Common ATLAS CMS Electronics Workshop, CERN, March 20, 2007

# Radiation Tolerant Silicon Sensors for Tracking Detectors

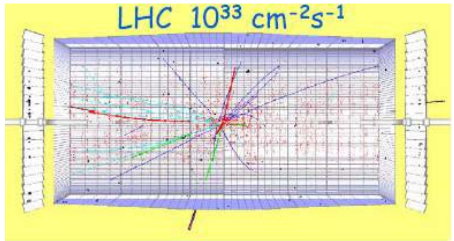
- On behalf of the RD50 collaboration -

**Michael Moll (CERN-PH-DT2)**

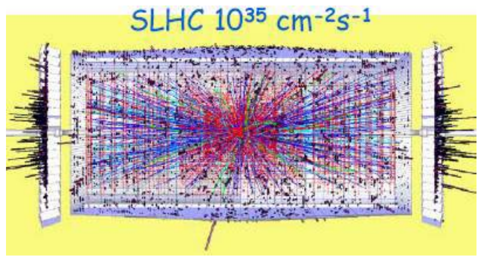
## OUTLINE

- Motivation
- Radiation Damage in Silicon Sensors
- Approaches to obtain radiation tolerant sensors
  - Material Engineering
  - Device Engineering
- Conclusions

# RD50 Motivation: SLHC




⇒




- **Super - LHC upgrade**

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

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

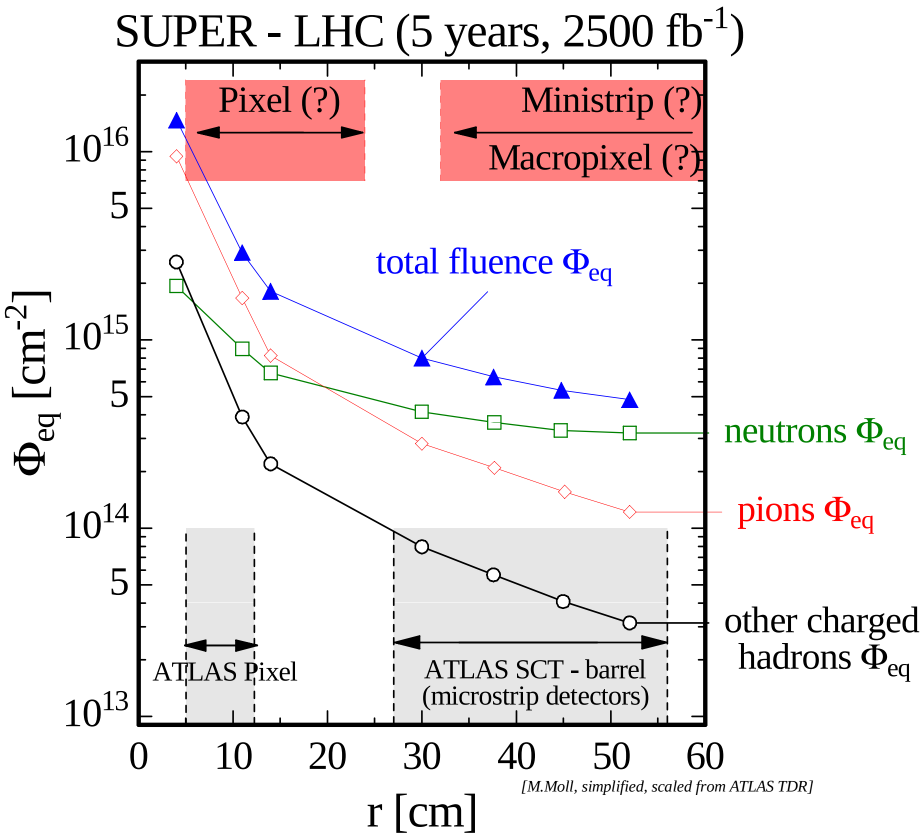
**× 5**

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

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

- **LHC upgrades**

  e.g. - LHCb Velo detectors
  - ATLAS Pixel B-layer



# RD50 Reminder: Radiation Damage in Silicon Sensors

- **Two general types of radiation damage:**

  - **Bulk (Crystal) damage due to Non Ionizing Energy Loss (NIEL)**
    - displacement damage, built up of crystal defects –

**Influenced by impurities in Si – Defect Engineering is possible!**

**I. Change of effective doping concentration**
⇒ type inversion, higher depletion voltage, under-depletion
⇒ loss of active volume ⇒ decrease of signal, increase of noise

**II. Increase of leakage current**
⇒ increase of shot noise, thermal runaway, power consumption…

**Same for all tested Silicon materials!**

**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 –
    ⇒ interstrip capacitance, breakdown behavior, …

- **Impact on detector performance and Charge Collection Efficiency**
  (depending on detector type and geometry and readout electronics!)

**Can be optimized!**

⇒ **Signal/noise ratio is the quantity to watch**

# RD50 Approaches

**Scientific strategies:**

I. Material engineering

II. Device engineering

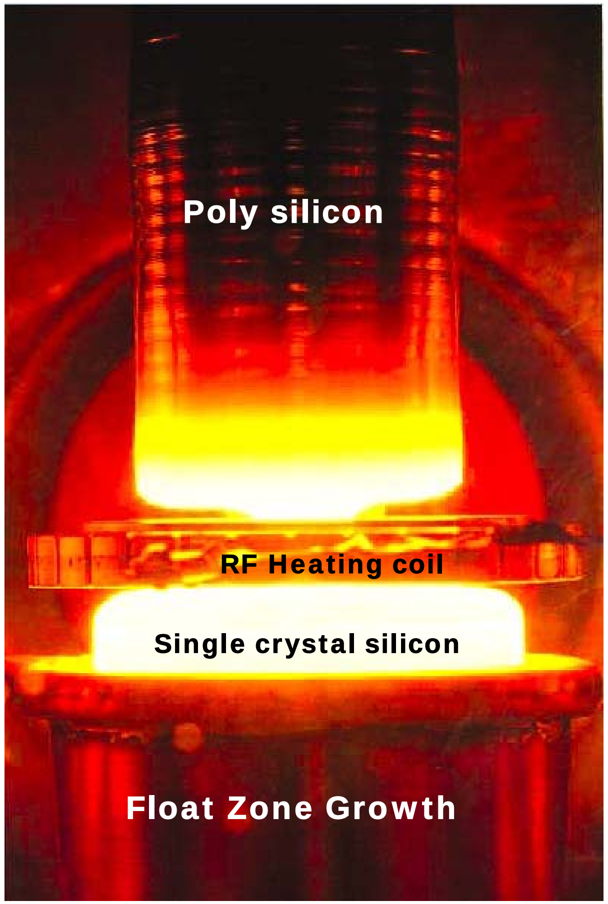
III. Change of detector operational conditions

CERN-RD39
**"Cryogenic Tracking Detectors"**

- **Defect Engineering of Silicon**
  - **Understanding radiation damage**
    - Macroscopic effects and Microscopic defects
    - Simulation of defect properties & kinetics
    - Irradiation with different particles & energies
  - **Oxygen rich silicon**
    - **DOFZ, Cz, MCZ, EPI**
  - Oxygen dimer or hydrogen enriched silicon
  - Pre-irradiated silicon
  - Influence of processing technology
- **New Materials**
  - Silicon Carbide (SiC), Gallium Nitride (GaN)
  - **Diamond: CERN RD42 Collaboration**
- **Device Engineering (New Detector Designs)**
  - **p-type silicon detectors (n-in-p)**
  - **Thin detectors**
  - **3D detectors** and Semi 3D detectors
  - Cost effective detectors
  - Simulation of highly irradiated detectors
  - Monolithic devices (not inside RD50)

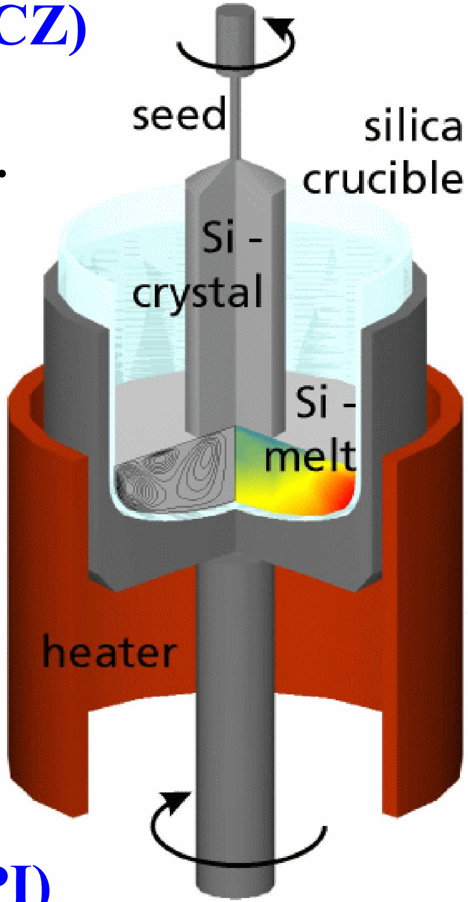
# Silicon Growth Processes

- **Floating Zone Silicon (FZ)**




- **Basically all silicon detectors made out of high resistivity FZ silicon**

- **Czochralski Silicon (CZ)**
  - **The growth method used by the IC industry.**
  - **Difficult to produce very high resistivity**


- **Epitaxial Silicon (EPI)**
  - **Chemical-Vapor Deposition (CVD) of Si**
  - **up to 150 µm thick layers produced**
  - **growth rate about 1µm/min**

# RD50 Silicon Materials under Investigation by RD50

standard for particle detectors

used for LHC Pixel detectors

"new" silicon material

| Material | Symbol | ρ (Ωcm) | $[O_i]$ ($cm^{-3}$) |
|---|---|---|---|
| Standard FZ (n- and p-type) | FZ | $1–7\times10^{3}$ | $< 5\times10^{16}$ |
| Diffusion oxygenated FZ (n- and p-type) | DOFZ | $1–7\times10^{3}$ | $\sim 1–2\times10^{17}$ |
| Magnetic Czochralski Si, Okmetic, Finland (n- and p-type) | MCz | $\sim 1\times10^{3}$ | $\sim 5\times10^{17}$ |
| Czochralski Si, Sumitomo, Japan (n-type) | Cz | $\sim 1\times10^{3}$ | $\sim 8-9\times10^{17}$ |
| Epitaxial layers on Cz-substrates, ITME, Poland (n- and p-type, 25, 50, 75, 150 μm thick) | EPI | 50 – 400 | $< 1\times10^{17}$ |
| Diffusion oxygenated Epitaxial layers on CZ | EPI–DO | 50 – 100 | $\sim 7\times10^{17}$ |

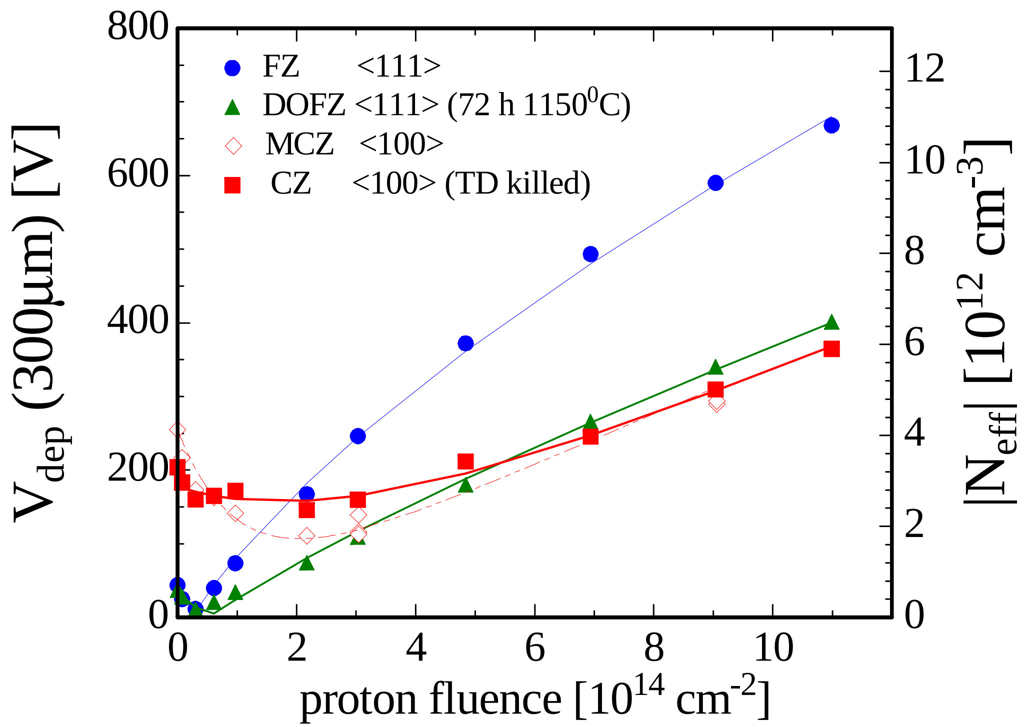
- **DOFZ silicon** - Enriched with oxygen on wafer level, inhomogeneous distribution of oxygen
- **CZ/MCZ silicon** - high Oi (oxygen) and $O_{2i}$ (oxygen dimer) concentration (homogeneous)
  - formation of shallow Thermal Donors possible
- **Epi silicon** - high $O_i$ , $O_{2i}$ content due to out-diffusion from the CZ substrate (inhomogeneous)
  - thin layers: high doping possible (low starting resistivity)
- **Epi-Do silicon** - as EPI, however additional $O_i$ diffused reaching homogeneous $O_i$ content

# Standard FZ, DOFZ, Cz and MCz Silicon

## 24 GeV/c proton irradiation

- **Standard FZ silicon**
  - **type inversion at ~ $2\times10^{13}$ p/cm²**
  - **strong $N_{eff}$ increase at high fluence**

- **Oxygenated FZ (DOFZ)**
  - **type inversion at ~ $2\times10^{13}$ p/cm²**
  - **reduced $N_{eff}$ increase at high fluence**




- **CZ silicon and MCZ silicon**
  - **<u>no type inversion</u> in the overall fluence range (verified by TCT measurements)**
    (verified for CZ silicon by TCT measurements, preliminary result for MCZ silicon)
    **Strong indications for a reduced reverse annealing in MCZ silicon (2006)**

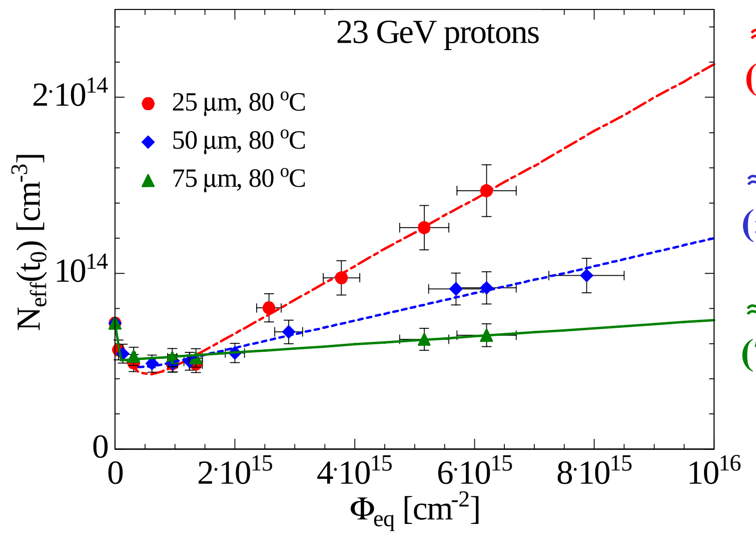
- **Common to all materials (after hadron irradiation):**
  - **reverse current increase**
  - **increase of trapping (electrons and holes) within ~ 20%**

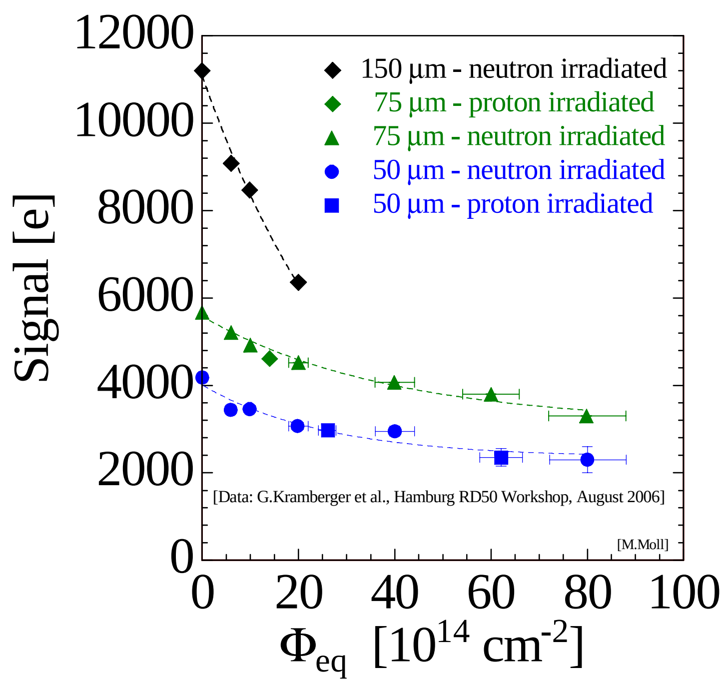
# EPI Devices – Irradiation experiments

- **Epitaxial silicon**

*G.Lindström et al.,10th European Symposium on Semiconductor Detectors, 12-16 June 2005*
*G.Kramberger et al., Hamburg RD50 Workshop, August 2006*

  - **Layer thickness: 25, 50, 75 μm** (resistivity: ~ 50 Ωcm); **150 μm** (resistivity: ~ 400 Ωcm)
  - **Oxygen: [O] ≈ 9×10$^{16}$cm$^{-3}$; Oxygen dimers** (detected via $IO_2$-defect formation)



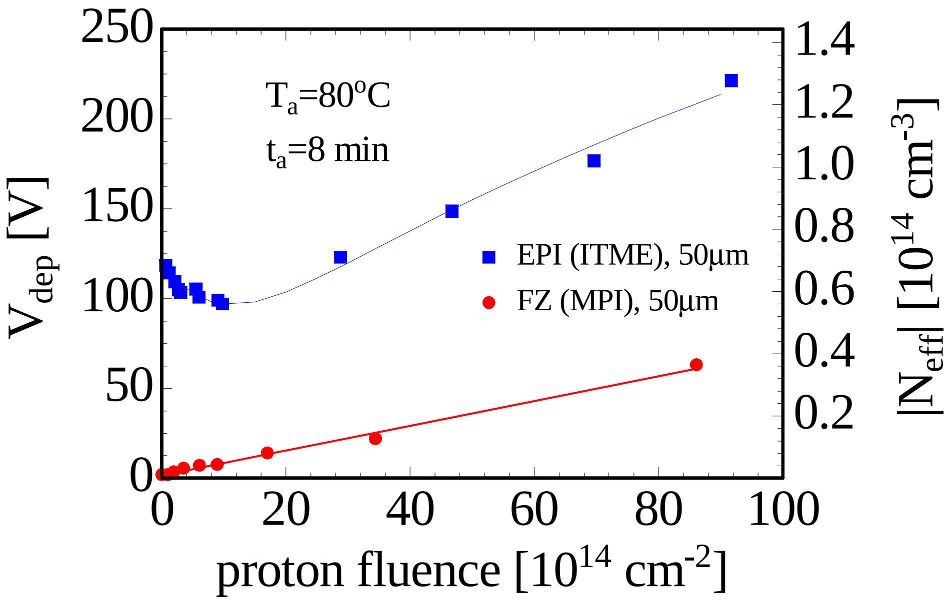

- **Only little change in depletion voltage**
- **No type inversion up to ~ $10^{16}$ p/cm$^2$ and ~ $10^{16}$ n/cm$^2$**
  **⇨high electric field will stay at front electrode!**
- **Explanation: introduction of shallow donors is bigger than generation of deep acceptors**

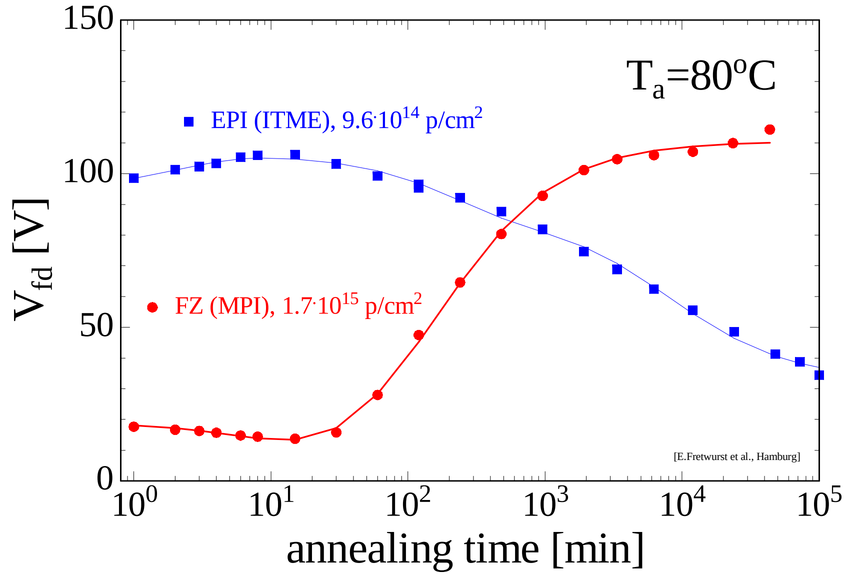
- **CCE (Sr$^{90}$ source, 25ns shaping):**
  **⇨ 6400 e (150 μm; 2x10$^{15}$ n/cm$^{-2}$)**
  **⇨ 3300 e (75μm; 8x10$^{15}$ n/cm$^{-2}$)**
  **⇨ 2300 e (50μm; 8x10$^{15}$ n/cm$^{-2}$)**

# RD50 Epitaxial silicon – Thin silicon - Annealing

- **50 μm thick silicon can be fully depleted up to $10^{16}$ cm$^{-2}$**
  **- Epitaxial silicon** (50Ωcm on CZ substrate, ITME & CiS)
  **- Thin FZ silicon** (4KΩcm, MPI Munich, wafer bonding technique)

**MPI Munich project:**
**Thin sensor interconnected to thinned ATLAS readout chip (ICV-SLID technique)**



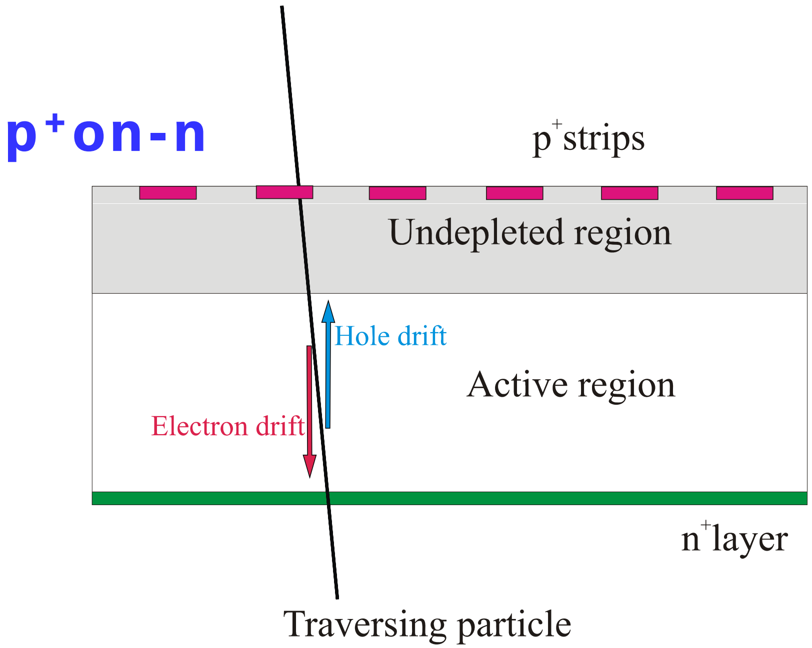

- **Thin FZ silicon: Type inverted, increase of depletion voltage with time**
- **Epitaxial silicon: No type inversion, decrease of depletion voltage with time**
  **⇒ No need for low temperature during maintenance of experiments!**

[E.Fretwurst et al., NIMA 552, 2005, 124]

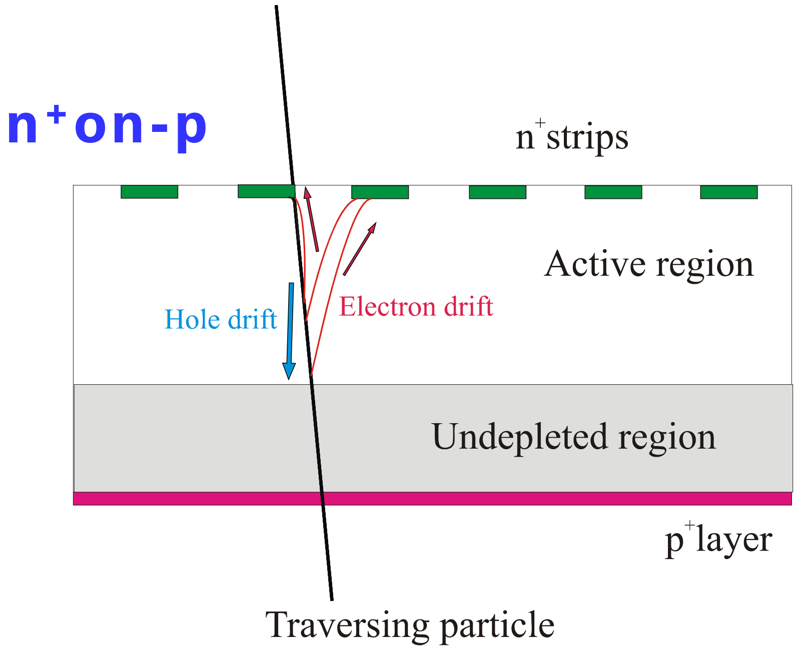
# Device engineering

## p-in-n versus n-in-p (or n-in-n) detectors

**n-type silicon after high fluences:**




**p-type silicon after high fluences:**




**p-on-n silicon, under-depleted:**

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

**n-on-p silicon, under-depleted:**

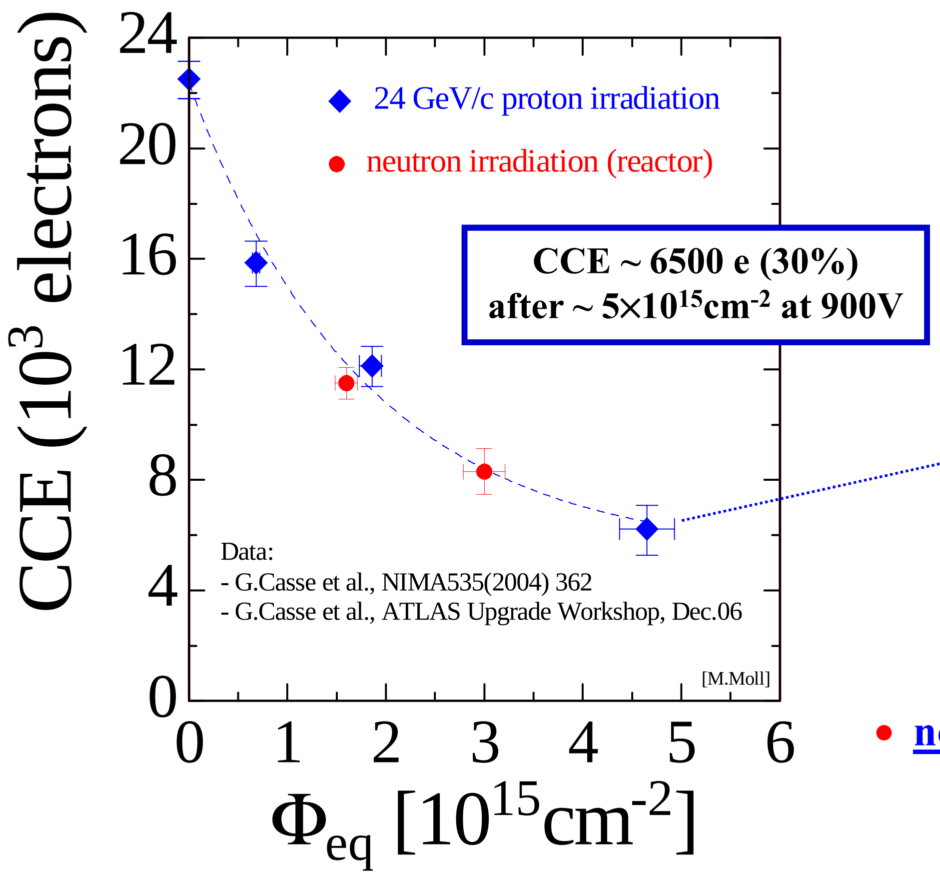
- **Limited loss in CCE**
- **Less degradation with under-depletion**
- **Collect electrons (fast)**

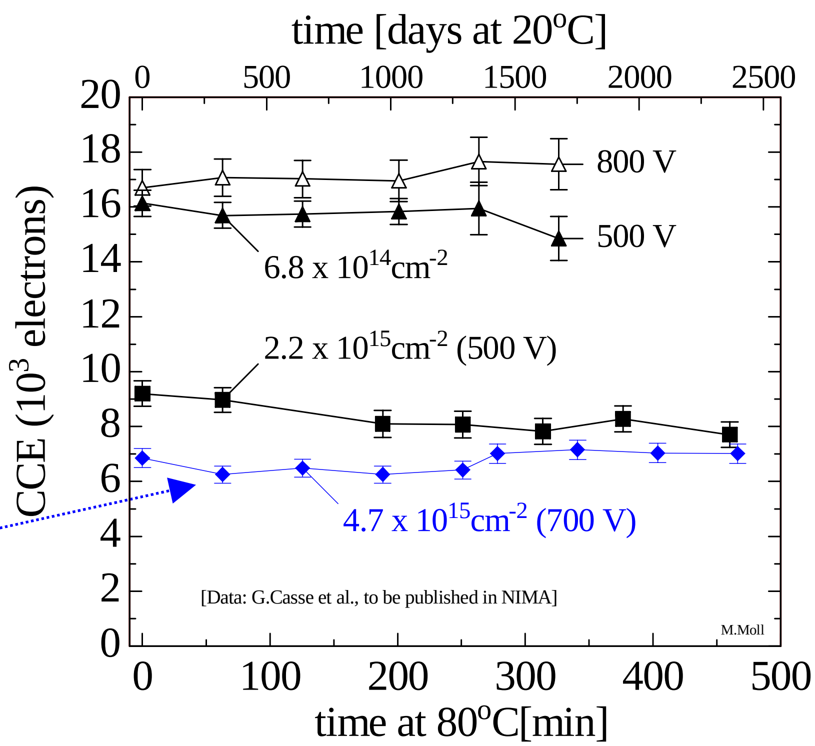
***Be careful, this is a very schematic explanation, reality is more complex !***

# n-in-p microstrip detectors

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

- n-in-p microstrip p-type FZ detectors (280µm thick, 80µm pitch, 18µm implant )
- Detectors read-out with 40MHz



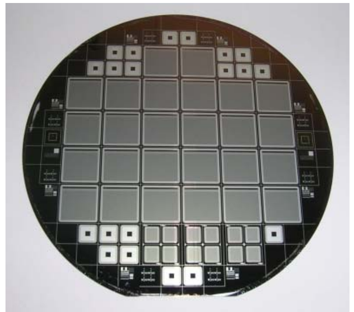



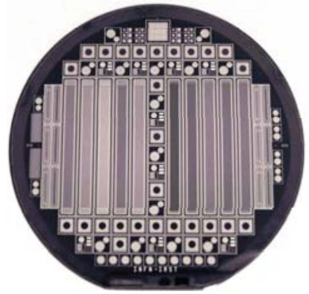

- **no reverse annealing visible in CCE measurement !**

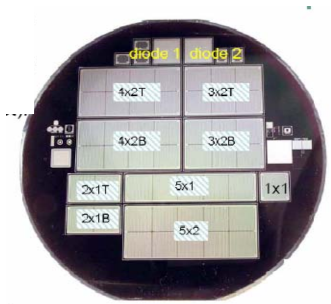
**e.g. for 4.7 × 10$^{15}$ cm$^{-2}$ increase of $V_{dep}$ from $V_{dep}$~ 2800V to $V_{dep}$ > 12000V is expected !**

# RD50 RD50 Test Sensor Production Runs (2005/2006)

- **Recent production of Silicon Strip, Pixel and Pad detectors (non exclusive list):**
  - **CIS Erfurt, Germany**
    - **2005/2006/2007 (RD50): Several runs with various epi 4” wafers only pad detectors**
  - **CNM Barcelona, Spain**
    - **2006 (RD50): 22 wafers (4”), (20 pad, 26 strip, 12 pixel),(p- and n-type),(MCZ, EPI, FZ)**
    - **2006 (RD50/RADMON): several wafers (4”), (100 pad), (p- and n-type),(MCZ, EPI, FZ)**
  - **HIP, Helsinki, Finland**
    - **2006 (RD50/RADMON): several wafers (4”), only pad devices, (n-type),(MCZ, EPI, FZ)**
    - **2006 (RD50) : pad devices, p-type MCz-Si wafers, 5 p-spray doses, Thermal Donor compensation**
    - **2006 (RD50) : full size strip detectors with 768 channels, n-type MCz-Si wafers**
  - **IRST, Trento, Italy**
    - **2004 (RD50/SMART): 20 wafers 4” (n-type), (MCZ, FZ, EPI), mini-strip, pad 200-500μm**
    - **2004 (RD50/SMART): 23 wafers 4” (p-type), (MCZ, FZ), two p-spray doses 3E12 amd 5E12 $cm^{-2}$**
    - **2005 (RD50/SMART): 4” p-type EPI**
    - **2006 (RD50/SMART): new SMART mask designed**
  - **Micron Semiconductor L.t.d (UK)**
    - **2006 (RD50): 4”, microstrip detectors on 140 and 300μm thick p-type FZ and DOFZ Si.**
    - **2006/07 (RD50): 93 wafers, 6 inch wafers, (p- and n-type), (MCZ and FZ), (strip, pixel, pad)**
  - **Sintef, Oslo, Norway**
    - **2005 (RD50/US CMS Pixel) n-type MCZ and FZ Si Wafers**
  - **Hamamatsu, Japan**
    - **In 2005 Hamamatsu started to work on p-type silicon in collaboration with ATLAS upgrade groups (surely influenced by RD50 results on this material)**







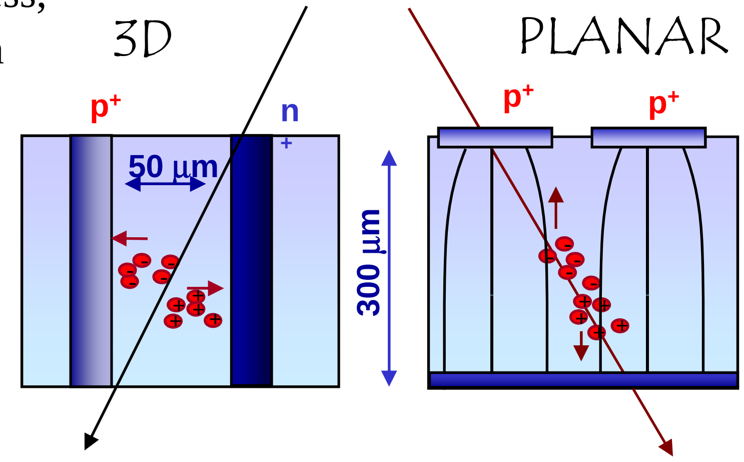

**Pad, strip and pixel sensors available for further tests**
**…… we are open for any collaboration.**

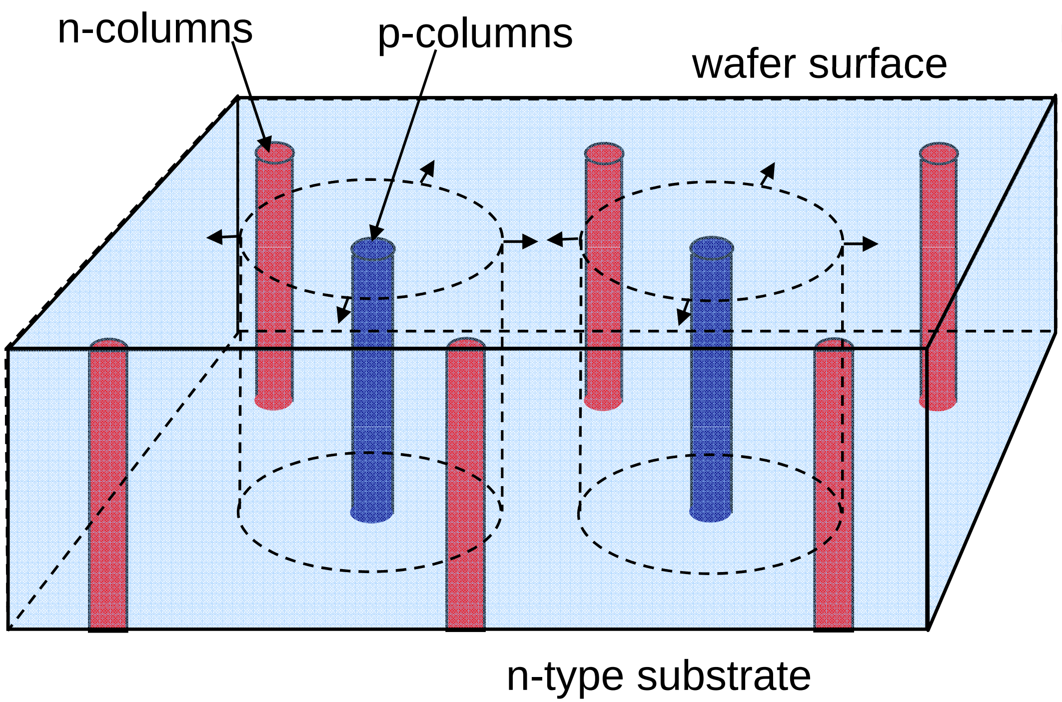
- M.Lozano, 8th RD50 Workshop, Prague, June 2006
- A.Pozza, 2nd Trento Meeting, February 2006
- G.Casse, 2nd Trento Meeting, February 2006
- D. Bortoletto, 6th RD50 Workshop, Helsinki, June 2005
- N.Zorzi, Trento Workshop, February 2005

# 3D detector - concept

**Introduced by:** S.I. Parker et al., 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
  - radiation hard



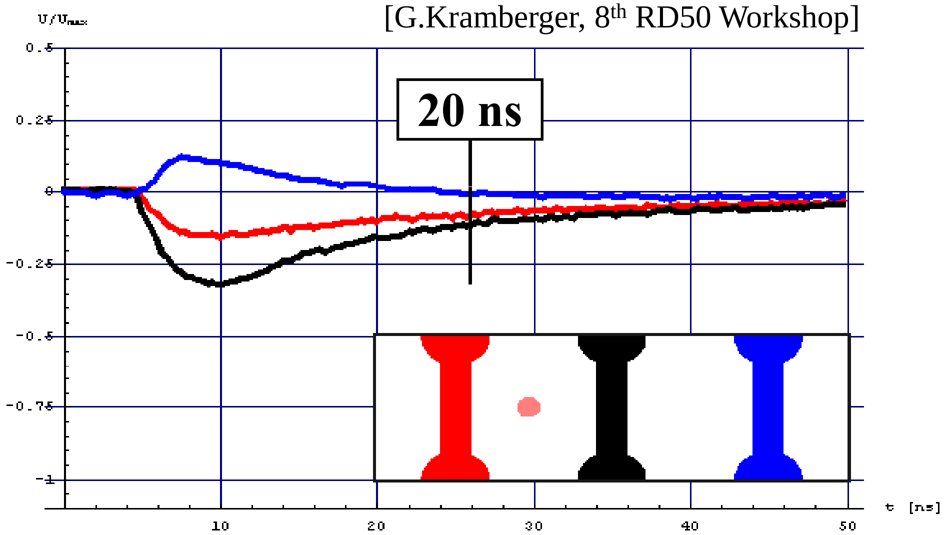




**"standard 3D"**
see talk of
**Kevin Einsweiler**
**'ATLAS – B-layer'**

# RD50 3D - SCT: Single Column Type

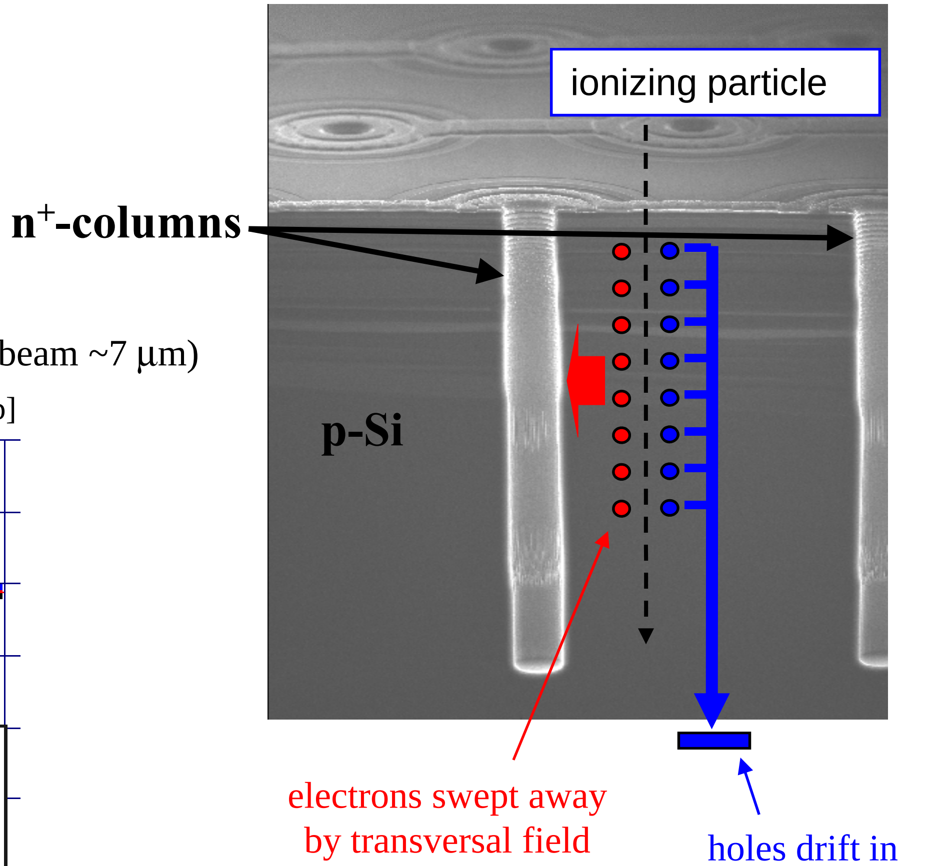
- **Simplified 3D architecture (proposed in 2005)**
  - $n^+$ columns in p-type substrate, $p^+$ backplane
- **Simplified process**
  - hole etching and doping only done once
  - no wafer bonding technology needed
  - single side process (uniform $p^+$ implant)
- **Position sensitive TCT on strip detector** (laser beam ~7 μm)

[G.Kramberger, 8th RD50 Workshop]




- **CCE measurements ($^{90}$Sr source)**
  - 100% reached at 30V for 300 μm thick detector [M.Scareingella STD06]

- **Fabricated in 2006 (strips, pads, ..)**
  - IRST(Italy), CNM Barcelona

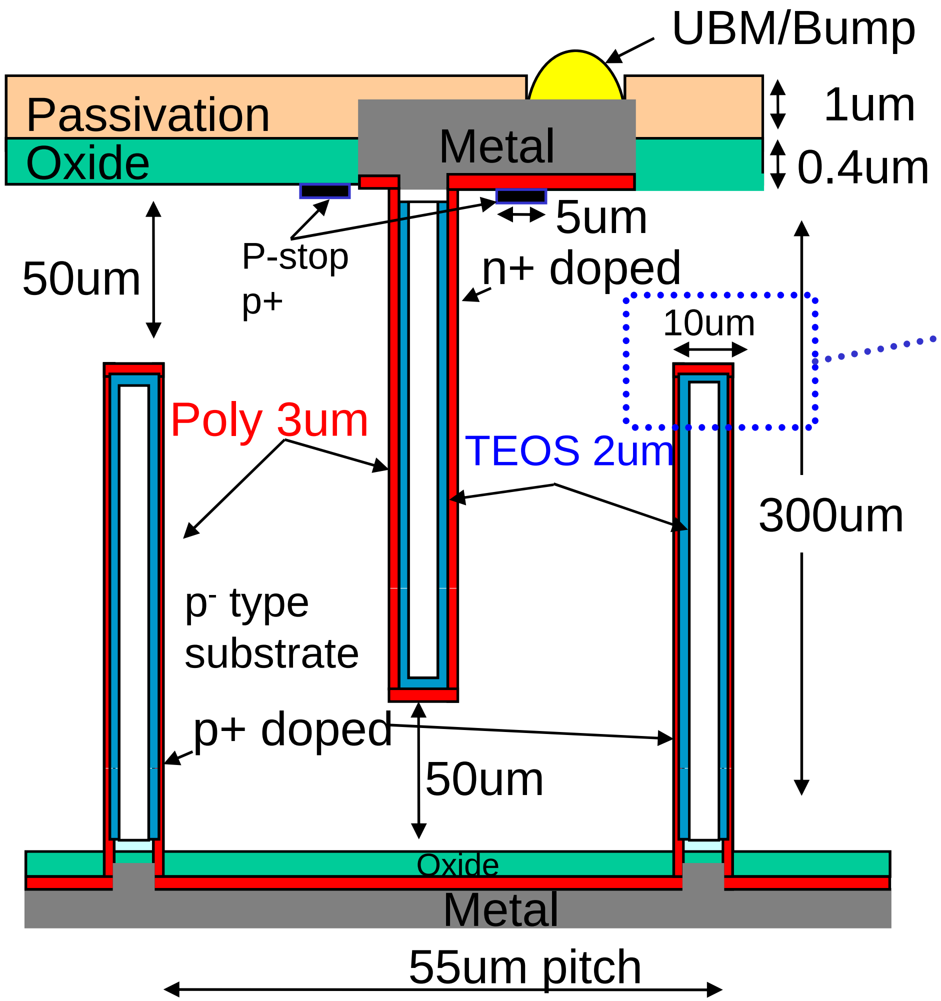



Hole depth 120-150μm
Hole diameter ~10μm

# RD50 Next step: Double-Sided 3D detectors

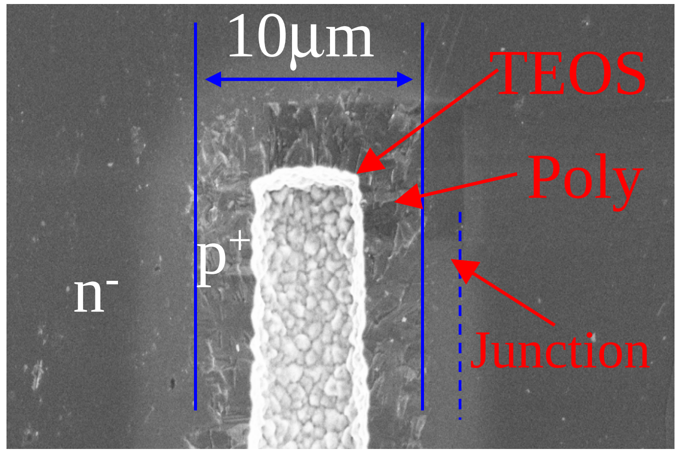
- **Under processing at CNM, Barcelona**

  RD50 collaborative work (CNM, Glasgow, Valencia, …)




[G.Pelegrini, CNM Dec.06]

- **Successful process evaluation runs:**
  - etching of holes with aspect ratio 24:1 (10 μm diameter, 250 μm depth)
  - polysilicon deposit, doping, TEOS, ..




- **Advantages against standard 3D:**
  - Less complicated (expensive) process:
    - No wafer bonding
    - $p^+$ and $n^+$ columns accessed from opposite surfaces
- **Disadvantages (?) :**
  - lower field region below/above columns

- **Similar work ongoing at IRST, Trento** (RD50, SMART)

# Comparison of measured collected charge on different radiation-hard materials and devices

- **In the following:**

  **Comparison of collected charge as published in literature**

- **Be careful:**

  **Values obtained partly under different conditions !!**

  - **irradiation**
  - **temperature of measurement**
  - **electronics used (shaping time, noise)**
  - **type of device – strip detectors or pad detectors**

  ⇒ This comparison gives only an indication of which material/technology could be used, to be more specific, the exact application should be looked at!

- **Remember:**

  **The obtained signal has still to be compared to the noise !!**

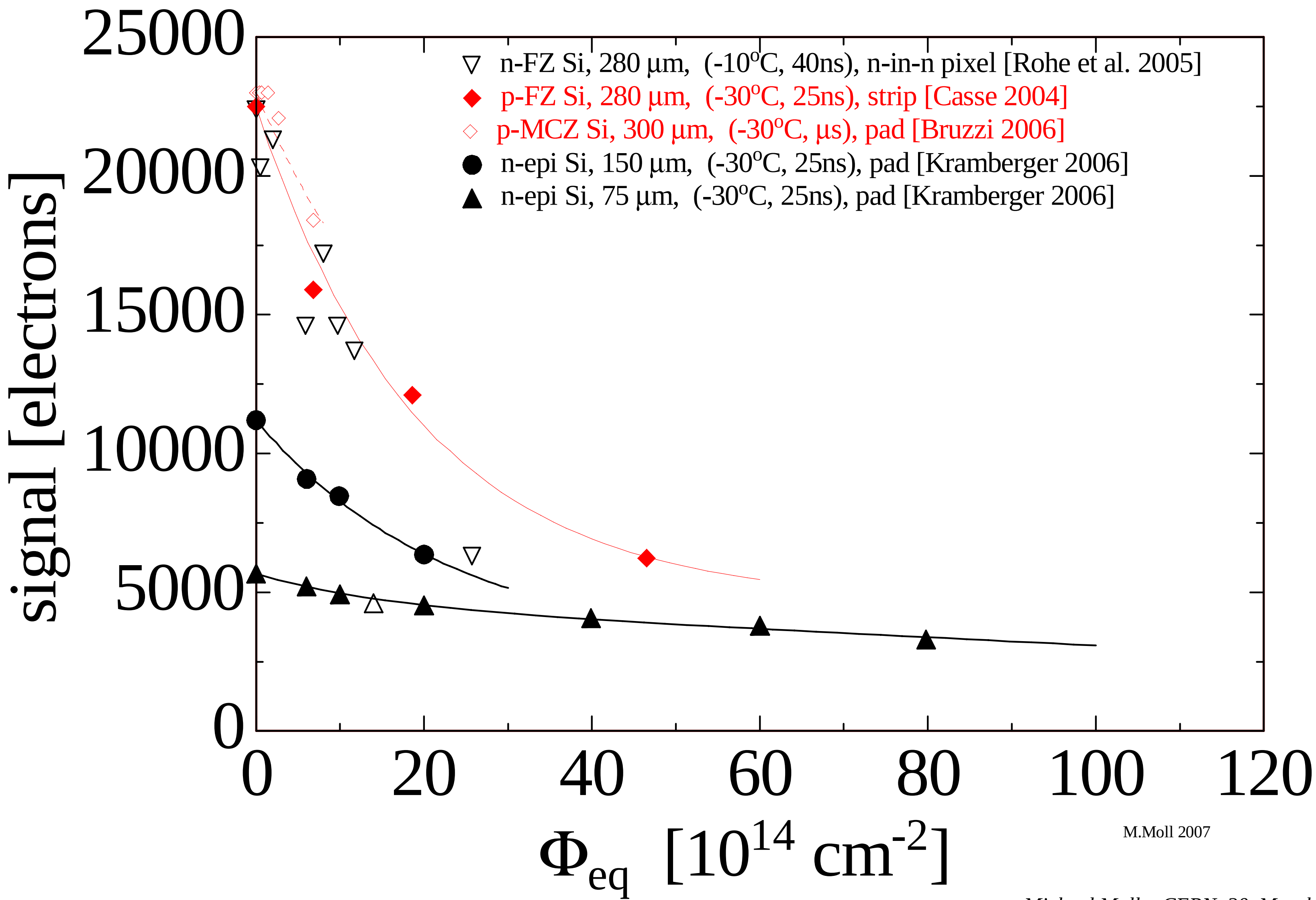
- **Acknowledgements:**



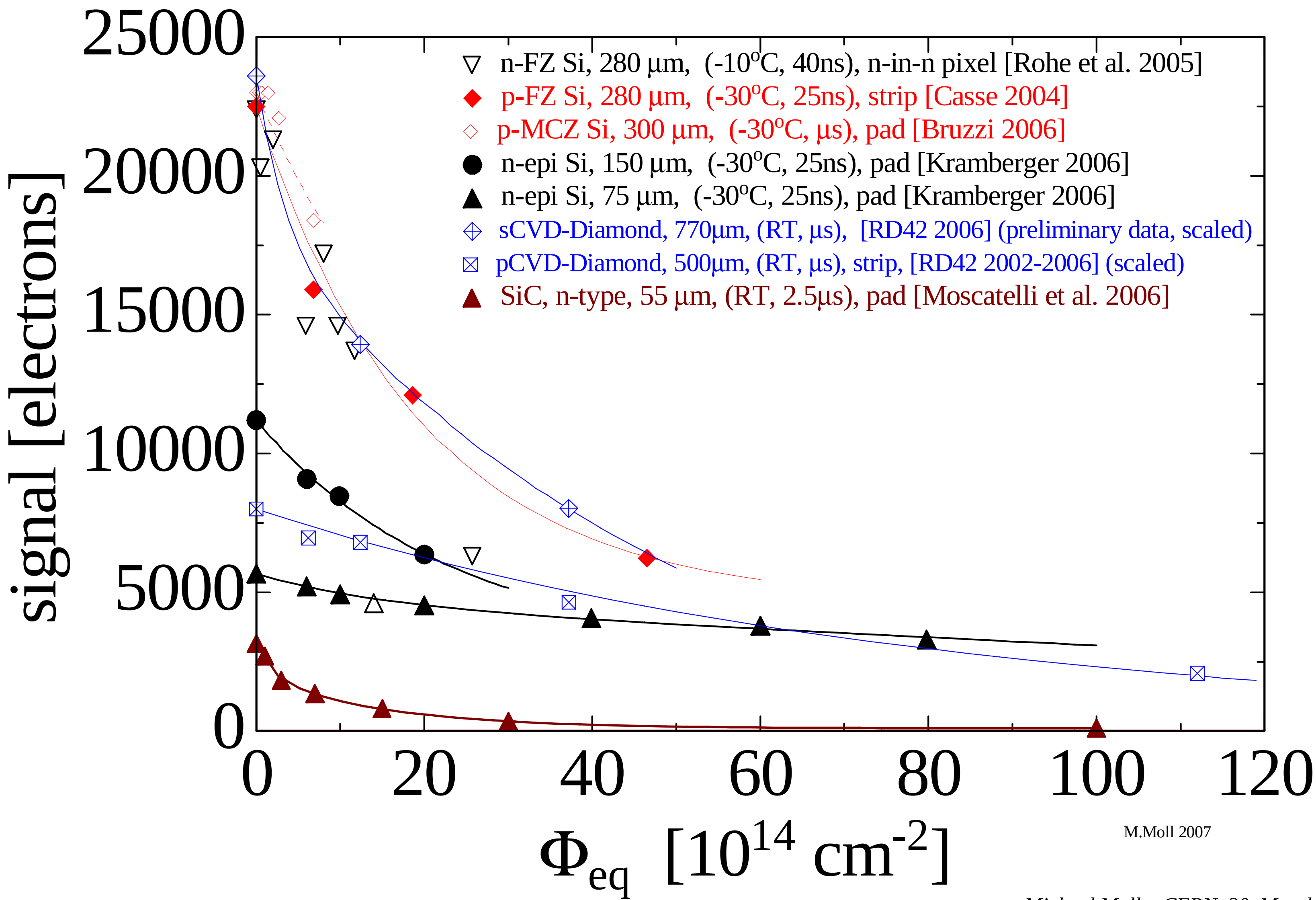
  - Recent data collections: Mara Bruzzi (Hiroshima conference 2006)

    Cinzia Da Via (Vertex conference 2006)

# RD50 Comparison of measured collected charge on different radiation-hard materials and devices

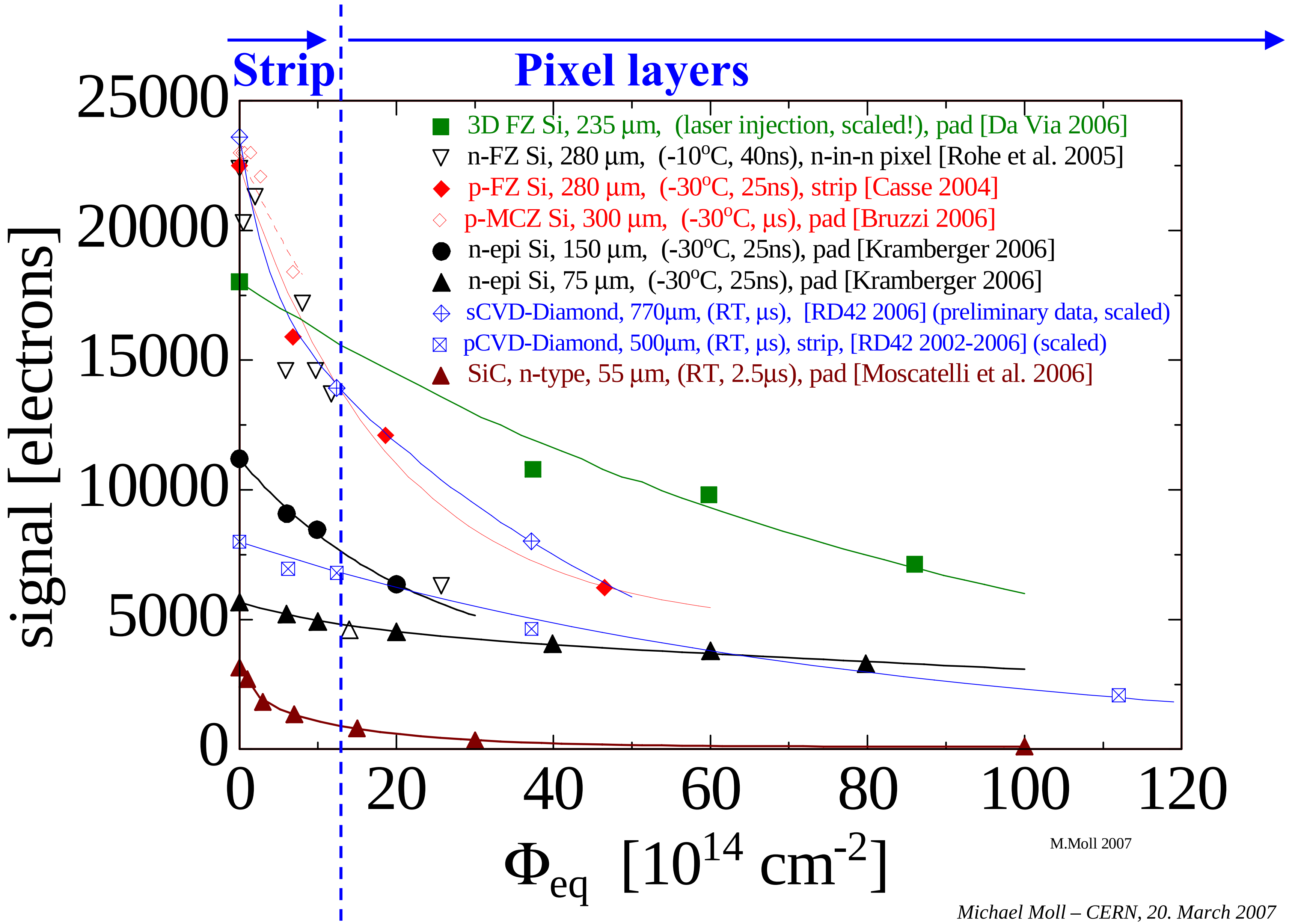


# Comparison of measured collected charge on different radiation-hard materials and devices



RD50

# Comparison of measured collected charge on different radiation-hard materials and devices



# RD50 Sensor Options for SLHC

- **Long strips ($\Phi < 5 \times 10^{14}$ cm$^{-2}$; R > 60 cm)**
  **⇒ Change of the depletion voltage and large area to be covered (costs!) are major problems.**
  - **Standard p-in-n technology on n-type FZ or MCZ**

- **Short strips ($5\times10^{14}$ cm$^{-2}$ < $\Phi$ > $10^{15}$cm$^{-2}$; 25 cm < R < 60 cm)**
  **⇒ Underdepleted operation necessary and trapping becomes important**
  **⇒ Collect electrons and use of n-strips!**
  - **p-type silicon (FZ or MCZ) with n-strips** (15000 e at $\Phi_{eq}$= $1\times10^{15}$ cm$^{-2}$, 280µm)
    ( 6500 e at $\Phi_{eq}$= $4\times10^{15}$ cm$^{-2}$, 280µm )

- **Pixel ($\Phi > 10^{15}$ cm$^{-2}$ up to above $10^{16}$ cm$^{-2}$; R < 25 cm)**
  **⇒ Active thickness significantly reduced for any Si material due to trapping**
  - **3D sensors (fast, big signal but technological challenge)**
  - **Epitaxial or thin sensors** (small signal: e.g. 3300e at $\Phi_{eq}$ $8\text{x}10^{15}$cm$^{-2}$, 75µm EPI)

- **Other semiconductors (e.g. SiC and GaN) have been abandoned by RD50.**
  **However, diamond is still an option (RD42).**

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

# Spares

# 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 and approved as RD50 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 $10^{16}$ $cm^{-2}$**
- **Fast signal collection** (25ns or 50 ns bunch crossing?)
- **Low mass** (reducing multiple scattering close to interaction point)
- **Cost effectiveness** (big surfaces have to be covered with detectors!)

- Presently 261 members from 52 institutes

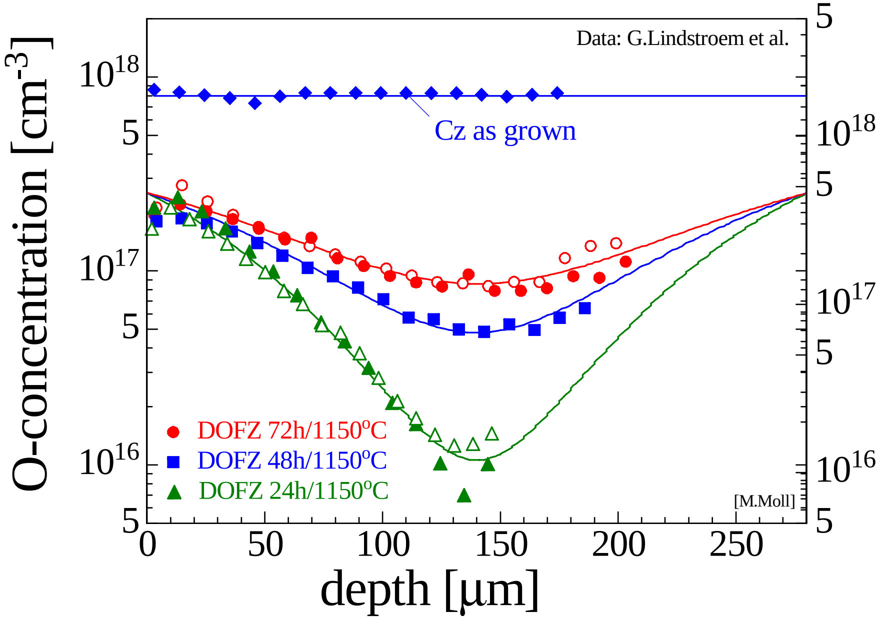
**Belarus (Minsk), Belgium (Louvain), Canada (Montreal), Czech Republic (Prague (3x)), Finland (Helsinki, Lappeenranta), Germany (Berlin, Dortmund, Erfurt, Freiburg, Hamburg, Karlsruhe), Israel (Tel Aviv), Italy (Bari, Bologna, Florence, Padova, Perugia, Pisa, Trento, Turin), Lithuania (Vilnius), The Netherlands (Amsterdam), 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 (Diamond, Exeter, Glasgow, Lancaster, Liverpool, Sheffield), USA (Fermilab, Purdue University, Rochester University, SCIPP Santa Cruz, Syracuse University, BNL, University of New Mexico)**

- Strong links to LHC-Experiments
  - **Most of RD50 institutes are member in one of the LHC experiments**

# Oxygen concentration in FZ, CZ and EPI

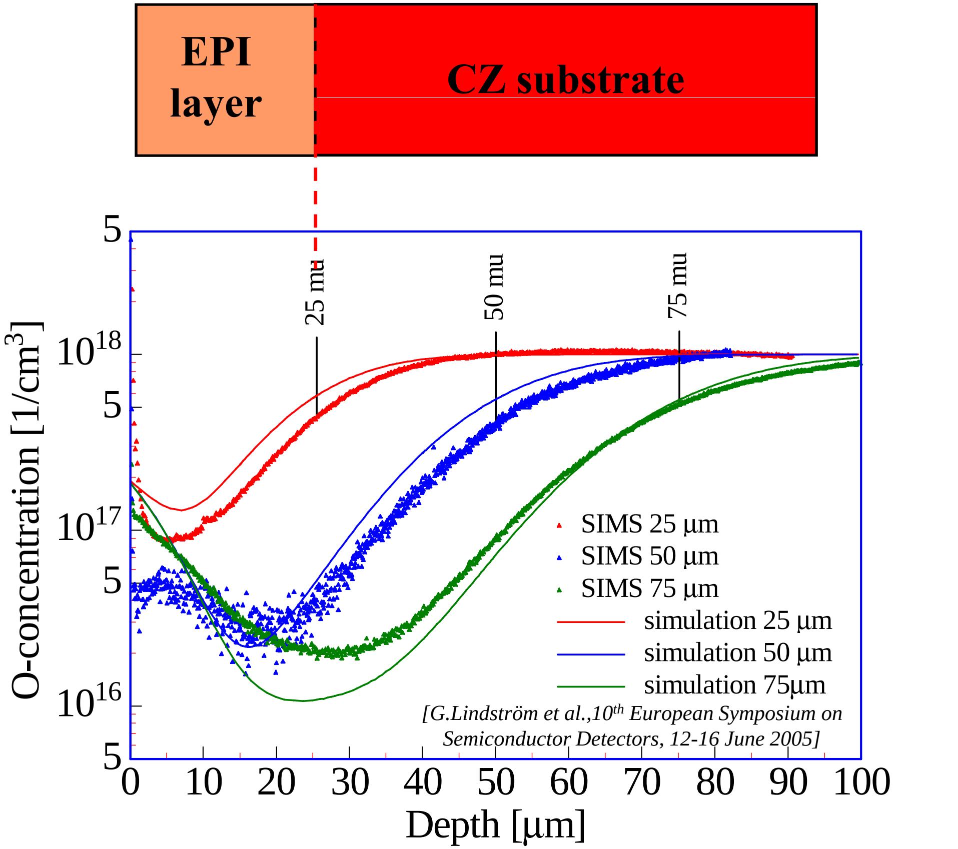
## DOFZ and CZ silicon

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




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

## Epitaxial silicon




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