HELSINKI INSTITUTE OF PHYSICS

Radiation hard silicon for medical, space and high energy physics applications

J. Härkönen[1)], E. Tuovinen[1)], P. Luukka[1)], E. Tuominen[1)], Z. Li[2)], V. Eremin[3)] and E. Verbitskaya[3)]

[1)]*Helsinki Institute of Physics*
CERN-PH (40-4A-002)
CH-1211 Geneva, Switzerland
jaakko.haerkoenen@cern.ch

[2)]*Brookhaven National Laboratory, USA*

[3)] *Ioffe Polytecnical Institute, Russian Academy of Sciences, St. Petersburg. Russia*

Outline

- What we do at CERN ?
- Radiation hardness of Si detectors
- Thermal Donors in high resistivity Cz-Si
- How we characterize TD's ?
- Summary
- References

Esa Tuovinen loading MCz-Si wafers into oxidation furnace at the Microelectronics Center of Helsinki University of Technoly, Finland.

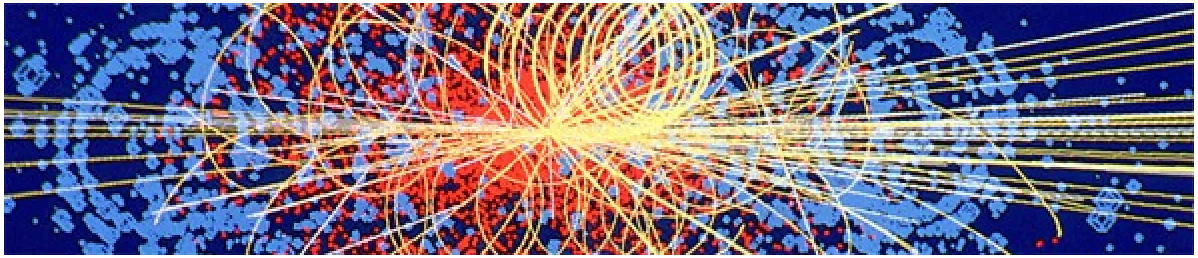
What we do at CERN ?

Aerial view of Large Hadron Collider

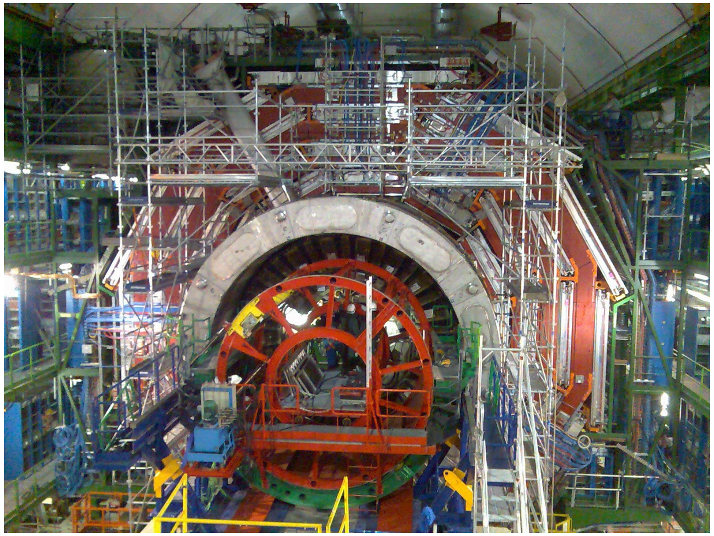
The modern physics understands poorly following

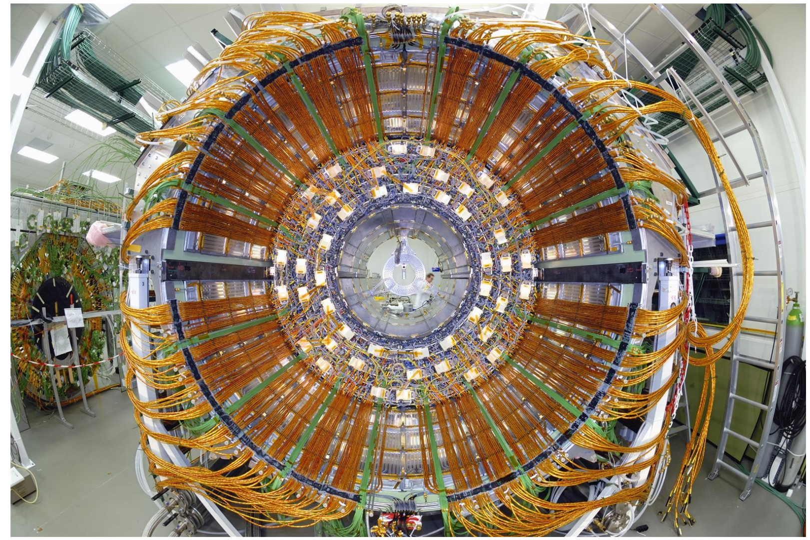
Why elementary particles have mass ?
Why are their masses different ?

In the physics Standard Model,there is an idea called the Higgs mechanism. Space is filled with a 'Higgs field', and by interacting with this field, particles acquire their masses. Particles which interact strongly with the Higgs field are heavy, whilst those which interact weakly are light. The Higgs field has at least one new particle associated with it, the Higgs boson



How do we measure particle tracks ?

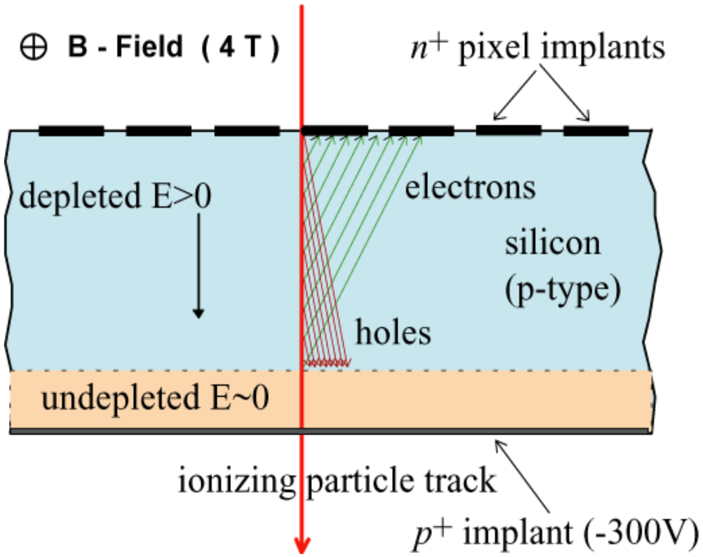


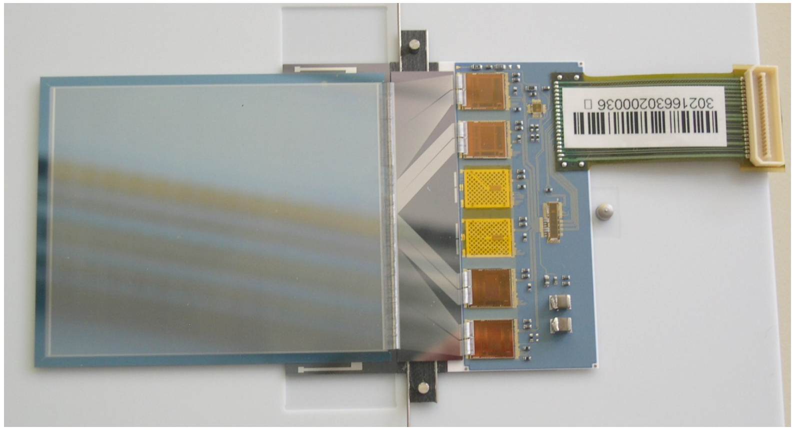


Compact Muon Solenoid (CMS) multi Purpose detector in the cavern 100m below the surface 05.May 2007.
During one second of CMS running, a data volume equivalent to 10,000 Encyclopedia Britannica is recorded
The data rate handled by the CMS event builder (~500 Gbit/s) is equivalent to the amount of data currently exchanged by the world's Telecom networks

The CMS Tracker implements 25000 silicon strip sensors covering an area of 210m^2. Connected to 75000 APV chips, one has to control 9600000 electronic readout channels, needing about 26 million microbonds.

Silicon particle detector





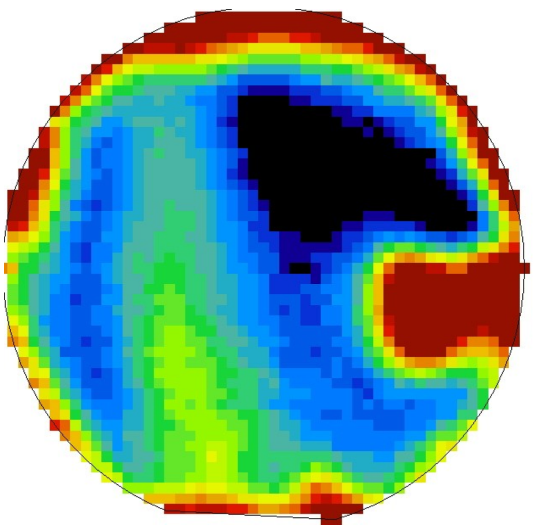
The charge transportation in particle detectors is based on drift of charge carriers, i.e. electrons and holes .

The detectors need to be therefore fully depleted, i.e the electric field extends over the entire bulk ~300um

$$V_{depl} = \frac{qN_d d^2}{2\varepsilon_0 \varepsilon_{Si}}$$

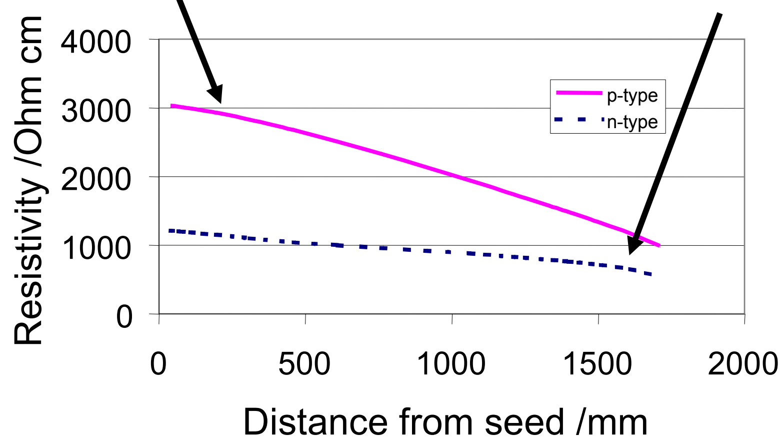
Requirements for detector applications

- ✓ High resistivity (low V_{fd})
- ✓ Oxygen concentration $5\text{-}10\times10^{17}\ \mathrm{cm}^{-3}$ (radiation hardness)
- ✓ Homogeneity
- ✓ High minority carrier lifetime



Oxygen donor compensation

Boron/Aluminum contamination



Radiation hardness challenge

- Luminosity increase by factor of 10 is foreseen after the 1st phase of the LHC experiments.
- Extensive R&D is required because

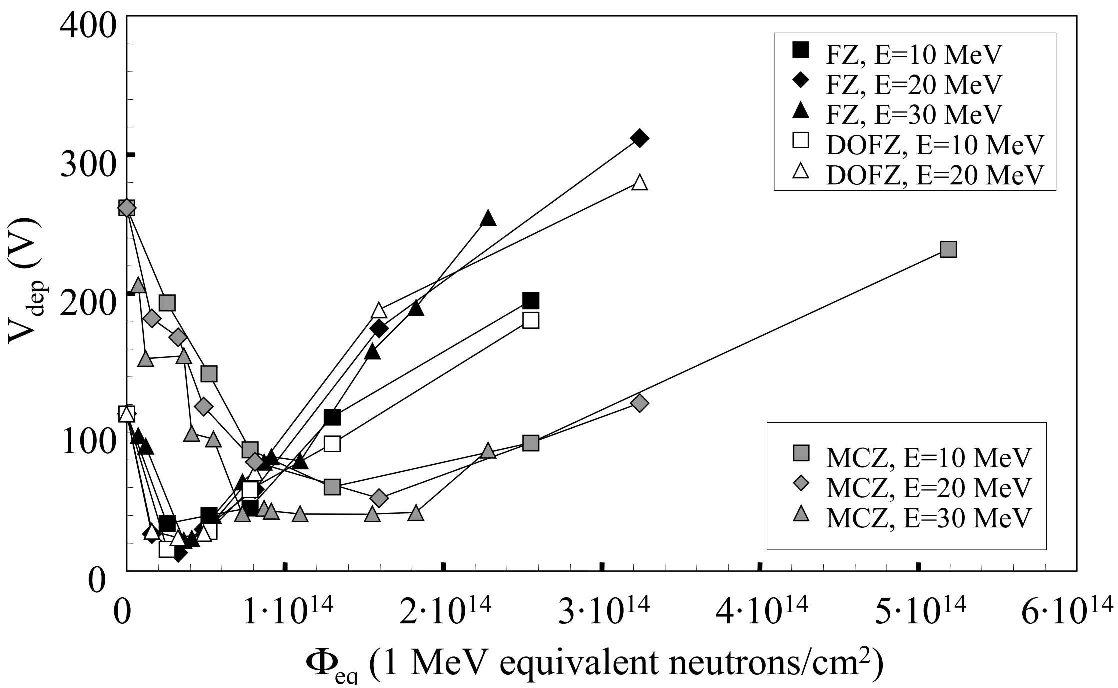
1. Leakage current (I_{leak}) increases 10 X
   - Increased heat dissipation
   - Increased shot noise

2. Full depletion voltage (V_{fd}) will be >1000V

3. Trapping will limit the Charge Collection efficiency (CCE).
   - CCE at $1\times10^{15}\,cm^{-2}$ ≈ 50% (strip layers of S-LHC Tracker)
   - CCE at $1\times10^{16}\,cm^{-2}$ ≈ 10-20% (pixel layers of S-LHC Tracker)

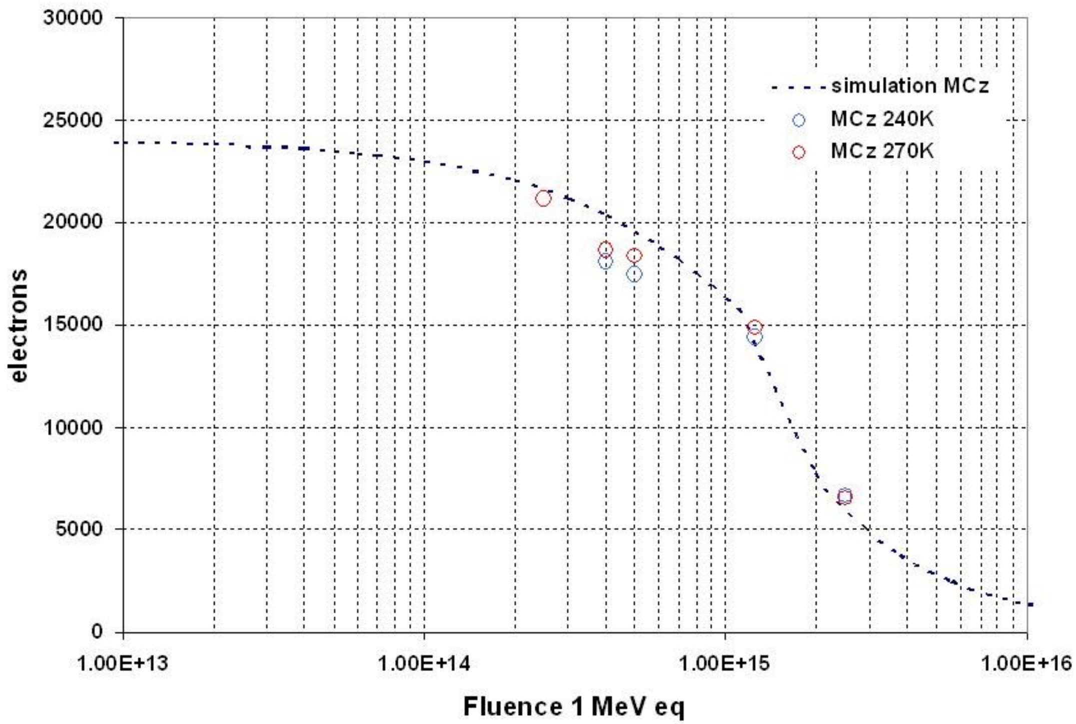
HELSINKI INSTITUTE OF PHYSICS

Full Depletion Voltage V_{fd}



- Radiation defects are dominantly acceptors
- With irradiation the N_{eff} first decreases, then type inversion occurs
- After type inversion the N_{eff} increases monotonically
- In the LHC experiments, the N_{eff} will evetually be 10x higher than initial phosporous doping→it is not possible to fully deplete the detectors with any reasonable voltage

Charge Collection Efficiency



Measurement with IR laser and 500V bias

Pad detectors >> no weighting field effect >> test beam for strip detectors needed

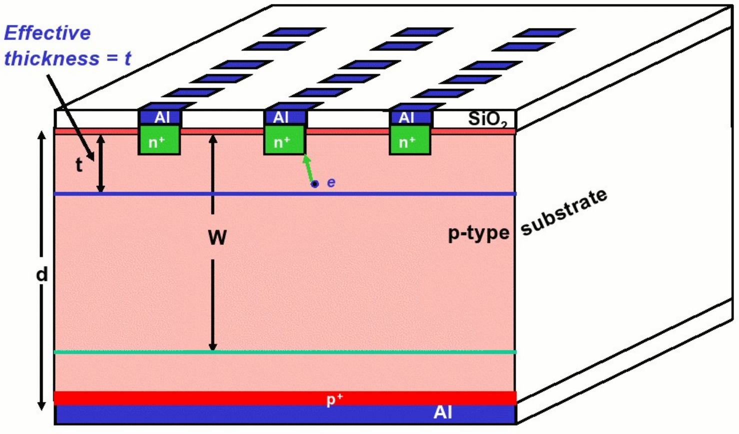
>1×10^{15} cm^{-2} fluence MCz (300µm) is under depleted

Unpublished preliminary data.
10% error bars should be assumed

$$CCE = CCE_{Geometrical} \times CCE_{trapping} = \frac{w}{d} \times e^{-t_{dr}/\tau_{trapping}}$$

How to improve radiation hardness - $n^+/p^-/p^+$

Detectors are traditionally $p^+/n^-/n^+$ structures, i.e. made of n-type wafers



Why to make p-type detectors ?

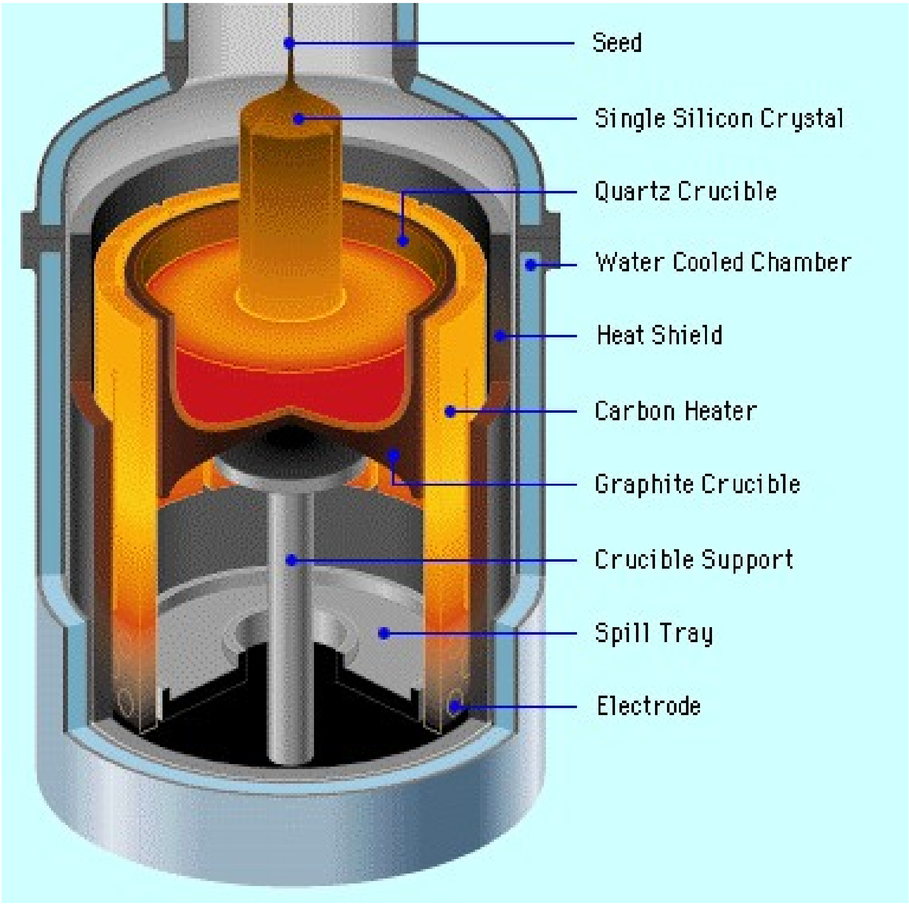
- No type inversion.
- Collecting junction remains on the segmented side (higher E-field due to the weighting field).
- Charge collection is dominantly electron current >> less trapping.
- V_{fd} can be tailored by Thermal Donors (TD) in MCz-Si

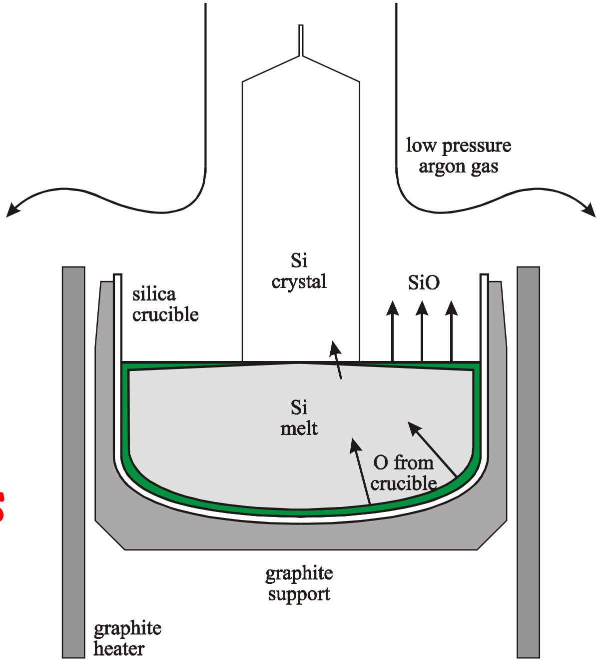
  >> CCE geometrical factor is improved.
- Single sided process.

CCE is product of V_{fd} and trapping→one has to improve both

This is our motivation to study Thermal Donors

Crystal growth





Growth parameters

- Gas flow
- Pressure
- Purge tubes (gas flow pattern
- Crucible rotation
- Crystal rotation
- Temperature distribution
- Magnetic field

Olli Anttila, Okmetic Oyj., 6th RD50 - Workshop on Radiation hard semiconductor devices for very high luminosity colliders Helsinki, 2-4 June, 2005. http://rd50.web.cern.ch/rd50/6th-workshop/default.htm

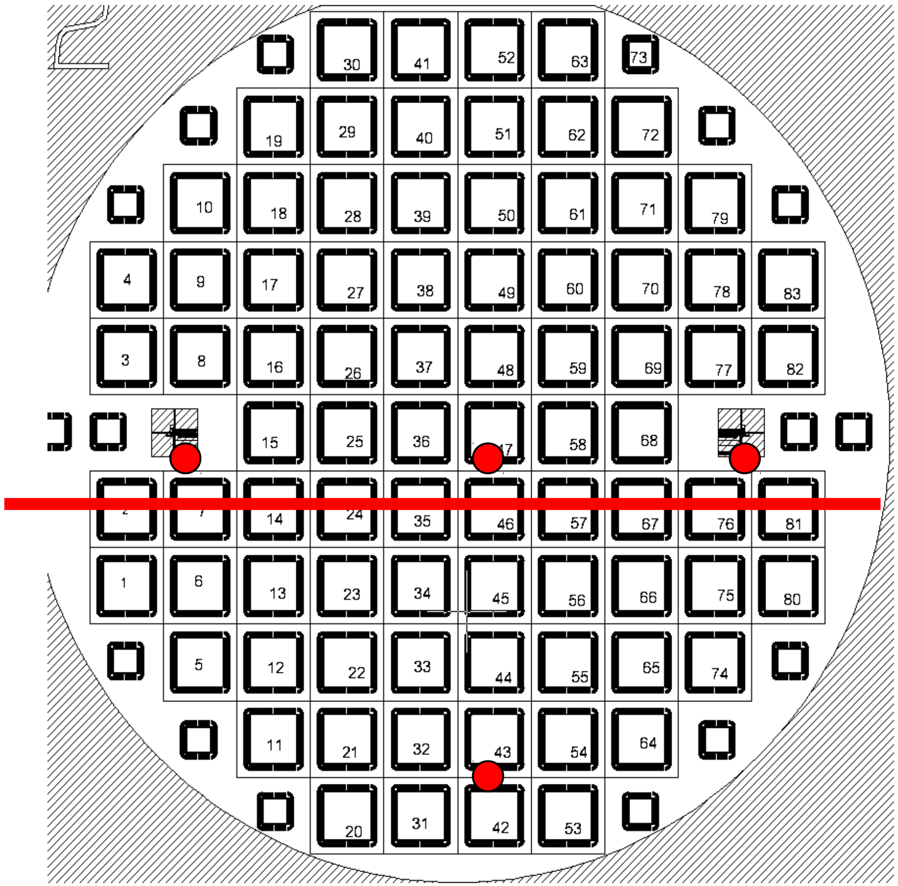
Why Cz-Si for particle detectors and other high radiation level applications ?

- Cz-Si available in larger diameters
- Lower wafer cost
- Better compatibility with advanced CMOS processes
- Oxygen brings significant improvement in thermal slip resistance
- Oxygen gives **significant radiation hardness** advantage.

Detectors have traditionally made on Fz-Si. Why not before Cz-Si ?

- No demand for high resistivity Cz-Si -> No availability
- Price for custom specified ingot 15,000 € - 20,000 € (too much for university lab)
- Now RF-IC industry shows interest on high resistivity Cz-Si (=lower substrate losses of RF-signal)

Oxygen concentration in MCz-Si



- O concentration from FTIR measurements (organized by RD50)
- 1mm thick reference wafer

- Center $4{,}95 \cdot 10^{17}$ cm^{-3}
- Right $4{,}89 \cdot 10^{17}$ cm^{-3}
- Left $4{,}93 \cdot 10^{17}$ cm^{-3}
- Right $4{,}93 \cdot 10^{17}$ cm^{-3}

Processing of Cz-Si Detectors

- Basically no difference from standard Fz-Si detector process, except…

- High O content leads to Thermal Donor (TD) formation at temperatures $400^{0}C$ – $600^{0}C$.

- TD formation can be enhanced if H is present.

- Typical process steps at $400^{0}C$ – $600^{0}C$
  - Aluminum sintering (e.g. 30min @ $450^{0}C$)
  - Passivation insulators over metals (LTO,TEOS etc ~$600^{0}C$ + H_2 from Si_3H_4 process gas)

HELSINKI INSTITUTE OF PHYSICS

Thermal Donors in Cz-Si

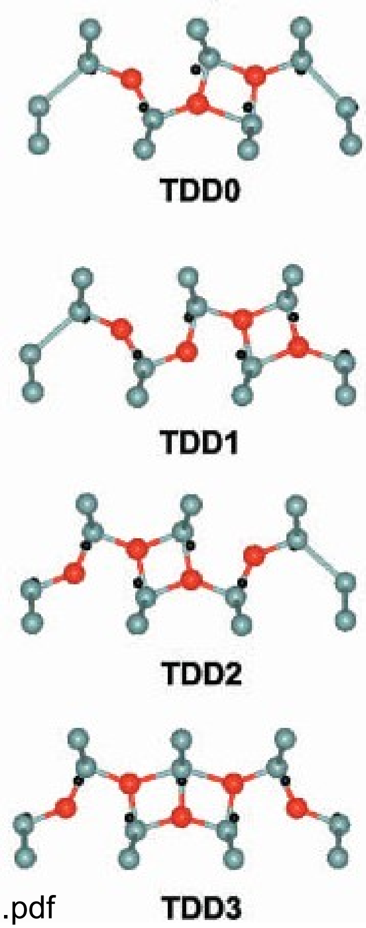
- TDs are oxygen complexes that form shallow states in Si band gap below the conduction band.

- High O content leads to Thermal Donor (TD) formation at temperatures 400°C – 600°C.
- TDs are dissolved at "high" temperatures.

- TD formation can be enhanced if H is present in the process (e.g. CVD).

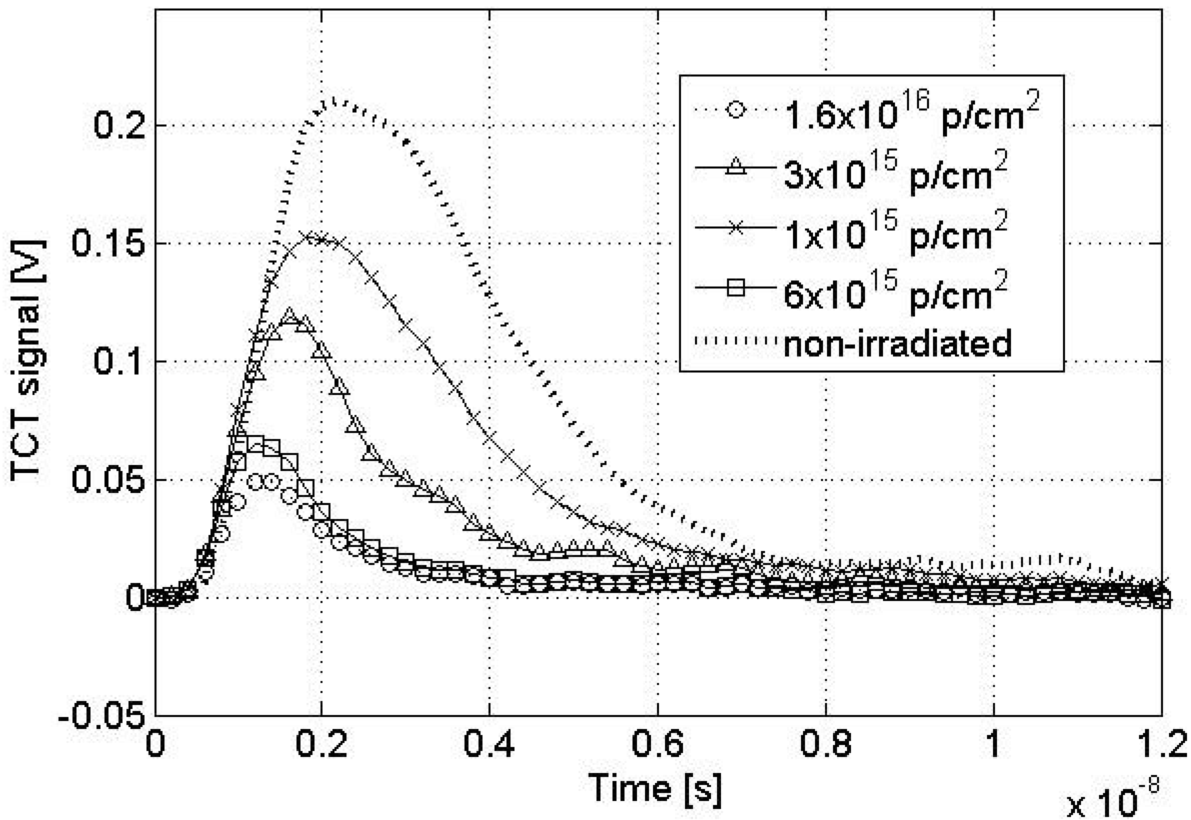
- Effective resistivity can be adjusted in p-type MCz-Si 500 Ωcm < σ < ~10 kΩcm

- With this method it is possible to engineer the V_{fd} of p-type MCz-Si n+/p-/p+ detectors



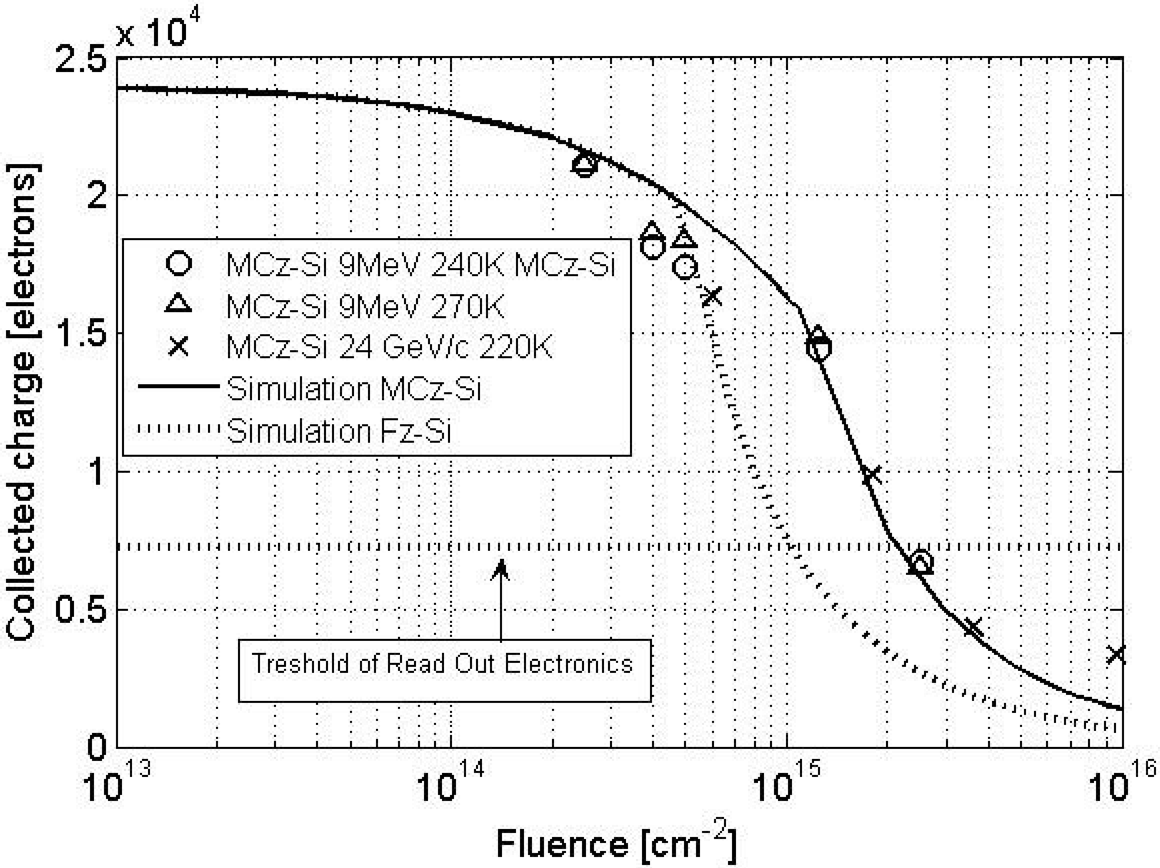
J. von Boehm, http://www.csc.fi/lehdet/tietoyhteys/TY3_2004.pdf

Performance of MCz-Si as detector material



Detector response
For infrared light
After different
irradiations

Expected Charge Collection Efficiency



MCz-Si provides 2x higher CCE than traditionally used Fz-Si at irradiation fluence expected in Super-LHC

HELSINKI INSTITUTE OF PHYSICS

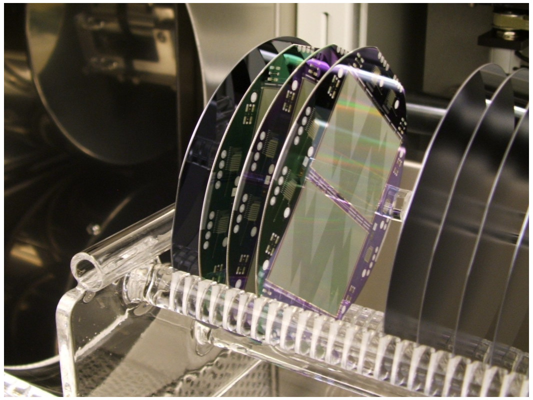
Summary I

•TDs form in high resistivity Cz-Si between 400-600°C. TDs are dissolved at temperatures >800°C.

•TD formation is explained by "chain" model, i.e. the capture of interstitial oxygens by diffusing oxygen chains and the escaping of interstitial oxygens from the chains fully dominate the formation kinetics.

•There are only few experimental studies about TDs in high resistivity MCz-Si. The data in literature is typically for CMOS resistivity wafers with O_i concnetration exceeding the precipitation limit.

•Our data shows almost linear TD generation in oxygen lean MCz-Si. The homogenuity of V_{fd} and O_i is significant in 100mm wafers.



•With TCT method it is possible to extract the bulk conductivity type and effective doping concentration.

Summary II

- MCz-Si shows better radiation hardness against protons than Fz-Si materials. No improvement against neutron and no difference in leakage current.
- CCE at 3×10^{15} cm^{-2} is about 25%. Thus, MCz-Si is feasible for strip layers but not for pixel barrel.
- CCE can further be improved by implementing $n^{+}/p^{-}/p^{+}$ structure and compensate V_{fd} by TDs .
- The CCE is limited by trapping and elevated V_{fd}.
- Material/defect engineering of Si does not provide any improvement for I_{leak}
- Current injection (CID) provides 2X higher CCE at 200K.
- Cooling is a demanding challenge.