Lithuania (Vilnius), Norway (Oslo (2x)), Poland (Warsaw(2x)), 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, SCIPP Santa Cruz, Syracuse University, BNL, University of New Mexico)

Radiation Damage in Silicon Sensors

A review
in 5 slides

- **Two general types of radiation damage to the detector materials:**
  - **Bulk (Crystal) damage due to Non Ionizing Energy Loss (NIEL)**
    - displacement damage, built up of crystal defects –
    - **I. Change of effective doping concentration (higher depletion voltage, under- depletion)**
    - **II. Increase of leakage current (increase of shot noise, thermal runaway)**
    - **III. Increase of charge carrier trapping (loss of charge)**
  - **Surface damage due to Ionizing Energy Loss (IEL)**
    - accumulation of positive in the oxide (SiO_2) and the Si/SiO_2 interface –
    affects: interstrip capacitance (noise factor), breakdown behavior, …
- **Impact on detector performance and Charge Collection Efficiency**
  (depending on detector type and geometry and readout electronics!)

Signal/noise ratio is the quantity to watch

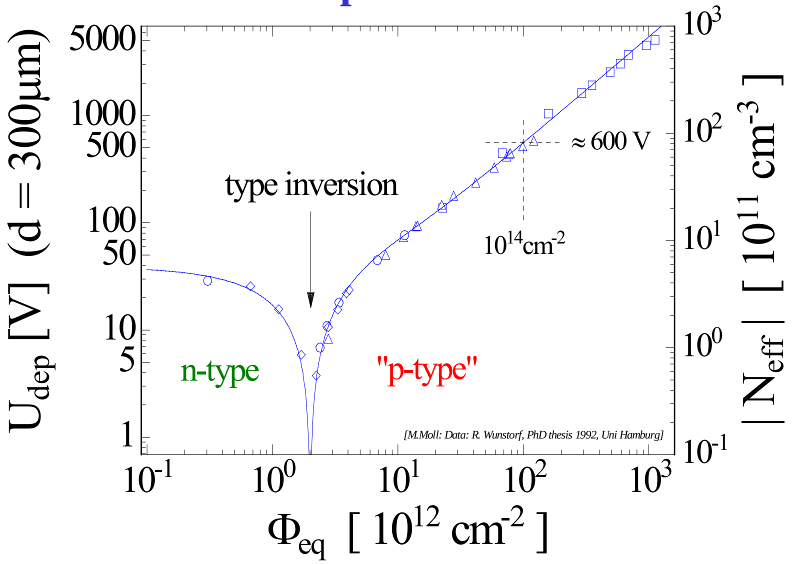
⇒ Sensors can fail from radiation damage !

RD50 Radiation Damage – I. Effective doping concentration

Review (2/5)

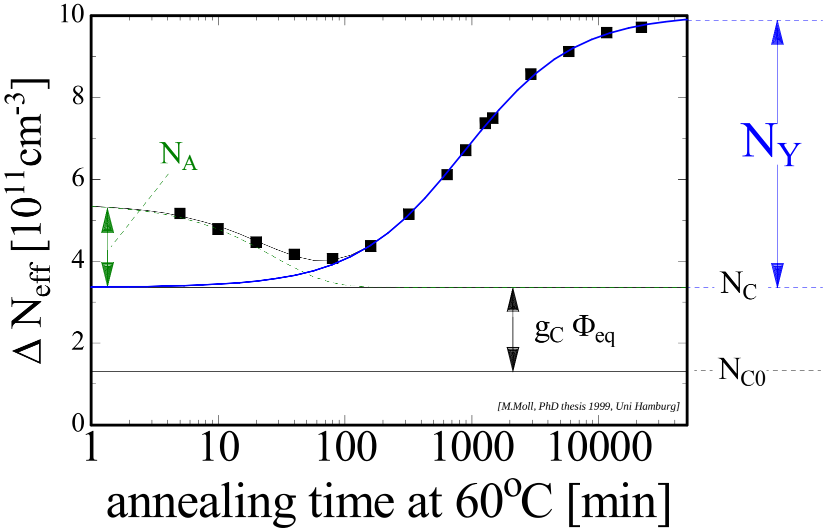
Change of Depletion Voltage V_{dep} (N_{eff})

…. with particle fluence:



[M.Moll: Data: R. Wunstorf, PhD thesis 1992, Uni Hamburg]

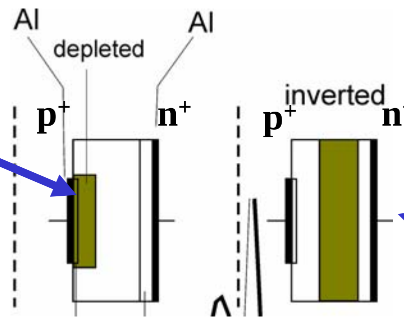
…. with time (annealing):



[M.Moll, PhD thesis 1999, Uni Hamburg]

- "**Type inversion**": N_{eff} changes from positive to negative (Space Charge Sign Inversion)

before inversion



after inversion

- Short term: "**Beneficial annealing**"
- Long term: "**Reverse annealing**"

- time constant depends on temperature:

~ 500 years (-10°C)
~ 500 days (20°C)
~ 21 hours (60°C)

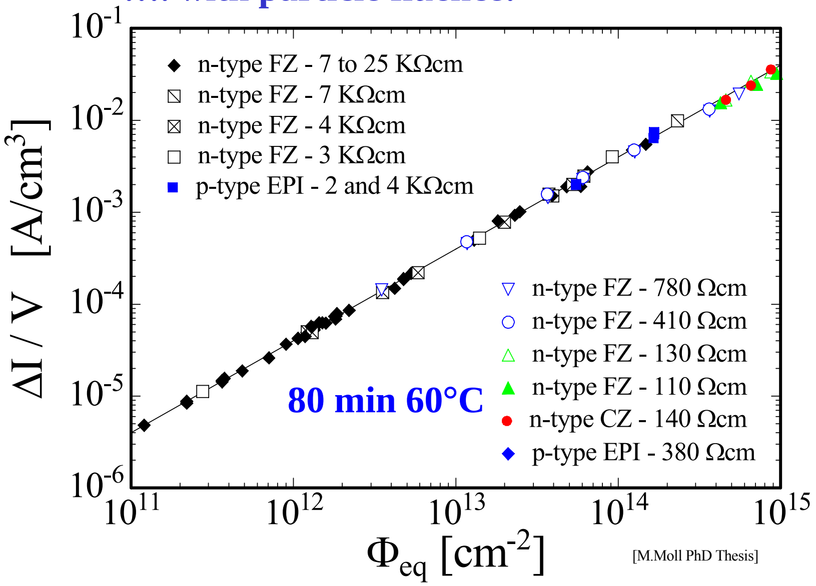
- Consequence: **Detectors must be cooled even when the experiment is not running!**

Radiation Damage – II. Leakage Current

Review (3/5)

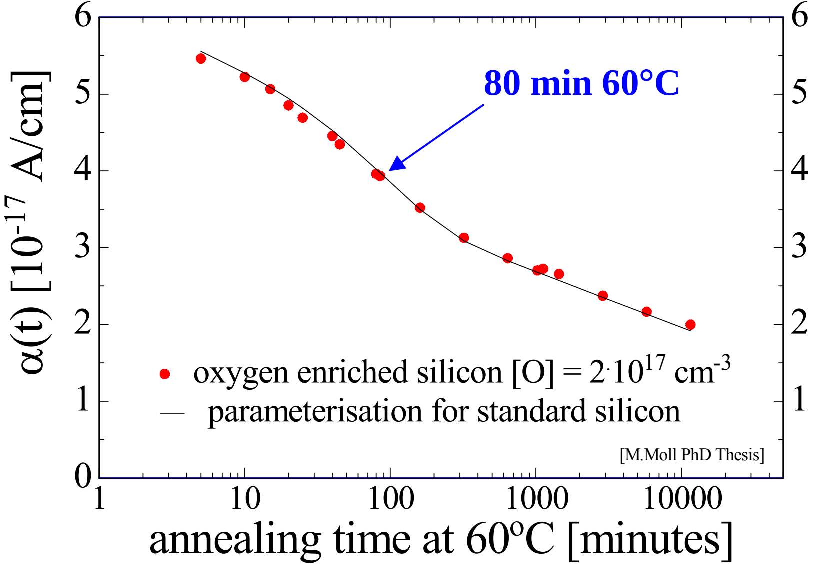
Change of Leakage Current (after hadron irradiation)

…. with particle fluence:



[M.Moll PhD Thesis]

…. with time (annealing):



[M.Moll PhD Thesis]

- **Damage parameter α (slope in figure)**

$$\boxed{\alpha = \frac{\Delta I}{V \cdot \Phi_{eq}}}$$

Leakage current per unit volume and particle fluence

- **α is constant over several orders of fluence and independent of impurity concentration in Si**
  ⇨ **can be used for fluence measurement**

- **Leakage current decreasing in time (depending on temperature)**
- **Strong temperature dependence**

$$I \propto \exp\left(- \frac{E_g}{2 k_B T} \right)$$

Consequence:

Cool detectors during operation!
Example: *I*(-10°C) ~1/16 *I*(20°C)

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Radiation Damage – III. Trapping

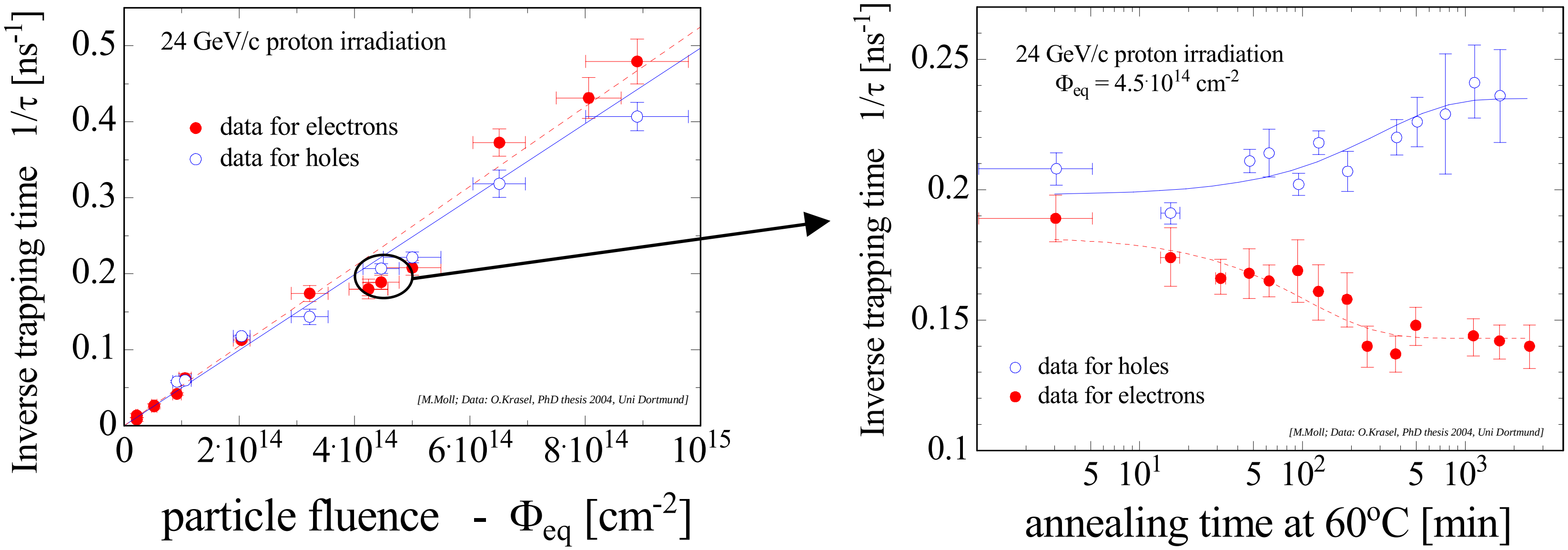
Review (4/5)

Deterioration of Charge Collection Efficiency (CCE) by trapping

Trapping is characterized by an effective trapping time τ_{eff} for electrons and holes:

$$Q_{e,h}(t) = Q_{0e,h} \exp\left(-\frac{1}{\tau_{eff\ e,h}} \cdot t\right) \qquad \text{where} \qquad \frac{1}{\tau_{eff\ e,h}} \propto N_{defects}$$

Increase of inverse trapping time (1/τ) with fluence ….. and change with time (annealing):



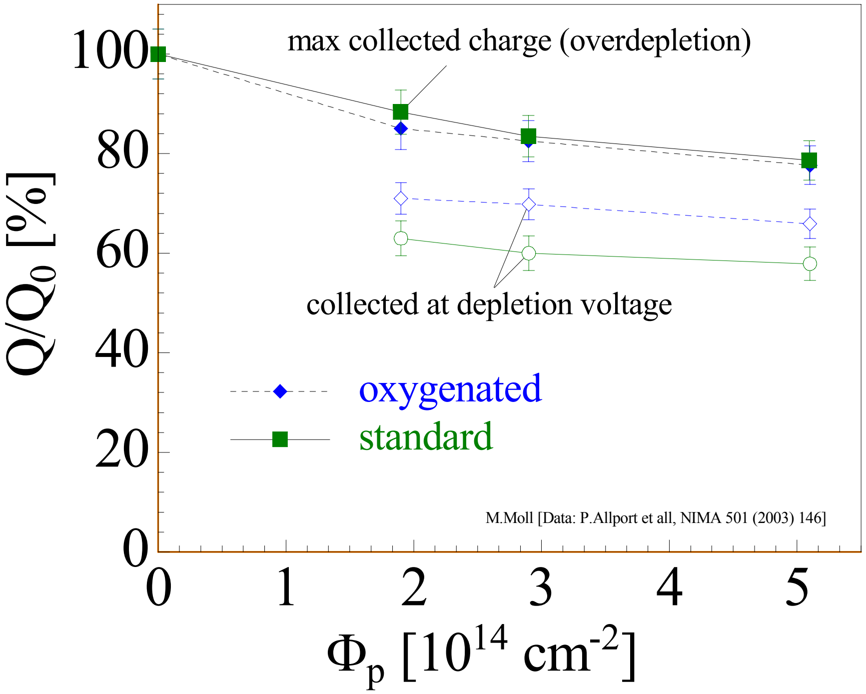
Impact on Detector: Decrease of CCE
- Loss of signal and increase of noise -

Review (5/5)

- **Two basic mechanisms reduce collectable charge:**
  - **trapping of electrons and holes ⇨ (depending on drift and shaping time !)**
  - **under-depletion ⇨ (depending on detector design and geometry !)**

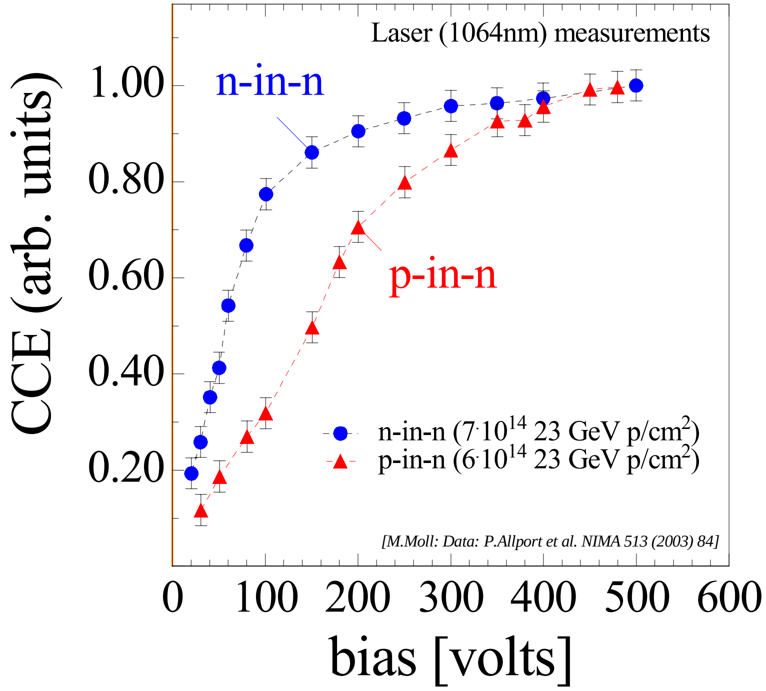
- **Example: ATLAS microstrip detectors + fast electronics (25ns)**

- **p-in-n : oxygenated versus standard FZ**
  - beta source
  - 20% charge loss after 5×10^{14} p/cm^2 (23 GeV)



M.Moll [Data: P.Allport et all, NIMA 501 (2003) 146]

- **n-in-n versus p-in-n**
  - same material, ~ same fluence
  - over-depletion needed



[M.Moll: Data: P.Allport et al. NIMA 513 (2003) 84]

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Approaches to develop radiation harder tracking detectors

Scientific strategies:

I. Material engineering

II. Device engineering

III. Change of detector operational conditions

CERN-RD39
“Cryogenic Tracking Detectors”

Talks this Workshop
H.Kagan, R.Stone
D.Moraes
S.Parker
M.Swartz

- **Defect Engineering of Silicon**
  - Understanding radiation damage
    - Macroscopic effects and Microscopic defects
    - Simulation of defect properties & kinetics
    - Irradiation with different particles & energies
  - Oxygen rich Silicon
    - DOFZ, Cz, MCZ, EPI
  - Oxygen dimer & hydrogen enriched Si
  - Pre-irradiated Si
  - Influence of processing technology
- **New Materials**
  - Silicon Carbide (SiC), Gallium Nitride (GaN)
  - Diamond: CERN RD42 Collaboration
  - Amorphous silicon
- **Device Engineering (New Detector Designs)**
  - p-type silicon detectors (n-in-p)
  - thin detectors
  - 3D and Semi 3D detectors
  - Stripixels
  - Cost effective detectors
  - Simulation of highly irradiated detectors
  - Monolithic devices

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  - **Material Engineering**
  - Device Engineering
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Sensor Materials

Property	**Diamond**	**GaN**	**4H SiC**	**Si**
E_g [eV]	**5.5**	**3.39**	**3.26**	**1.12**
$E_{breakdown}$ [V/cm]	10^7	$4\cdot10^6$	$2.2\cdot10^6$	$3\cdot10^5$
μ_e [cm^2/Vs]	1800	1000	800	1450
μ_h [cm^2/Vs]	1200	30	115	450
v_{sat} [cm/s]	$2.2\cdot10^7$	-	$2\cdot10^7$	$0.8\cdot10^7$
Z	6	31/7	14/6	14
ε_r	5.7	9.6	9.7	11.9
e-h energy [eV]	**13**	**8.9**	**7.6-8.4**	**3.6**
Density [g/cm3]	3.515	6.15	3.22	2.33
Displacem. [eV]	**43**	**≥15**	**25**	**13-20**

- **Wide bandgap (3.3eV)**

⇒ lower leakage current than silicon

- **Signal:**

Diamond	**36 e/µm**
SiC	**51 e/µm**
Si	**89 e/µm**

⇒ more charge than diamond

- **Higher displacement threshold than silicon**

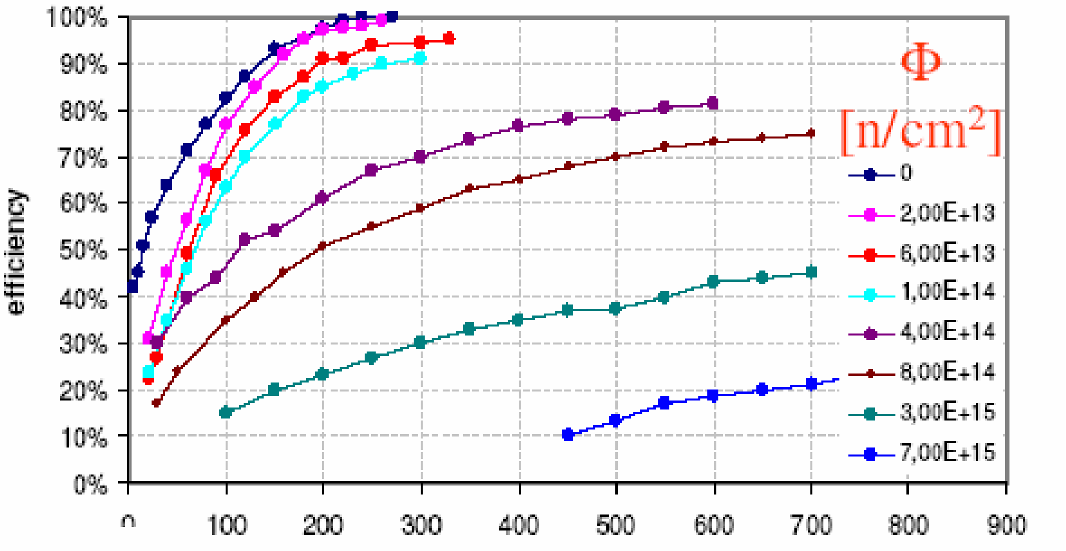
⇒ radiation harder than silicon (?)

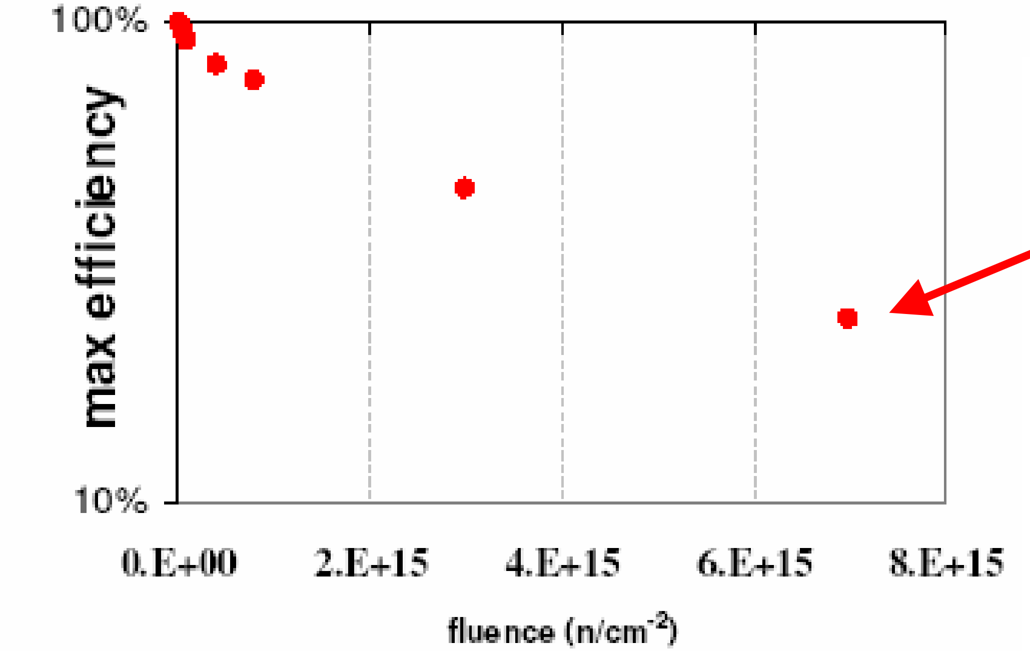
R&D on diamond detectors:
RD42 – Collaboration
http://cern.ch/rd42/

Recent review: P.J.Sellin and J.Vaitkus on behalf of RD50 “New materials for radiation hard semiconductor detectors”, submitted to NIMA

SiC: CCE after irradiation

- **CCE before irradiation**
  - **100 % with α particles and MIPS**
  - **tested on various samples 20-40µm**
- **CCE after irradiation**
  - **with α particles**
  - **neutron irradiated samples**
  - **material produced by CREE**
  - **25 µm thick layer**





[S.Sciortino et al., presented on the RESMDD 04 conference, in press with NIMA]

20% CCE (α)
after 7x10^{15} n/cm^2!

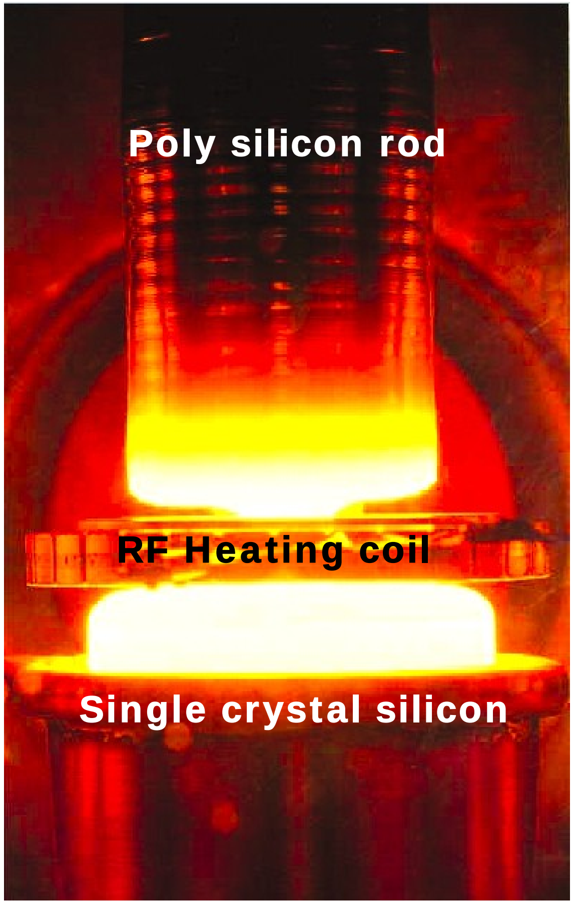
35% CCE(β) (CCD ~6µm ; ~ 300 e)
after 1.4x10^{16} p/cm^2

➔ much less than in silicon (see later)

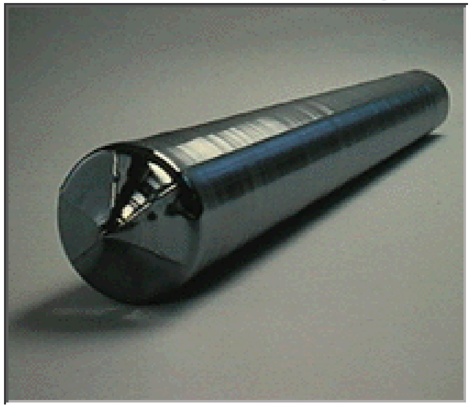
Material: Float Zone Silicon (FZ)

Float Zone process

- Using a single Si crystal seed, melt the vertically oriented rod onto the seed using RF power and "pull" the monocrystalline ingot



Mono-crystalline Ingot



Wafer production

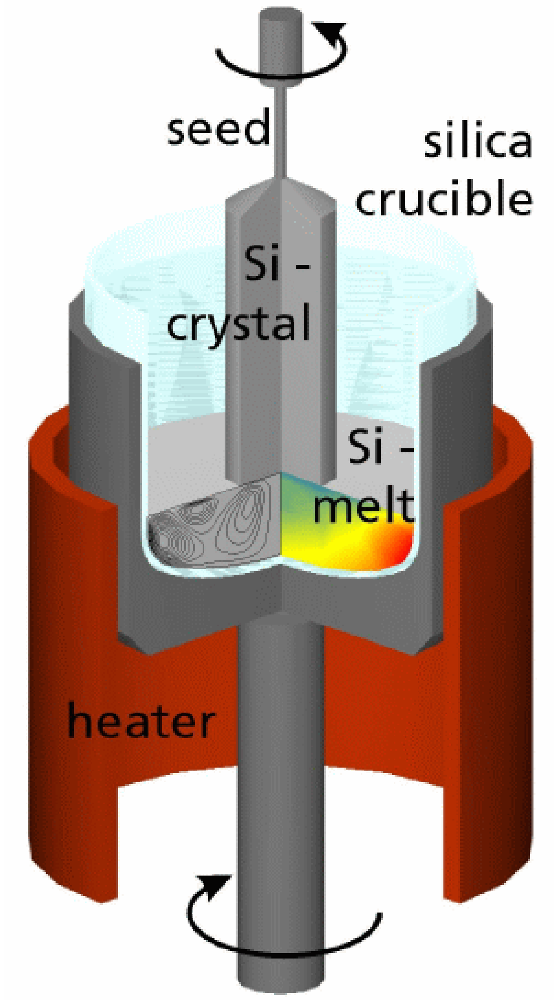
- Slicing, lapping, etching, polishing

Oxygen enrichment (DOFZ)

- Oxidation of wafer at high temperatures

RD50 Czochralski silicon (Cz) & Epitaxial silicon (EPI)

Czochralski silicon



- Pull Si-crystal from a Si-melt contained in a silica crucible while rotating.
- Silica crucible is dissolving oxygen into the melt ⇨ high concentration of O in CZ
- Material used by IC industry (cheap)
- Recent developments (~2 years) made CZ available in sufficiently high purity (resistivity) to allow for use as particle detector.

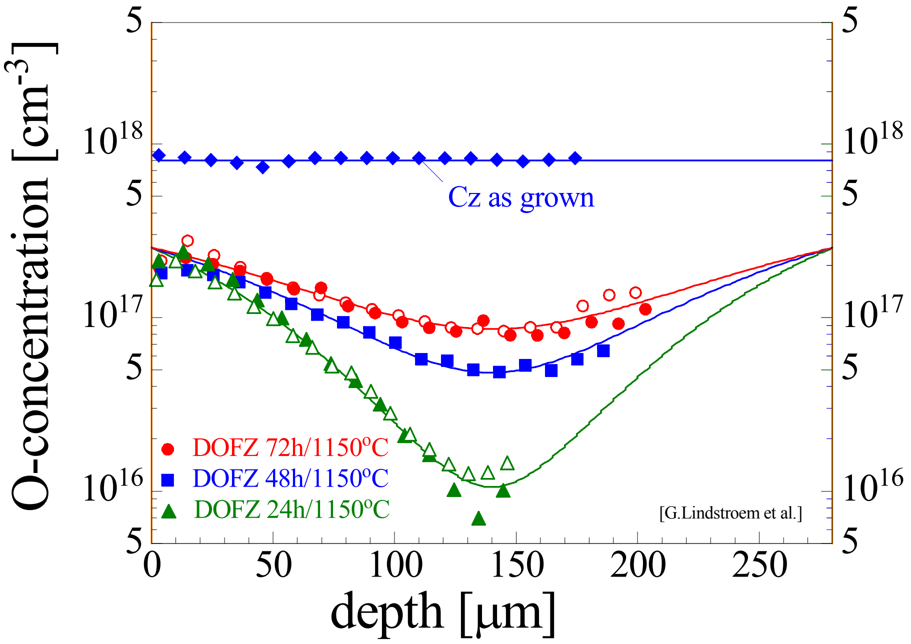
Epitaxial silicon

- Chemical-Vapor Deposition (CVD) of Silicon
- CZ silicon substrate used ⇨ in-diffusion of oxygen
- growth rate about 1μm/min
- excellent homogeneity of resistivity
- up to 150 μm thick layers produced (thicker is possible)
- price depending on thickness of epi-layer but not extending ~ 3 x price of FZ wafer

RD50 Oxygen concentration in FZ, CZ and EPI

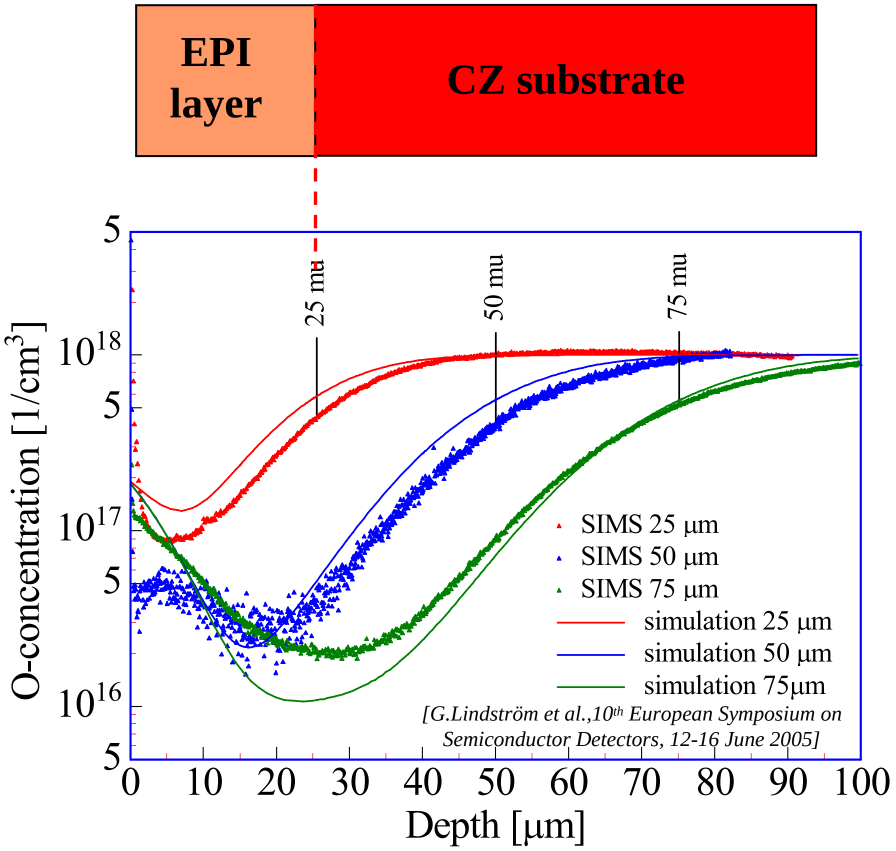
Cz and DOFZ silicon

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



- DOFZ: inhomogeneous oxygen distribution
- DOFZ: oxygen content increasing with time at high temperature

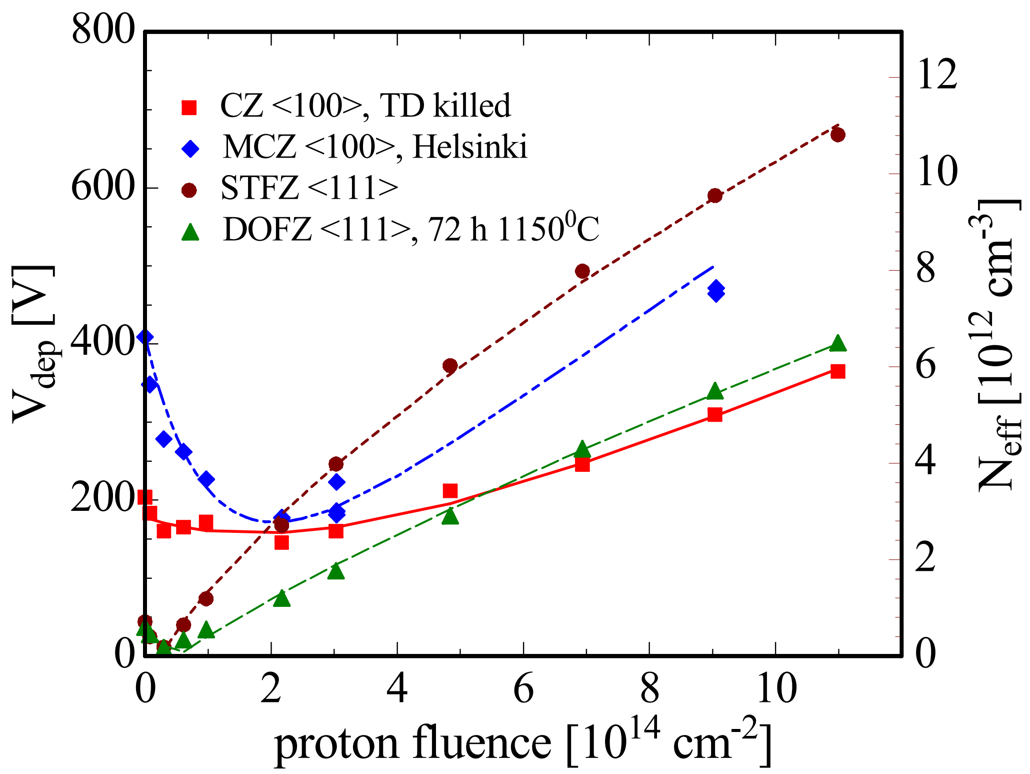
Epitaxial silicon



- EPI: O_i and O_{2i} (?) diffusion from substrate into epi-layer during production
- EPI: in-homogeneous oxygen distribution

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)**
    (verified for CZ silicon by TCT measurements, preliminary result for MCZ silicon)
    ⇒ **donor generation overcompensates acceptor generation in high fluence range**

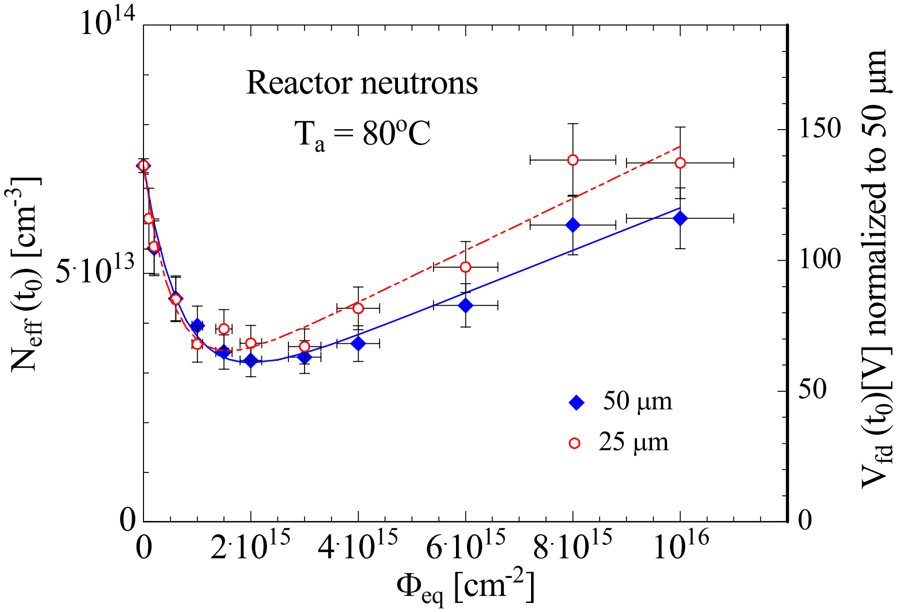
- **Common to all materials (after hadron irradiation):**
  - **reverse current increase**
  - **increase of trapping (electrons and holes) within ~ 20%**

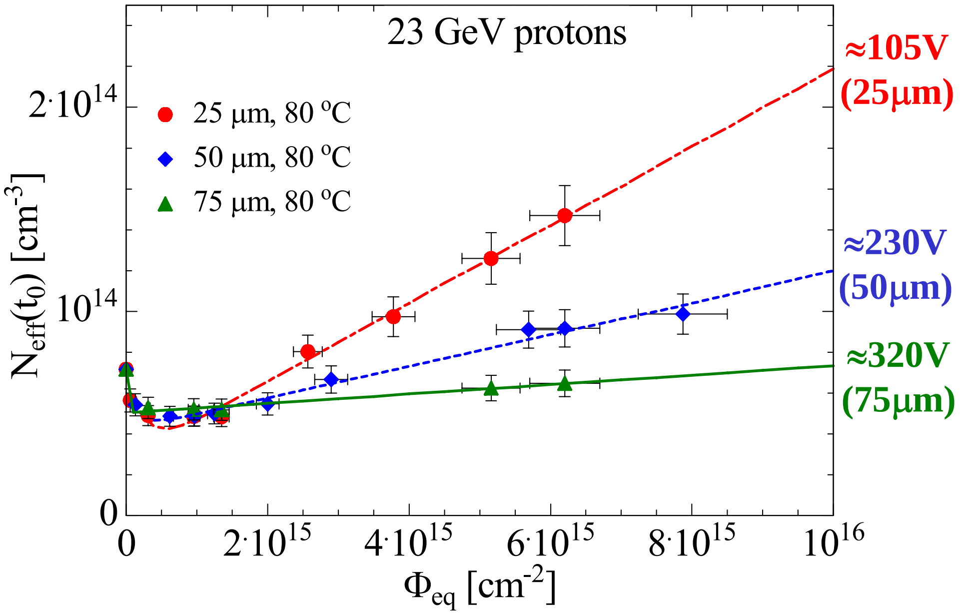
EPI Devices – Irradiation experiments

- **Epitaxial silicon grown by ITME**

G.Lindström et al.,10th European Symposium on Semiconductor Detectors, 12-16 June 2005

  - **Layer thickness: 25, 50, 75 μm; resistivity: ~ 50 Ωcm**
  - **Oxygen: [O] ≈ 9×10^{16}cm^{-3}; Oxygen dimers (detected via IO_2-defect formation)**





- **No type inversion in the full range up to ~ 10^{16} p/cm^2 and ~ 10^{16} n/cm^2**
  (type inversion only observed during long term annealing)

- **Proposed explanation:**
  introduction of shallow donors bigger than generation of deep acceptors

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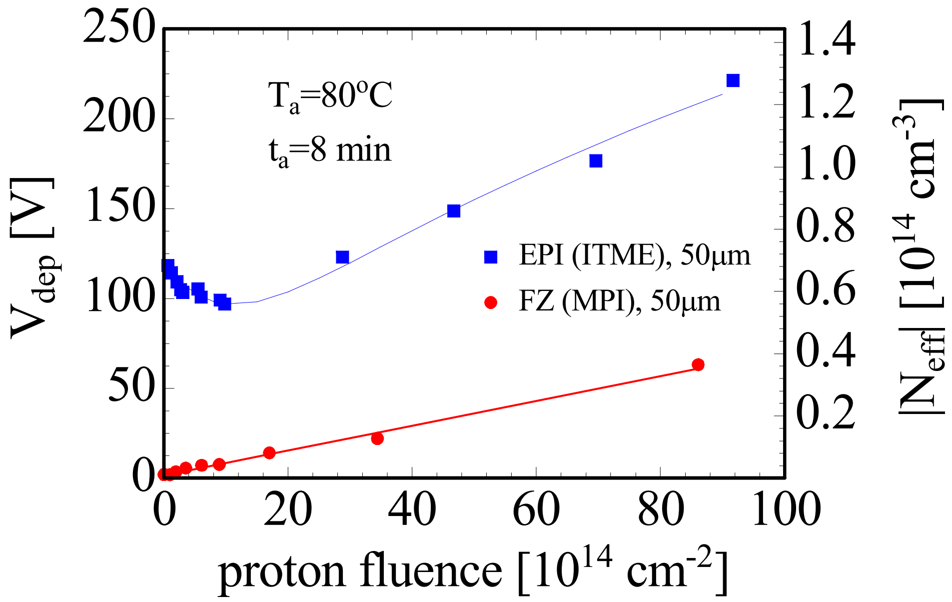
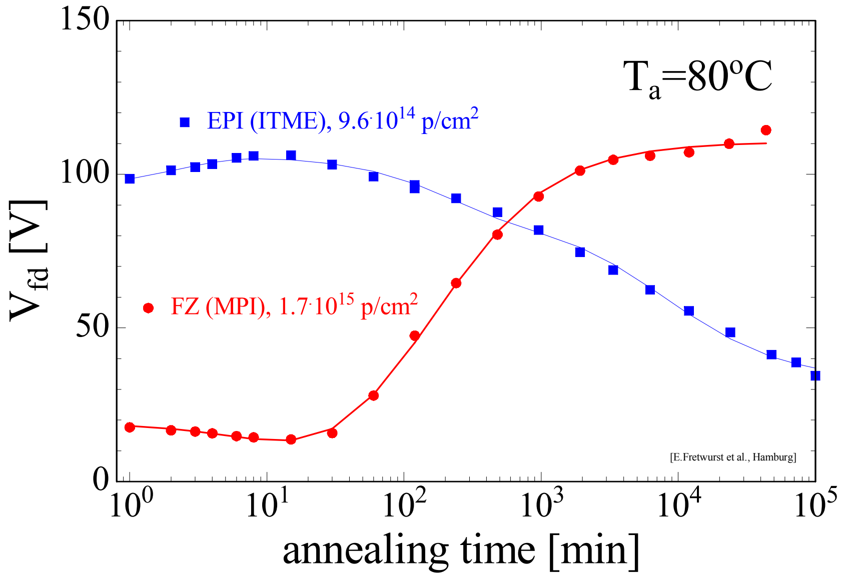
Epitaxial silicon - Annealing

- **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]

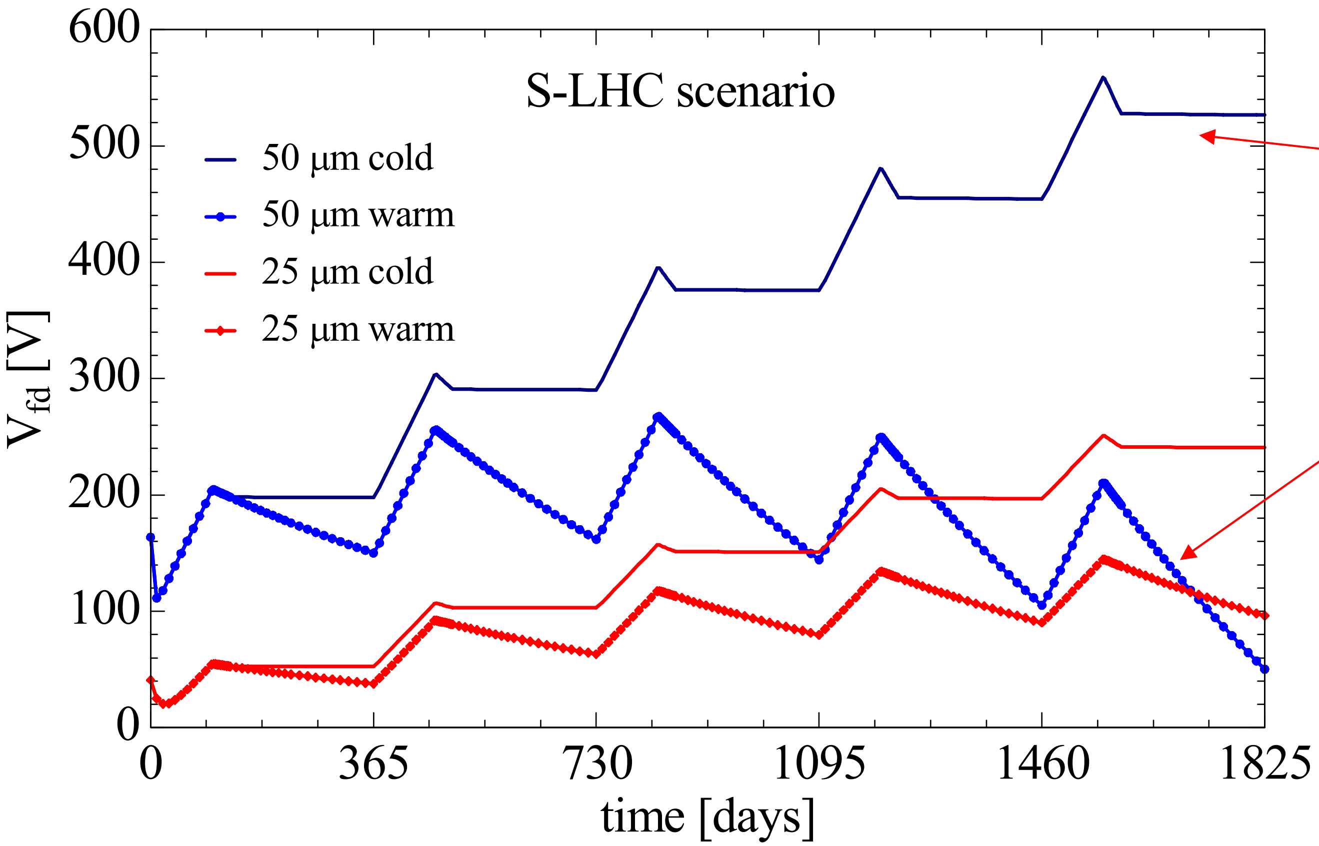
- **Thin FZ silicon: Type inverted, increase of depletion voltage with time**
- **Epitaxial silicon: No type inversion, decrease of depletion voltage with time**

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

Damage Projection – SLHC
- 50 µm EPI silicon: a solution for pixels ?-

G.Lindström et al.,10th European Symposium on Semiconductor Detectors, 12-16 June 2005 (Damage projection: M.Moll)

- **Radiation level (4cm):** $\Phi_{eq}(\text{year}) = 3.5 \times 10^{15}\ \text{cm}^{-2}$
- **SLHC-scenario:** 1 year = 100 days beam (-7°C)
  30 days maintenance (20°C)
  235 days no beam (-7°C or 20°C)

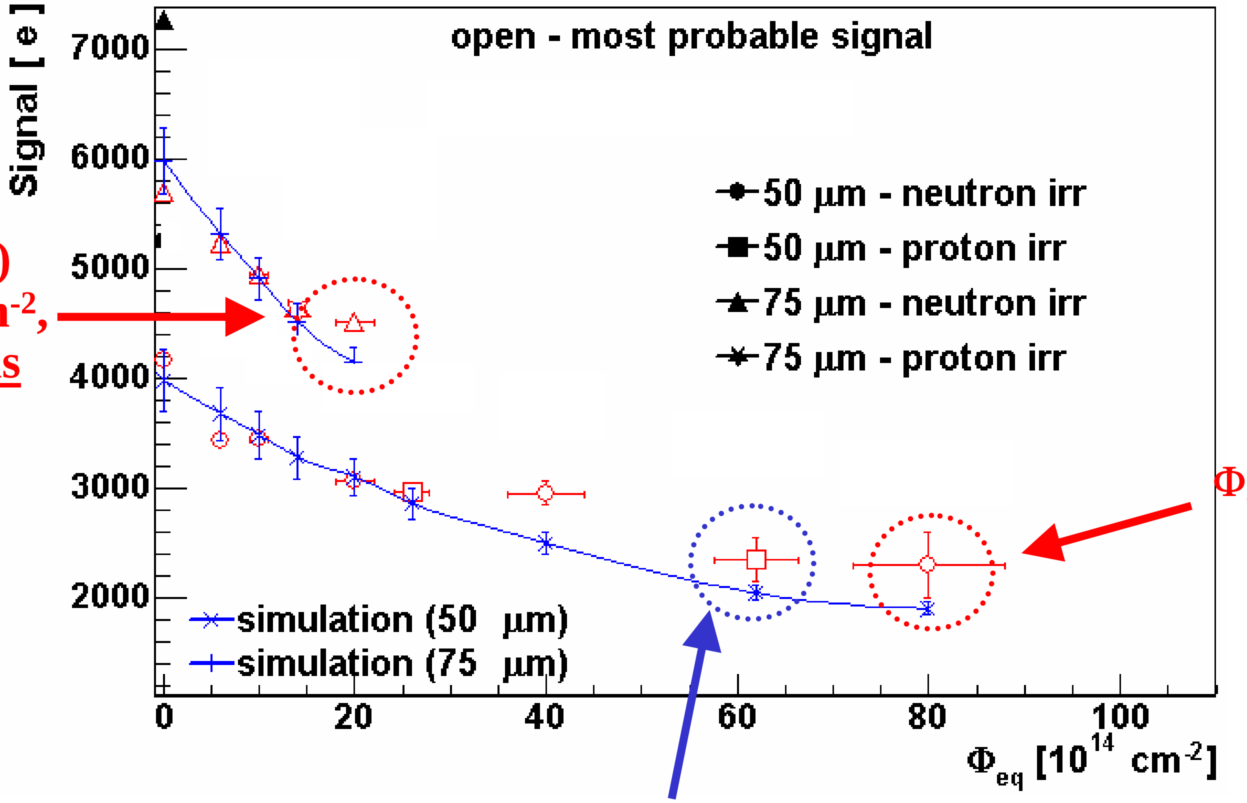


Detector with cooling when not operated

Detector without cooling when not operated

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)
$\Phi = 2\times10^{15}$ n/cm^{-2},
4500 electrons

CCE (50 µm)
$\Phi_{eq} = 8\times10^{15}$ n/cm^{-2},
2300 electrons

CCE (50 µm): $\Phi = 1\times10^{16}$cm^{-2} (24GeV/c protons)
2400 electrons

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

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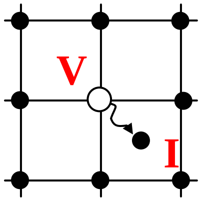
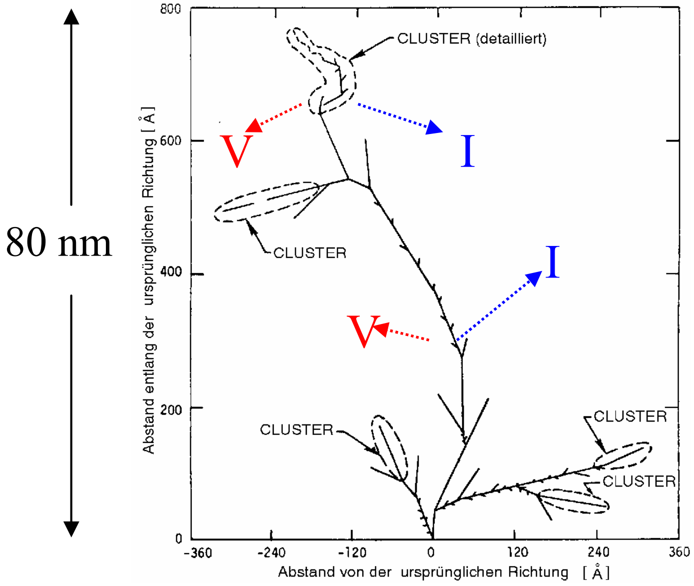
Microscopic defects

- **Damage to the silicon crystal:** Displacement of lattice atoms

- **particle** ⟶ Si_S $\xrightarrow{E_K>25\ eV}$ **Vacancy + Interstitial** ⇔ “point defects”, mobile in silicon, can react with impurities (O,C,..)



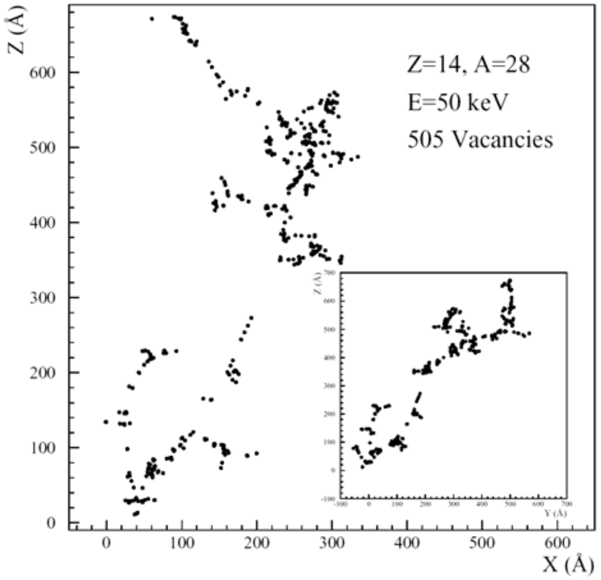
$E_K > 5\ keV$ ⟶ **point defects and clusters of defects**



Distribution of vacancies created by a 50 keV Si-ion in silicon (typical recoil energy for 1 MeV neutrons):

⟵ **Schematic**
[Van Lint 1980]

Simulation ⟶
[M.Huhtinen 2001]



- **Defects can be electrically active (levels in the band gap)**
  - capture and release electrons and holes from conduction and valence band

  ⇒ can be charged - can be generation/recombination centers - can be trapping centers

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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**

Levels responsible for depletion voltage changes after proton irradiation:

Almost independent of oxygen content:

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

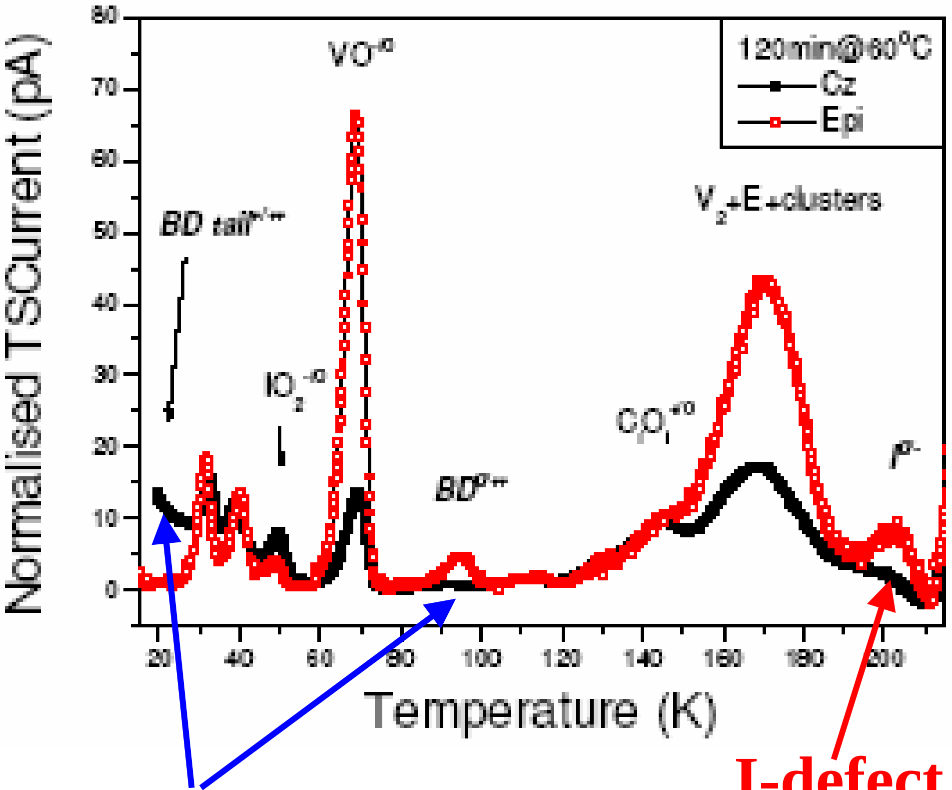
Influenced by initial oxygen content:

- **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**

[I.Pintilie, RESMDD, Oct.2004]



BD-defect

I-defect

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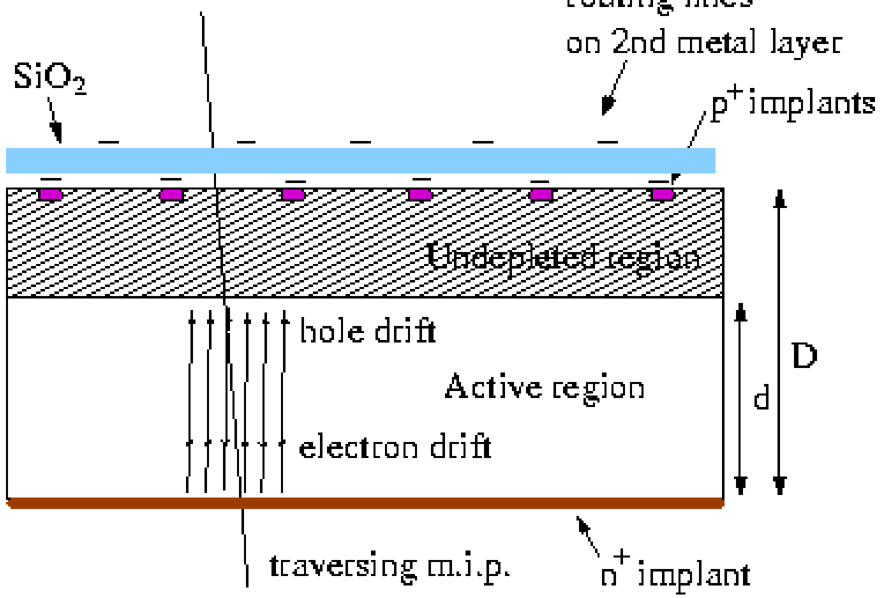
Device engineering

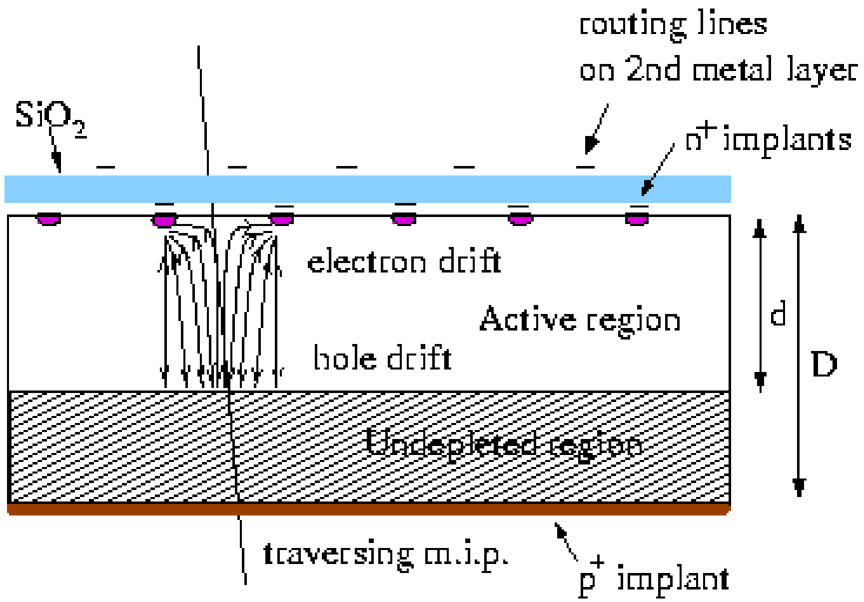
p-in-n versus n-in-n detectors

n-type silicon after type inversion:

p^+on-n



n^+on-n



p-on-n silicon, under-depleted:

- **Charge spread – degraded resolution**
- **Charge loss – reduced CCE**

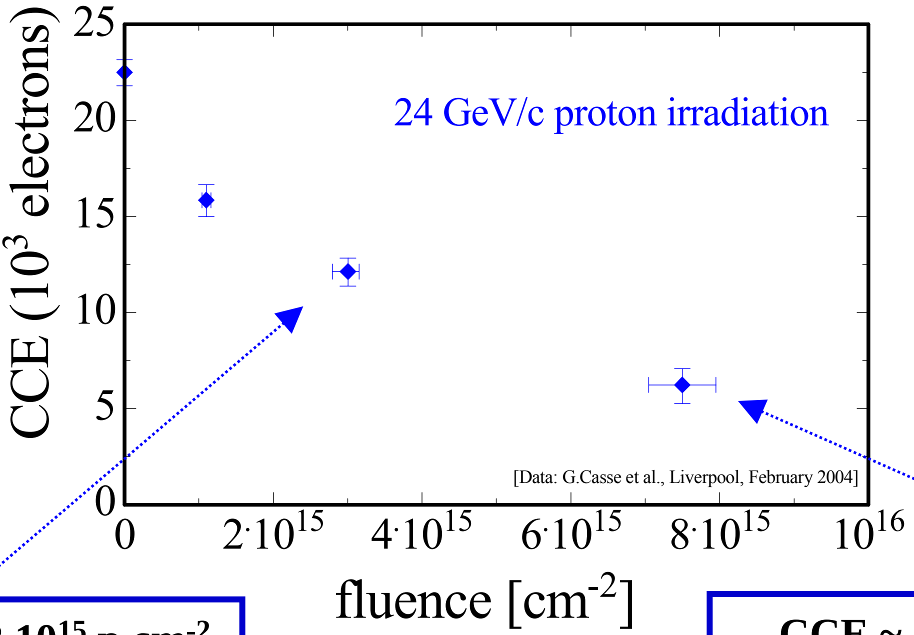
n-on-n silicon, under-depleted:

- **Limited loss in CCE**
- **Less degradation with under-depletion**
- **Collect electrons (fast)**

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:



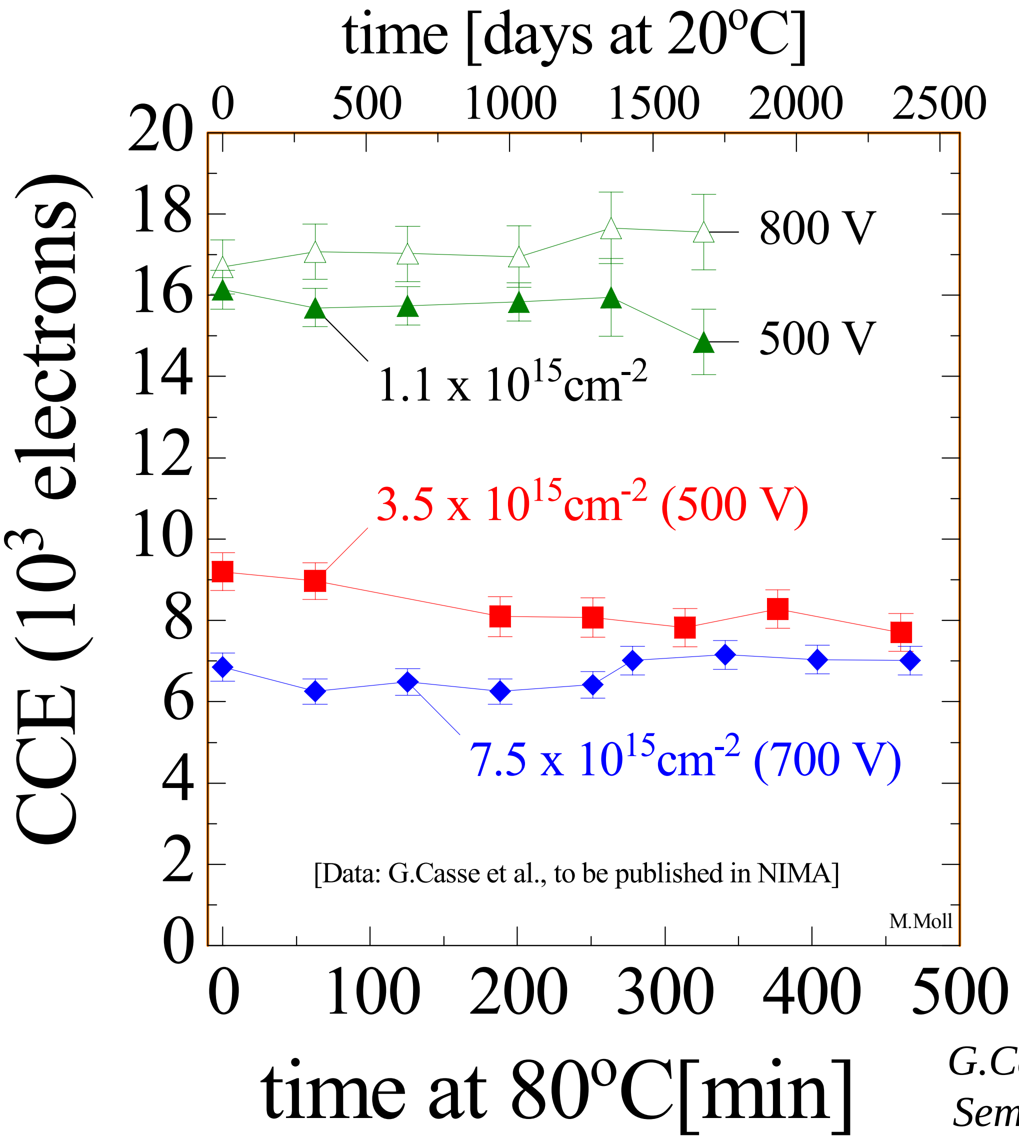
G. Casse et al.,
NIMA535(2004) 362

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

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)

Annealing of p-type sensors



- **p-type strip detector (280μm) irradiated with 23 GeV p (7.5×10^{15} p/cm^2)**
- **expected from previous CV measurement of V_{dep}:**
  - before reverse annealing:

  V_{dep}~ 2800V

  - after reverse annealing

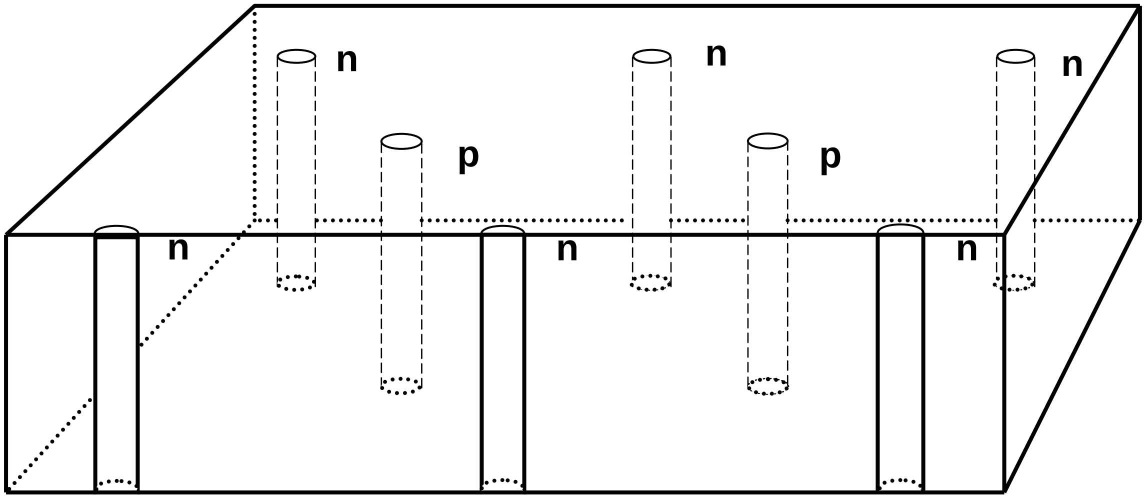
  V_{dep} > 12000V
- **no reverse annealing visible in the CCE measurement !**

G.Casse et al.,10th European Symposium on Semiconductor Detectors, 12-16 June 2005

3D detectors

- **Introduced by:** - S.I. Parker C.J. Kenney and J. Segal, NIMA 395 (1997) 328
- **“3D” electrodes:** - narrow columns along detector thickness,
  - diameter: 10μm, distance: 50 - 100μm
- **Lateral depletion:** - lower depletion voltage needed
  - thicker detectors possible
  - fast signal

See presentation on Thursday Morning:
S.Parker “3D sensors”



3D & Single Type Column 3D detectors

- **Introduced by:** - S.I. Parker C.J. Kenney and J. Segal, NIMA 395 (1997) 328
- **“3D” electrodes:** - narrow columns along detector thickness,
  - diameter: 10μm, distance: 50 - 100μm
- **Lateral depletion:** - lower depletion voltage needed
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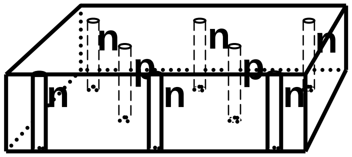
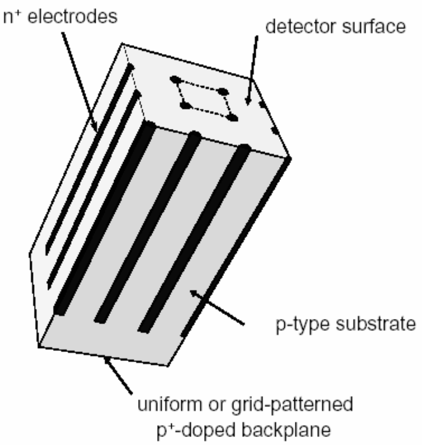


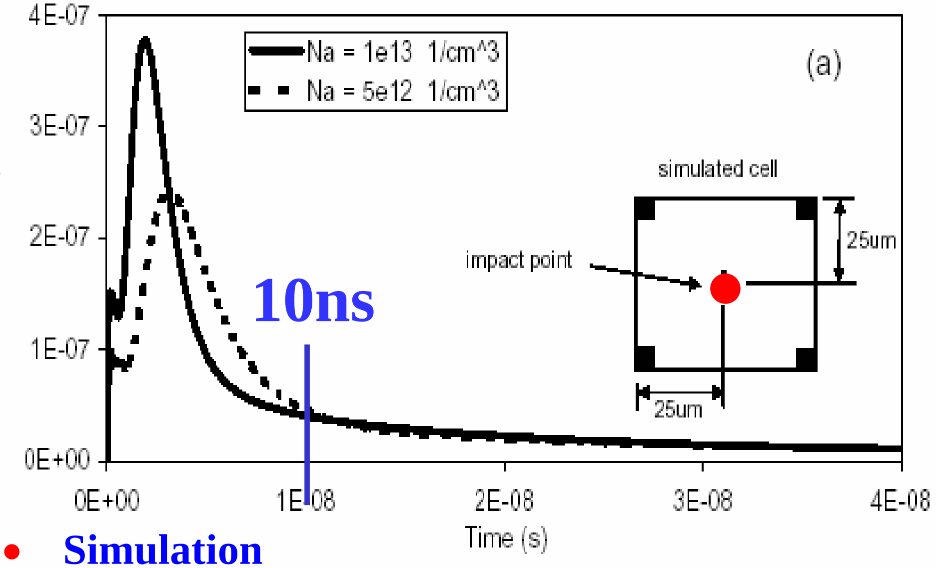
See presentation on Thursday Morning:
S.Parker “3D sensors”

- **Simplified 3D architecture**
  - n^+ columns in p-type substrate, p^+ backplane
  - operation similar to standard 3D detector

[C. Piemonte et al.,
NIM A541 (2005) 441]



- **Simplified process**
  - hole etching and doping only done once
  - no wafer bonding technology needed



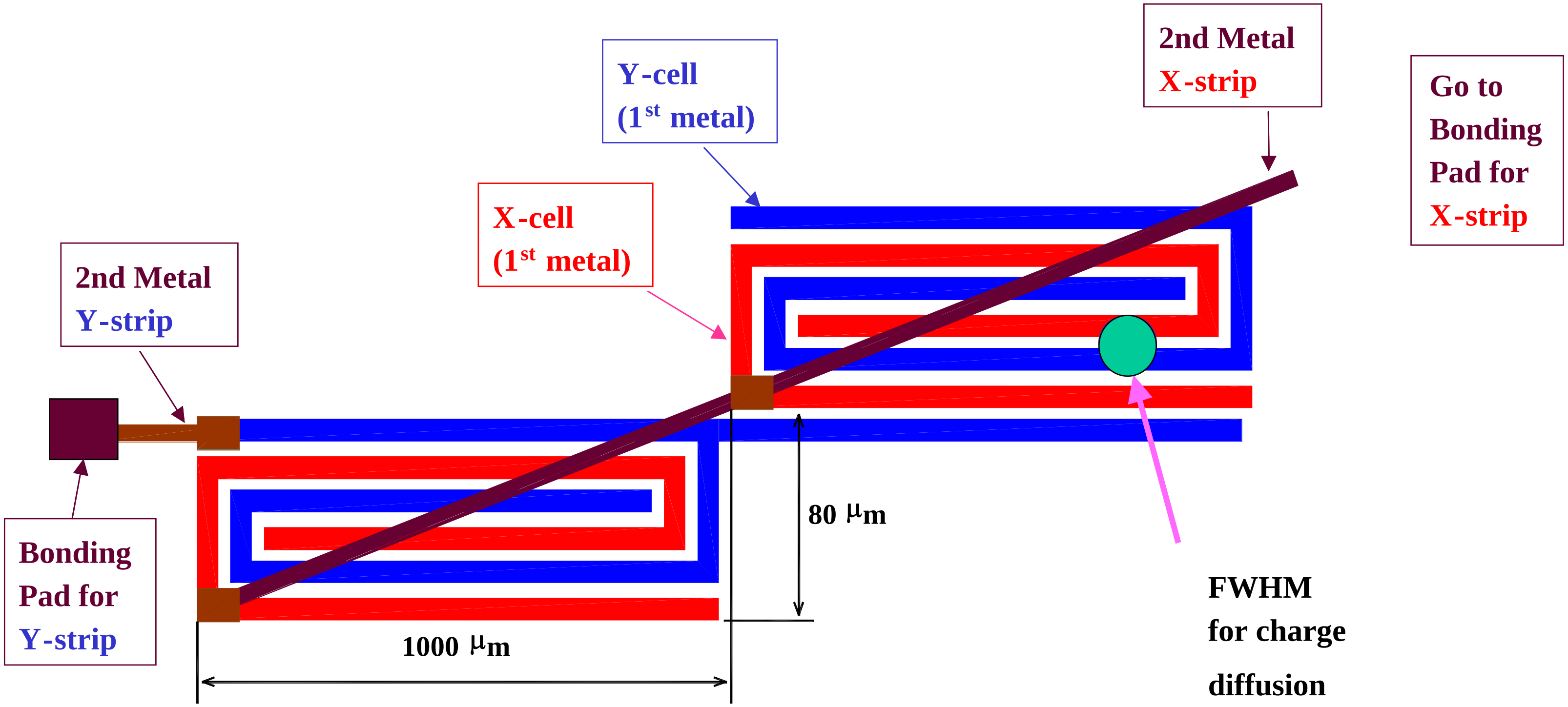
- **Simulation**
  - worst case shown (hit in middle of cell)
  - still CCE below 10ns possible
- **Fabrication:**
  - under way IRST(Italy), CNM Barcelona

RD50

Example for new structures - Stripixel

- **New structures: There is a multitude of concepts for new** (planar and mixed planar & 3D) **detector structures aiming for improved radiation tolerance or less costly detectors** (see e.g. Z.Li - 6th RD50 workshop)

- **Example: Stripixel concept:**



Z. Li, D. Lissauer, D. Lynn, P. O'Connor, V. Radeka

Summary

- **At fluences up to 10^{15}cm^{-2} (Outer layers of a SLHC detector) the change of 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)
  - **p-type silicon microstrip detectors show very encouraging results:**
    CCE ≈ 6500 e; $\Phi_{eq} = 4\times10^{15}$ cm^{-2}, 300μm, collection of electrons,
    no reverse annealing observed in CCE measurement!

- **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 promising new options are:
  Thin/EPI detectors : drawback: radiation hard electronics for low signals needed
  e.g. 2300e at Φ_{eq} 8×10^{15}cm^{-2}, 50μm EPI,
  …. thicker layers will be tested in 2005/2006
  3D detectors : drawback: technology has to be optimized
  ….. steady progress within RD50

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

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