Radiation-hard silicon detectors
RD50 status report

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on behalf of the RD50 collaboration

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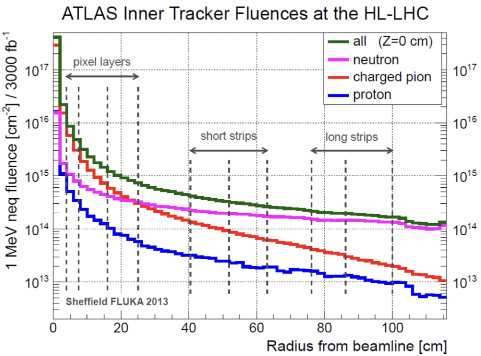
25.10.2022

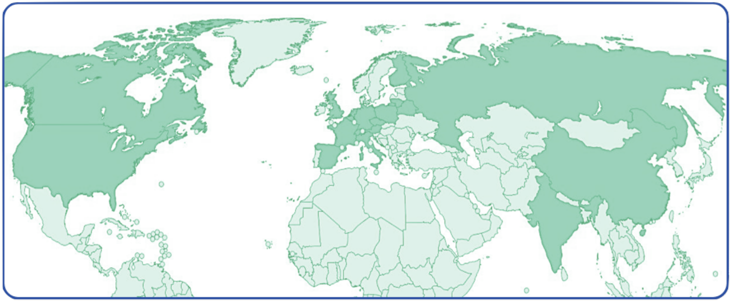
- Increasing radiation levels
  - Semiconductor detectors will face >1e16 n_{eq}/cm^2 (HL-LHC) and >7e17 n_{eq}/cm^2 (FCC-hh) → detectors used at LHC cannot be operated after such irradiation
- New requirement and new detector technologies
  - New requirements or opportunities lead to new technologies (e.g. HV-CMOS, LGAD,...) which need to be evaluated and optimized in terms of radiation hardness and/or 4D tracking capabilities



[I. Dawson, P. S. Miyagawa, Sheffield University, Atlas]

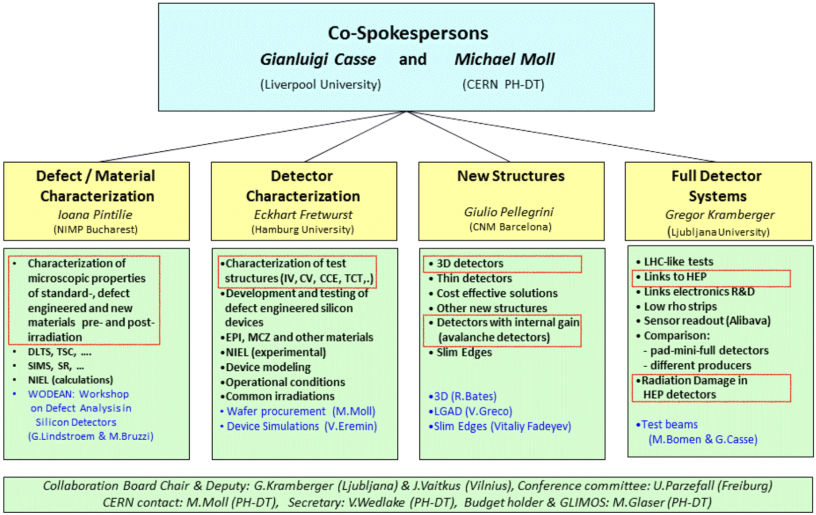
The RD50 collaboration

66 institutes and 430 members (51 European, 8 NA, 7 from Asia):
Austria (HEPHY), Belarus (Minsk), Czech Republic (Prague (3x)), Finland (Helsinki, Lappeenranta), France (Marseille, Paris, Orsay), Germany (Bonn, Dortmund, Freiburg, Göttingen, Hamburg (Uni & DESY), Karlsruhe, Munich (MPI & MPG HLL)), Greece (Demokritos), Italy (Bari, Perugia, Pisa, Trento, Torino), Croatia (Zagreb), Lithuania (Vilnius), Montenegro (Montenegro), Netherlands (NIKHEF), Poland (Krakow), Romania (Bucharest), Russia (Moscow, St.Petersburg), Slovenia (Ljubljana), Spain (Barcelona(3x), Santander, Sevilla (2x), Valencia), Switzerland (CERN, PSI, Zurich), United Kingdom (Birmingham, Glasgow, Lancaster, Liverpool, Oxford, Manchester, RAL), Canada (Ottawa), USA (BNL, Brown Uni, Fermilab, LBNL, New Mexico, Santa Cruz, Syracuse), China (Beijing-IHEP, Dalian, Hefei, Jilin, Shanghai), India (Delhi), Israel (Tel Aviv)

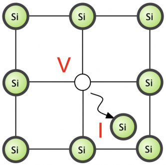


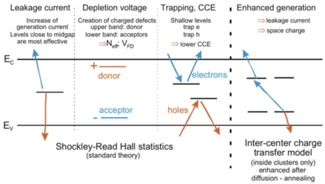
The RD50 research lines

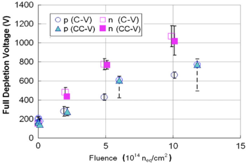
RD50 studies radiation hard semiconductor detectors
Focus concentrates on four main research lines:

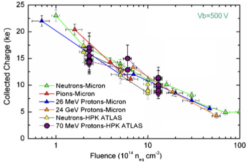


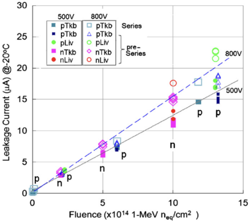
Radiation damage in Silicon











[K. Hara, et al., NIMA 636 (2010)]

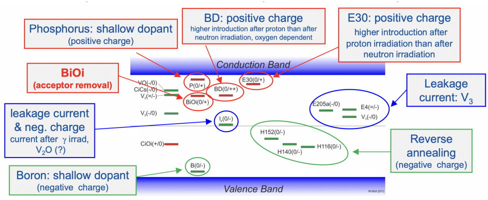
Microscopic effects

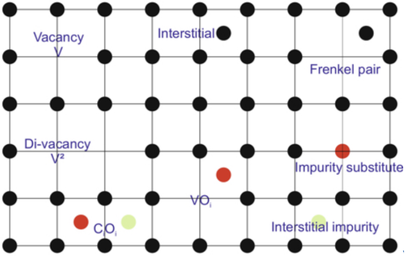
- Caused by non-ionizing energy loss (NIEL)
- Vacancies lead to point defects and clusters
- Interstitials are mobile and react with impurities
- Lattice defects create additional energy states within the bandgap
- Defects states classified as Donors or Acceptors

Macroscopic effects

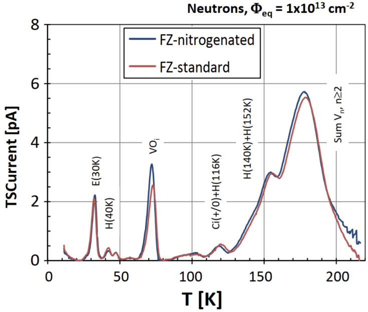
- Increase in V_{FD} & N_{eff} $\rightarrow$ Capacitance-voltage (CV) measurements
- Decrease in the signal $\rightarrow$ Charge-collection (CC) measurements
- Increase in the leakage current $\rightarrow$ Current-voltage (IV) measurements

Defect characterization



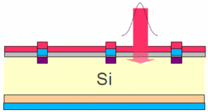


- Defects are mobile & react:
  - V+O→VO
  - V+P→VP (P deactivated)
  - I+Cs →Ci →Ci+O→CiO
  - I+Bs→Bi→Bi+O→BiO (B deactivated)
- Need to identify defects responsible for macroscopic effects:
  - V_{FD} & N_{eff}
  - Signal loss & trapping
  - Annealing behavior of observbables
- Techniques for identifying defects:
  - Thermally Stimulated Current (TSC)
  - Deep Level Transient Spectroscopy (DLTS)



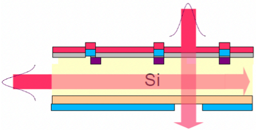
[J.C. Hönig et al 2020 JINST 15 P05006]

Detector characterization: Transient Current Technique (TCT)



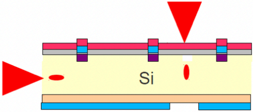
TCT (red laser)

- short penetration length (650nm = 1.9eV)
- carriers deposited in a few μm from surface
- front and back TCT: study electron and hole drift separately
- 2D spatial resolution (5-10μm)



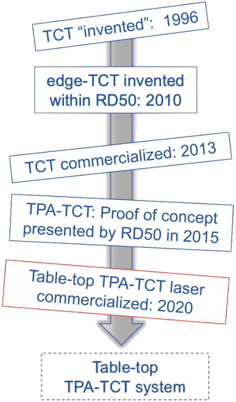
TCT (infrared laser)

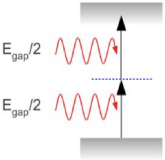
- long penetration (1064nm = 1.17 eV)
- similar to MIPs (though different dE/dx)
- top and edge-TCT
- 2D spatial resolution (5-10μm)



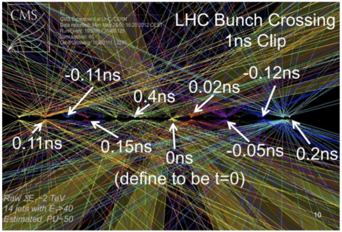
TPA-TCT (far infrared)

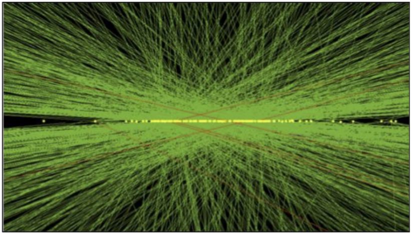
- No single photon absorption in silicon
- 2 photons produce one electron-hole pair
- Point-like energy deposition in focal point
- 3D spatial resolution ($1 \times 1 \times 10$ μm^3)

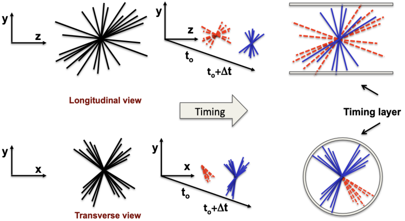




4D tracking at the HL-LHC





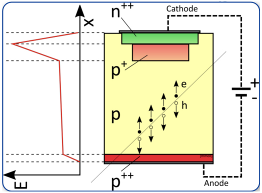


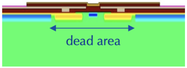
- HL-LHC leads to vertex density smaller than spatial resolution of tracking detectors
  $\rightarrow$ Timing precision needed to distinguish overlapping vertices ($\sim$ 10s of ps)
  $\rightarrow$ Critical for physics analyses
- Fast timing sensors:
  - Low Gain Avalanche Detectors (LGAD)
  - 3D detectors

- Add a thin p-layer to conventional Si detectors $\rightarrow$ Thin layer with moderate gain (10-50) at readout electrode
- Intrinsic gain of devices allows for excellent timing performance (< 50 ps)
- Growing number of manufacturers: CNM (Barcelona, ES), FBK(Trento,IT), HPK (Japan), IHEP(Bijing, China), Micron(UK), BNL(USA), CIS(Erfurt, Germany)
- Will be implemented in fast timing layers of CMS Endcap Timing Layer (ETL) & ATLAS High Granularity Timing Detector (HGTD)

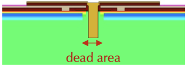
Areas of R&D

- Geometry:
  - Between pixels no gain (fill factor < 1)
  - HD-LGAD with trench isolation, Deep Gain Layer LGAD, AC LGAD, inverted LGAD...
- Radiation hardness:
  - Acceptor removal leads to reduction of gain $\rightarrow$ increase bias
  - Chose Carbon as extra dopant to shield Boron, dose critical
  - Modification of gain layer profile

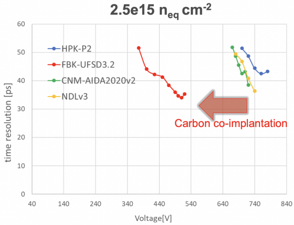




traditional gain isolation



trenches isolation (HD-LGAD)



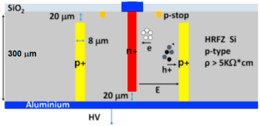
[A. Howard, 37th RD50 Workshop]

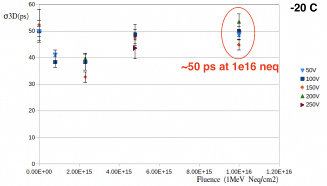
New Structures: 3D detectors

- First introduced by S.I. Parker and C. Kennedy in 1997
- Based on the use of vertical columns of electrodes that penetrate the bulk detector
- Geometry intrinsically radiation tolerant
  - reduced power dissipation
  - smaller signal rise time
  - reduced trapping
- Manufacturers: CNM (Barcelona, ES), FBK(Trento, IT)

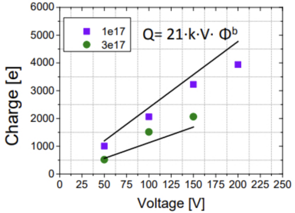
Areas of R&D

- Geometry:
  - From columns to trenches
  - Hexagonal cell shape
- Timing:
  - 50 ps measured at 1e16 n_{eq}
- Extreme fluences:
  - Signal of 4ke- at 1e17 n_{eq}, still alive at 3e17 n_{eq}





[C. Betancourt et al., Instruments 6, 1 (2022)]



[M. Manna, 35th RD50 Workshop, CERN, 2019]

RD50 achievments

RD50 has given important contributions to the LHC and LHC upgrade detectors

- p-type silicon (brought forward by RD50 community) is used for the ATLAS and CMS Strip Tracker upgrades
- MCZ and oxygenated silicon (introduced by RD50) can improve performance in mixed radiation fields
- Double column 3D detector technology (developed within RD50 with CNM and FBK) was picked up by ATLAS and further developed for ATLAS IBL needs, followed by AFP and TOTEM and now also within CMS/ATLAS upgrades.
- RD50 results on highly irradiated planar segmented sensors demonstrated: planar devices are a feasible option for LHC upgrade
- RD50 data and damage models are essential input for operation scenarios of LHC experiments and sensor designs
- Precision timing sensors: LGAD (Low Gain Avalanche Detectors) were developed within the RD50 community
- New characterization techniques and simulation tools for the community: Edge-TCT, Alivaba readout, TPA-TCT, ... are now available through spin-off companies

RD50 funded projects

- 2017-01 LGAD based on EPI wafers (G.Pellegini, CNM, Barcelona)
- 2017-02 TPA TCT on CMOS sensors (I.Vila, Santander)
- 2017-03 LGAD fabricated with epitaxial layer (G.Pellegrini, CNM, Barcelona)
- 2017-04 RD50 CMOS submission (Gianluigi Casse, Liverpool, UK / Vitaliy Fadeyev, SCIPP, USA)
- 2017-05 50 μm thin LGAD fabricated with Ga multiplication layer (Joern Lange, IFAE Barcelona)
- 2017-06 Thin LGADs characterization using IBIC and time-resolved IBIC at CAN (Carmen Jimenez-Ramos, Sevilla)
- 2017-07 MPW run with LFoundry (Eva Vilella, Liverpool)
- 2017-08 50 μm thin AC-LGAD (Mar Carulla, CNM Barcelona)
- 2018-01 Development of Segmented LGAD with small pixels and high Fill-Factor (Giovanni Paternoster, FBK)
- 2019-01 RD50-MPW2 (Eva Vilella, Liverpool)
- 2019-02 Proof of concept of 3D detectors fabricated in Silicon Carbide (SiC) semiconductor layers (Sofia Otero-Ugobono, CNM Barcelona)
- 2019-03 Schottky diodes on Epitaxial Silicon for Radiation Damage Characterization of CMOS MAPS (Giulio Villani, STFC Rutherford Appleton Laboratory)
- 2020-01 3D detectors optimized for timing applications (Gregor Kramberger, JSI,Ljubljana) - 2020-02 Proof-of-concept and radiation tolerance assessment of thin pixelated Inverse Low Gain Avalanche Detectors (ILGAD) (Ivan Vila, UC-CSIC, Santander)
- 2021-01 Production of Caribou CaR boards for RD50 DMAPS developments (Dominik Dannheim, CERN)
- 2021-02 Characterisation of GaN Based Materials, Electronics, and Sensors, Subject to Large Radiation Doses (T. Koffas Carleton)
- 2021-03 Defect engineering for sensors with intrinsic gain (Gkougkousis Evangelos – Leonidas, CERN)
- 2021-04 RD50-MPW3 (Eva Vilella, Liverpool)
- 2022: Defect studies on carbon enriched p-type sensors I.Pintilie)

RD50 - 5 year work plan

- 5 year work plan submitted in May 2018
  $\rightarrow$ Approved by CERN Research Board in June 2018
- Work plan (70 milestones)
  - **Defect and Material Characterization [16 MS]**
  p-type silicon [7 MS]
  Cluster defects [4 MS]
  Theory of defects [5 MS]
  - **Device Characterization & Device Simulation [21 MS]**
  Silicon materials [5 MS]
  Extreme fluences [5 MS]
  Experimental techniques [3 MS]
  Surface damage [1 MS]
  TCAD simulations [7 MS]
  - **New structures [21 MS]**
  3D sensors [6 MS] ; LGAD [4 MS]
  CMOS [6 MS] ; New Materials [5 MS]
  - **Full Detector Systems [12 MS]**
  LHC [7 MS]; HL-LHC [3 MS]

  FCC [2 MS]
- June 2023 - End of the existing Work Plan
- RD50 should end at the end of 2024 and be replace with a newly formed collaboration called "DRD3" within a new reviewing scheme proposed by ECFA and approved by the CERN council

Summary

- RD50 investigates radiation-hard semiconductors for high-luminosity colliders
- Comprises 66 institutes, 430 members
- Four research lines: Defect/Material characterization, Detector characterization, New structures, Full detector systems
- RD50 has contributed significantly to the LHC and LHC upgrade detectors
- Current collaboration comes to an end in 2024
  $\rightarrow$ Replaced by DRD3 collaboration