Development of radiation hard semiconductor detectors for very high luminosity colliders

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Motivation

The development of tracking detector systems has greatly advanced in the last ten years, in the attempt to face the extremely severe radiation environment at the Large Hadron Collider (LHC), where the luminosity will achieve values up to $10^{34}cm^{-2}s^{-1}$. Recently, a luminosity upgrade to $10^{35}cm^{-2}s^{-1}$ has been proposed [1]. The full physics potential can only be exploited if the current b-tagging performance is maintained: this requires a tracking layer down to R = 4cm, where one would face fast hadron fluences above $10^{16}cm^{-2}$ (2500fb^{-1}).

The current silicon detectors are unable to cope with such an environment. Dedicated radiation hardness studies are mandatory to develop reliable and cost-effective radiation hard HEP detector technologies for such radiation levels.

The CERN RD50 Collaboration

CERN RD50 project "Development of Radiation Hard Semiconductor Devices for Very High Luminosity Colliders" started in 2002 with the aim to develop a new reliable detector technology available for an LHC upgrade or a future high luminosity hadron collider.

The increase of radiation hardness and improvement in the understanding of the radiation damage mechanisms will be also highly beneficial for the interpretation of LHC detector parameters and a possible replacement of pixel layers.

Scientific strategies to increase radiation hardness

- **Material Engineering**: Modification of the detector material bulk.
  - *Defect engineering of Si*: Diffused Oxygenated Float Zone (DOFZ), high resistivity Czochralski (CZ) ([O]?$10^{18}cm^{-3}$), creation of oxygen dimers, doping with other impurities….
  - *New materials*: development of detectors made with wide band gap materials as e.g. SiC or GaN
- **Device Engineering**: Improvement of present planar detector structures
  - *Modification of the electrode configuration*: development of new detector geometries as the "3D" and "semi-3D" detectors
  - *Development of thinned detectors*: by micromachining or use of epitaxial (EPI) Si
- **Variation of the operational conditions**: Investigations of the optimum detector operational conditions (*forward bias, low temperature, carrier injection, …)*

Material Engineering	Device Engineering
• Defect/material Characterisation	•Pad Detector Characterisation
•Defect Engineering	•New Structures
•New Materials	•Full Detector Systems

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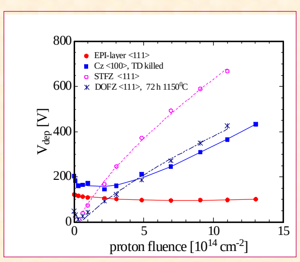
Scientific organization of RD50. Two research lines coordinated by spokesperson and deputy are each subdivided into three projects managed by project conveners.

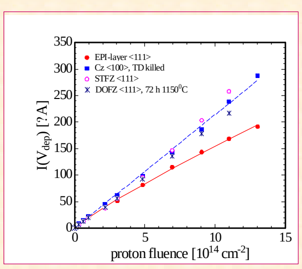
Defect Engineering of Si

Comparison of STFZ-, DOFZ-, CZ- AND EPI-Si after hadron irradiation up to $10^{15}cm^{-2}$

CZ- Si:
- Smaller change of the depletion voltage V_{dep} than in DOFZ-, STFZ-
- No type inversion up to 10^{15} cm^{-2} (24GeV/c p, 190MeV ?)
- Type inversion observed after neutron irradiation as in STFZ-
- No difference in reverse current between STFZ, DOFZ & CZ

EPI-Si:
- Smaller change in V_{dep} than CZ Si
- NO type inversion up to $1.3\cdot10^{15}$ cm^{-2} 24GeV/c p
- Type inversion after ~ $2\cdot10^{15}$cm^{-2} neutrons, V_{dep}= 96V at $8\cdot10^{15}$ cm^{-2}
- Small leakage current reduction at high proton fluences

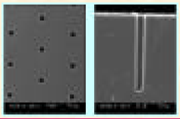




- **DOFZ-Si:** Wacker, ? = 1-6 kOcm, oxygen diffused up to 72h/ 1150C, CiS/ SINTEF process
- **Cz-Si:** Sumitomo-Sitix; ITME: TD-kill and TD-generation - ? > 600Ocm - CiS or Helsinki process
- **EPI Si:** W = 50µm ; ? = 60 ? cm; [O] ? 6.2? 10^{16} cm^{-3}, CiS process

New Structures

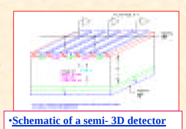
- **3D detectors:** Columns created in Si by dry etching. Full depletion of the detector at low voltage due to the columnar structure of the electrodes. Irradiated with 300 MeV/c pions up to 10^{14} cm^{-2} and 24 GeV/c p up to 4.610^{14} cm^{-2}.



•3D holes created in Si by dry etching

•Schematic of a 3D detector

- **Semi-3D p^+-n^+/n/n^+ Si detectors**: implemented using only single-sided processing, utilize the space charge sign inversion to fully deplete the detector with lower voltage than in standard planar structures.



•Schematic of a semi- 3D detector

New Materials: SiC and GaN

Physical properties lying in between those of Si and diamond.

Property	Diamond	4H-SiC	Si	GaN
E_g [eV]	5.5	3.27	1.12	3.39
μ_e [cm^2/Vs]	1800	800	1500	1000
μ_h [cm^2/Vs]	1200	115	450	30
e-h energy [eV]	13	8.4	3.6	~8-10
Displacem. [eV]	43	25	13-20	~10-20
Density [g/cm^3]	3.52	3.21	2.33	6.15
Radiation length X_0 [cm]	12.2	8.7	9.4	2.7
e-h pairs / X_0 [10^6 cm^{-1}]	4.4	4.5	10.1	~2-3

☺
- Low leakage current after high fluence of irradiation
- Energy to create an e-h pair lower than in diamond
- Potentially radiation harder than Si

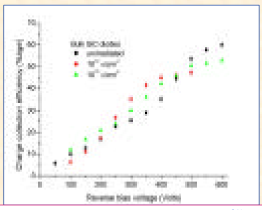
☹
- CCE depend on native defects (pumping and polarisation effects as in diamond)
- Epitaxial layers (low native defect concentrations) only available with low thickness

Devices investigated by RD50

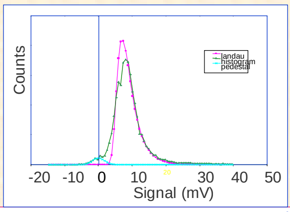
•Semi-Insulating epitaxial GaN
- Ohmic and Schottky contacts
- Active thickness W = 1-3? m
- 100% CCE with ? (^{241}Am) after X-ray 600MRad
- 77% CCE with ? (^{241}Am) after $5\cdot10^{14}$ cm^{-2} neutrons

•Semi-Insulating SiC:
- Ohmic contacts
- ? > 10^{11}? cm, W = 100? m
- Small changes of the CCE with ? (^{241}Am) up to $1.3\cdot10^{15}$ cm^{-2} 24GeV/c p

•Epitaxial 4H SiC from CREE / IKZ, Berlin:
- Schottky Barriers
- V_{dep} = 60V
- active thickness W = 40? m
- 100 CCE% with mips from ^{90}Sr ? -source
- No polarisation/ pumping effects
- Radiation hardness study in progress



•Semi-Insulating SiC W = 300? m. 60% CCE (? ? from ^{241}Am) in non-irradiated samples and 50% after 10^{13}? /cm^2



Epitaxial SiC: W = 40? m. Pulse height spectrum with mips from ^{90}Sr

CONCLUSIONS

Possible scientific strategies to develop ultra radiation hard tracking detectors for very high luminosity colliders have been identified by the CERN-RD50 collaboration including Defect Engineering, Device Engineering and the Optimization of Operational Conditions. It is expected that in order to achieve ultra radiation hard sensors a combination of the above mentioned approaches depending on the radiation environment, application and available electronics will be the best solution for the next generation of high luminosity tracking detectors.

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