Radiation Hard Silicon Particle Detectors for Phase-II LHC Trackers

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1. Introduction.
2. The timeline of LHC and experiments.
3. Radiation induced changes in properties of the silicon tracking detectors.
4. Development of new structures:
   - 3D Pixels,
   - HVCMOS,
   - LGAD.
5. Measurement technique: TCT.

Simulation of 400 proton-proton collisions in just one 25 ns bunch crossing at the HL-LHC
1. LHC was planned for 10 years of operation \( \mathcal{L} = 300 \, fb^{-1} \), i.e. till the end of Run 3 (2023).

2. It was assumed that tracking detectors will have to be replaced due to radiation damage and ageing (or new physics program).

3. Based on experience from Run I, with new technologies in mind, it’s the right time to design them NOW!

4. Two major shutdowns (LS2 & LS3) – main accelerator and detector upgrades.
5.1. Upgrade of the silicon tracking detector.

Phase 1 Upgrade (24 months):
- CMS - Pixel detector replacement,
- LHCb - VELO strip detector replacement by pixels, new strip UT.
5.2. Upgrade of the silicon tracking detector.

**LHC / HL-LHC Plan**

Phase 2 Upgrade (30 months):
- LHC: new quadrupoles in the collision region, crab cavities,
- CMS: new tracker, HGCAL,
- ATLAS: replacement of the Inner Detector,
- LHCb major detector upgrade during LS4
1. LHC will produce collisions at a rate of about \(5 \cdot 10^9\) s\(^{-1}\).

2. The annual dose at HL-LHC will be similar to the total dose until LS3:
   - end of Run III (300 fb\(^{-1}\)) \(\Phi \sim 2 \cdot 10^{15}\) n\(_\text{eq}\) cm\(^{-2}\)
   - HL-LHC (3000 fb\(^{-1}\)) \(\Phi \sim 2 \cdot 10^{16}\) n\(_\text{eq}\) cm\(^{-2}\)

4. The main objective for RD50 is development of radiation hard semiconductor detectors for HL-LHC.

5. The radiation hardness above \(10^{16}\) n\(_\text{eq}\) cm\(^{-2}\) (while maintaining the S/N ratio > 10) is required with fast signal collection and affordable cost. Current LHC detector can operate up to fluence \(10^{15}\) n\(_\text{eq}\) cm\(^{-2}\).

6. Defect induced by particle radiation and their influence on detector performance are of major interest to RD50.
First radiation problems

The LHCb silicon vertex detector will not be replaced. The main VELO upgrade (pixels) is planned for LS2 (2018).

The new innermost layer of ATLAS Inner Tracker was installed (IBL) inside the Pixel Detector during LS1.

VELO replacement is currently on display at LHCb Pit.
1. The main source of radiation is from particles produced in soft p-p interactions (neutrons, pions, protons) and secondary interactions with the detector material.

2. Non-Ionizing Energy Loss ($E_k > 15$ eV) of impinging particle may displace a silicon atom from the lattice.

3. Creation of defects depends on the kind of particle and its energy.

4. Displacements of silicon atoms produce vacancies and interstitials.

5. Crystal impurities interact with defects causing the change in electrical properties of detector.

**Point defects + cluster defects + impurities = degradation of the detector**
Radiation induced changes in properties and structures of the silicon tracking detectors are observed as...

**macroscopic effects** ... caused by **microscopic defects**

1. Change of depletion voltage:

   ![Graph showing change of depletion voltage](image)

   Defects change the effective doping concentration and has impact on bias voltage used to fully deplete the sensor. Significant progress on identifying defects was performed within RD50 group.

   Due to excess of acceptor-like defects and donor removal (V-P defect), initially n-type sensor changes into p-type sensor (at LHC first observed in LHCb VELO).
Radiation damage effects (2)

Radiation induced changes in properties and structures of the silicon tracking detectors are observed as ...

**macropscopic effects** ... caused by **microscopic defects**

2. Increase of leakage current:

- Bulk current due to generation/recombination centers in the mid-gap.

Defects are able to capture and emit electrons and holes – source of the reverse-bias current. Higher noise and power consumption.
Radiation induced changes in properties and structures of the silicon tracking detectors are observed as ... macroscopic effects ... caused by ... microscopic defects

3. Decrease of charge collection efficiency:

- due to damage induced trapping centers.

Defects act as a trapping centers - electrons and holes are re-emitted with some time delay. The signal charge is trapped and may be released too late for 25 ns read-out. This is the most serious problem for detector irradiated with fluence above $10^{15} \text{n}_{\text{eq}} \text{cm}^{-2}$. 

04.10.2016 A. Obląkowska-Mucha (AGH UST Kraków) IPRD16 Siena
RD50 - Radiation hard semiconductor devices for very high luminosity colliders.


2. The main objective is:

   Development of radiation hard semiconductor detectors for the luminosity upgrade of the LHC to $7.5 \times 10^{34} \text{cm}^{-2}\text{s}^{-1}$.

3. Challenges:
   - radiation hardness up to $10^{16} \text{cm}^{-2}$ required,
   - fast signal collection – plan for 10 ns bunch crossing,
   - low mass to reduce multiple scattering close to interaction point,
   - affordable cost.

4. The current activities of RD50 include:

   a) identifying the defects through dedicated measurement techniques (DLTS, TSC, TCT) or monitoring the macroscopic changes in HEP experiments.

   b) work out how to get rid of damage (or avoid it) – new technologies, new structures (3D sensors, HV CMOS, LGAD, simulation (FLUKA, GEANT4, TCAD...).

   c) test the solution:
      - neutron exposition in nuclear reactor,
      - proton irradiation at cyclotrons and synchrotrons,
      - new dedicated irradiation center @ CERN.

   d) incorporate the feedback from experiments.
RD50 - Radiation hard semiconductor devices for very high luminosity colliders

Co-Spokespersons

Gianluigi Casse and Michael Moll
(Liverpool University, UK & FBK-CMM, Trento, Italy)

Defect / Material Characterization
Ioana Pintilie
(NIMP Bucharest)

- Characterization of microscopic properties of standard-, defect engineered and new materials pre- and post-irradiation
- DLTS, TSC, ...
- SIMS, ESR, ...
- NIEL (calculations)
- WODEAN: Workshop on Defect Analysis in Silicon Detectors (I. Pintilie)

Detector Characterization
Eckhart Fretwurst
(Hamburg University)

- Characterization of test structures (IV, CV, CCE, TCT,..)
- Development and testing of defect engineered silicon devices
- EPI, MCZ and other materials
- NIEL (experimental)
- Device modeling
- Operational conditions
- Common irradiations
- Wafer procurement (M.Moll)
- Device Simulations (–)
- Acceptor removal (Kramberger)

New Structures
Giulio Pellegrini
(CNM Barcelona)

- 3D detectors
- Thin detectors
- Cost effective solutions
- Other new structures
- Detectors with internal gain (avalanche detectors)
- LGAD: Low Gain Avalanche Det.
- Deep depleted Avalanche Det.
- Slim Edges
- HVCMOS
- 3D (R.Bates)
- LGAD (S.Hidalgo)
- Slim Edges (V.Fadeyev)

Full Detector Systems
Gregor Kramberger
(Ljubljana University)

- LHC-like tests
- Links to HEP (LHC upgrade, FCC)
- Links electronics R&D
- Low rho strips
- Sensor readout (Alibava)
- Comparison:
  - pad-mini-full detectors
  - different producers
- Radiation Damage in HEP detectors
- Test beams
  (M.Bomben & G.Casse)

Collaboration Board Chair & Deputy: G.Kramberger (Ljubljana) & J.Vaitkus (Vilnius), Conference committee: U.Parzefall (Freiburg)

M.Moll September 2016
3D Pixels / Strips

1. Currently a well known technology (S.I. Parker et al., NIMA 395(1997)328).

2. 3D pixel sensors are installed in ATLAS IBL, AFP, CMS Totem.

3. They are designed as vertical narrow columnar p and n electrodes penetrating the silicon substrate.

3. Advantages:
   • diameter: 10 µm, distance L: 50 – 100 µm (small drift distance, less trapping),
   • lower depletion voltage: 10-200V (lower power), thinner detectors possible,
   • fast signal formation,
   • radiation hard,
   • active or slim edges technology.

4. Problems:
   • Non uniform spatial response (electrodes are inefficient regions).
   • Higher capacitance, higher noise.
   • Complicated fabrication technology (time, cost, yield).
3D pixel sensors for LHC

For LHC a few devices were projected and tested for radiation hardness:

- 230 μm thick sensors by CNM and FBK
- FEI4s: 50x250 μm 2E, 67 μm inter-el. distance

Double sided (DDTC) technique:

- n+ and p+ columns are etched from the two sides of the sensor wafer.
- Slim edges (200 μm)

3D sensors irradiated (protons, neutrons, pions, electrons) up to IBL fluence $5 \cdot 10^{15} \text{n}_{\text{eq}} \text{cm}^{-2}$

Double sided (DDTC) technique:

- n+ and p+ columns are etched from the two sides of the sensor wafer.
- Slim edges (200 μm)

CNM 3D pixels for IBL

Radiation hardness up to $5 \cdot 10^{15} \text{n}_{\text{eq}} \text{cm}^{-2}$ established:
Efficiency for CNM sensors reached 99%.

Promising for HL-LHC!

G. Pellegrini et. al. NIMA 592(2008), 38
G. Pellegrini et. al. NIMA 699(2013), 27
Development of new generation 3D pixel sensors for HL-LHC:

- radiation hardness up to $2 \cdot 10^{16} \text{n}_{\text{eq}} \text{cm}^{-2}$.
- reduced pixel size: $50 \times 50 \ \mu m^2$ or $25 \times 100 \ \mu m^2$.
- small inter-electrode distance (less trapping).
- reduced thickness $100 - 150 \ \mu m$ (small leakage current).

First prototype of new generation 3D pixels finished (January 2016).

Three different technologies tested:

**SNF (Stanford) / SINTEF (Oslo)**

- single sided, active edge

**FBK (Trento)**

- double sided
The signal efficiency is about 60-70% at $5 \times 10^{15}$ $n_{eq}$cm$^{-2}$ and 30% at almost $10^{16}$ $n_{eq}$cm$^{-2}$ with not much increase of $V_{bias}$.

Signal efficiency was improved with decreasing electrode distance.


Compilation by C. Da Via

**RD 50 project:**
Joint MPW pixel run for ATLAS, CMS, LHCb.

**Motivations:**
1. Manufacture smaller area pixels on thin sensors.
2. Study of radiation hardness.
Joint 3D MPW pixel run

Joint Multi Project Wafer pixel run for ATLAS, CMS, LHCb.

Test of different configurations for various read out chips and pitch size:

- A: standard Fe-I4
- B: 25x100um2 ("25x500" 1E, with 3DGR - a la GP).
- C: 50x50um2 with the rest connected to GND with 3DGR
- D: 25x100um2 (2E - version 4x100+grid to GND - a la GF)
- E: 50x50um2 with the rest connected to GND without 3DGR
- F: FEI3 device: x 50x50um2 with rest to GND with 3D GR
- G: ROC4sens 50x50um2
- H: PSI46dig
- I FERMILAB RD ROC 30x100um2
- L: Velopix 55x55um2
- M: Strip 50x50um2
- M Strip 25x100um2
- O Strip 30x100um2f

Also single sided technology:
- 50μm thick detectors with SOI support wafer (350 μm ),
- Possible to thin down the detectors.
- 5μm hole diameter.
- Detector tested, good I-V,
- more complicated technology
High Voltage CMOS

- n-wells are implanted in low resistivity (~10 Ωcm) p-type substrate and play role of electrode implant,
- biased with 60 V but allows only shallow (10 − 20 μm) depletion zone, signal 1-2 kel.
- thin active layer,
- low drift distance, small drift time (fast collection),
- radiation hard (less trapping),
- possible to use capacitive coupling through glue instead of bump-bonding,
- industrial process enables large volume production in relatively short time,
- both pixel and strip detector possible,
- fully monolithic devices don’t require a bump-bonded read-out.

RD50 started to work on HV-CMOS devices in 2014 with a focus on characterizing the radiation damage.
High voltage is used to deplete a part of the substrate:

- The main charge collection mechanism is drift,
- Part of the signal originates from the undepleted region and is collected by diffusion,
- Edge-TCT measurements showed drift and diffusion component

The charge collection profiles of irradiated samples show quick disappearance of drift constituent.
HV CMOS – irradiation tests

Charge collection properties studied after irradiation to high neutron fluences with Edge-TCT techniques.

AMS 350\textit{nm} production, CHESS-1 sensors
- 2 mm x 2 mm passive sensor (400 pixel)
- Sr90 electrons for CCE, 25 ns shaping, 120 V, TCT

AMS 180\textit{nm} production, HV2FEI4
- 100 µm x 100 µm passive pixel,
- IR-laser, 5ns integration

- CCE decreases for fluence up to $2-5\cdot10^{14}$ \textit{n}_eq\textit{cm}^{-2} due to diffusion decrease.
- For higher fluence the signal is rising due to increase of active volume (acceptor removal).
- Finally CCE degrades due to more intense trapping caused by space charge.
- For fluence $2\cdot10^{16}$ \textit{n}_eq\textit{cm}^{-2} @ 80V charge collection is 90% of signal before irradiation!

Very promising for high radiation environments!
Charge multiplication in Si detectors

Charge multiplication:

• signal larger than expected from conventional silicon devices observed after irradiation $2 \cdot 5 \cdot 10^{15} \text{n_{eq}cm}^{-2}$,

• irradiation causes negative space charge in detector bulk that increases the electric field ($>15 \text{ V/\mu m}$), impact the ionisation which manifests through charge multiplication,

• observed in different types of devices (diode, strip, 3D), at very high bias voltages, heavy irradiated,

• could be beneficial for sensors and give extra signal – usable for HL-LHC.

RD50 project: exploit charge multiplication detectors:

• 1 cm x 1 cm, n-in-p FZ strip detectors,

• LGAD sensors (first segmental sensors on thin substrates).

Aims:

• exploit the charge multiplication effect,

• fabricate, test and irradiate sensors,

• simulate and predict (TCAD),

• measure with TCT setup.
The Low Gain Avalanche Detector (LGAD): a new concept of silicon radiation detector with intrinsic multiplication of the charge.

Advantages:
- higher charge collection efficiency,
- short drift time,
- signal shorter and steeper while retaining a large amplitude due to the multiplication mechanism.

After irradiation (reactor neutrons and 800 MeV protons):
- decrease of charge collection,
- decrease of multiplication (before irradiation it was 3 times higher than standard diode), after irradiation with fluence $2 \cdot 10^{15}$ n$_{eq}$cm$^{-2}$ the gain was lost.

New technology – Gallium instead of Boron or add Carbon to prevent Boron removal
**Edge Transient Charge Technique:**

Method of reconstruction of electric field pioneered by Ljubljana group and promoted by RD50.

- photon pulses from an infrared laser are directed towards the detector edge, perpendicular to the strips and focused to the region below the readout strip, electron-hole pairs are produced,

- scans across the detector thickness enables relative measurement of the induced current at given depth, extrapolate rise time, drift velocity and charge collection profiles,

- finally, the electric field can be reconstructed by determination of drift velocity.

**Edge-TCT is widely used ideal tool to study substrate properties!**
**HV-CMOS** – different structures:
- irradiated by reactor neutrons and PS protons,
- charge profiles at different depth and vs. bias voltage,
- width of charge collection,
- determination of $N_{\text{eff}}$

AMS CHESS1 chips (20 Ωcm)

**Results:**
- neutron irradiation up to $2 \times 10^{15} \ n_{\text{eq}} \ cm^{-2}$ - initial acceptor removal,
- increase of space charge and charge collection is degrading with fluence
3D pixels (CNM) –
irradiated by reactor neutrons with $5 \times 10^{15} n_{eq} \ cm^{-2}$

Signal amplification in strip-LGAD

Electron injection

Measured Bottom Red TCT strip LGAD

Multiplication on-set

Primary Electrons
(faster fall time)

Secondary Holes
(Slower rise time)

20 ns
RD50 is especially helpful for irradiation of the silicon devices in cyclotrons, synchrotrons, reactors, etc. (full list is [here](#)).

- **CERN** – 24 GeV protons, 1 MeV neutrons,
- **University of Karlsruhe** (25 MeV protons)
- **Jožef Stefan Institute** (neutrons)
- **Paul Scherrer Institut** (300 MeV/c pions)

**IRRAD2** - new CERN proton irradiation facility

Typical: $1 \times 10^{16} \text{p/cm}^2 (5\text{days})^{-1}$

- 24 GeV/c proton beam
  (IRRAD1, IRRAD3, IRRAD5, ...)
- Mixed field produced in cavity after C (50cm) - Fe (30cm) - Pb (5cm) ‘target’
  (IRRAD2)
17 Nov. 2014: first irradiation experiments in the new IRRAD2!

- 9 irradiation tables operational from Oct. 1st 2015
- 6x RT irradiation (IRRAD 3, 7, 9, 13, 17, 19)
- 2x water-cooled cold boxes down to -25°C (IRRAD 5, 11)
- 1x dedicated to the cryogenic setup (IRRAD 15)

30 weeks of beam time in 2015
- 28 user teams from 18 institutes /experiments/R&D’s
- >300 samples (active/passive)
- >250 dosimeters measured (Al foils)

1 × 10^{16} p/cm^{-2}(5days)^{-1}

EA-IRRAD upgrade project: Joint effort of many CERN groups. PH-DT, EN-MEF, EN-STI (core teams), HSE and EN-HDO (Project Safety), DGS-RP, EN-CV (ventilation), EN-HE (transports), GS-ASE (access control), BE-BI and TE-CRG (IRRAD cryogenic system), ...
1. Silicon detectors currently installed in LHC experiments need to be replaced by 2023 at the latest.

2. Current technologies are not sufficient to withstand fluence at the level of $10^{16} \, n_{eq} \, cm^{-2}$.

3. RD50 Collaboration has been working on:
   - new technologies in silicon sensors production and new designs of detectors,
   - description of defects and material characterization,
   - simulation of the structures and radiation effects,
   - methods of measurements and test of irradiated devices.

4. RD50:
   - funds common projects with cooperation between member institutions,
   - helps and supports study of silicon detectors performed in LHC experiments,
   - is a platform where pioneering researches in new technologies meet with the final implementation in huge experiments.

5. RD50 recommends the structures to be studied by High Luminosity LHC experiments:
   - 3D sensors (small drift time – less trapping, pixel or strip detector),
   - HV-CMOS (industrial production of pixel/strip detectors, low cost, low bias, low mass, rad hard),
   - LGAD (sensor with intrinsic gain),
   - Slim/active edge sensors to reduce dead space of lower efficiency.
RD50 is a community of 282 physicist and engineers from 52 institutes.