Lunch Meeting, Louvain la Neuve, 21st February 2007

Development of radiation hard semiconductor Devices for SLHC

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Outline

- **Part I : Super – LHC : Context**

    ➔ **Motivation for SLHC**

    ➔ **Upgrade**

        Three main phases

        Beam parameters

    ➔ **Motivation for new radiation hard detector**

- **Part II : Radiation hard sensors**

- **Part III : Conclusion**

SLHC – Motivations

- **The SLHC is an upgrade to the LHC designed to increase the delivered integrated luminosity by an order of magnitude over the design luminosity of the LHC**
  - **10^{35} cm^{-2} s^{-1} peak luminosities**

- **Timescale for upgrade of the LHC is around 2015**
  - **Detectors and machine elements are reaching their effective lifetimes (due to radiation damage)**
  - **Potential for further discovery at LHC is reduced : Timescale for decreasing statistical errors becomes very long**

    (8 years in 2012 after only 2 years at full luminosity)

➔The LHC luminosity upgrade extends the LHC program in an efficient way into the 2020 era and allows to extend the LHC discovery mass/scale range by 25-30%

Basics

- **Definition of the luminosity**

The event rate R in a collider is proportional to the interaction cross section and the factor of proportionality is called the luminosity :

$$R = L\sigma$$

where L is proportional to N^2/β^*

N is the number of protons per bunch and β the amplitude function. This function is a beam optics quantity and is determined by the accelerator magnet configuration.

To achieve high luminosity, we have to make high population bunches to collide at high frequency at locations where the beam optics provides as low values of the amplitude functions as possible

Phases of LHC upgrades

Sadrozinski et al, *Tracking detectors for the sLHC, the LHC upgrade*, NIM, 2005

LHC Phase	CM energy (TeV)	Luminosity ($10^{34}cm^{-2}s^{-1}$)	Changes wrt LHC	Hardware changes
LHC	14	1	-	-
sLHC0	14	2.3	Beam current	Interaction regions
sLHC1	14	5-10	Bunch spacing, β^*	Final focus
sLHC2	25	10?	Higher B-field	Magnets 9T-> 15T

First Phase : Higher Luminosity

➔ Change in the detectors

Second Phase : Higher Energy

➔ Extensive R&D and
a rebuilding of the machine

Beam parameters emerging from LUMI06

parameter	symbol	ultimate	25 ns - minimal β*	50 ns- long bunch
protons per bunch	N_b [10^{11}]	1.7	1.7	4.9
bunch spacing	Δt [ns]	25	25	50
beam current	I [A]	0.86	0.86	1.22
beta* at IP1&5	β* [m]	0.5	0.08	0.25
peak luminosity	L [10^{34} $cm^{-2}s^{-1}$]	2.3	15.5	8.9
events per crossing		44	296	340

Basic idea of the machine upgrade

- **Increase the current in the machine**
- **Increase the focusing (β* from 0.5 m to 0.25 m)**
- **Change optics to avoid parasitic beam interactions**

Would likely require a long shutdown

- **Time enough for new optics for the IR**
- **Also gives time for replacement of CMS tracking detectors and other required upgrades**

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

- **LHC upgrade**

LHC (2007), L = 10^{34}cm^{-2}s^{-1} SUPER-LHC (2015 ?), L = 10^{35}cm^{-2}s^{-1}

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

5 years → **2500 fb^{-1}** f(r=4cm) ~ $1.6 \cdot 10^{16}$cm^{-2}

× 5

Linear collider experiments (generic R&D)

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

Part II : Radiation Hard Detectors

➔ Radiation Damage in Silicon Detectors (A very brief review)

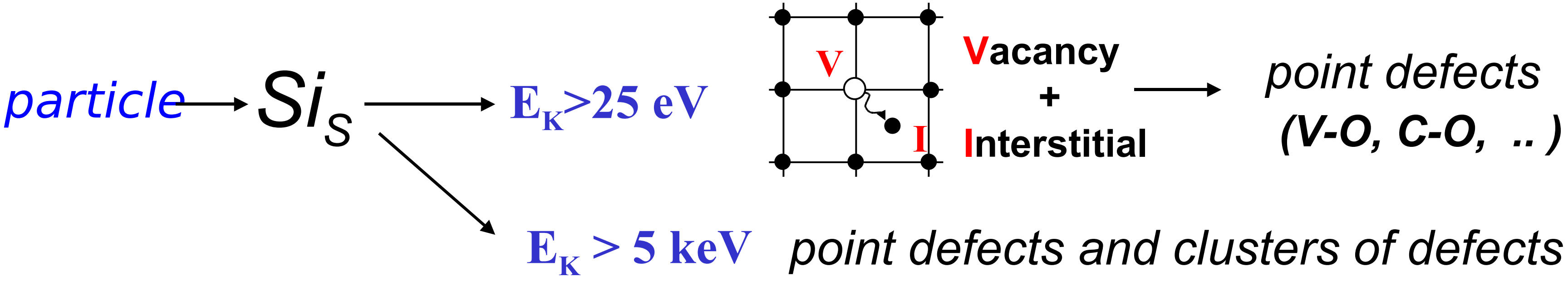
- **Microscopic defects** **(changes in bulk material)**
- **Macroscopic damage** **(changes in detector properties)**

➔ RD50 - Approaches to obtain radiation hard sensors

- **Material Engineering**
- **Device Engineering**

Radiation Damage – Microscopic Effects

Displacement of a *primary knock on atom (PKA)* out of its lattice site resulting in a Silicon interstitial and a left over vacancy (Frenkel pair).



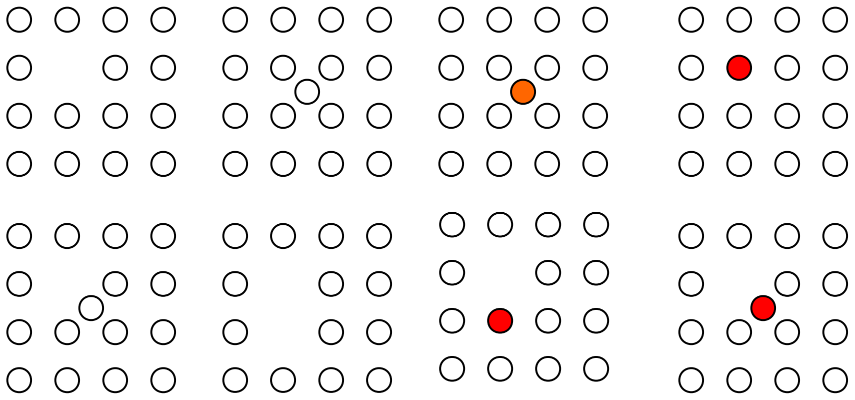
particle → Si_S → $E_K>25$ eV → **Vacancy + Interstitial** → *point defects (V-O, C-O, ..)*

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

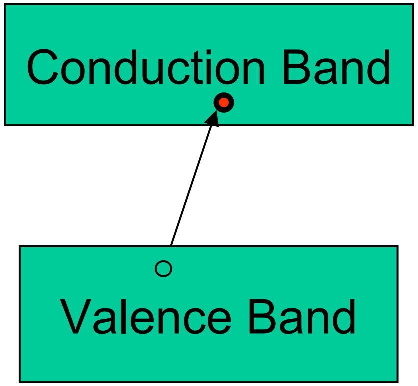
Interstitials and vacancies are very mobile at T>150 K

➔ Some Frenkel pairs annihilate and no damage remains

➔ The remaining vacancies and interstitials migrate and interact with each other and the impurity atoms existent in the silicon (C, O, P)



Semiconductors



Intrinsic semiconductor

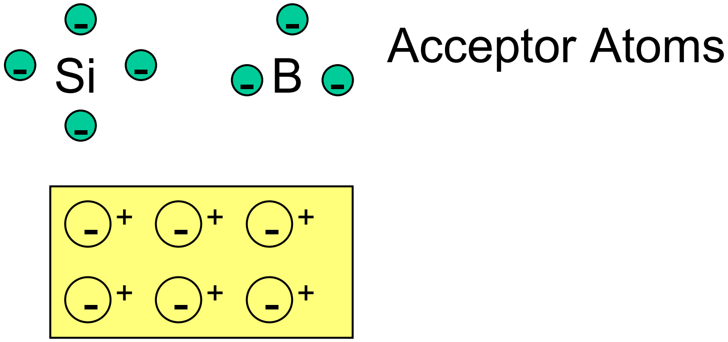
No doping

Electrons in the conduction band due to thermal energy

P type Silicon

Bore doping

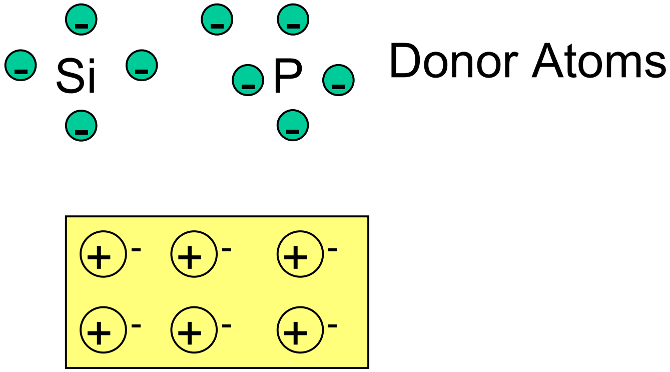
Number of holes bigger than the number of electrons



N type Silicon

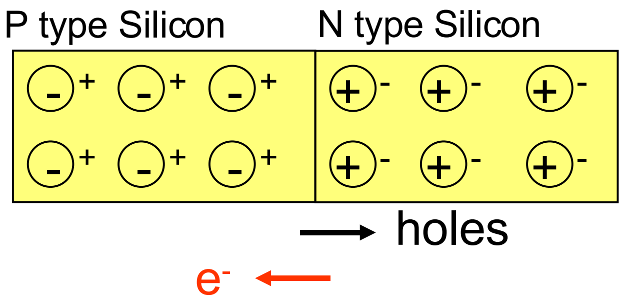
Phospohorous doping

Number of electrons bigger than the number of holes



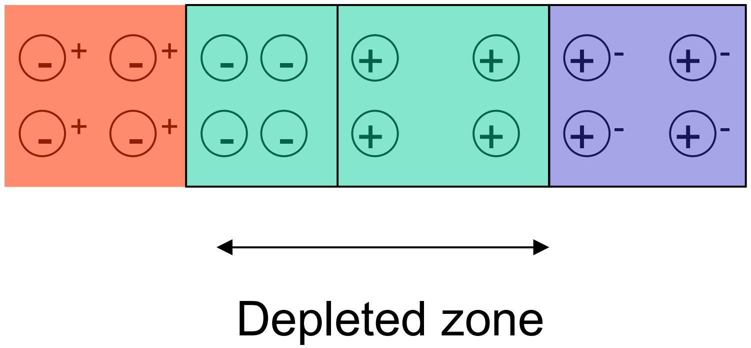
Diode – Junction PN

- **Contact between a P and a N type material**



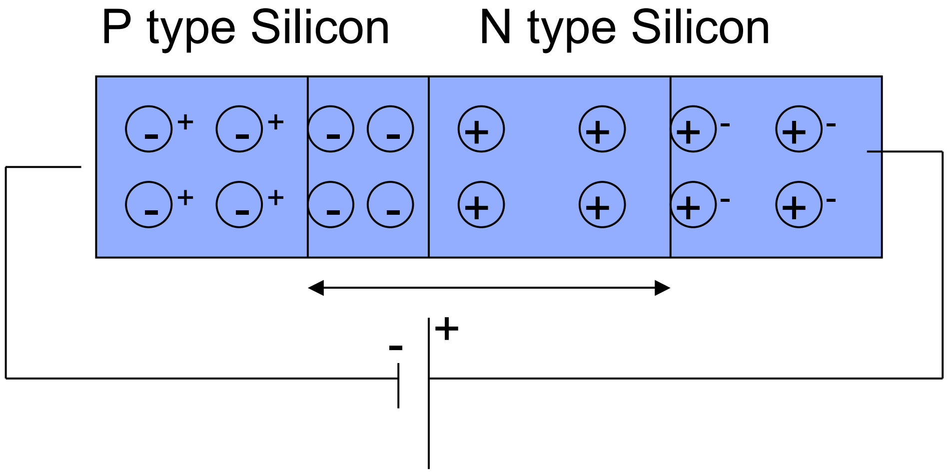
➔ Diffusion of e^- to the P type material and diffusion of holes in the N type material

➔ Creation of an electric field in the central region called the depleted zone

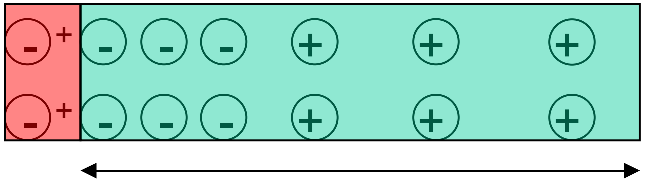


Reverse biased diode – Particle Detector

- **Reverse Diode : negative polarity on the P type material**



➔ Increase of the depleted zone width



➔ No free charge in this zone : if a particle crosses the depleted zone, it creates a e-/hole pair that is separated by the electriel field

➔ Possible to measure the e^- or hole current

Fundamental Parameters

- **Effective doping concentration**

Neff = $N_D - N_A$ (inside the depletion region)

- **Depletion Voltage : the voltage needed to fully deplete the detector**

$$V_{dep} = \frac{q_0}{\varepsilon\varepsilon_0} \cdot |N_{eff}| \cdot d^2$$

$\uparrow$ Detector thickness

This voltage has to be limited!

- **Leakage current : current of a reverse biased diode (influenced by the impurities, contaminations and process induced defects in the silicon)**

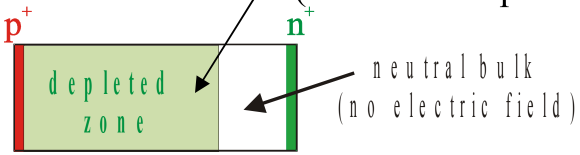
This current has to be as low as possible!

Reverse biased abrupt p^+-n junction

Poisson's equation

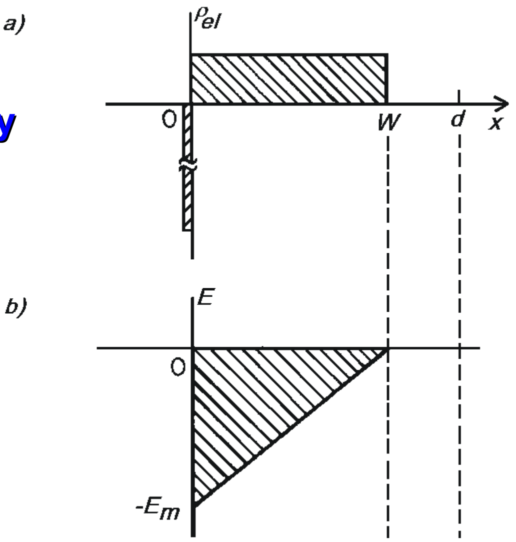
$$-\frac{d^2}{dx^2}\varphi(x)=\frac{q_0}{\varepsilon\varepsilon_0}\cdot N_{eff}$$

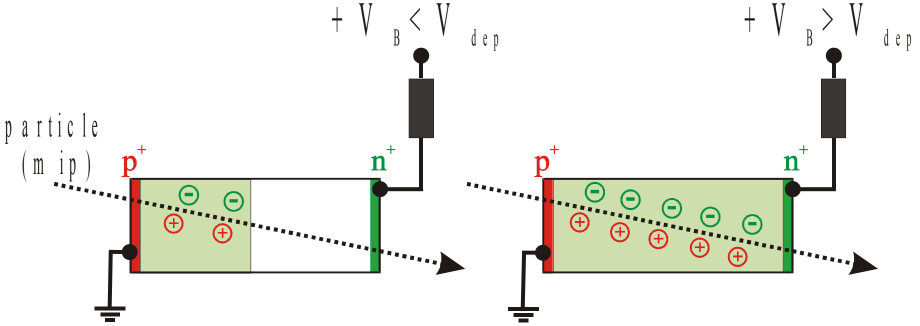
Positive space charge, $N_{eff}=[P]$
(ionized Phosphorus atoms)



Electrical charge density

Electrical field strength





Full charge collection only for $V_B > V_{dep}$!

depletion voltage

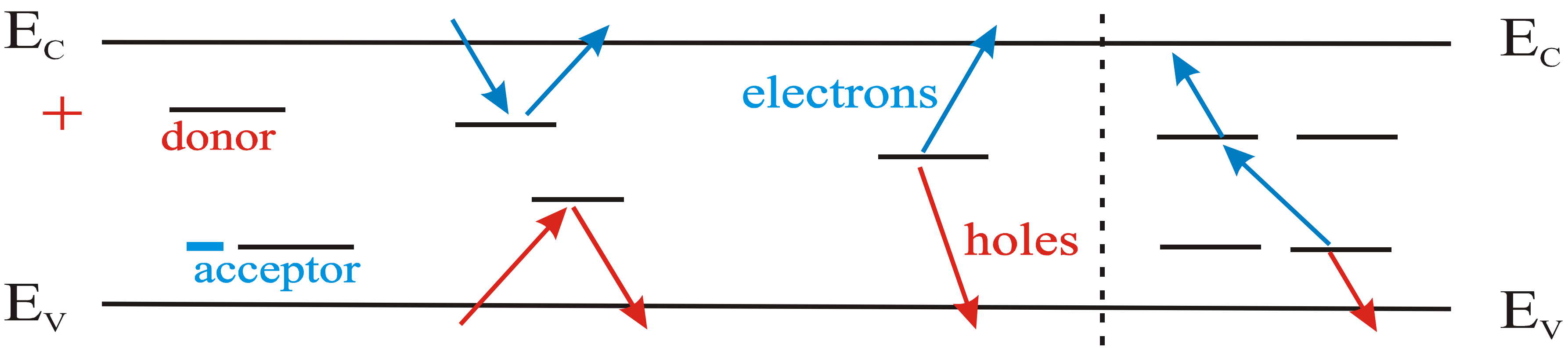
$$V_{dep}=\frac{q_0}{\varepsilon\varepsilon_0}\cdot|N_{eff}|\cdot d^2$$

effective space charge density

Impact of Defects on Detector properties

Shockley-Read-Hall statistics
(standard theory)

Inter-center charge
transfer model
(inside clusters only)



charged defects

⇒ **N_{eff} , V_{dep}**
e.g. donors in upper and acceptors in lower half of band gap

Trapping (e and h)
⇒ **CCE**
shallow defects do not contribute at room temperature due to fast detrapping

generation
⇒ **leakage current**
Levels close to midgap most effective

enhanced generation
⇒ **leakage current**
⇒ **space charge**

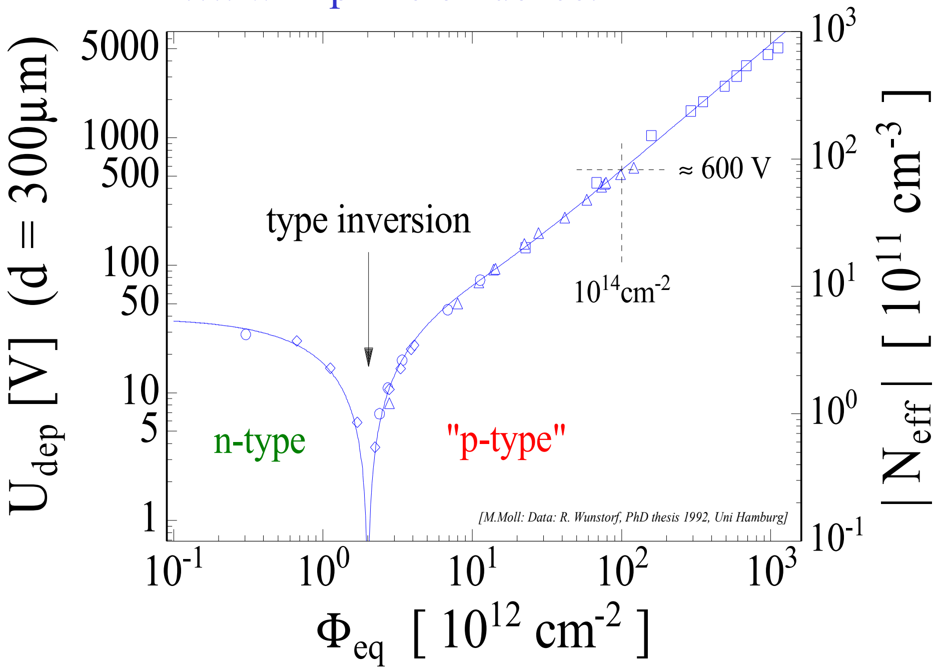
Impact on detector properties can be calculated if all defect parameters are known:

$\sigma_{n,p}$: cross sections **ΔE : ionization energy** **N_t : concentration**

Macroscopic Effects – I. Depletion Voltage

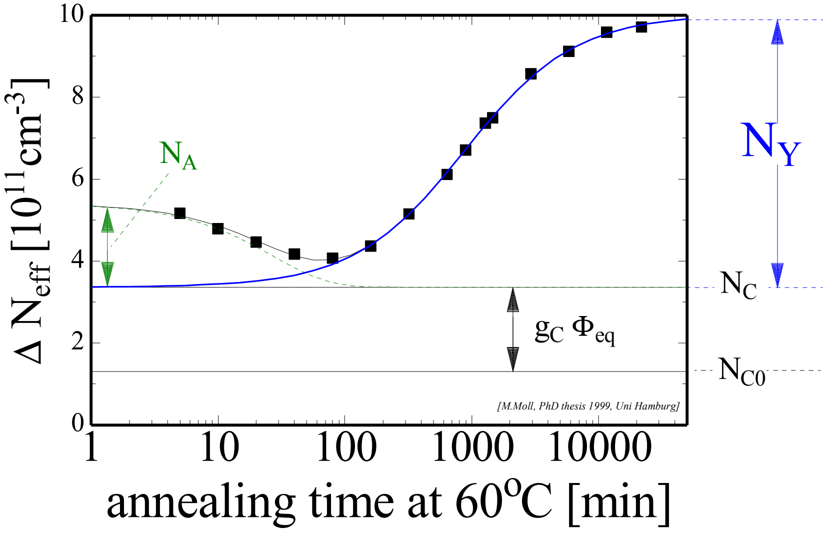
- Change of Depletion Voltage V_{dep} (N_{eff}) [Depends on the material!]

…. with particle fluence:



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

…. with time (annealing):



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

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

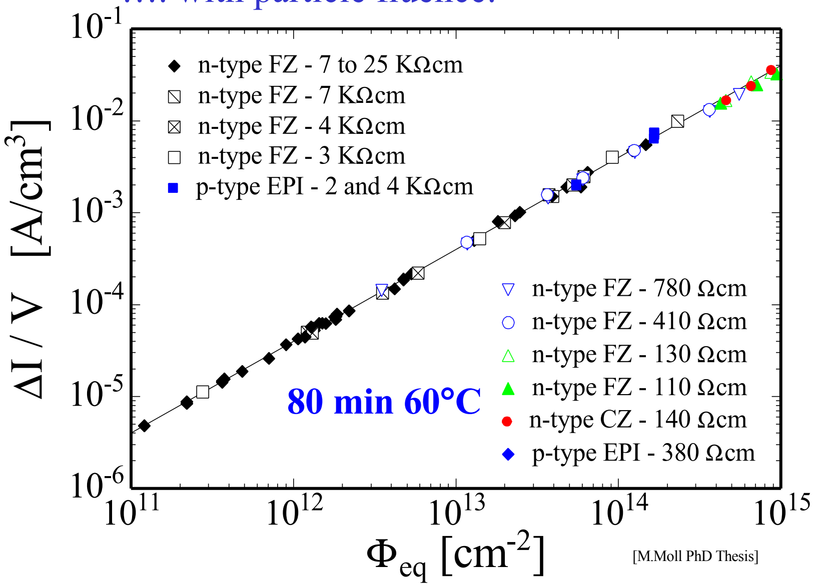
- "**Type inversion**": N_{eff} changes from positive to negative (Space Charge Sign Inversion)

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

Radiation Damage – II. Leakage Current

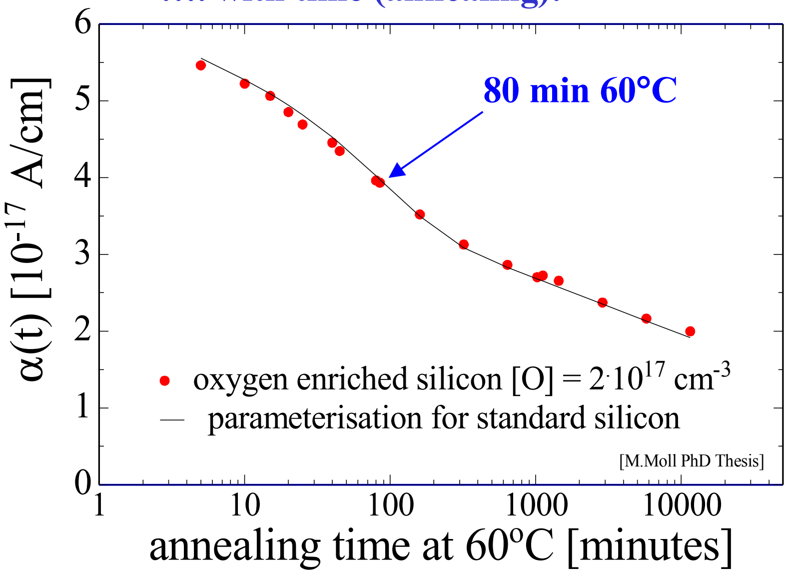
- Change of Leakage Current (after hadron irradiation)

…. with particle fluence:



[M.Moll PhD Thesis]

…. with time (annealing):



[M.Moll PhD Thesis]

- Damage parameter α (slope in figure)

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

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

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

Consequence:

Cool detectors during operation!

Example: I(-10°C) ~1/16 I(20°C)

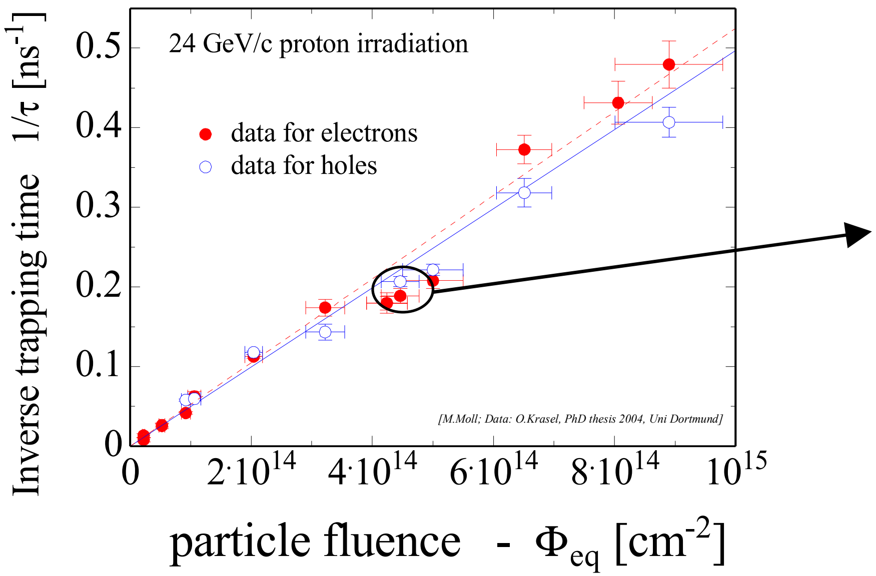
Radiation Damage – III. CCE (Trapping)

- Deterioration of Charge Collection Efficiency (CCE) by trapping

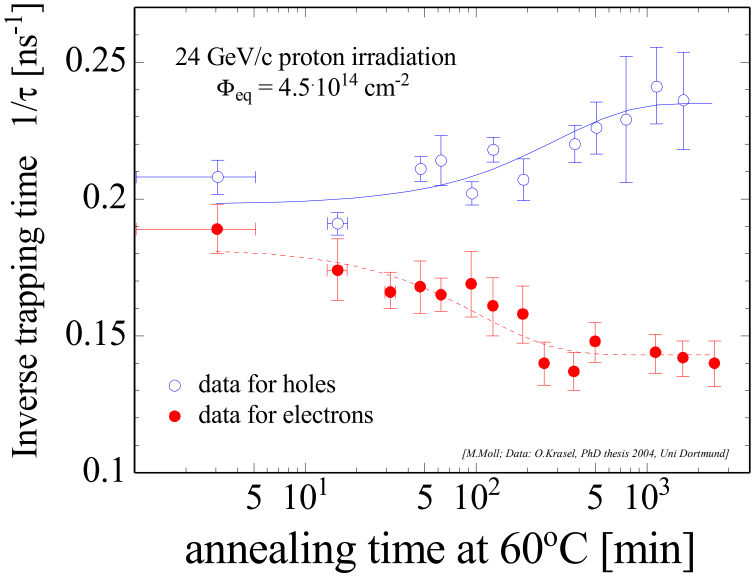
Trapping is characterized by an effective trapping time τ_{eff} for electrons and holes:

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

Increase of inverse trapping time (1/τ) with fluence



and change with time (annealing):



Summary: Radiation Damage in Silicon Sensors

- 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 –

Influenced by impurities in Si – Defect Engineering is possible!

I. Change of effective doping concentration (higher depletion voltage, under- depletion)

II. Increase of leakage current

III. Increase of charge carrier trapping (loss of charge)

Same for all tested Silicon materials!

- 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

⇒ Sensors can fail from radiation damage !

Approaches of RD39 and RD50 to develop radiation harder tracking detectors

Scientific strategies:

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

- **Defect Engineering of Silicon (RD 50)**
  - **Understanding radiation damage**
    - **Macroscopic effects and Microscopic defects**
  - **Oxygen rich silicon**
    - **DOFZ, Cz, MCZ, EPI**
- **Device Engineering (New Detector Designs) (RD 50)**
  - **p-type silicon detectors (n-in-p)**
  - **Thin detectors**
- **Cryogenic Tracking Detector (RD39)**

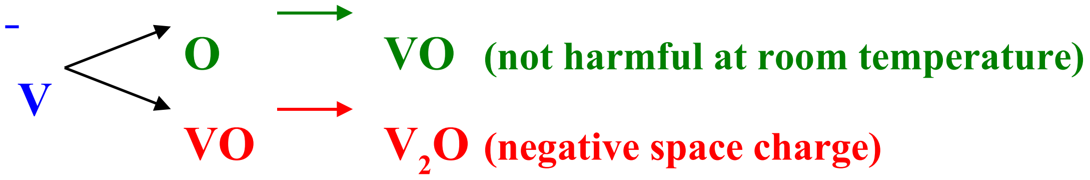
Defect Engineering of Silicon

- **Influence the defect kinetics by incorporation of impurities or defects**
- **Best example: <u>Oxygen</u>**

Initial idea: Incorporate Oxygen to getter radiation-induced vacancies
⇒ prevent formation of Di-vacancy (V_2) related deep acceptor levels

Observation: Higher oxygen content ⇒ less negative space charge
(less charged acceptors)

- **One possible mechanism: V_2O is a deep acceptor**



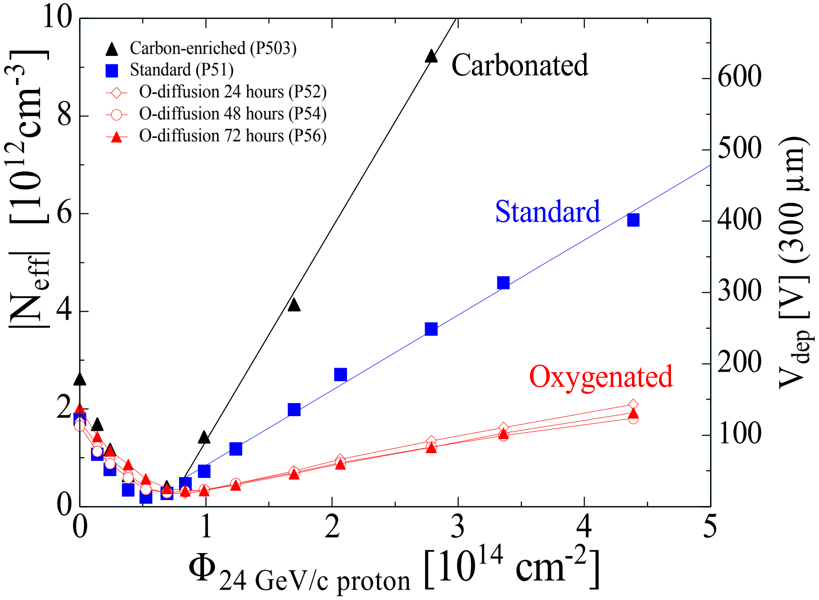
V
O → **VO (not harmful at room temperature)**
VO → **V_2O (negative space charge)**

Oxygen enriched silicon – DOFZ

- proton irradiation -

- **DOFZ (Diffusion Oxygenated Float Zone Silicon)**

First tests in 1999 show clear advantage of oxygenation

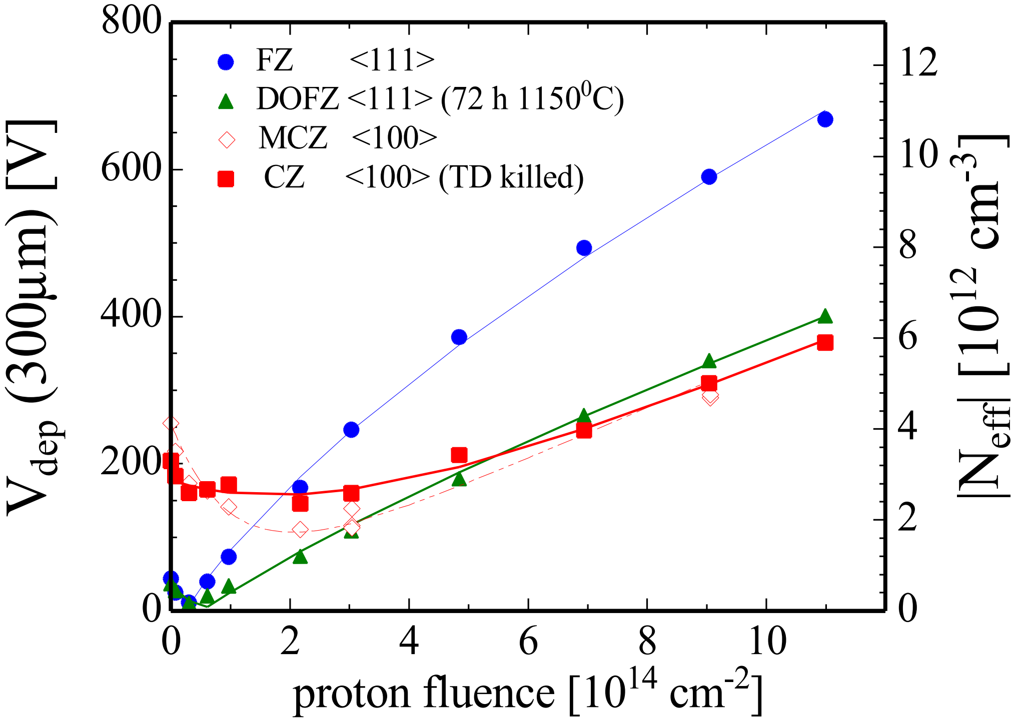


[RD48-NIMA 465(2001) 60]

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

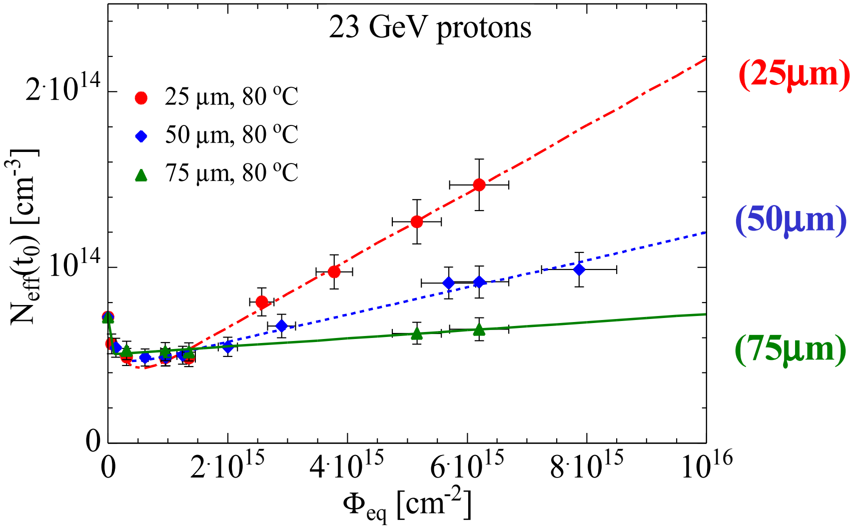
- Common to all materials (after hadron irradiation):
  - reverse current increase
  - increase of trapping (electrons and holes) within ~ 20%

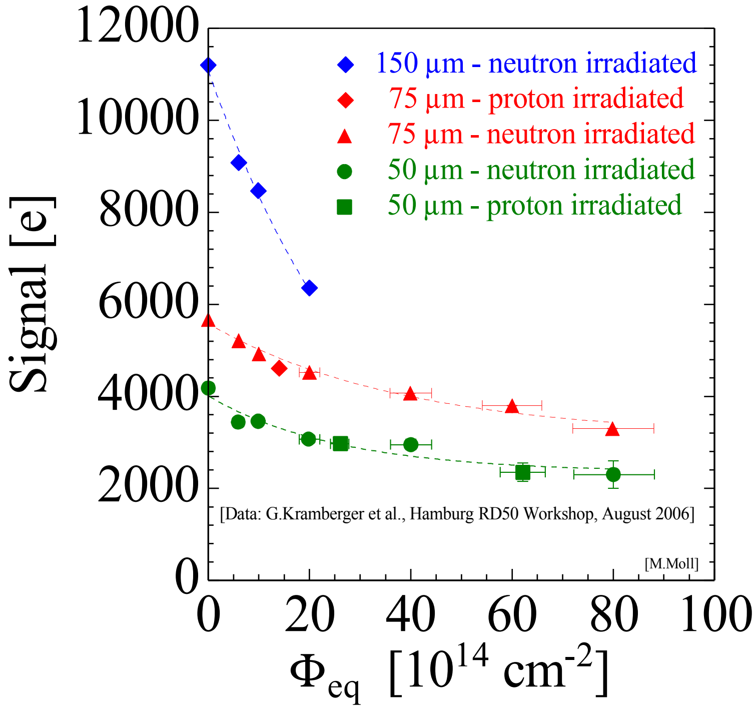
EPI Devices – Irradiation experiments

- Epitaxial silicon

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!
  ⇨ reverse annealing will decreases depletion voltage!

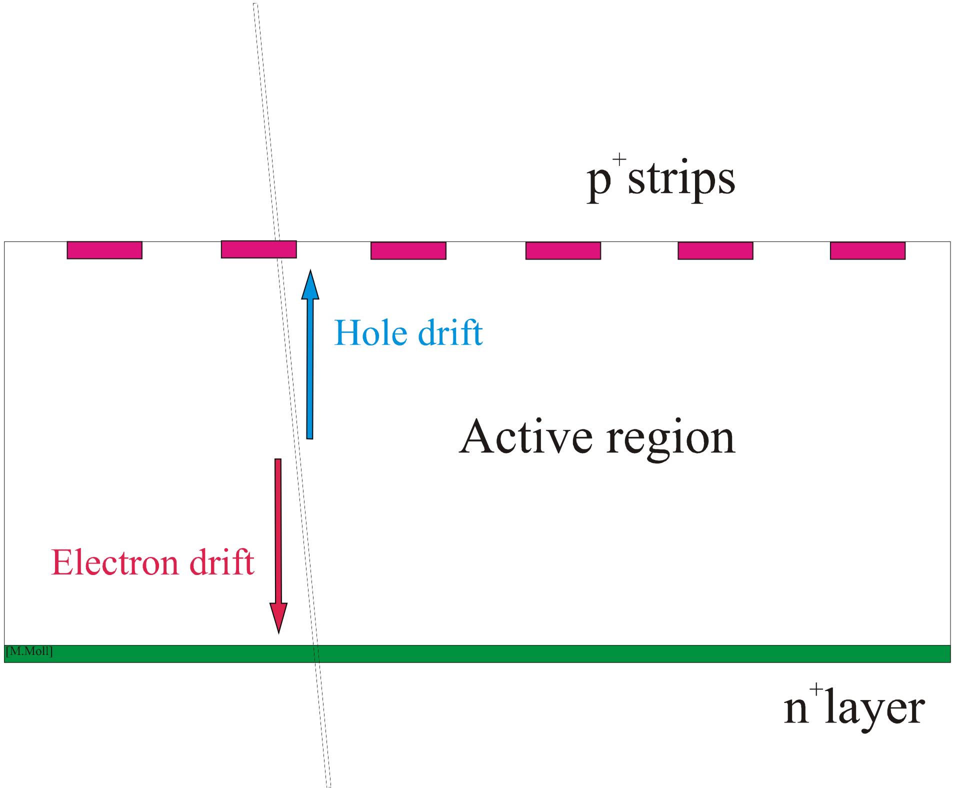
- Explanation: introduction of donors is bigger than generation of acceptors

- CCE (Sr^{90} source, 25ns shaping):
  ⇨ 6400 e (150 µm; 2×10^{15} n/cm^{-2})
  ⇨ 3300 e (75µm; 8×10^{15} n/cm^{-2})
  ⇨ 2300 e (50µm; 8×10^{15} n/cm^{-2})

Advantage of non-inverting material

p-in-n detectors (schematic figures!)

Fully depleted detector (non – irradiated):



p$^+$strips

Hole drift

Active region

Electron drift

[M.Moll]

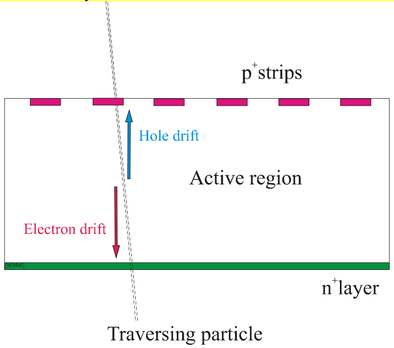
n$^+$layer

Traversing particle

Advantage of non-inverting material

p-in-n detectors (schematic figures!)

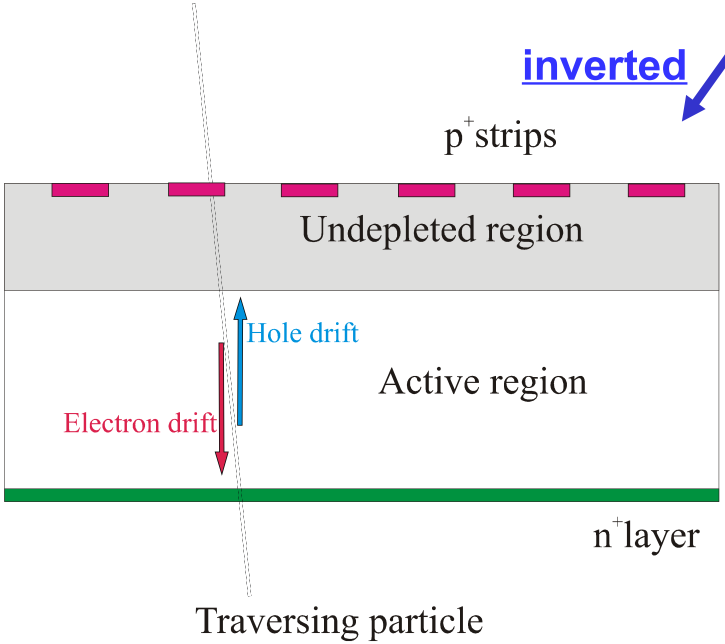
Fully depleted detector (non – irradiated):

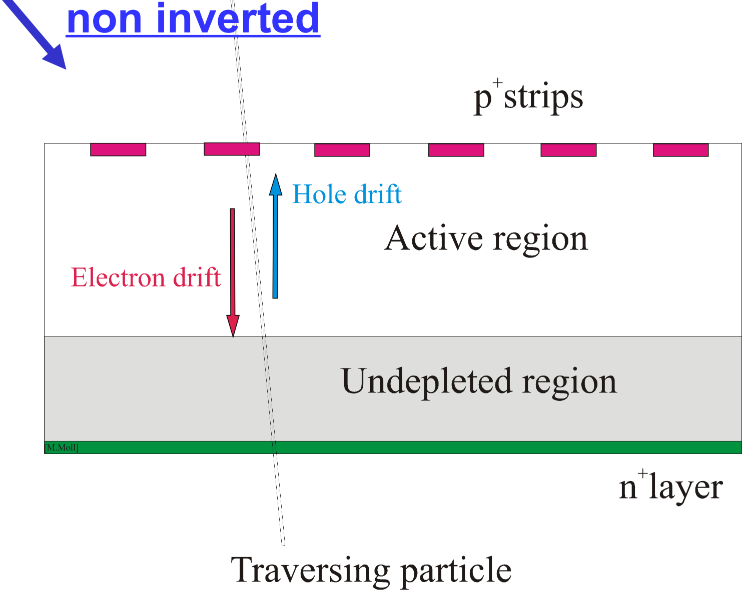


heavy irradiation

inverted

non inverted





inverted to "p-type", under-depleted:

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

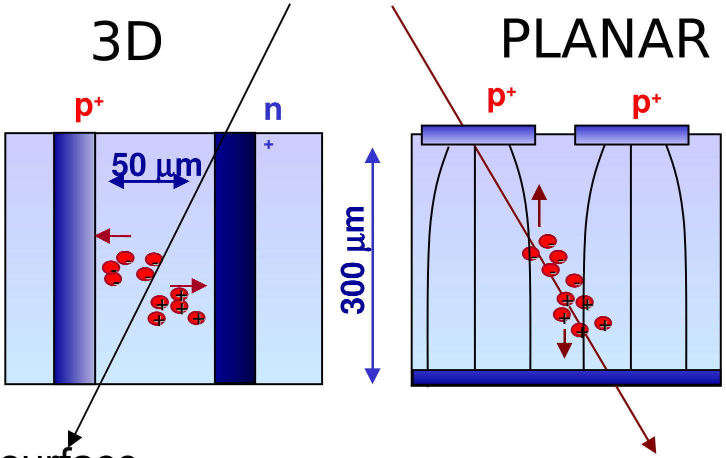
non-inverted, under-depleted:

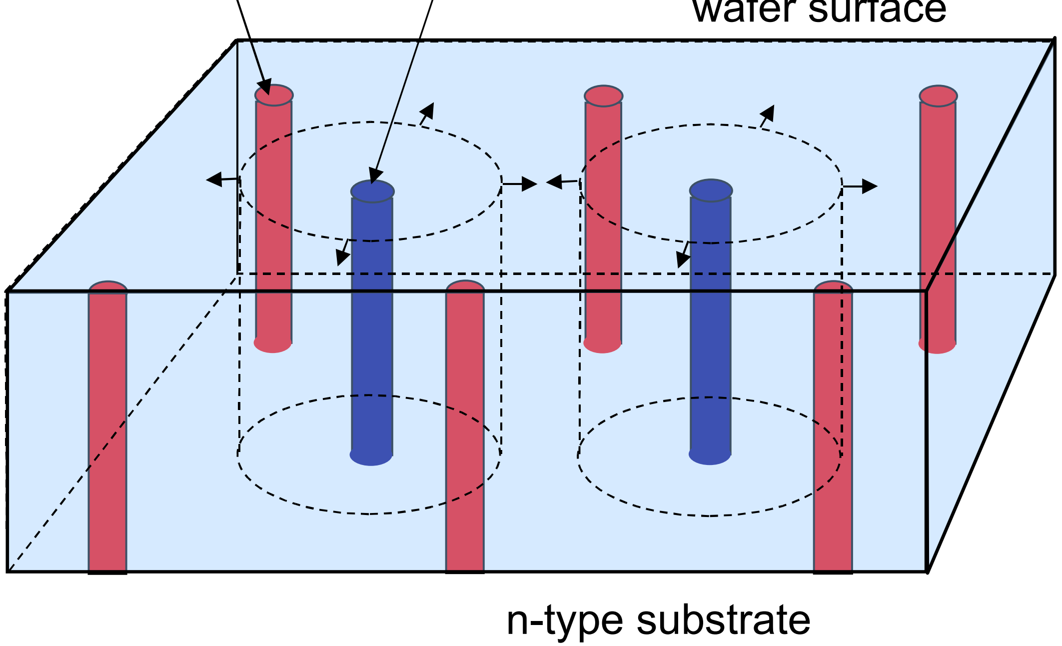
- **Limited loss in CCE**
- **Less degradation with under-depletion**

3D detector - concepts

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





Summary – Detectors for SLHC

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

  - CZ silicon detectors could be a cost-effective radiation hard solution
    no type inversion (to be confirmed), use cost effective 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 layers of SLHC detector) the active thickness of any silicon material is significantly reduced due to trapping.

  The two most promising options besides regular replacement of sensors are:
  Thin/EPI detectors : drawback: radiation hard electronics for low signals needed
  (e.g. 2300e at Φ_{eq} 8x10^{15}cm^{-2}, 50µm EPI)

  3D detectors : drawback: technology has to be optimized

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

Part III : Conclusion

Research and Development in Louvain la Neuve

➔ Neutron Irradiation

- **Irradiation of new materials**
- **Beam telescope (spatial resolution of MCZ materials)**

➔ Charge collection efficiency

- **Laser setup**
- **Radioactive source setup**

SLHC – Motivations (2)

➔ **Measurement of jets, measurements of the proton structure using other probes such as W/Z bosons (with leptonic decays) or photons might be extended to higher Q^2 values.**

➔ **Higgs Search : the uncertainties on rate measurements are expected to be dominated by statistics and by the knowledge of the luminosity whereas the determination of coupling ratios is going to be mostly statistically limited at LHC**

➔**SUSY searches – measurements :study of objects with very large masses, leading to signatures with very large p_T jets and large E_T^{miss} (being less influences by event pile-up)**

➔ **Other signatures beyond the Standard Model :**

Triple-Gauge boson couplings : increase in the sensitivity

Compositeness (using an inclusive jet cross-section measurement as function of E_T) : 50% increase in reach

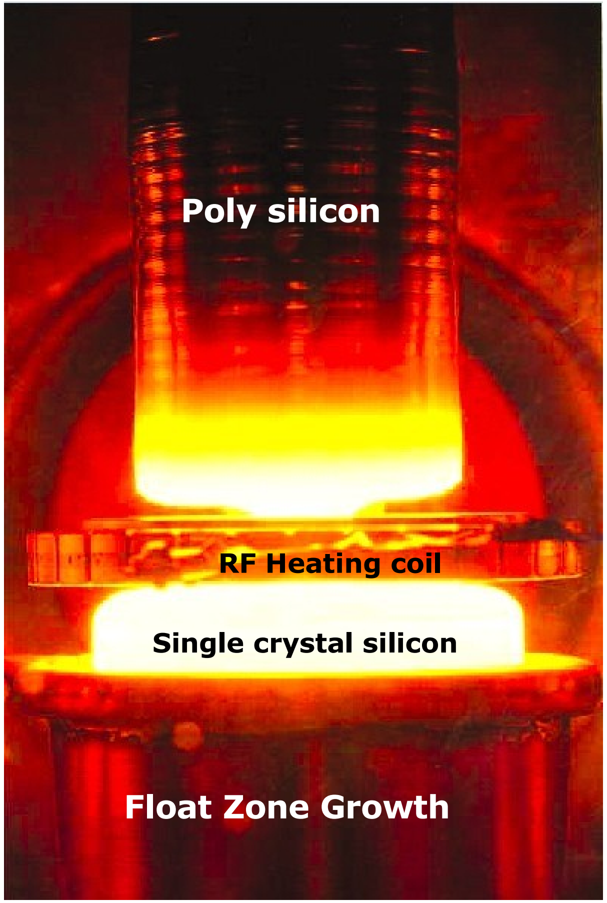
Large extra dimensions (using final states with high p_T jets and large E_T^{miss} via the direct production of gravitons) : 15-30% increase in reach

New heavy gauge bosons : reach in the mass of a Z’ is extended by about 25%

If no Higgs found : Strong $V_L V_L$ scattering

Silicon Growth Processes

- **Floating Zone Silicon (FZ)**

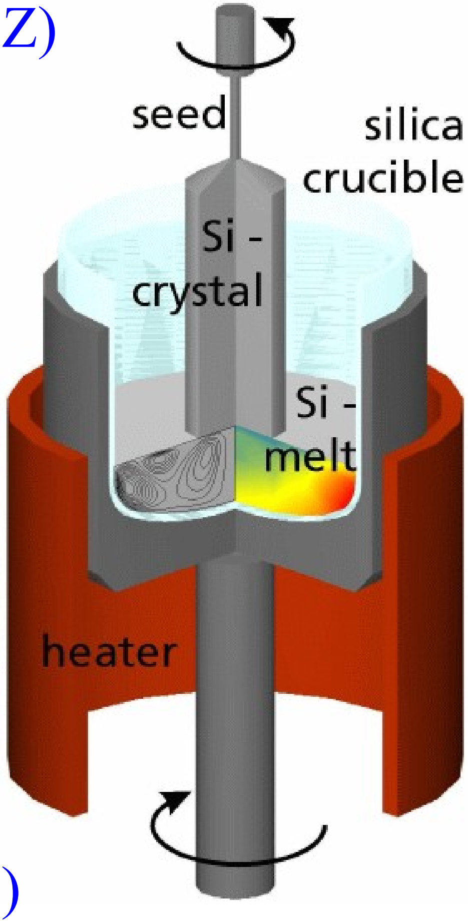


Float Zone Growth

- Basically all silicon detectors made out of high resistivety FZ silicon

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

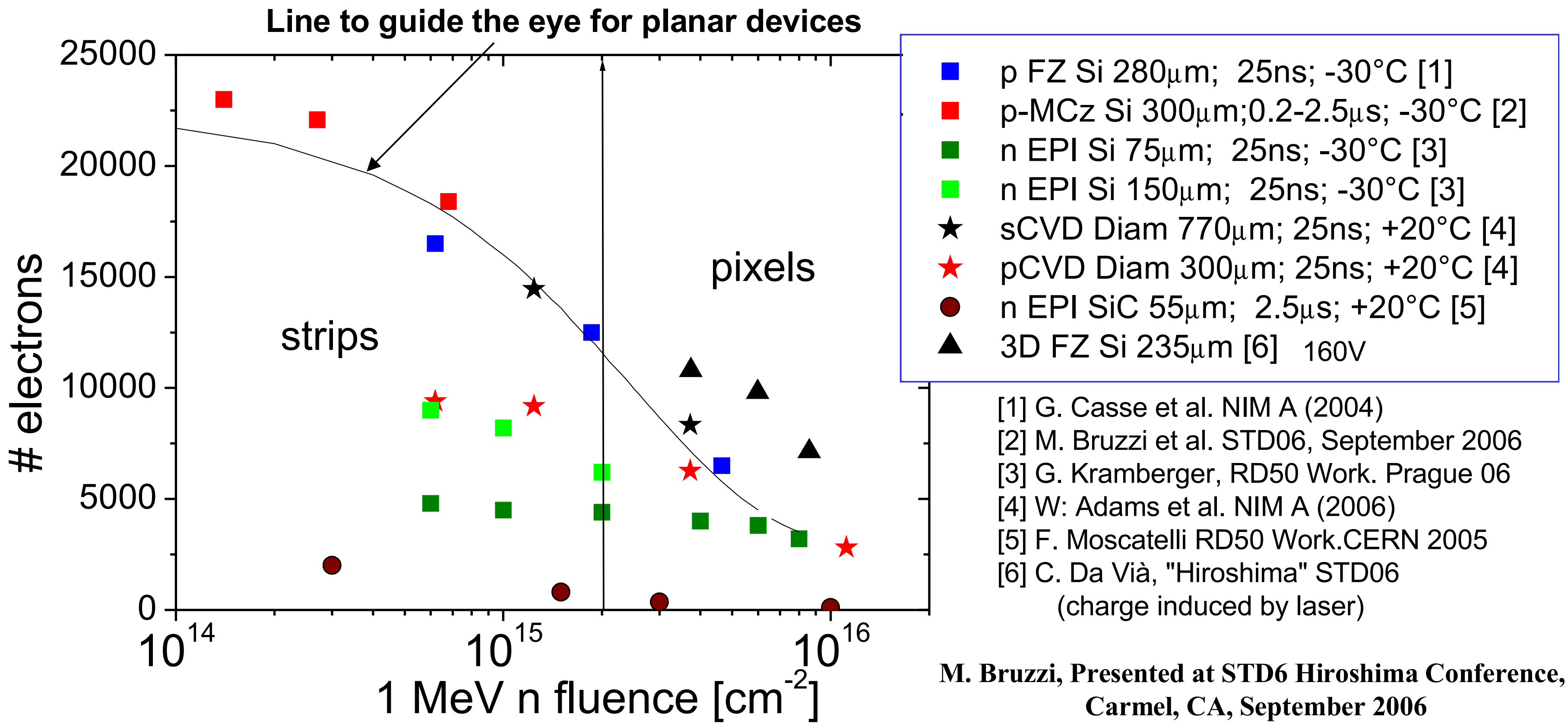
Czochralski Growth



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

Pierre Rodeghiero – 21 February 2007

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



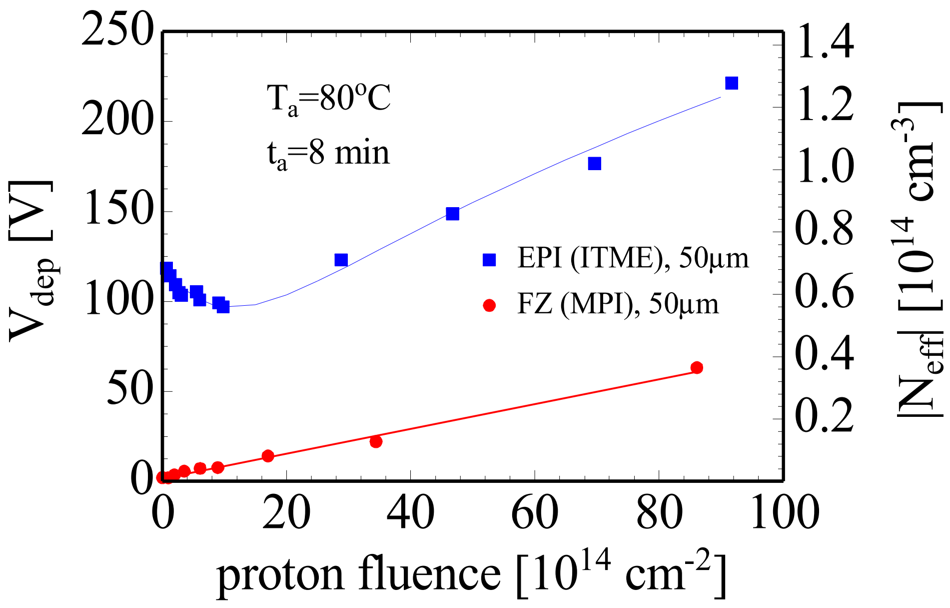
[1] G. Casse et al. NIM A (2004)
[2] M. Bruzzi et al. STD06, September 2006
[3] G. Kramberger, RD50 Work. Prague 06
[4] W: Adams et al. NIM A (2006)
[5] F. Moscatelli RD50 Work.CERN 2005
[6] C. Da Vià, "Hiroshima" STD06
(charge induced by laser)

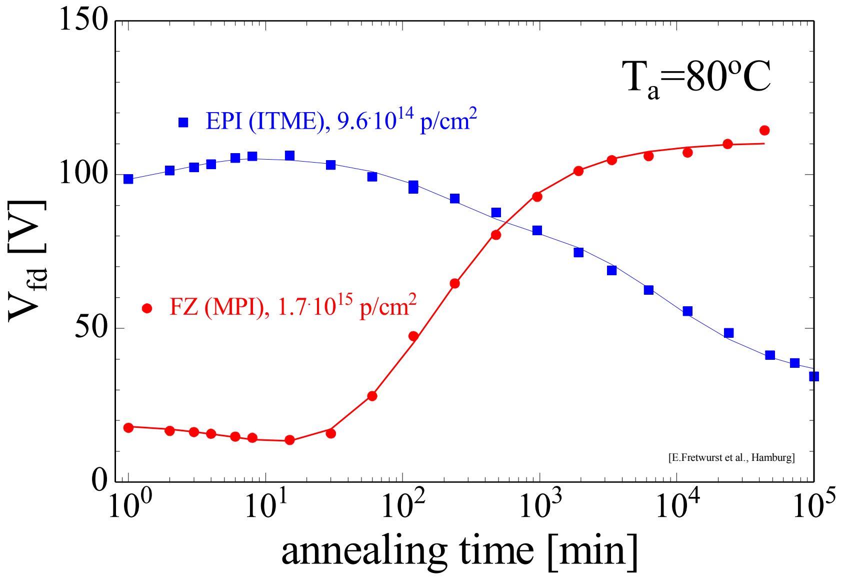
M. Bruzzi, Presented at STD6 Hiroshima Conference, Carmel, CA, September 2006

- Thick (300µm) p-type planar detectors can operate in partial depletion, collected charge higher than 12000e up to 2x10^{15}cm^{-2}.
- Most charge at highest fluences collected with 3D detectors
- Silicon comparable or even better than diamond in terms of collected charge (BUT: higher leakage current – cooling needed!)

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!

Radiation Damage – Microscopic Effects

- ^{60}Co-gammas

Only point defects

TI in FZ
but not in DOFZ or MCZ

- Protons

point defects & clusters

TI in FZ and DOFZ
At low proton energies (10-30 MeV) :
TI in MCZ
At high proton energies (24 GeV) :
No TI in MCZ

- Neutrons (elastic scattering)
  - $E_n > 185$ eV for displacement
  - $E_n > 35$ keV for cluster

Mainly clusters

TI whatever
the material