Silicon Detectors for the sLHC

Jessica Metcalfe, on behalf of the RD50 Collaboration
RD50: Radiation Hard Semiconductor Devices for Very High Luminosity Colliders

254 scientists and engineers from 47 member institutes:


Ljubljana, Louvain, Minsk, Montreal, Moscow ITEP, Munich, New Mexico, Nikhef, Uni. Oslo, Padova, Perugia, Pisa, Prague Academy, Prague Charles, Prague CTU, PSI, Purdue, Rochester, UC Santa Cruz, SINTEF, Syracuse, Tel Aviv, Trento, Valencia, Vilnius
Motivation

Radial distribution of sensors determined by Occupancy < 2%, still emerging

Predicted fluences \( n_{eq} \), including safety factor 2:
- B layer \( r = 3.7 \text{ cm} \): \( 2.5 \times 10^{16} \) (1140 MRad)
- Inner pixel layer \( r = 5 \text{ cm} \): \( 1.4 \times 10^{16} \) (712 MRad)
- Second pixel layer \( r = 7 \text{ cm} \): \( 7.8 \times 10^{16} \) (420 MRad)
- Outer pixel layer \( r = 11 \text{ cm} \): \( 3.6 \times 10^{15} \) (207 Mrad)
- Short strips \( r = 38 \text{ cm} \): \( 6.8 \times 10^{14} \) (30 Mrad)
- Long strips \( r = 85 \text{ cm} \): \( 3.2 \times 10^{14} \) (8.4 Mrad)

Outline

Damage Mechanisms
- Microscopic (crystal defects)
- Macroscopic (detector properties)

Technologies
- p-type silicon sensors
- Czochralski silicon
- 3D technologies

For more complete information please see http://rd50.web.cern.ch/rd50/
Radiation Damage

Microscopic:

Surface damage due to Ionizing Energy Loss (IEL)
- accumulation of + charges in the oxide (SiO2) and the Si/SiO2 interface
- interstrip capacitance, breakdown behavior

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

Macroscopic:

I. Change of effective doping concentration ($N_{eff}$)
- type inversion, higher depletion voltage, under-depletion
- loss of active volume leads to decrease of signal
  - different for neutron and proton irradiation

II. Increase of leakage current
- increase of electronic noise, thermal runaway, power consumption
- need for cooling

III. Increase of charge carrier trapping
- loss of charge
  - different for electrons and holes
**Microscopic Defects**

- **WODEAN project** (initiated in 2006, 10 RD50 institutes, guided by Gunnar Lindstroem, Hamburg)
  - **Aim:** Identify defects responsible for Trapping, Leakage Current, Change of $N_{\text{eff}}$
  - **Method:** Defect Analysis on identical samples performed with the various tools available inside the RD50 network:
    - **C-DLTS** (Capacitance Deep Level Transient Spectroscopy)
    - **I-DLTS** (Current Deep Level Transient Spectroscopy)
    - **TSC** (Thermally Stimulated Currents)
    - **PITS** (Photo Induced Transient Spectroscopy)
    - **FTIR** (Fourier Transform Infrared Spectroscopy)
    - **RL** (Recombination Lifetime Measurements)
    - **PC** (Photo Conductivity Measurements)
    - **EPR** (Electron Paramagnetic Resonance)
    - **TCT** (Transient Charge Technique)
    - **CV/IV**
  - ~240 samples irradiated with protons and neutrons
  - first results presented on 2007 RD50 Workshops, further analyses in 2008 and publication of most important results in Applied Physics Letters

Example: TSC measurement on defects (acceptors) responsible for the reverse annealing

[I. Pintilie, E. Fretwurst, G. Lindstrom, APL V 92, 2008]
Microscopic Defects

Point defects

- \( E_i^{BD} = E_c - 0.225 \text{ eV} \)
- \( \sigma_n^{BD} = 2.3 \cdot 10^{-14} \text{ cm}^2 \)
- \( E_i^1 = E_c - 0.545 \text{ eV} \)
  - \( \sigma_n^1 = 1.7 \cdot 10^{-15} \text{ cm}^2 \)
  - \( \sigma_p^1 = 9 \cdot 10^{-14} \text{ cm}^2 \)

Cluster related centers

- \( E_i^{116K} = E_v + 0.33 \text{ eV} \)
- \( \sigma_p^{116K} = 4 \cdot 10^{-14} \text{ cm}^2 \)
- \( E_i^{140K} = E_v + 0.36 \text{ eV} \)
- \( \sigma_p^{140K} = 2.5 \cdot 10^{-15} \text{ cm}^2 \)
- \( E_i^{152K} = E_v + 0.42 \text{ eV} \)
- \( \sigma_p^{152K} = 2.3 \cdot 10^{-14} \text{ cm}^2 \)
- \( E_i^{30K} = E_c - 0.1 \text{ eV} \)
- \( \sigma_n^{30K} = 2.3 \cdot 10^{-14} \text{ cm}^2 \)

Positive charge

(higher introduction after proton irradiation than after neutron irradiation)

positive charge
(high concentration in oxygen rich material)

leakage current
+ neg. charge
(current after \( \gamma \) irradiation)

Reverse annealing
(neg. charge)
Microscopic Defects

- Epitaxial silicon irradiated with 23 GeV protons vs reactor neutrons

Development of $N_{\text{eff}}$ for EPI-DO after neutron and proton irradiation

TSC results after neutron and proton irradiation

- SCSI after neutrons but not after protons
- Donor generation enhanced after proton irradiation
- Microscopic defects explain macroscopic effects at low fluence
  - Defect levels forecast annealing behavior at 80 °C

June 9th, 2010
RD50 Report
Jessica Metcalfe
Macroscopic Properties

Microscopic defects lead to Macroscopic Changes:
• TCT Measurements probe electric field profile determined by build up of + and – space charge

1480-13, 1.5x10^{14} n/cm^2 (22 d RT anneal), MCZ n-type Si, p⁺/n/n⁺ structure
Laser front, electron current from p⁺ to n⁺
Double junction, and SCSI seen

[Z. Li, J. Metcalfe et al., RD50 Workshop June 2008]
Macroscopic Properties

- Space charge effects depletion voltage, beneficial/reverse annealing

![Graph showing depletion voltage vs. anneal time]

- Beneficial annealing observed for the first 80 minutes anneal time, then $V_{fd}$ begins to increase for samples shown to have neg space charge after proton irradiation:
  - n-on-p Fz
  - p-on-n Fz
  - n-on-p MCz

- p-on-n MCz shows annealing behavior typical of n-type devices that have +sc after proton irradiation.

---

manufacturer HPK  |  Micron  |  Micron  |  Micron
resistivity 13 kΩ-cm  |  3.3 kΩ-cm  |  1.9 kΩ-cm  |  1.4 kΩ-cm
active area 3mmx3mm  |  3mmx3mm  |  3mmx3mm  |  3mmx3mm
thickness 300 μm  |  300 μm  |  300 μm  |  300 μm
initial $V_{fd}$ [V] 75  |  95  |  520  |  220

[J. Metcalfe, M. Hoeferkamp, et al., RD50 Workshop June 2009]

800 MeV protons @Los Alamos
60° C anneal
June 9th, 2010

[Image of RD50 logo]
**New Technologies**

**p-type silicon sensors:** collect electrons instead of holes \(\Rightarrow\) yields lower trapping probability due to higher electron mobility

**Czochralski silicon sensors:** higher oxygen content \(\Rightarrow\) shown to require lower bias voltage for full depletion

**3D sensors:** new column electrode geometry \(\Rightarrow\) shorter distance for charge collection and depletion reduces trapping and full depletion voltage
Sensors in p-type bulk

Benefits:
• collect electrons
• no radiation-induced type inversion
• single-sided processing reduces cost
Signal comparison for various Silicon sensors

Silicon Sensors
- p-in-n (EPI), 150 µm [7,8]
- p-in-n (EPI), 75µm [6]
- n-in-p (FZ), 300µm, 500V, 23GeV p [1]
- n-in-p (FZ), 300µm, 500V, neutrons [1]
- n-in-p (FZ), 300µm, 500V, 26MeV p [1]
- n-in-p (FZ), 300µm, 800V, 23GeV p [1]
- n-in-p (FZ), 300µm, 800V, neutrons [1]
- n-in-p (FZ), 300µm, 26MeV p [1]
- p-in-n (FZ), 300µm, 500V, 23GeV p [1]
- p-in-n (FZ), 300µm, 500V, neutrons [1]

Other materials
- SiC, n-type, 55 µm, 900V, neutrons [3]

References:
Note: For n-in-p, substrate damage may occur for SiC (0.62)
p-type Fz (ATLAS-HPK) strip sensors irradiated by 26 MeV protons to $\Phi = 1 \times 10^{15}$ n$_{eq}$/cm$^2$

**Signal/Noise**

Benefit: Signal-to-Noise ratio fairly stable during annealing
- may be possible to maintain stable operation during maintenance periods without cooling

[G. Casse, Trento Workshop, Feb 2010]
Cz and MCz silicon materials have higher oxygen concentration
• Makes the formation of shallow Thermal Donors possible

24 GeV/c proton irradiation (n-type silicon)

$V_{fd}$ @ 80 minutes anneal at 60 °C
(800 MeV proton irradiation)

[M. Bruzzi presented on behalf of RD50, MPGD2009]

[J. Metcalfe, M. Hoeferkamp, et al., RD50 Workshop June 2009]
Exposure of FZ & MCZ silicon sensors to ‘mixed’ irradiations:

- First step: Irradiation with protons or pions
- Second step: Irradiation with neutrons


- MCZ shows space charge compensation for mixed irradiations!!
Motivation: decouple thickness from charge collection distance

- **“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
• Fabrication of 3D detectors challenging: modified design under investigation within RD50
  • Columnar electrodes of both doping types are etched into the detector from both wafer sides
  • Columns are not etched through the entire detector: no need for wafer bonding technology but column overlap defines the performance.

• Two manufacturers: CNM (Barcelona): 14 wafers (p- and n-type)  
  FBK (Trento): 3 3D-DDTC batches fabricated with different overlaps
3D-Trench Electrode Detectors

- Concept of the new Independent Coaxial Detector Array (ICDA) ----- US patent pending (3D-Trench Electrode Detectors), any projects related to this subject must sign official agreements with BNL Office of Technology Commercialization and Partnership (Kimberley Elicess, Principal Licensing Specialist, elcess@bnl.gov, 001-631-344-4151)

At least one electrode is a trench, each cell can be an independent detector
Homogeneous electric field, no saddle point

New electrode geometry

- Novel, asymmetric electrode configurations produce homogeneous, well-defined $E$.
- Total collected charge 39%
- Dead space can be reduced to <14% for sLHC
**Summary**

- **Signal comparison for various Silicon sensors**
  - Lines to guide the eye (no modeling!)
  - Higher Voltage leads to charge multiplication
  - Beware: Signal shown and not S/N!
  - All sensors suffer from radiation damage
  - Presently three options for innermost pixel layers under investigation:
    - 3-D silicon sensors (decoupling drift distance from active depth)
    - Diamond sensors
    - Silicon planar sensors

---

*Note: Measured partly under different conditions!*

---

June 9th, 2010  
RD50 Report  
Jessica Metcalfe

Summary

- Major advances have been made in correlation of microscopic defect properties with observed materials properties.

- New information is provided on Czochralski and p-bulk silicon substrates.

- New geometries including 3D and Independent Coaxial Detector Array continue to evolve.