Silicon Particle Detectors for Future High Energy Physics Experiments

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Outline

- Motivation and background
- What is the radiation hardness
  * Microscopic effects
  * Macroscopic effects
- Improvement of RadHard
  - Defect engineering
    * Cz-Si
    * Thermal Donors in Cz-Si
  - Charge Collection Efficiency (CCE)
- Summary
Background

LHC is the first experiment to use Si detectors in large scale.

Only very few proton-proton collisions produce Higgs.

Luminosity of LHC beam is very high causing hostile radiation environment to Si devices.

Radiation Hardness of Si devices is currently extensively studied topic. There are ~100 institutes within CERN’s RD50 and RD39.
Background

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

\[ V_{depl} = \frac{qN_d d^2}{2\varepsilon_0 \varepsilon_{Si}} \]
Strip detector processing

The devices were processed at Helsinki University of Technology Microelectronics Center

- with simple 5-8 level mask process:
  - 4 lithographies
  - 2-3 ion implantations
  - 2 thermal dry oxidations
  - 3 sputter metal depositions

AC-pad, bonded to read out
DC-pad, for testing
Bias resistors
Bias line
Guard Ring for isolation
multi GR
Corner of Helsinki pad detector.
- Multi-guard ring structure (16µm)
- Wide guard ring (100µm)
- Detector's active area.
The distance between the active area implant and the first guard ring is 10µm.
Radiation induced defects and impact on device performance

\[ \text{Particle} \rightarrow \text{Si} \rightarrow \text{Frenkel pair} \]

\[ \text{Vacancy + Interstitial} \]

\[ E_K > 25 \text{ eV} \]

\[ E_K > 5 \text{ keV} \]

\[ \text{Point Defects (V-V, V-O ..)} \]

\[ \text{clusters} \]

Influence of defects on the material and device properties

\[ E_C \]

+ \[ \text{donor} \]

- \[ \text{acceptor} \]

\[ E_V \]

charged defects
\[ \Rightarrow N_{\text{eff}}, V_{\text{dep}} \]

e.g. donors in upper half of band gap and acceptors close to midgap

trapping (e and h)
\[ \Rightarrow \text{CCE} \]

shallow defects do not contribute at room temperature due to fast detrapping

generation leakage current
\[ \Rightarrow \text{levels close to midgap most effective} \]
What is radiation hardness?

In irradiation the particles create electrically active defects into silicon. These defects change the effective doping concentration for Si.

![Graph showing typical depletion voltage evolution in traditional Fz-Si detector.](image)

- **Point of n > p type inversion**: 
  - Adding oxygen into the Si lattice has proved to improve radiation hardness!

- **Breakdown**:
  - Every pn-junction device has a finite breakdown voltage...

- **Major problem in HEP experiments!!**

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DEFECT ENGINEERING
Why Cz-Si as a detector substrate?

1. **Radiation hardness**
   * Oxygen increases the radiation hardness of silicon detectors
   * Cz-Si intrinsically contains oxygen, $10^{17}-10^{18}$ cm$^{-3}$
2. **Cost-effectiveness**
* Cz-Si wafers are cheaper than traditional Fz-Si wafers
* Large area wafers available
  -> possibility for large detectors
  -> cost-effectiveness for front-end electronics, interconnection and module assembly

3. **High oxygen concentration allows some additional benefits**
* Depletion voltage of detectors can be tailored by adjusting
  a) oxygen concentration in the bulk
  b) thermal history of wafers
* Possibility for internal gettering
* Higher mechanical strength
* Less prone to slip defect formation

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Radiation hardness of Cz-Si

![Graph showing the relationship between $V_{dep}$ (V) and $\Phi_{eq}$ ($1 \text{ MeV equivalent neutrons/cm}^2$) for different energy levels (FZ, E=10 MeV, FZ, E=20 MeV, FZ, E=30 MeV, DOFZ, E=10 MeV, DOFZ, E=20 MeV, MCZ, E=10 MeV, MCZ, E=20 MeV, MCZ, E=30 MeV).]
Thermal Donor generation

\[ N_{TD} = \left( \frac{a}{b} \right) C_{io} \chi \frac{1}{|N_d - N_A|^2} \left\{ 1 - e^{-bD_i C_{io} t} \right\} \]

\[ D_i = 0.13 e^{-\frac{E_A}{kT}} \]

\[ \chi = 2.45 \quad E_A = 2.53 \text{eV} \]


Cz-Si,
\[ O_i \approx 8 \times 10^{17} \text{ cm}^{-3} \]

MCz-Si,
\[ O_i \approx 4 \times 10^{17} \text{ cm}^{-3} \]

Oxygenated Fz-Si,
\[ O_i \approx 1 \times 10^{17} \text{ cm}^{-3} \]

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Thermal Donor generation (experimental results)

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Super-LHC

* Luminosity $10^{35}$ cm$^{-2}$s$^{-1}$ leading to fluence $10^{16}$ cm$^{-2}$

* $V_{fd}$ will be very high

* $I_{leak}$ will be very high

* Charge loss due to trapping will be severe

$| = 10$ years in LHC

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Charge Collection Efficiency in S-LHC

\[ CCE = CCE_{GF} \cdot CCE_t = \frac{w}{d} \cdot e^{-t \frac{d}{\tau_t}} \]

- **Depletion term**
- **Trapping term**

\[ CCE_{GF} \] is a geometrical factor

\[ CCE_t \] is related with trapping

\[ w = \sqrt{\frac{2\varepsilon \varepsilon_0 V}{eN_{eff}}} \quad \text{and} \quad \frac{w}{d} = \sqrt{\frac{V}{V_{fd}}} \]

For fluence less than \( 10^{15} \) n/cm\(^2\), the trapping term \( CCE_t \) is insignificant.

For fluence \( 10^{16} \) n/cm\(^2\), the trapping term \( CCE_t \) is a limiting factor of detector operation!
Trapping

\[ \tau_I = \frac{1}{\sigma v_{th} N_t} \]
The trapping time-constant is not dependent on \( T \)

The thermal velocity \( v_{th} \) saturates at 20 kV/cm E-field to \( \approx 10^7 \text{cm/s} \)

\( 10^{16} \text{cm}^{-2} \) irradiation produces \( N_T \approx 3-5 \times 10^{13} \text{ cm}^{-3} \) with \( \sigma \approx 10^{-15} \text{cm}^2 \)

Particle generated charge carrier drifts 20-30\( \mu \text{m} \) before it gets trapped regardless whether the detector is fully depleted or not!

In S-LHC conditions, 80-90\% of the volume of \( d=300 \mu \text{m} \) detector is dead space!
What good can p-type do?

* No type inversion
* Charge collection is electron current
  >> 3 times higher mobility
  >> 3 times less trapping

Full depletion voltage of thick detectors can be tailored with TD’s!
SUMMARY

• We have demonstrated first full-sized particle detectors ever made of Cz-Si

• Cz-Si shows superior radiation hardness properties in proton beams

• Cz-Si shows positive space charge built-up due to the Thermal Donor TD formation

• This gives possibility to further improvements in terms on compensation of SC of different sign

• The main focus of our research is detectors made on p-type Cz-Si wafers