Silicon Detectors Beyond the LHC
RD50 Status Report

Albert-Ludwigs-Universität Freiburg

Ulrich Parzefall

on behalf of the RD50 Collaboration

based on input and results from many many RD50 colleagues

RD50

- RD50 is a CERN-Collaboration connecting 400+ members, from all LHC experiments, plus many others
- RD50 mandate
  “Radiation Hard Semiconductor Devices for Very High Luminosity Colliders “
- Original RD50 target: radiation hard silicon for Phase-2 LHC upgrades (HL-LHC)
  – Radiation dose $3 \cdot 10^{16}\ n_{eq}\ /cm^2$
- New: collider experiments beyond LHC: e.g. FCC
  – Radiation dose $> 5 \cdot 10^{17}\ n_{eq}\ /cm^2$, 200 MGy

The RD50 Collaboration

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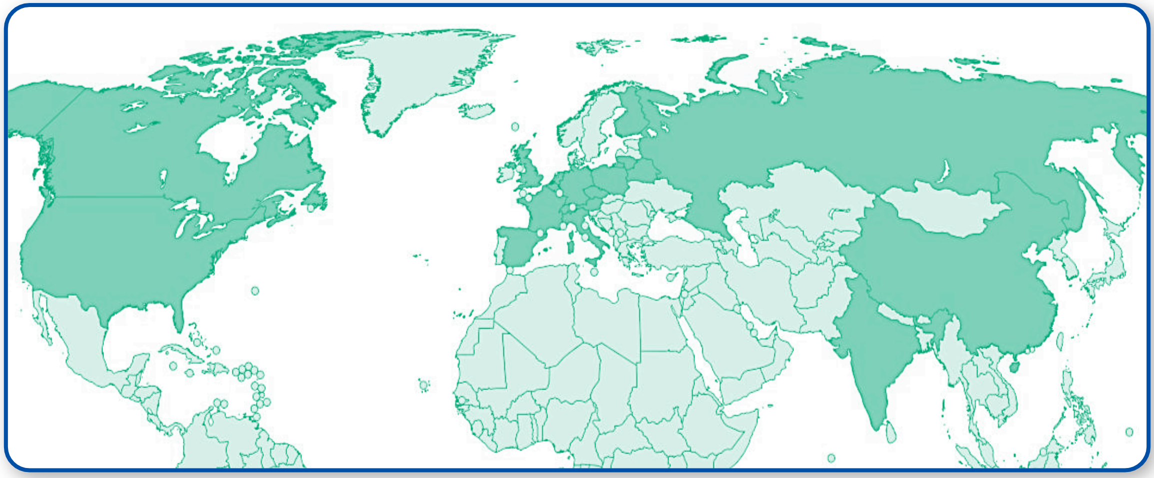
Worldwide Collaboration: 64 institutes, more than 410 members

(see http://cern.ch/rd50)

51 European institutes

Austria (Wien), Belarus (Minsk), Czech Republic (Prague (3x)), Finland (Helsinki, Lappeenranta), France (Marseille, Orsay, Paris), Germany (Bonn, DESY, Dortmund, Freiburg, Göttingen, Hamburg, Karlsruhe, Munich (2x)), Italy (Bari, Perugia, Pisa, Trento, Torino), Croatia (Zagreb), Lithuania (Vilnius), Netherlands (NIKHEF), Poland (Krakow, Warsaw (2x)), Romania (Bucharest (2x)), Russia (Moscow, St. Petersburg), Slovenia (Ljubljana), Spain (Barcelona (3x), Santander, Sevilla (2x), València), Switzerland (CERN, PSI, Zürich), United Kingdom (Birmingham, Glasgow, Lancaster, Liverpool, Manchester, Oxford, RAL)



8 North-American institutes

USA (BNL, Brown Uni, Fermilab, LBNL, New Mexico, Santa Cruz, Syracuse), Canada (Carleton)

1 Middle-Eastern institute

Israel (Tel Aviv)

4 Asian institutes

China (Beijing-IHEP, Hefei, Jilin), India (Delhi)

RD50

RD50 Structure

- Today examples from four main research lines, with bias

Co-Spokespersons

Gianluigi Casse and *Michael Moll*

(Liverpool University, UK & FBK-CMM, Trento, Italy) (CERN EP-DT)

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, SR, …
- NIEL (calculations)
- Cluster and Point defects
- Boron related defects

Detector Characterization
Eckhart Fretwurst
(Hamburg University)

- Characterization of test structures (IV, CV, CCE, TCT,.)
- Development and testing of defect engineered devices
- EPI, MCZ and other materials
- NIEL (experimental)
- Device modeling
- Operational conditions
- Common irradiations

- Wafer procurement (M.Moll)
- Acceptor removal (Kramberger)
- TCAD simulations (J.Schwandt)

New Structures
Giulio Pellegrini
(CNM Barcelona)

- 3D detectors
- Thin detectors
- Cost effective solutions
- Other new structures
- Detectors with internal gain
- LGAD: Low Gain Avalanche Det.
- Deep depleted Avalanche Det.
- Slim Edges
- HVCMOS

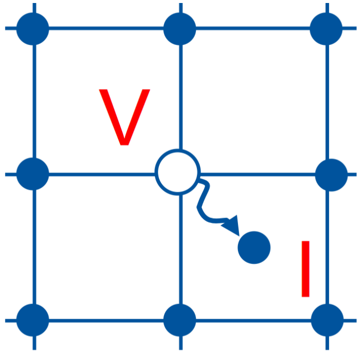
- LGAD (S.Hidalgo)
- HVCMOS (E. Vilella)
- Slim Edges (V.Fadeyev)

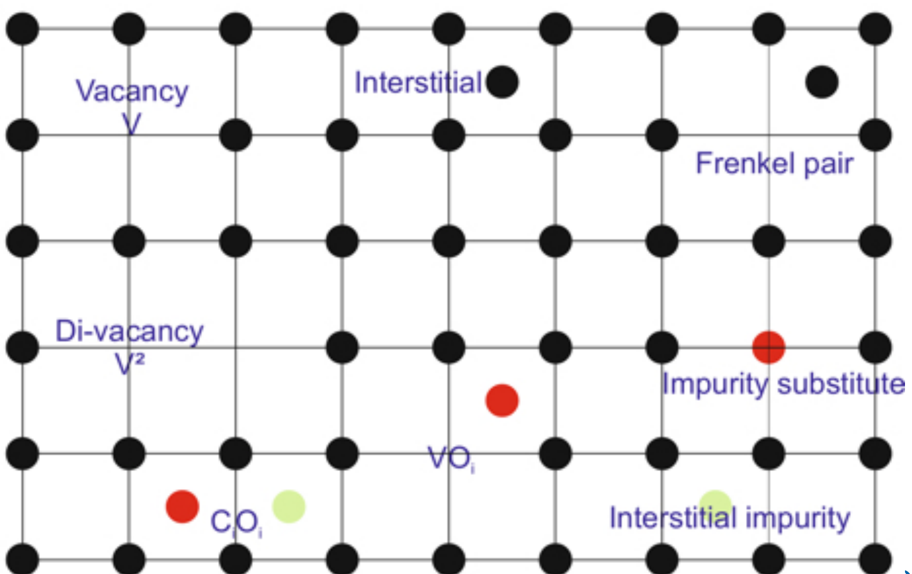
Full Detector Systems
Gregor Kramberger
(Ljubljana University)

- 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
- Timing detectors
- Test beams (M.Bomben & G.Casse)

Defect Characterization: Displacement Damage

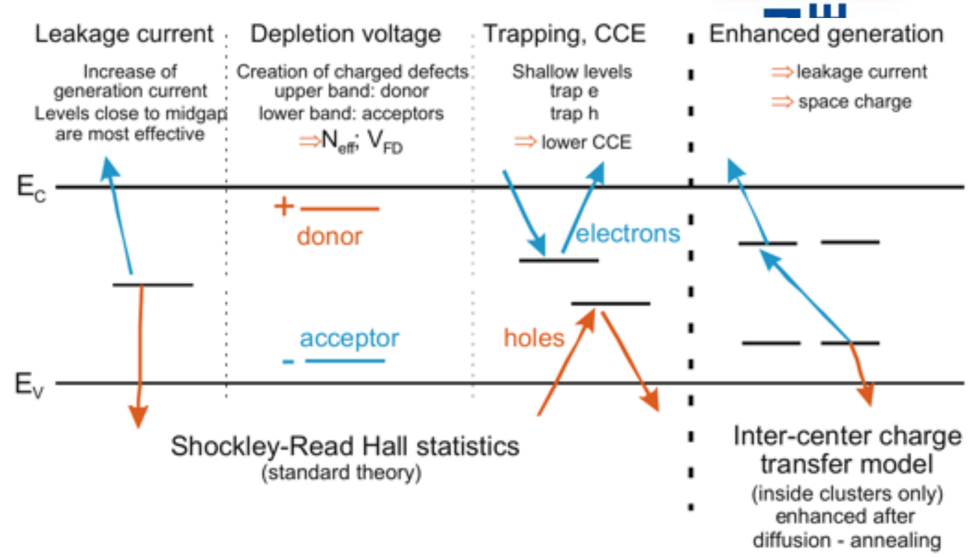
- Particle hits Silicon atom, creates **V**acancy and **I**nterstitial
- Wide range of point defects (E_k>25keV)
- **V** and **I** can react:
  V+O → VO
  V+P → VP (P deactivated)
  I+C_s → C_i → C_i+O → C_iO
  I+B_s → B_i → B_i +O → B_iO (B deactivated)
- Removal of dopants impacts detector performance, mostly undesired
- Defects are mobile, with strong temperature dependence
- High-T annealing to "move defects around" and improve performance
- Cluster defects also possible for lower energies (E_k>5keV)

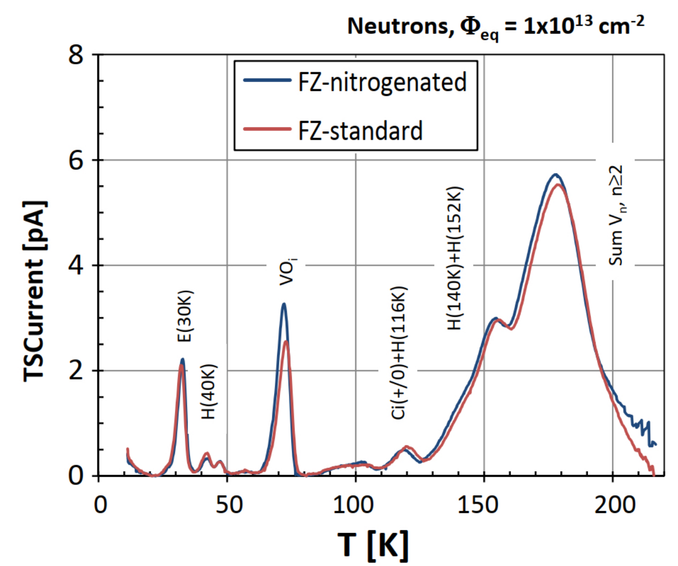




Defect Characterization

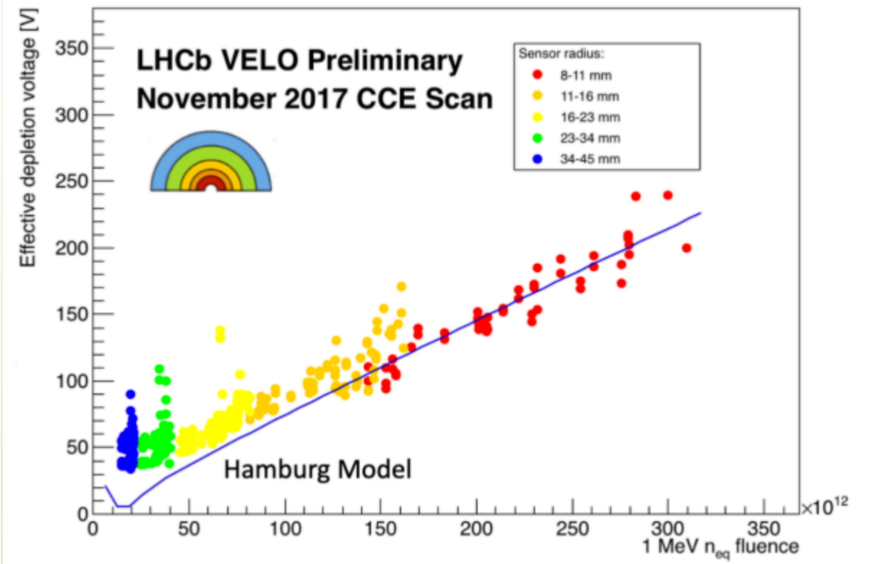
- Main goal of defect studies
  - Identify defects responsible for external observables: effective doping N_{eff}, leakage current I_{leak}, full depletion Voltage V_{FD}, trapping and signal loss
  - Effect of defect depends on its energy level in band gap
  - Mid-band gap defects increase I_{leak}
  - Very shallow charged defects defects increase N_{eff} (type inversion n -> p) and increase V_{FD}, often resulting in radiation limit
  - Defects can capture drifting charges (trapping), reducing signal and Charge Collection Efficiency (CCE)
- Defects identified with e.g. Thermally Stimulated Current (TSC) or Deep Level Transient Spectroscopy (DLTS)
  - Exploit info to reduce unwanted effects

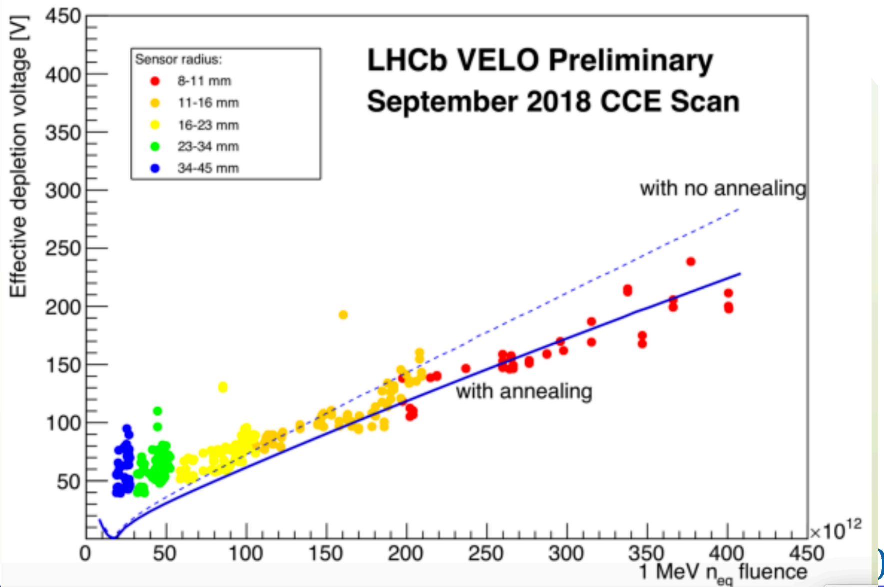




The Hamburg Model: Time Evolution of Silicon Doping Concentration

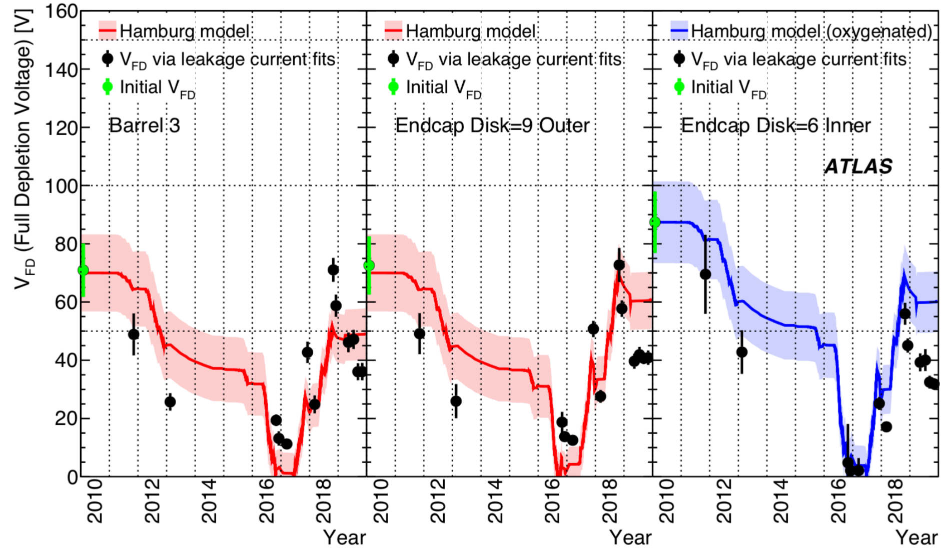
- Radiation damage effect on leakage current described by **RD50 Hamburg model**, including annealing
- **LHCb** vertex locator among the most irradiated detectors at LHC
- LHCb performs evolution of leakage current and depletion voltage with Hamburg Model
- In July 2018 monitoring suggested that VELO can have troubles coping with radiation
- VELO warmed up to accelerate beneficial annealing, based on Hamburg Model
- Full depletion voltage successfully reduced

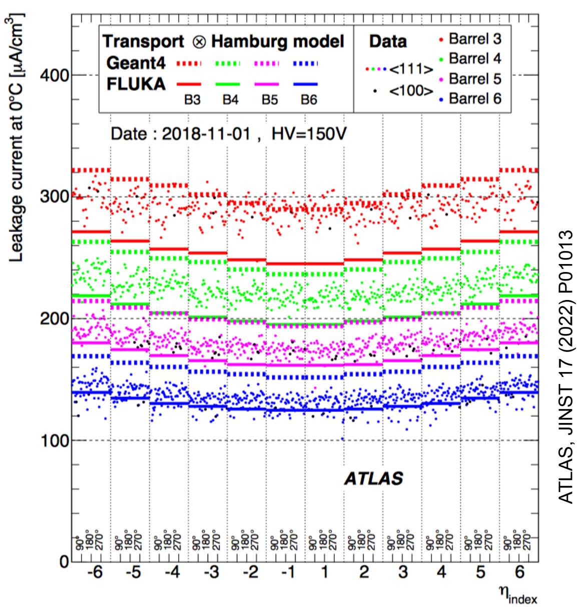


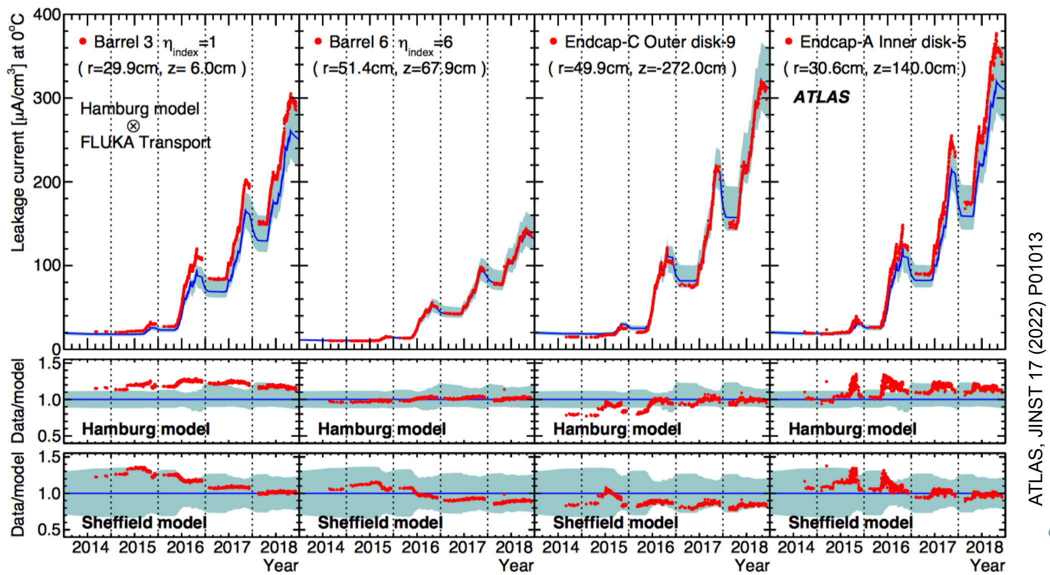


The Hamburg Model: Time Evolution of Current

- Leakage current and V_{FD} in ATLAS and CMS Si Strip trackers measured
- Current increases with luminosity, then anneals especially in shutdown
- Sensors are p-in-n, type inversion of N_{eff}
- V_{FD} drops until 2016, then growing
- Correctly described by simulation
- Measured currents slightly higher than predicted, but within errors

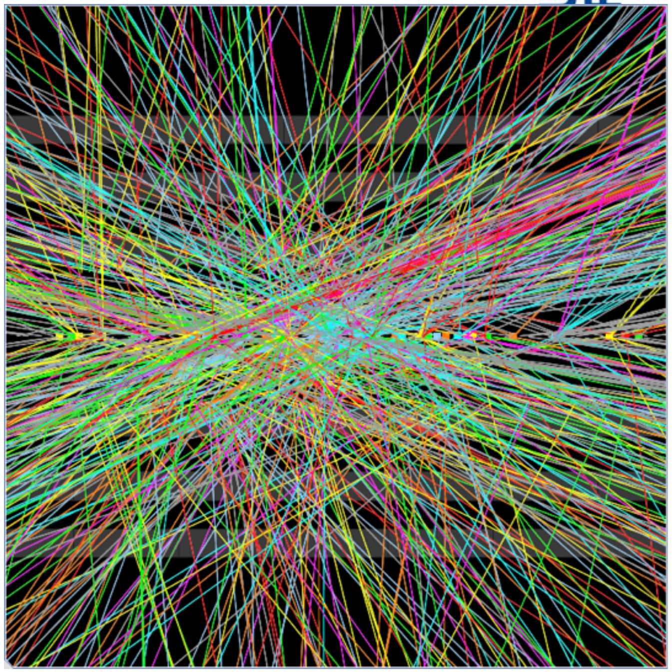






New Structures: Fast Silicon - LGAD

- HL-LHC: need to separate 300 simultaneous collisions every 25ns (pileup)
- FCC will have pileup of O(1000)
- Idea: use time as 4th dimension.
  - Traditional detectors far too slow
  - Add a thin p-layer to conventional Si-detectors
- **Low Gain Avalanche Diodes (LGAD)**
  - Multiplication layer with very high E-field -> thin avalanche region with moderate gain (10-50) at readout electrode
  - 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)
  - LGAD subject of intense research (also here ☺)



- Poster by Giovanni Paternoster “Low Gain avalanche Diodes Technology: state of the art and future developments”
- Jenny Ott’s talk right now “Development of AC-LGADs for large-scale high-precision time and position measurements”
- Leena Diehl’s talk “Time resolution of LGADs and 3D silicon sensors”
- Waleed Khalid poster “Proof of pricinple for pLGAD detector concept for low energy particles”
- Jenny Ott’s poster “An LGAD-based full active target for the PIONEER experiment”
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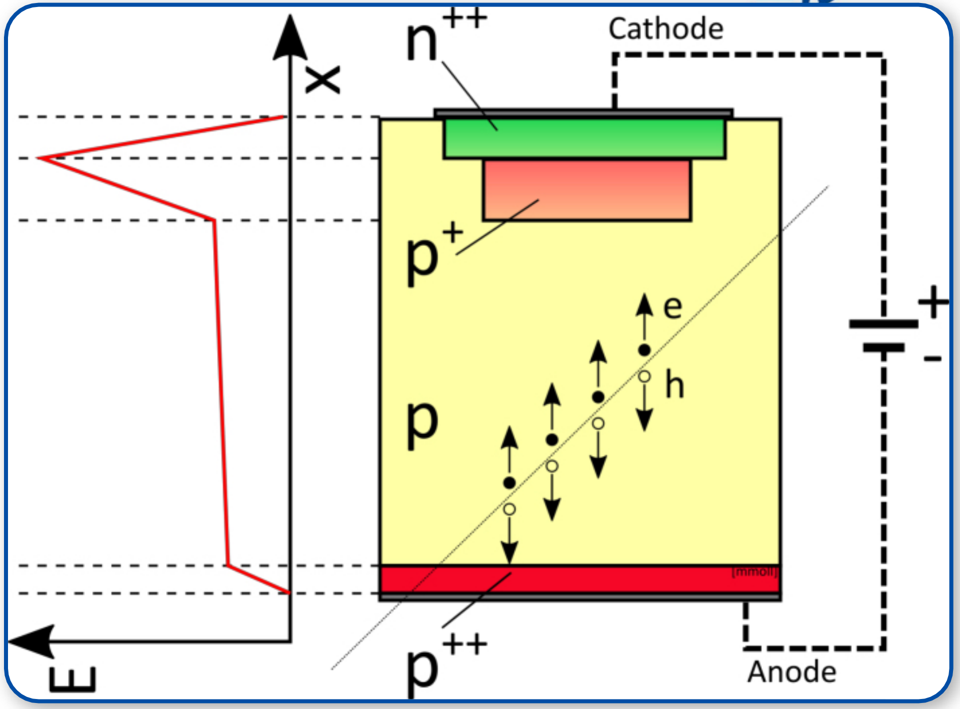

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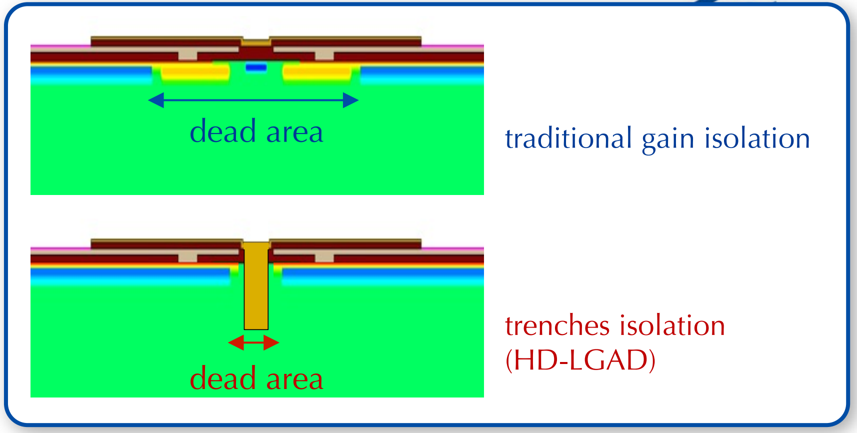
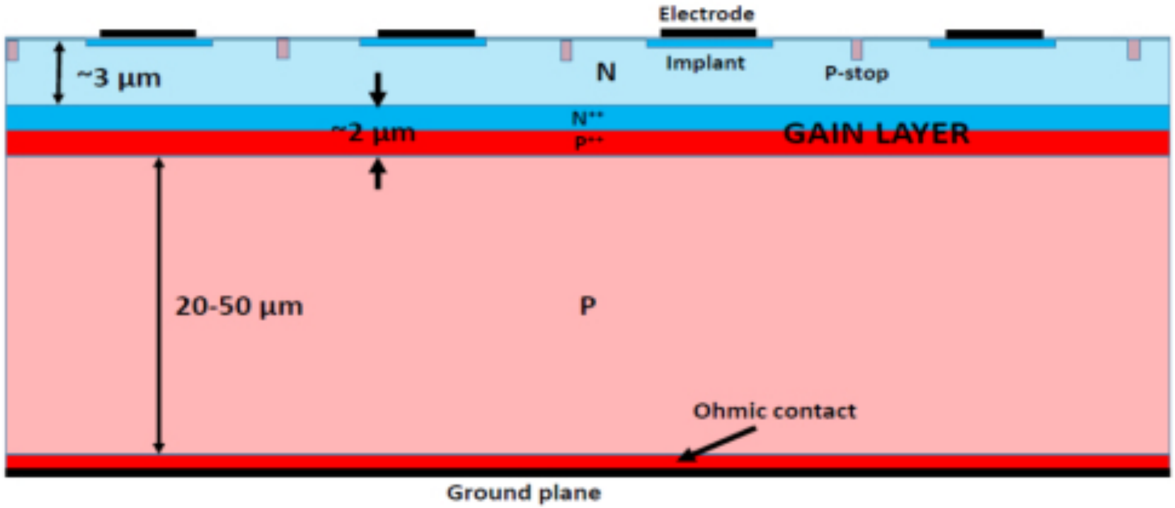
LGAD: Areas of R&D

- Geometry: isolation between pixels has no gain, is dead area (fill factor < 1)
  - Designs with improved fill factor, e.g.:
    HD-LGAD with trench isolation,
    Deep Gain Layer LGAD,
    AC LGAD, inverted LGAD
    other ideas & designs under way
- Radiation hardness: gain is dropping as acceptor doping of gain layer is reduced. Can be mitigated by increased bias voltage, but only until HV limit reached
  - Chose Carbon as extra dopant to shield Boron, "*carbon helps*", dose is also critical



Deep Gain Layer LGAD



Y. Zhao, 35 RD50 Workshop,;
B. Schumm CPAD 03/2021,
S. Ayyoub et al. arXIV 1/2021

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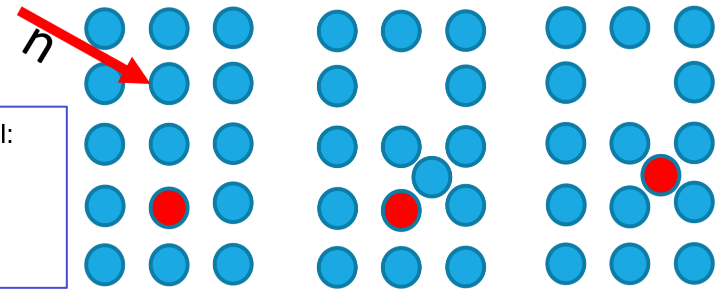
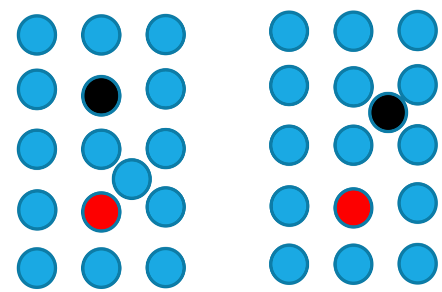
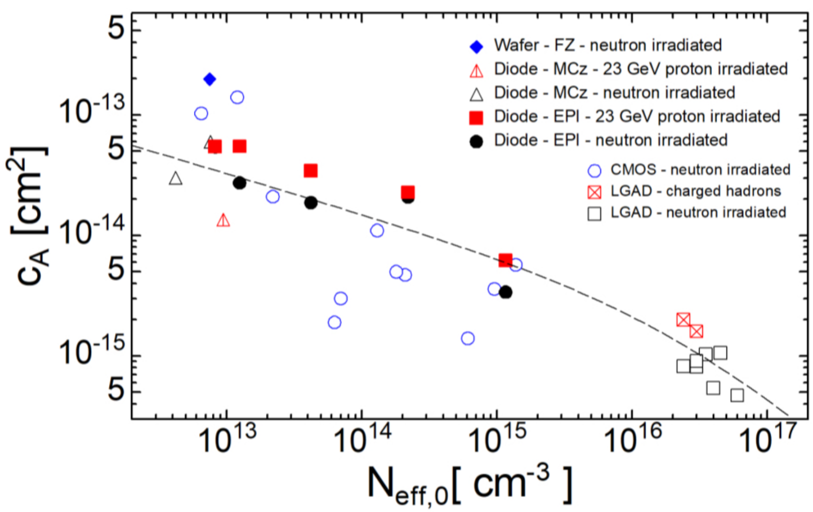
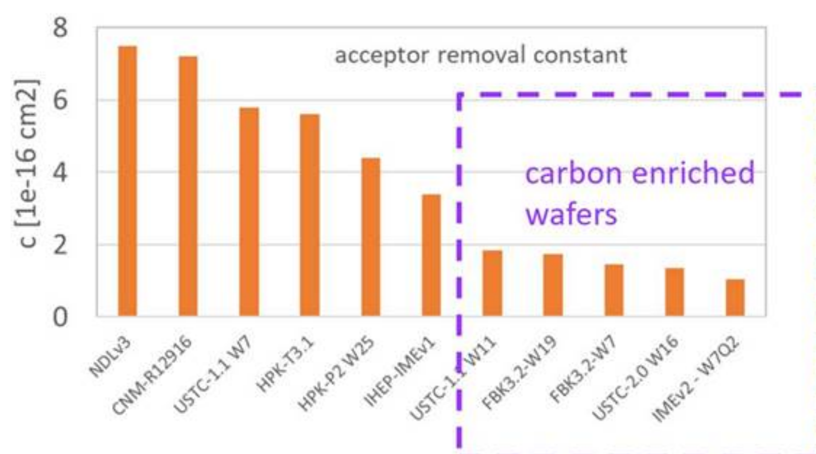
Boron acceptor removal:
Hadron hits Si from site
Si interstitial + B ➔
Boron Interstitial ➔
Boron deactivated



Carbon captures
Si interstitial ➔
Boron stays active



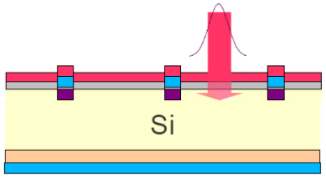


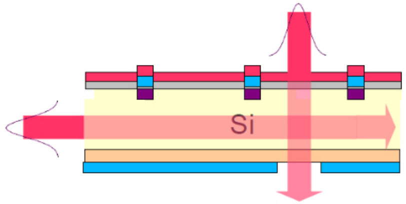


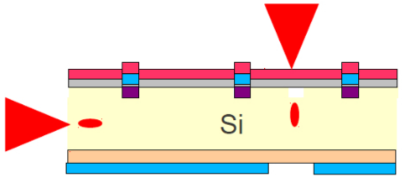
G. Kramberger, CERN EP Seminar May 2021

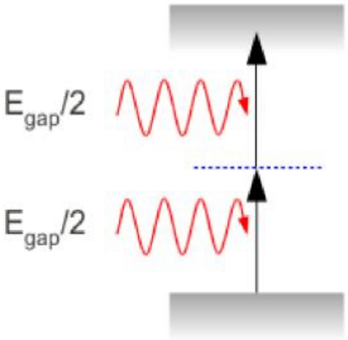
Sensor Characterization: TCT

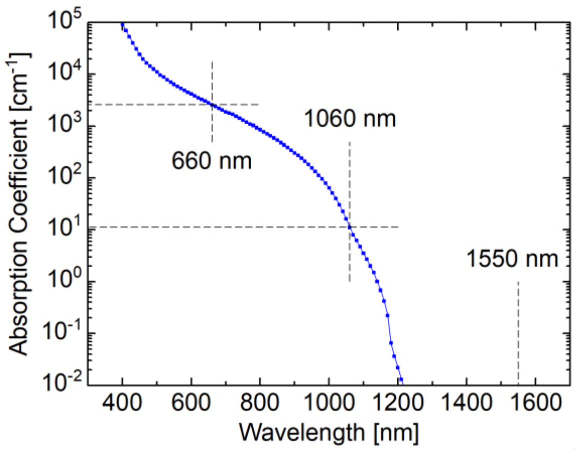
- Send a short laser pulse into silicon:
  Transient Current Technique (TCT) since 1996
- Edge TCT invented in RD50 2010, commercialized 2013
- Red laser TCT (660nm, single-photon absorption)
  - Short penetration depth, charge generation few µm under surface
  - Front- or backside TCT, can study hole or electron drift separately
  - 2D spatial resolution 5-10µm
- IR laser TCT (1060nm, single-photon absorption)
  - Goes through Si bulk. Top-TCT or edge-TCT configurations
  - 2D spatial resolution 5-10µm
- Recent development: Two-Photon Absorption (TPA-TCT)
  (far infrared 1550nm) since 2015, commercial 2021
  - No singe photon absorption, two photons create one e-h- pair
  - Point-like energy resolution in focal point



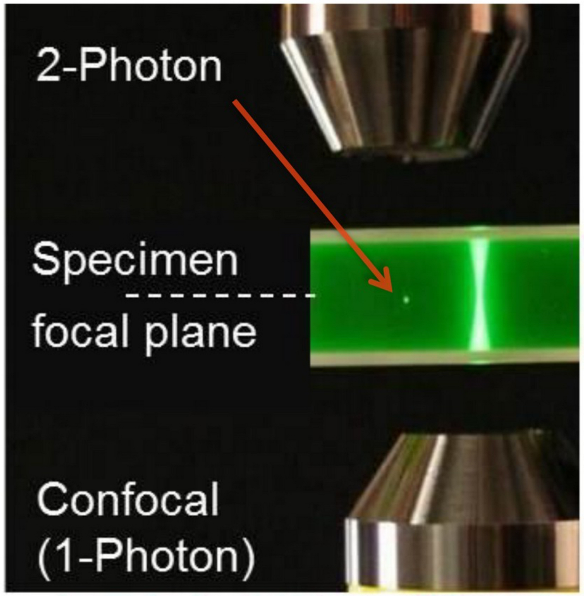






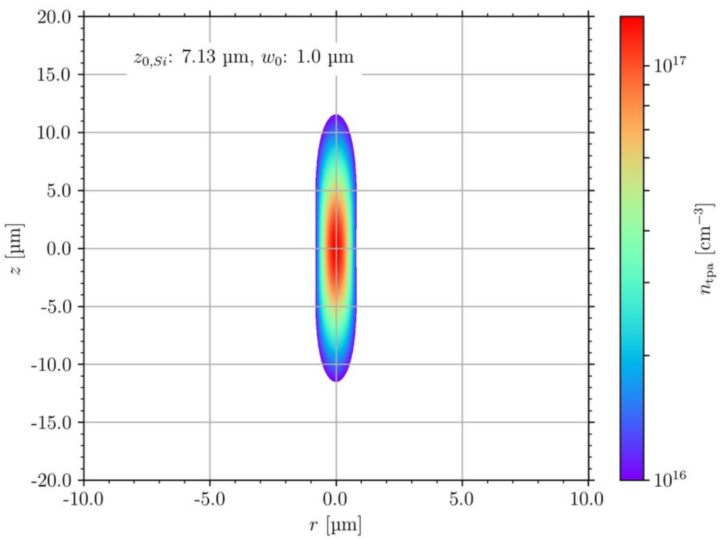


TPA-TCT

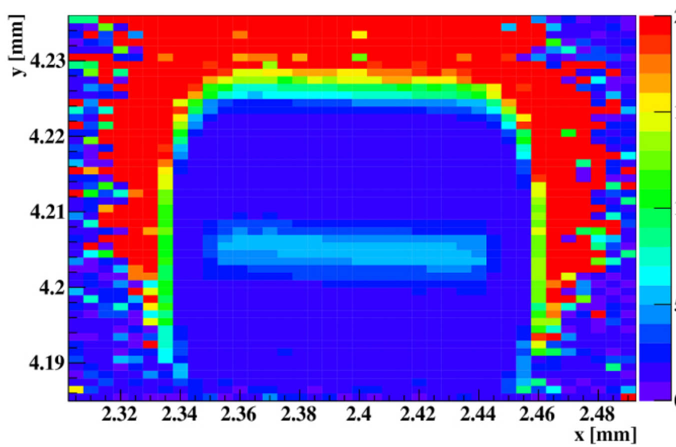


Photography: Ciceron Yanez, University of Central Florida

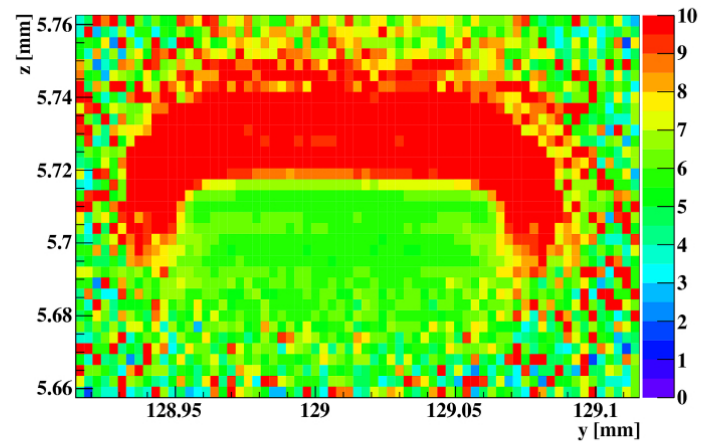
CERN table top
TPA System:
3D spatial resolution
roughly 1 x 1 x 10µm^3



TPA



SPA

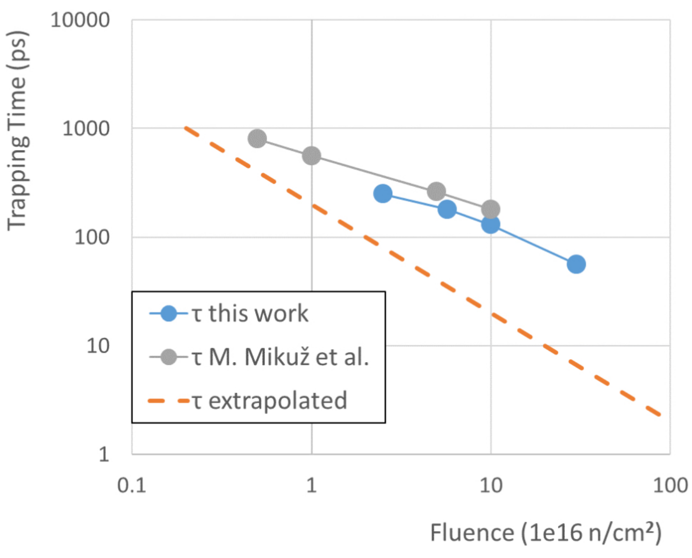


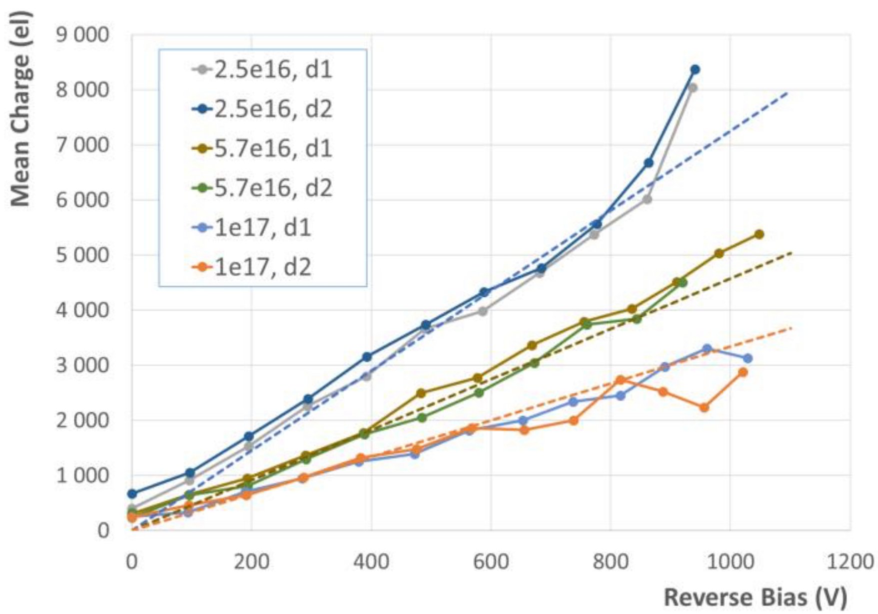
Comparison of SPA
(edge TCT) and TPA:
only TPA resolves
deep n-well
in HV-CMOS sensor

M. Wiehe, PhD Thesis 2021

Silicon at Extreme Fluences: Planar

- FCC will require radiation hardness to a few $10^{17} n_{eq}$
- Planar sensors (75µm thick ~~LGAD~~ pad sensors) tested up to $1 \cdot 10^{17} n_{eq}$
- Increase of trapping less than expected, no more gain,
  but clear signs of life
- Sensors show 3ke$^-$ signal at $1 \cdot 10^{17} n_{eq}$ but
  high voltage stability crucial
- Looks encouraging.... but accompanied by increased noise (S/N is ~1)

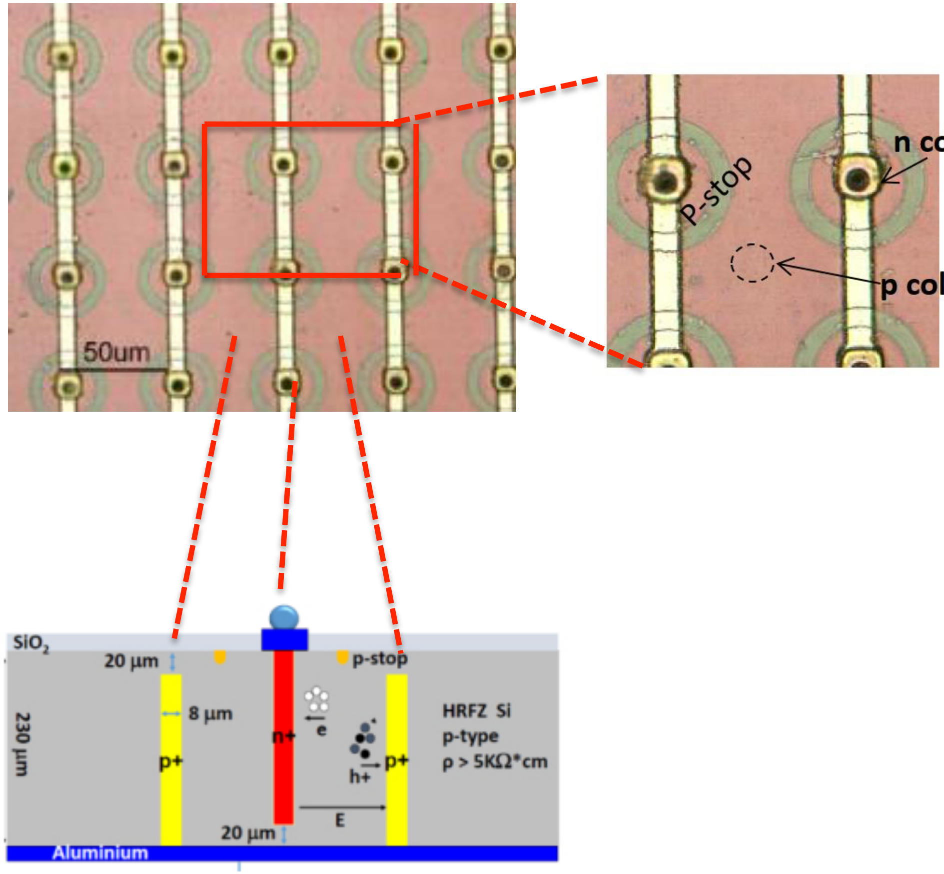


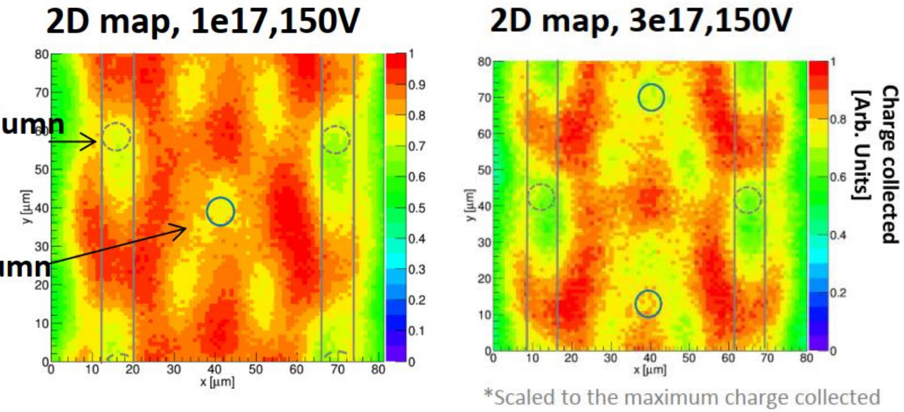


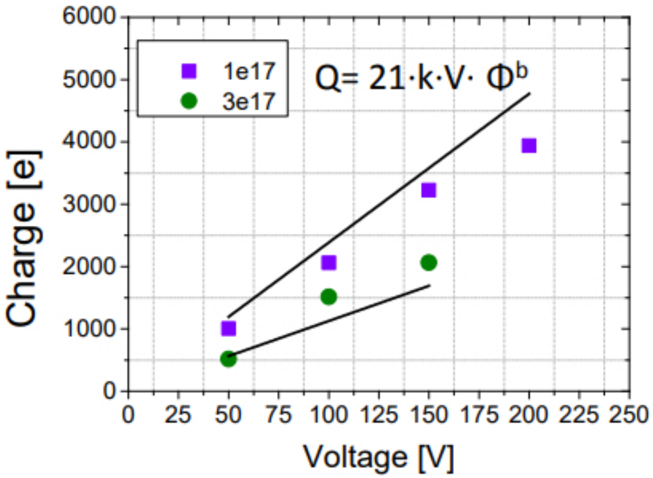
I. Mandiic, 2020 JINST 15 P11018

Silicon at Extreme Fluences: 3D

- Double sided 3D sensors irradiated to $1 \cdot 10^{17} n_{eq}$ and $3 \cdot 10^{17} n_{eq}$, then measured with TCT and beta source
- Signal of $4ke^-$ at $1 \cdot 10^{17} n_{eq}$, still alive at $3 \cdot 10^{17} n_{eq}$







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

Main RD50 Achievements & Summary

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This talk was biased and covered only very few highlights. Other key RD50 achievements:

- Sensor material: ***p*-type Silicon replacing n-type** (no type inversion, collection of electrons instead of holes), applied at Phase-II LHC trackers
- Sensor technologies: CMOS processed silicon, 3D sensors, …
- Original RD50 R&D mission (HL-LHC) completed successfully. Construction of Phase-II detectors starting...
- RD50 continues to be your must-have friend if you are serious about installing silicon in a harsh radiation experiment
- RD50 now focusing on new generation of colliders (FCC), pushing the radiation boundary by an order of magnitude.
- Will be difficult, but we have ideas, and useable signals from beyond $10^{17} n_{eq}$. We need above everything more young people with new thinking, and creative ideas!

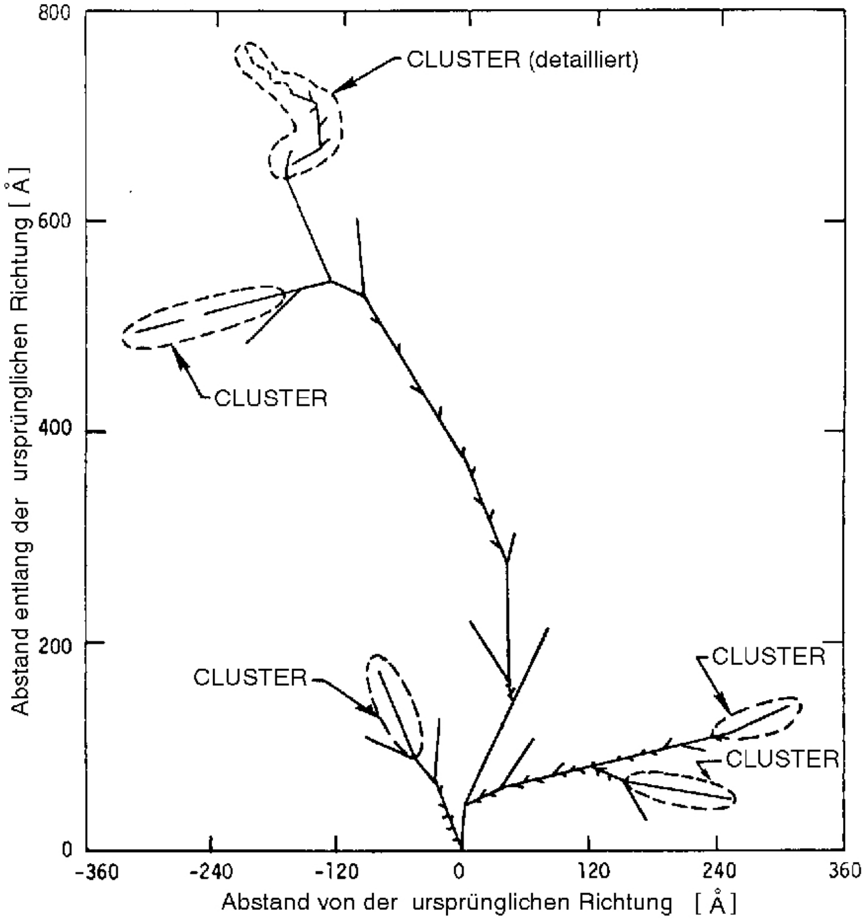
RD50

RD50 Members at Torino Meeting

Albert-Ludwigs-Universität Freiburg

Back Up Only Beyond this Point

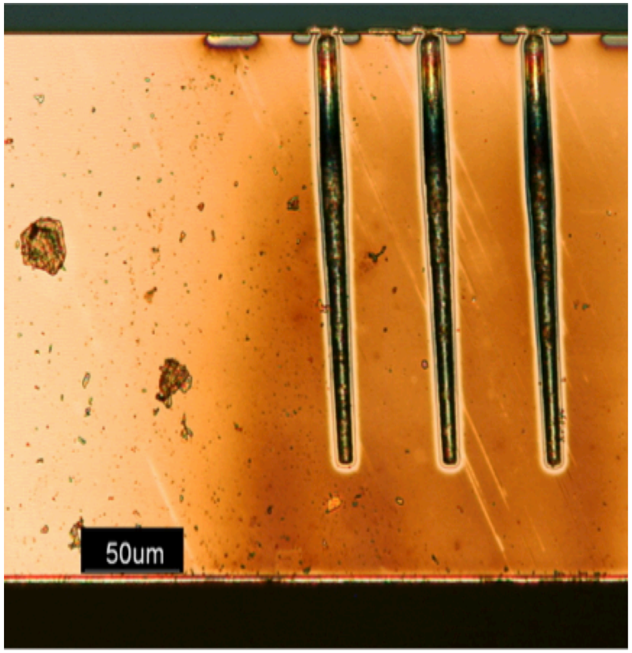
Defects: Point and Cluster

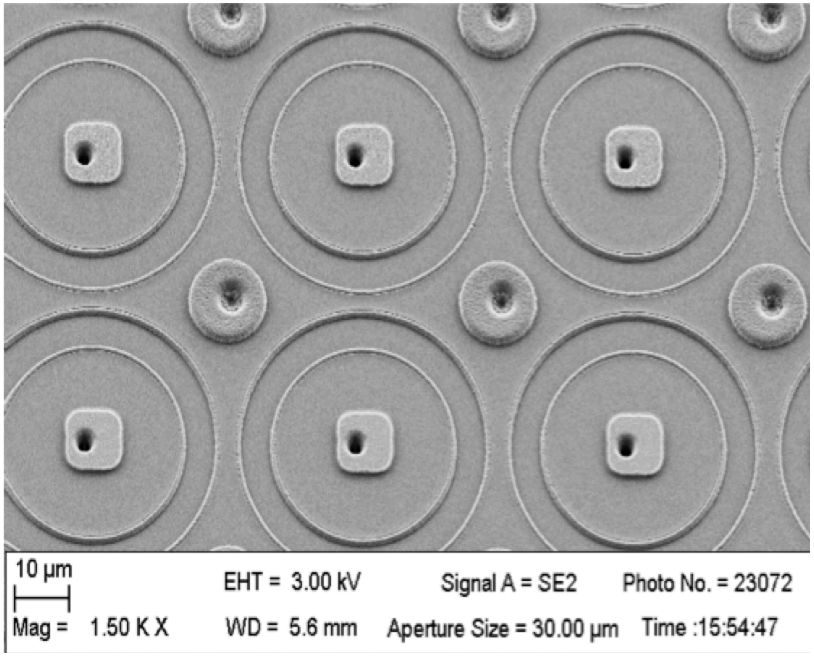


Van Lint 1980

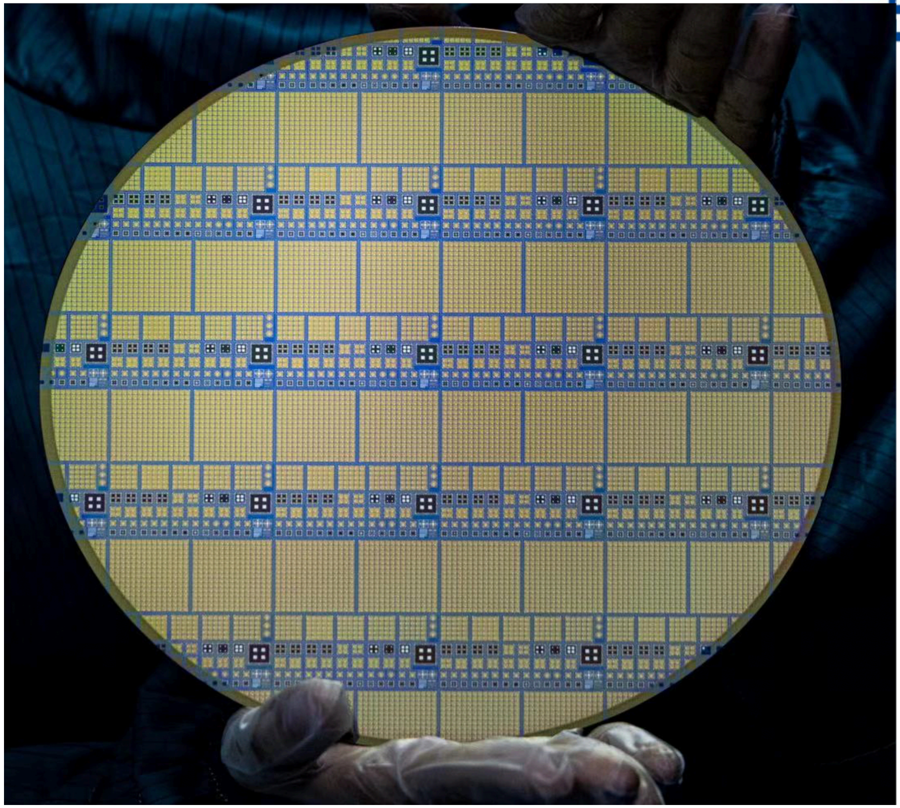
3D

- *Microscope images of 3D pixel sensors produced at CNM Barcelona. Cross-section with a sensor cut at the columns (left) and SEM image of sensor surface (right).*





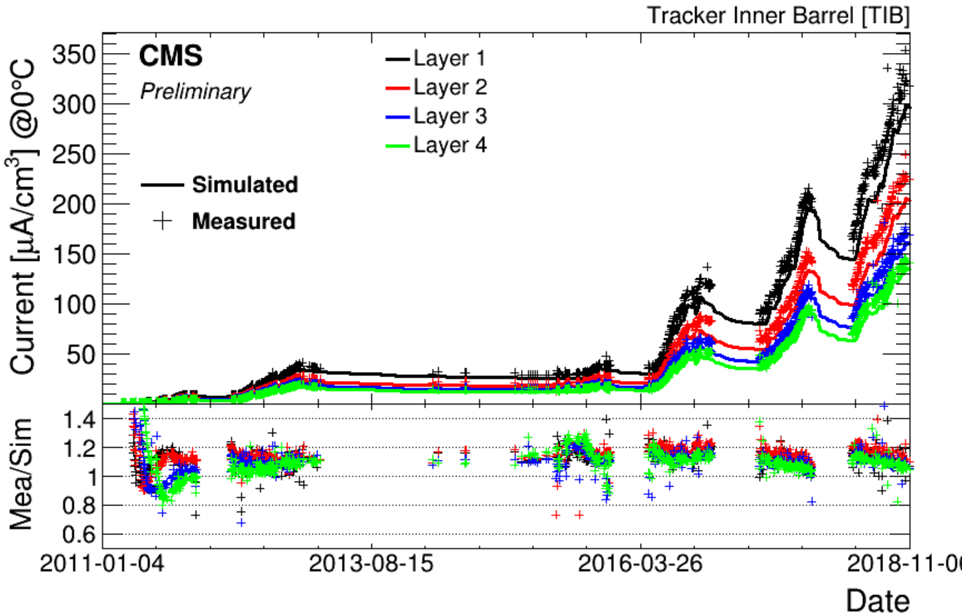
LGAD

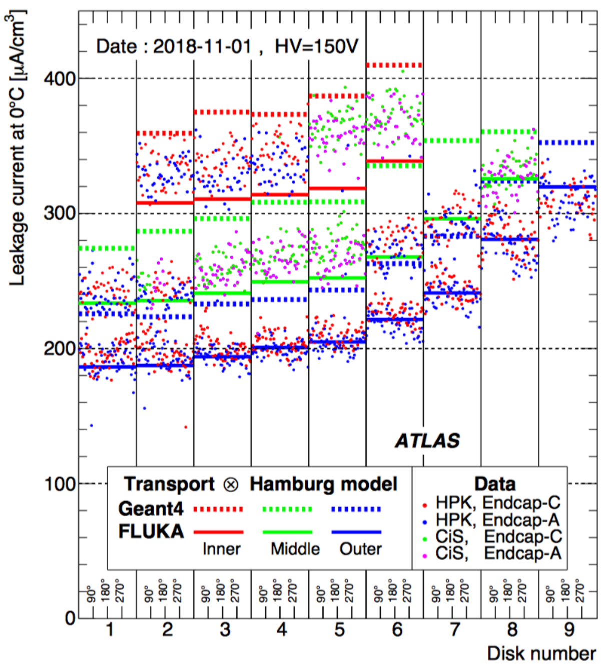


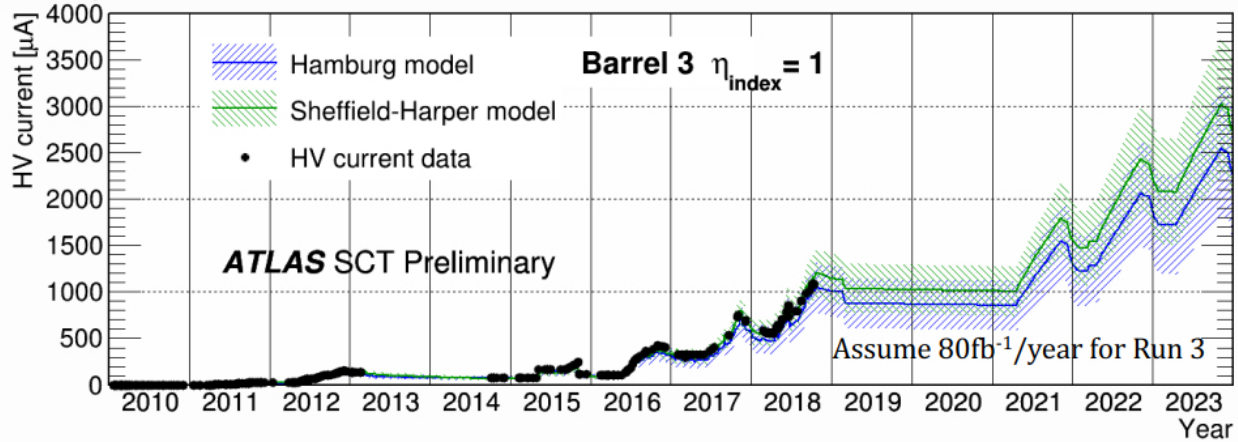
- *Carbon-implanted LGAD sensors on an 8 inch wafer designed by the Institute of High Energy Physics (IHEP) and fabricated by the Institute of Micro Electronics (IME) of the Chinese Academy of Sciences [1]*
- *Xuwei Jia et al., 39th RD50 Workshop Valencia, (2021), https://indico.cern.ch/event/1074989/ contributions/4601959/*

Hamburg Model

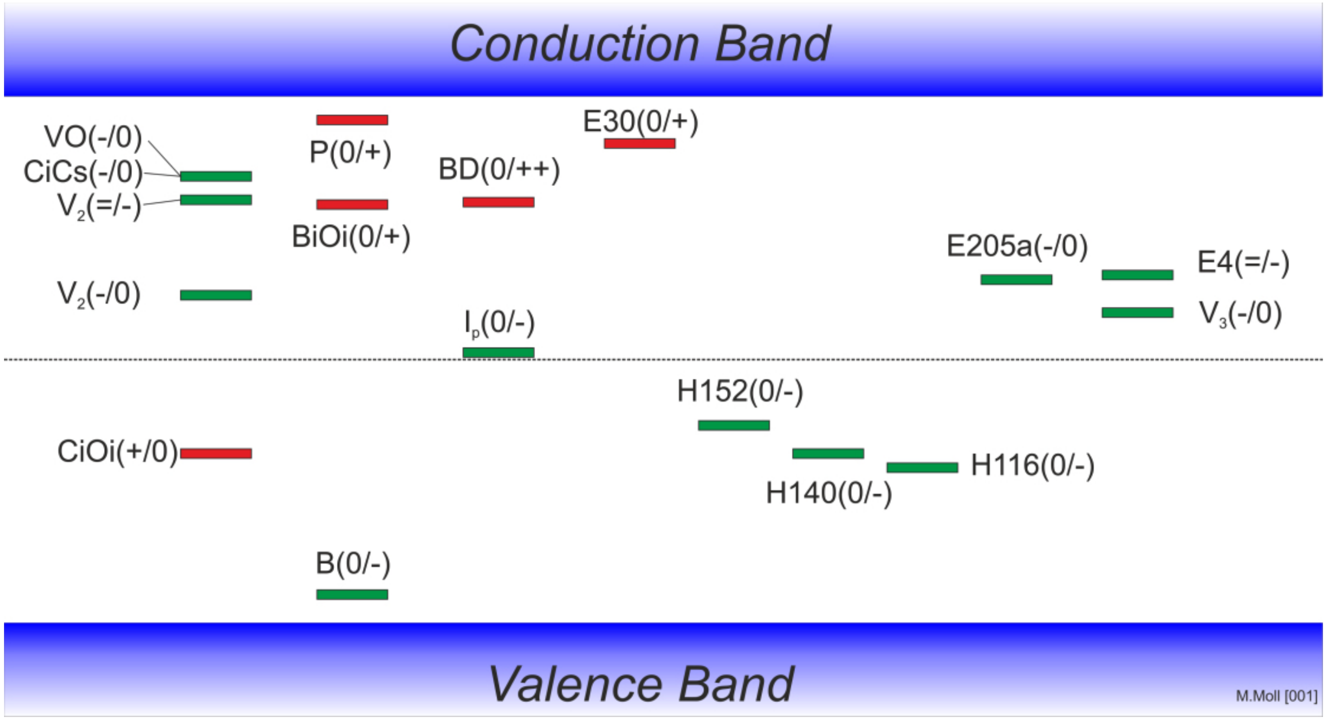
- CMS leakage plot
- ATLAS SCT EC leakage plot
- ATLAS SCT leakage evolution prediction (superseded by SCT performance paper)



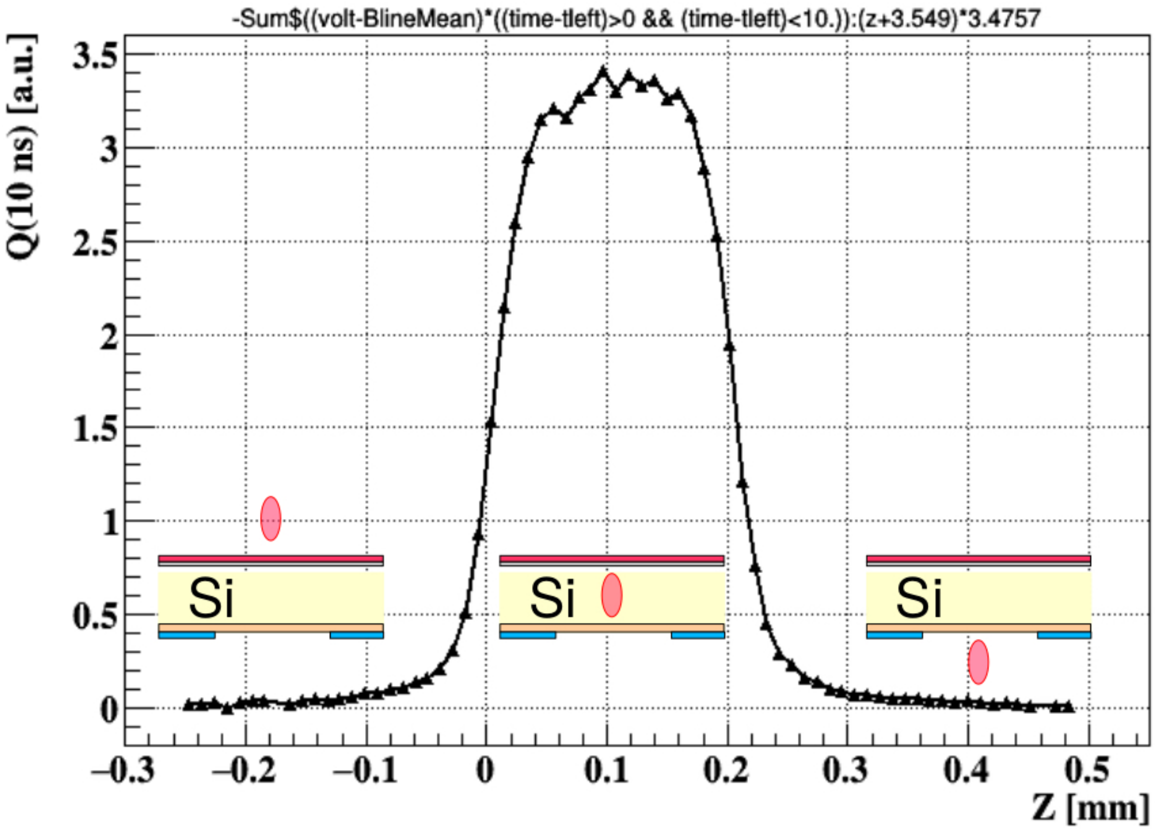




Defects and Impact on Silicon Performance



TPA-TCT



- CERN TPA System

Doping Concentration

- The classic RD50 Plot