Recent advances in the development of semiconductor Detectors for very high luminosity colliders

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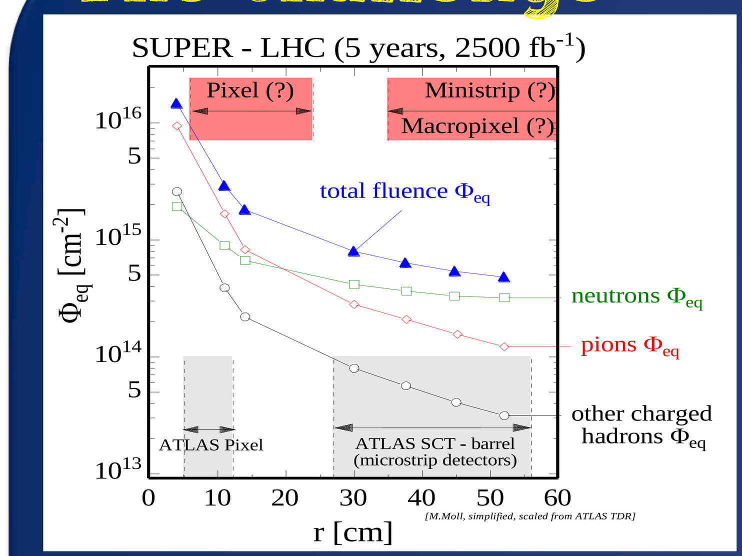
http://www.cern.ch/rd50

The challenge



SLHC compared to LHC:

- Higher radiation levels ⇨ Higher radiation tolerance needed!
- Higher multiplicity ⇨ Higher granularity needed!

⇨ Need for new detectors & detector technologies

The Mission of RD50

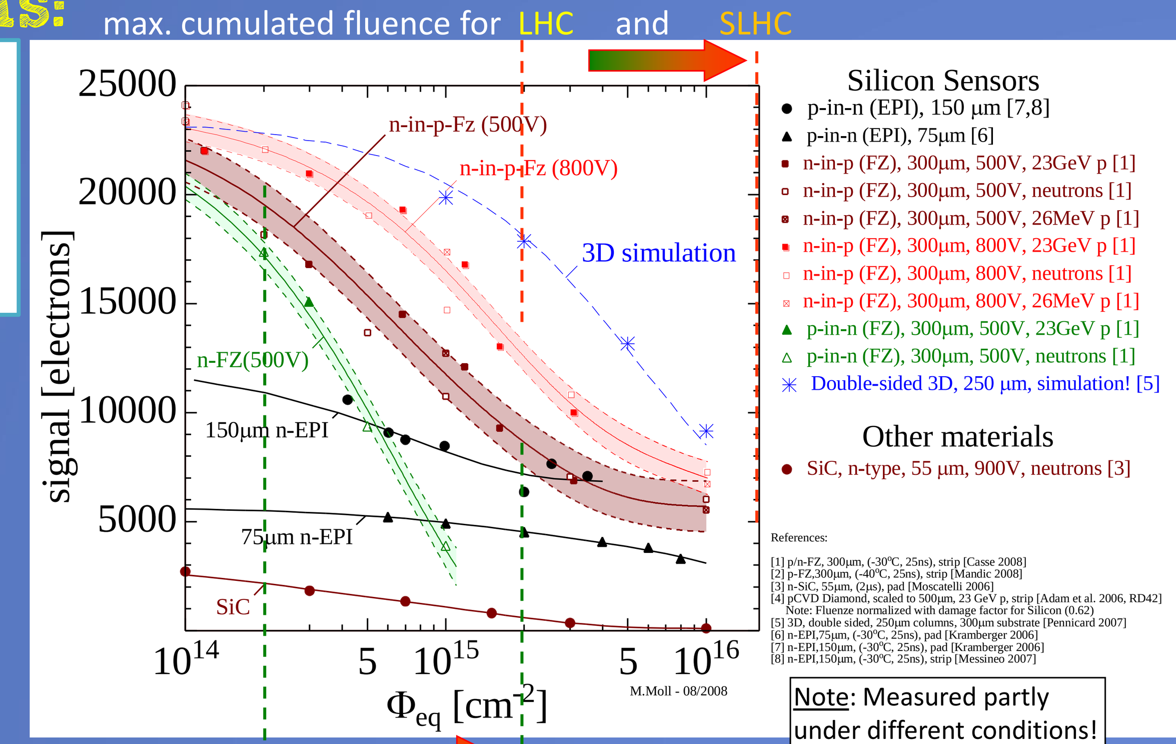
- Material characterization & defect engineering
  - Understanding of radiation damage
    - Macroscopic effects and microscopic defects
    - Irradiation with different particles (n. p, π)
  - Oxygen enrichment
    - DOFZ, Cz, MCz, EPI, (SIC & GaN evaluated/abandoned)
  - Understanding /tuning of influence of processing technology
- Device engineering
  - p-type silicon (n-in-p)
  - thin sensors
  - 3D detectors

➔ Proposal/understanding which sensor material and/or sensor configuration can be used at which radius to the beam for the SLHC and beyond

Implications:

Signal comparison for various silicon sensors

Pixel sensors: max. cumulated fluence for LHC and SLHC



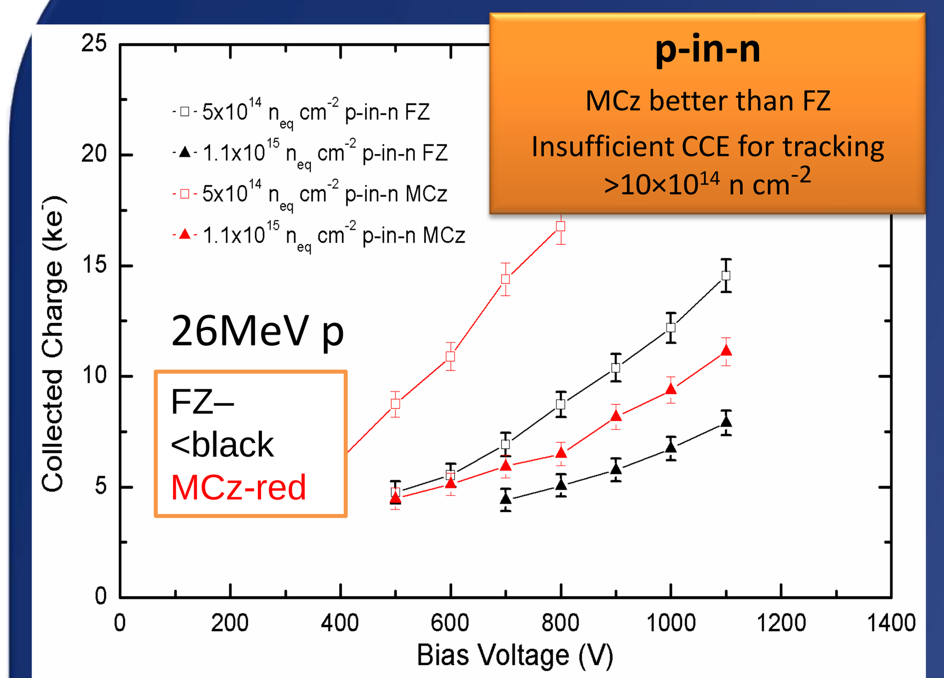
Strip sensors: max. cumulated fluence for LHC and SLHC

Note: Measured partly under different conditions! Lines to guide the eye (no modeling)!

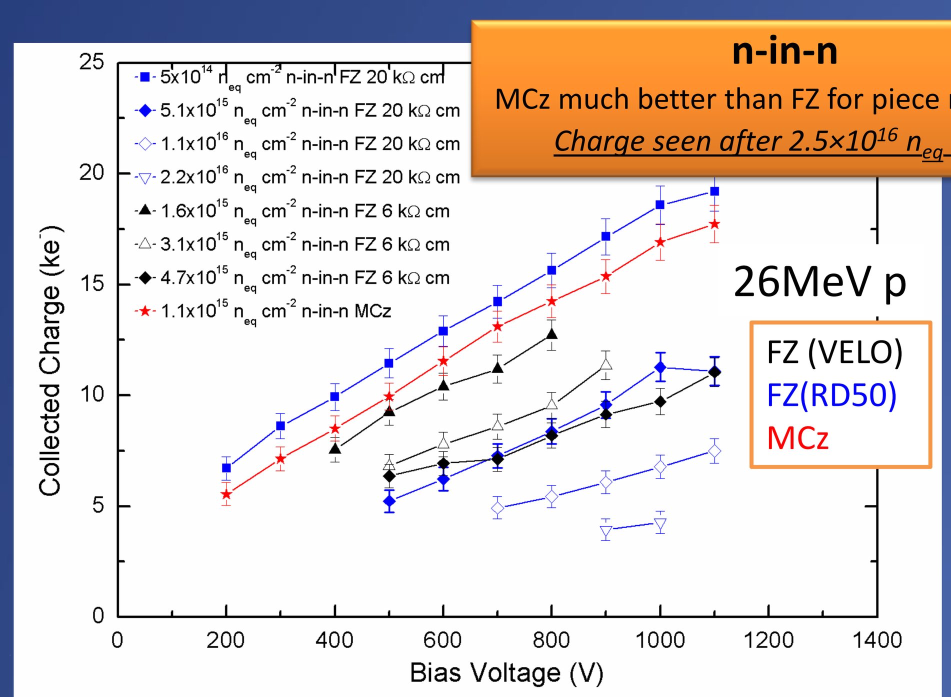
Technology: n-in-p vs. n-in-n vs. n-in-p, FZ vs. MCz (selection)

Affolder, Casse et al.

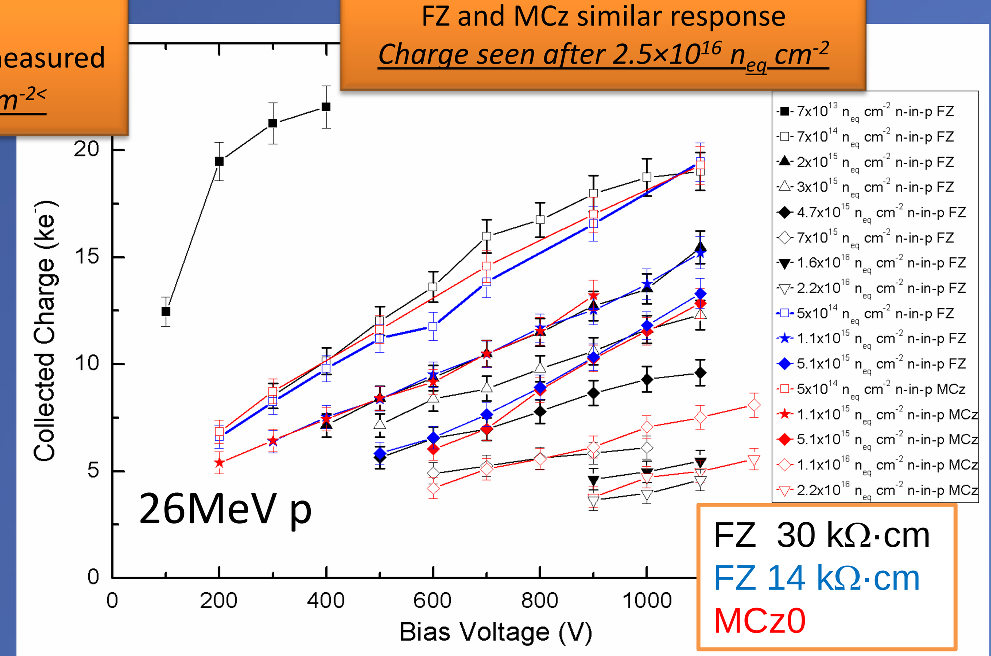
p-in-n — MCz better than FZ. Insufficient CCE for tracking >10×10^{14} n cm^{-2}



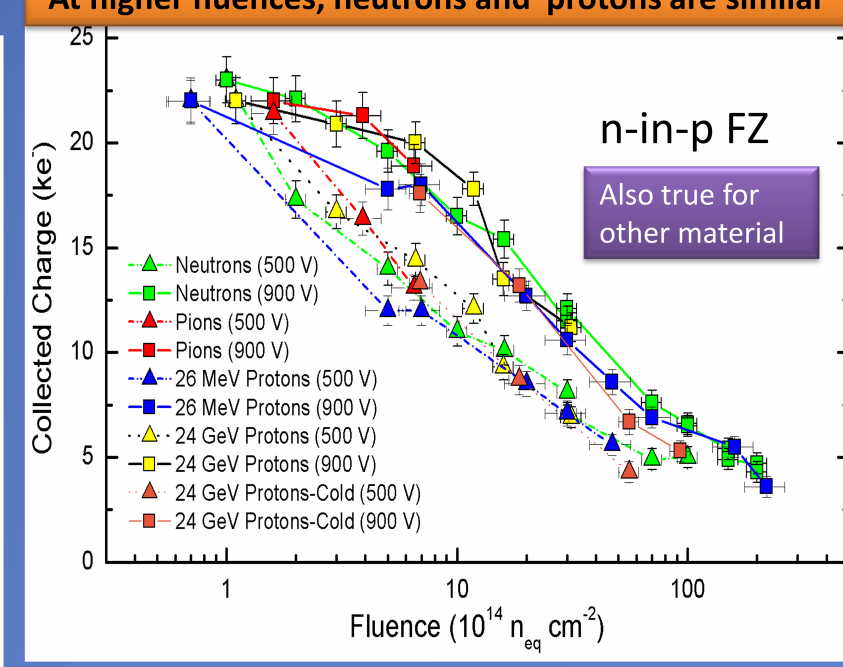
n-in-n — MCz much better than FZ for piece measured. Charge seen after 2.5x10^{16} n$_{eq}$ cm^{-2}!



n-in-p — FZ and MCz similar response. Charge seen after 2.5x10^{16} n$_{eq}$ cm^{-2}

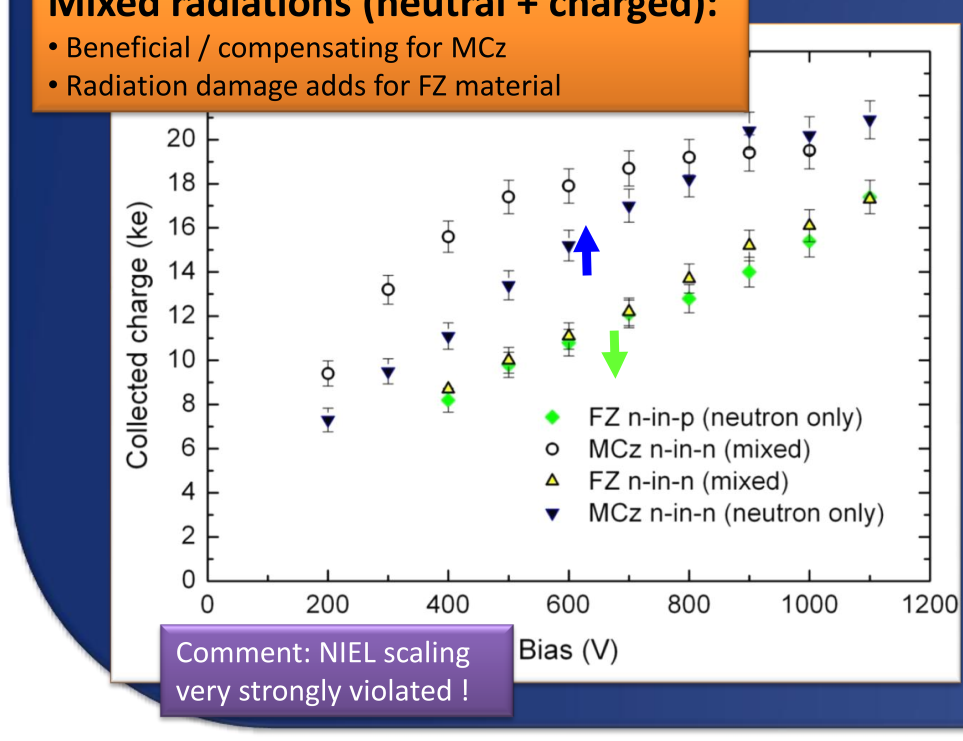


At higher fluences, neutrons and protons are similar



Mixed radiations (neutral + charged):

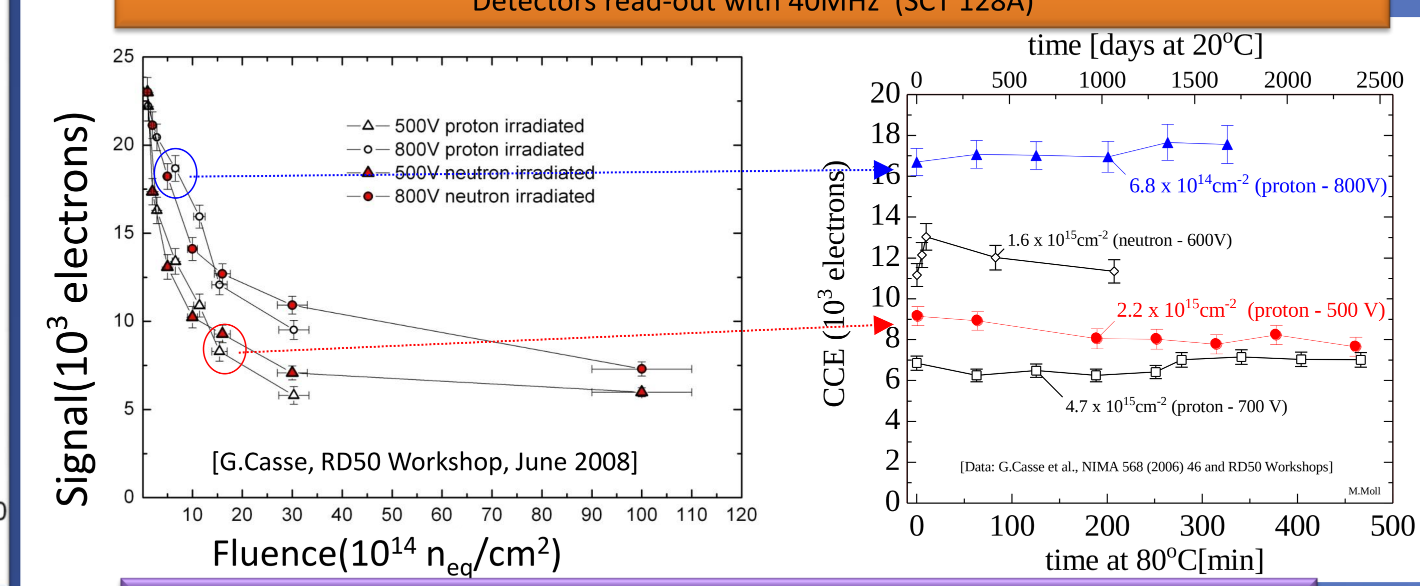
- Beneficial / compensating for MCz
- Radiation damage adds for FZ material



Comment: NIEL scaling very strongly violated !

CCE annealing

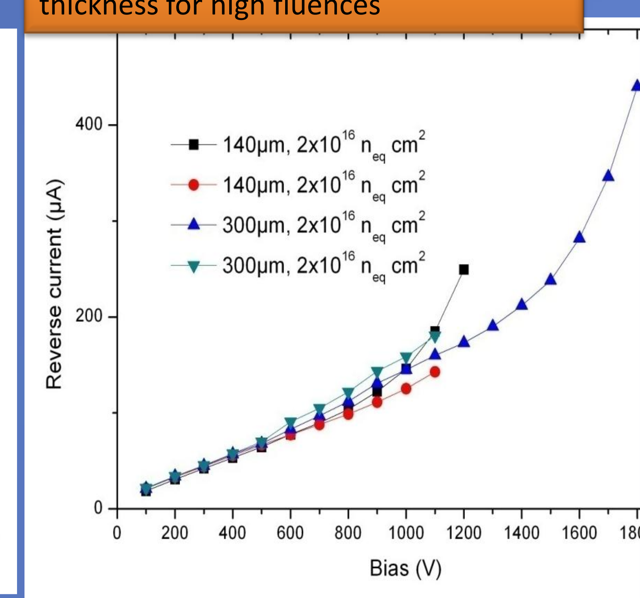
n-in-p microstrip p-type FZ detectors (Micron, 280 or 300µm thick, 80µm pitch, 18µm implant) Detectors read-out with 40MHz (SCT 128A)



No reverse annealing in CCE measurements for neutron and proton irradiated detectors

Surprise:

leakage current does not scale with thickness for high fluences



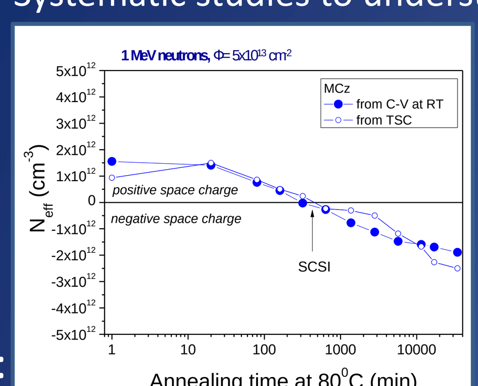
- **CCE/trapping and power is the main topic for very high fluences**
- Many different bulk materials irradiated with neutrons, protons, pions
- p-in-n FZ/MCz not radiation tolerant enough for inner SLHC radii
- No CCE annealing observed for p-bulk
- Leakage current does „not" scale with thickness at high fluences

n-strip readout devices have sufficient CCE for even innermost SLHC radii

• Higher bias voltages, better cooling & lower threshold electronics are needed!!

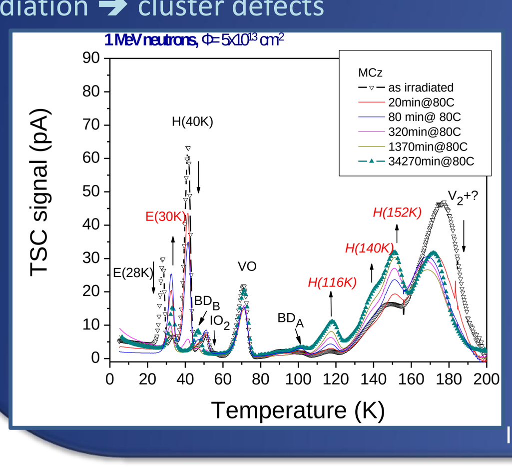
Microscopic studies RD50 / WODEAN

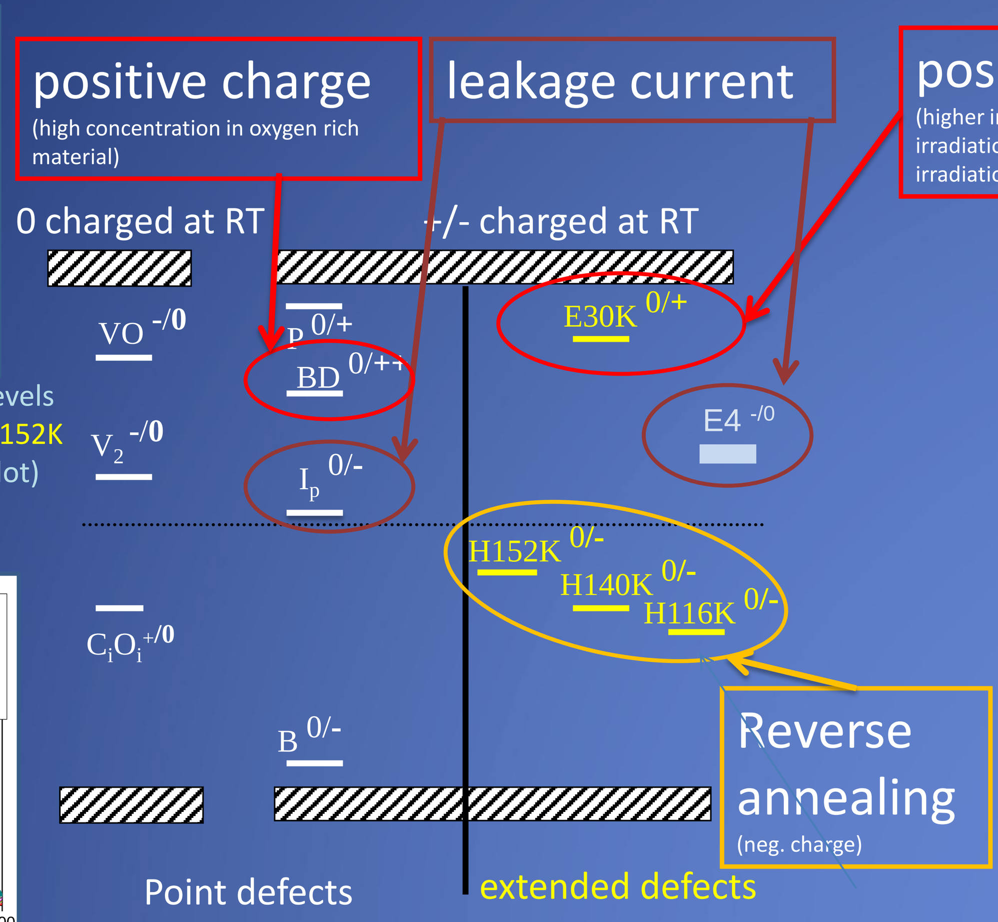
Systematic studies to understand microscopic band levels correspondence to their macroscopic behaviour



E.g.:

- N_{eff} follows concentration of acceptor levels (negative space charge) H116K, H140K, H152K which increase with annealing (see TSC plot)
- H116K, H140K, H152K do not form with γ radiation ➔ cluster defects





Point defects

- $E_i^{BD} = E_c - 0.225$ eV, $\sigma_n^{BD} = 2.3\cdot10^{-14}$ cm^2
- $E_i^{I} = E_c - 0.545$ eV
  - $\sigma_n^{I} = 2.3\cdot10^{-14}$ cm^2
  - $\sigma_p^{I} = 2.3\cdot10^{-14}$ cm^2

Cluster related centers

- $E_i^{116K} = E_v + 0.33$eV, $\sigma_p^{116K} = 4\cdot10^{-14}$ cm^2
- $E_i^{140K} = E_v + 0.36$eV, $\sigma_p^{140K} = 2.5\cdot10^{-15}$ cm^2
- $E_i^{152K} = E_v + 0.42$eV, $\sigma_p^{152K} = 2.3\cdot10^{-14}$ cm^2
- $E_i^{30K} = E_c - 0.1$eV, $\sigma_n^{30K} = 2.3\cdot10^{-14}$ cm^2

I. Pintilie, E. Fretwurst, G. Lindström, A. Junkes (e.g. Appl. Phys. Lett. 92, 024101, 2008)

Device engineering: 3D

Introduced by: S.I. Parker et al., NIMA 395 (1997) 328

Short collection path/time = almost no trapping; charge of the complete volume is collected

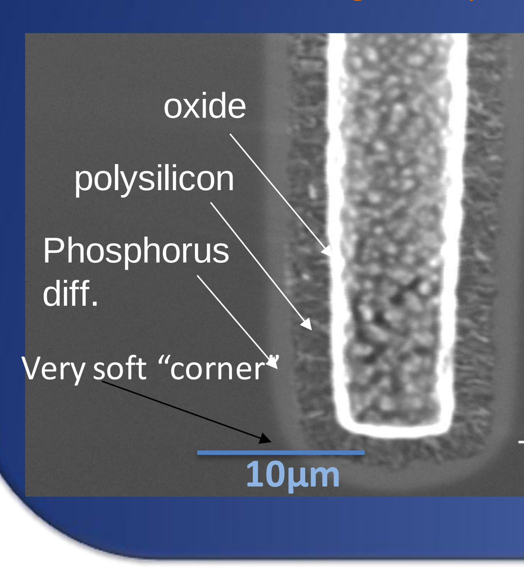
"3D" electrodes:
- narrow columns along detector thickness
- diameter: 10µm, distance: 50 - 100µm

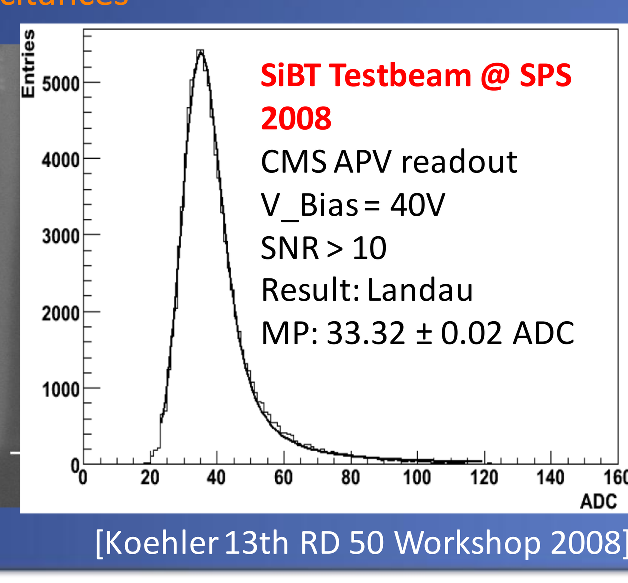
Lateral depletion:
- lower depletion voltage
- thicker detectors possible
- fast signal

☺ smaller trapping probability - radiation hard

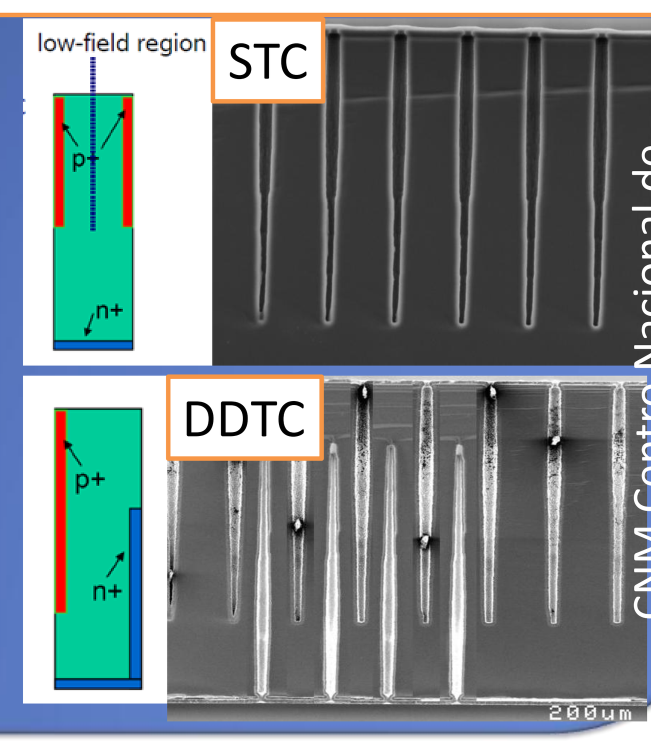
☹ higher capacitances

1. 3D single column type (STC)
   - suffer from a low field region between columns
2. 3D double-sided double type columns (DDTC)
   - more complicated
   - full field





[Koehler 13th RD 50 Workshop 2008]



Conclusions

- Radiation Damage in Silicon Detectors
  - Change of Depletion Voltage (type inversion, reverse annealing, …) (can be influenced by defect engineering!)
  - Increase of Leakage Current (same for all silicon materials)
  - Increase of Charge Trapping (same for all silicon materials)

Signal to Noise ratio is quantity to watch (material + geometry + electronics)

- Microscopic defects
  - Good understanding of damage after γ-irradiation (point defects)
  - Damage after hadron damage still to be better understood (cluster defects), however enormous progress in last 2 years
- CERN-RD50 collaboration working on:
  - Material Engineering (Silicon: DOFZ, MCZ, EPI, …) (RD42: Diamond)
  - Device Engineering (3D, thin sensors, n-in-p, n-in-n,..) (RD39: Cryogenic, CI)

⇨ To obtain ultra radiation hard sensors a combination of material and device engineering approaches depending on radiation environment, application and available readout electronics will be the best solution

- 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.

- MCZ silicon detectors could be a solution (some more work needed!)

n-MCZ : No 'standard' space charge sign inversion under proton irradiation (double junction) , excellent performance in mixed fields due to compensation of charged hadron damage and neutron damage (N_{eff} compensation)

- p-type silicon microstrip detectors show very encouraging results: CCE ≈ 6500 e; Φ_{eq}= 4×10^{15} cm^{-2}, V=500V, 300µm, immunity against reverse annealing! This is presently the baseline option for the ATLAS SCT upgrade

- 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. Collection of electrons at electrodes essential: Use n-in-p or n-in-n detectors!

- Recent results show that planar silicon sensors might still give sufficient signal, still some interest in epitaxial silicon and thin sensor options
- 3D detectors : looks promising, drawback: technology has to be optimized! Many collaborations and sensor producers working on this.

- Diamond has become an interesting option for the innermost pixel layers

Some last and obvious remarks:

- n-strip readout (n-in-n or n-in-p) looks promising
- Trapping is the main villain at high fluences
  - Consider high voltage (800-1000V) operation to achieve adequate CCE
- High and homogeneous oxygen content (e.g. MCz) is more radiation tolerant vs. charged particle radiation (see already RD48)
- p-material does not show significant annealing behaviour for CCE
- In all cases, RD50 gives only recommendations:

THE SPECIFIC APPLICATION HAS TO BE CHECKED!

- Especially SNR with specific electronics, final geometry and process technology must be considered
- All simulation fit parameters need adaptions to the specific case