Silicon Detectors Beyond LHC
RD50 Status Report

Radiation hard semiconductor devices for very high luminosity colliders

Gabriele D'Amen (Brookhaven National Laboratory, US)
on behalf of the **RD50 collaboration**

17th (Virtual) "*Trento*" Workshop on Advanced Silicon Detectors
March 2 - 4, 2022, University of Freiburg

The RD50 collaboration

- RD50: 64 *institutes and 410 members*

51 European institutes

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)

Full member list: www.cern.ch/rd50

8 North-American institutes

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

1 Middle East institute

Israel (Tel Aviv)

4 Asian institutes

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

The RD50 collaboration

Organizational overview

Defect 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
- SiC/GaN based detectors

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

RD50

Co-Spokespersons:

G.Casse and M. Moll
(Liverpool University, UK
(CERN EP-DT) & FBK-CMM,
Trento, Italy)

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
- Very high radiation fluences

Full Detector System

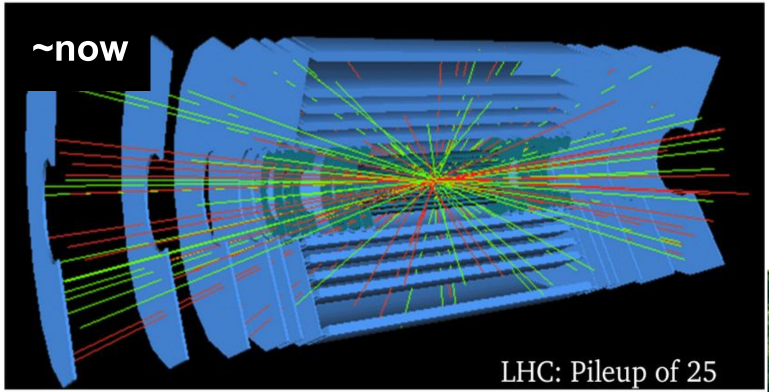
(Gregor Kramberger, Ljubljana University)

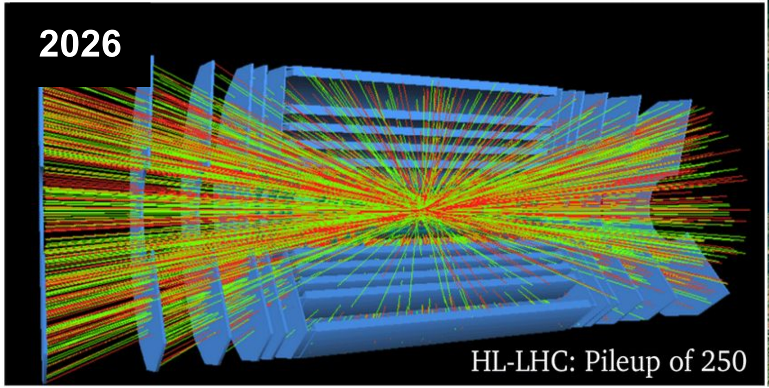
- LHC-like tests
- Links to HEP (LHC P2, FCC)
- Links electronics R&D
- Low rho strips
- Sensor readout (Caribou,Alibava)
- Comparison: - pad-mini-full detectors - different producers
- Radiation Damage in HEP detectors
- Timing detectors
- Test beams

Collaboration Board Chair & Deputy: G.Kramberger (Ljubljana) & tbc, Conference committee: U.Parzefall (Freiburg) CERN contact: M.Moll (EP-DT), Secretary: V.Wedlake (EP-DT), Budget holder: M.Moll & M.Glaser (EP-DT) , EXSO: R.Costanzi (EP-DT)

LHC, HL-LHC, FCC-hh

Moving forward



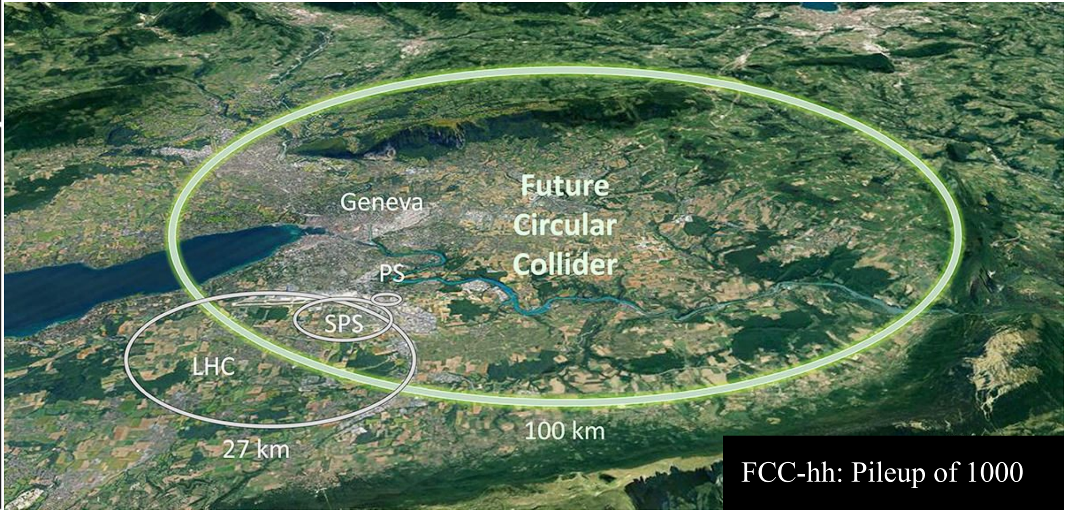


HEP moving forward

Higher statistics + higher energy = higher fluence and busier environment

additional proton-proton collisions (**pileup**) masking events of interest must be disentangled

strict requirements on **resolution** and **radiation hardness** for future silicon sensors



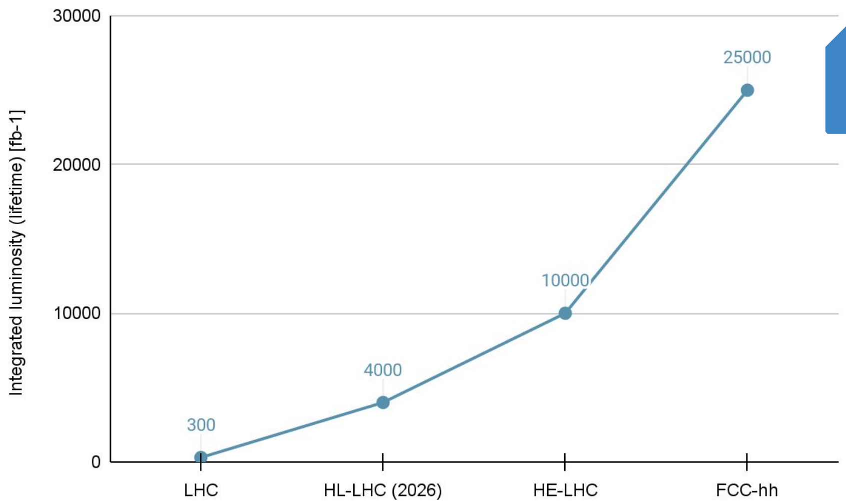
Tackling Fluence

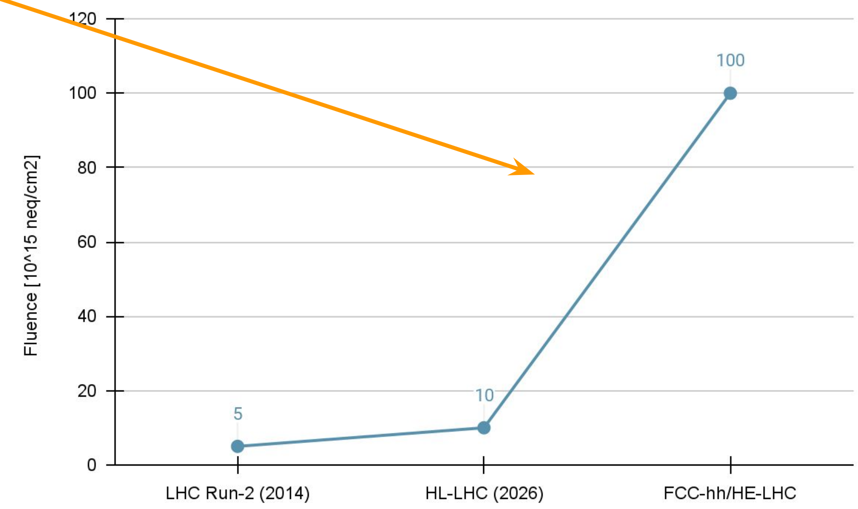
How to cope with radiation

Defect characterization essential to cope with large fluences and integrated radiation expected in future hadronic experiments@CERN (*HL-LHC, HE-LHC, FCC-hh*):

- Factor 2x in fluence on inner pixel layers expected by 2026 (HL-LHC)
- **Factor 20x in fluence** needs to be accounted for next big physics and engineering challenge: **FCC-hh**

Timing capabilities degradation and **sensor distruction** (**!!!**) quite likely

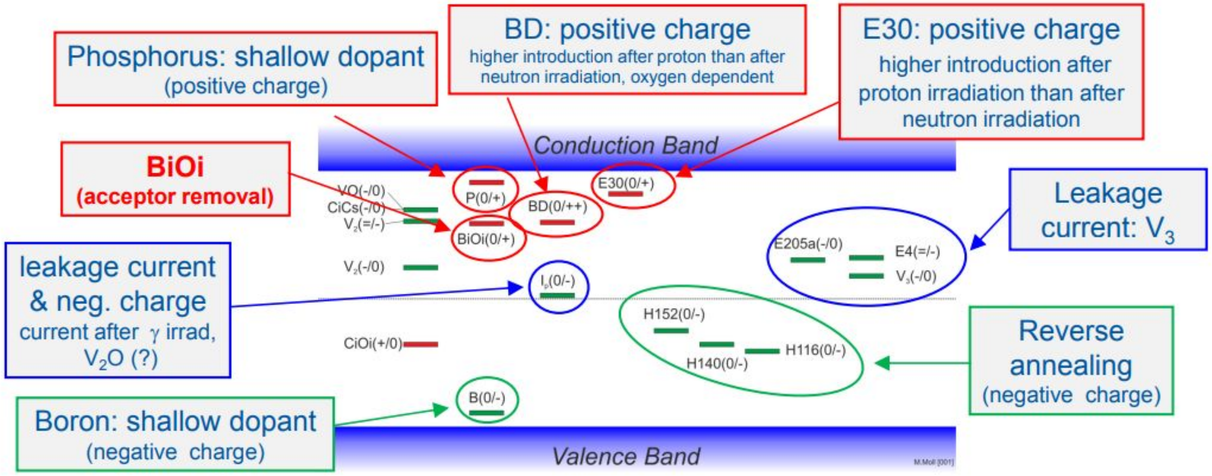




Tackling Fluence

Defect characterization

RD50 map of **most relevant defects** for device performance near room temperature



Radiation damage of p-type diodes is dominated by acceptor removal in the beginning and afterwards by acceptor generation

B^- turning to $B_iO_i^+$

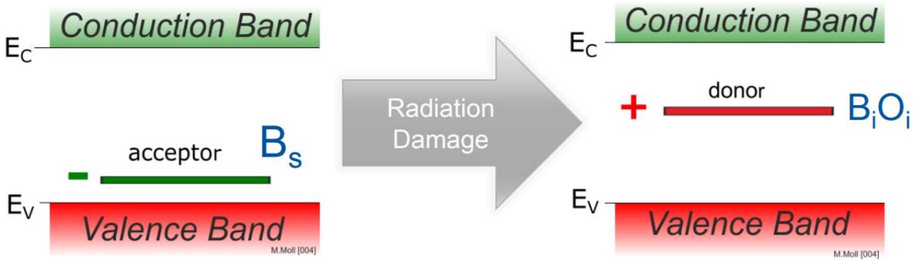
Acceptor removal: Radiation induced de-activation of acceptors (p-type doping, Boron)

Impact:

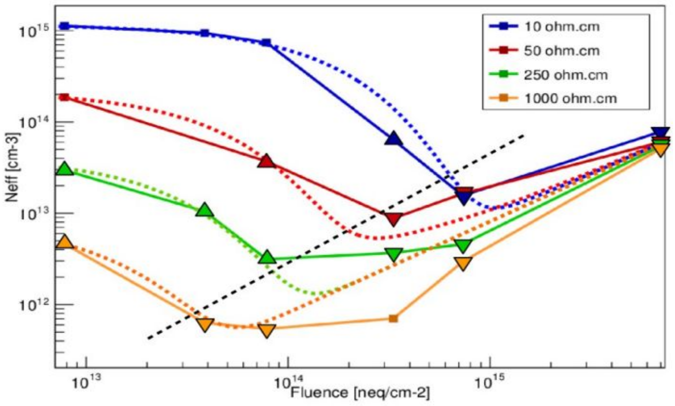
- Change of silicon conductivity
- Change of sensor depletion voltage and/or active volume
- Loss of gain in LGAD sensors, sets radiation harness limits for timing detectors

Tackling Fluence

Defect characterization



Microscopic origin: Formation of defects containing Boron that no longer acts as shallow dopant



"Study of BiOi defects"

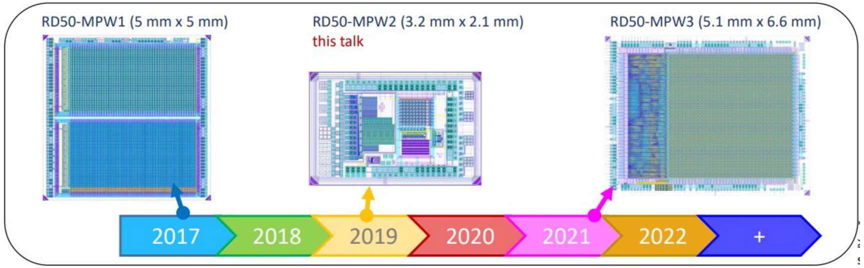
by C. Liao, Institut für Experimentalphysik, Universität Hamburg

Current status @RD50:

- Converging on consistent set of defects observed after *p, n,* π, γ, *e* irradiation
- **Parameterization of acceptor removal** established within RD50 covering six orders of magnitude in resistivity (10 kΩcm to 5 mΩcm)
- Defect introduction rates are depending on particle type and energy, and some on material!
- **Damage predictions are possible**
- Extensive amount of data allowing to apply this knowledge to multiple areas of expertise @ RD50 (HV-CMOS, LGAD, etc.)

Tackling Fluence

HV-CMOS programme



CERN-RD50 CMOS Working Group

(>40 people, 14 institutes)

Programme to study and develop monolithic CMOS sensors with:

- High granularity
- High **radiation tolerance**
- Lower material budget and cost
- Built on LFoundry 150 nm HV-CMOS tech

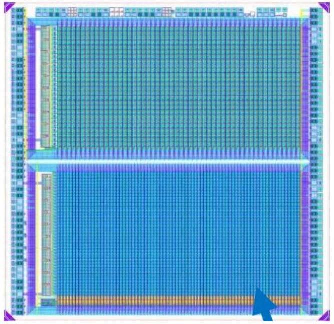
Programme includes:

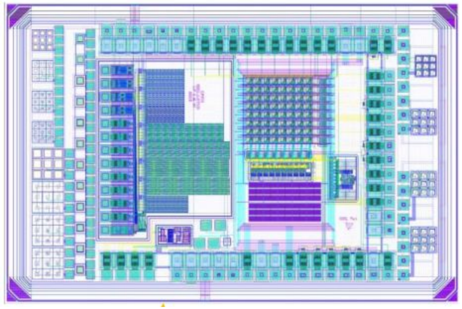
- ASIC design
- TCAD simulations
- DAQ development
- Performance evaluation

RD50-MPW1 (April 2018)

Matrix of HV-CMOS pixels

- 50 µm x 50 µm pixel size
- Analogue & digital readout in sensing area of the pixel
- Continuous readout (FE-I3)
- 40 rows x 78 columns





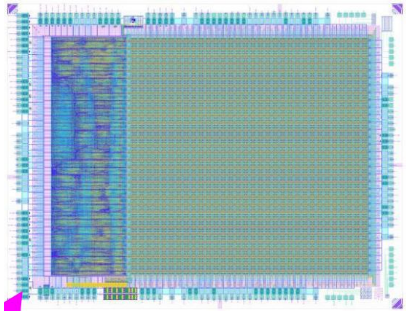
RD50-MPW2 (January 2020)

Matrix of HV-CMOS pixels

- 60 µm x 60 µm pixel size
- Improved analogue readout in sensing area of the pixel
- Fast response rate
- 8 rows x 8 columns
- Improved I^{LEAK} and V_{BD}

RD50-MPW3 (December 2021)

…expected in 2022



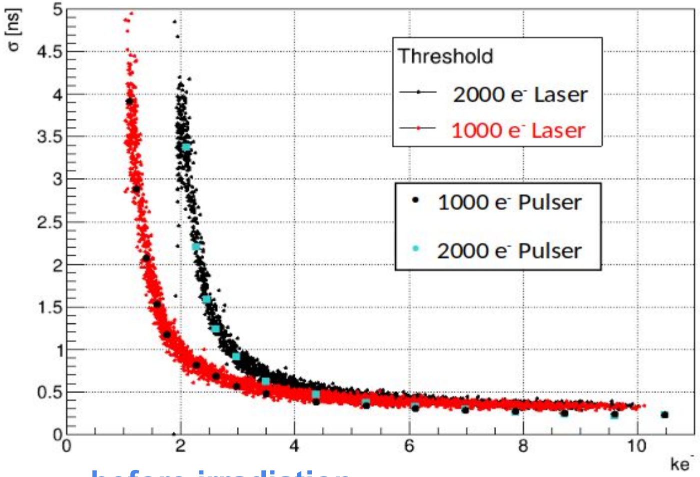
For more information, see the talk:

Timing properties of the RD50-MPW2 CMOS detector, *Bojan Hiti,* Jozef Stefan Institute (SI)

Tackling Fluence

HV-CMOS programme

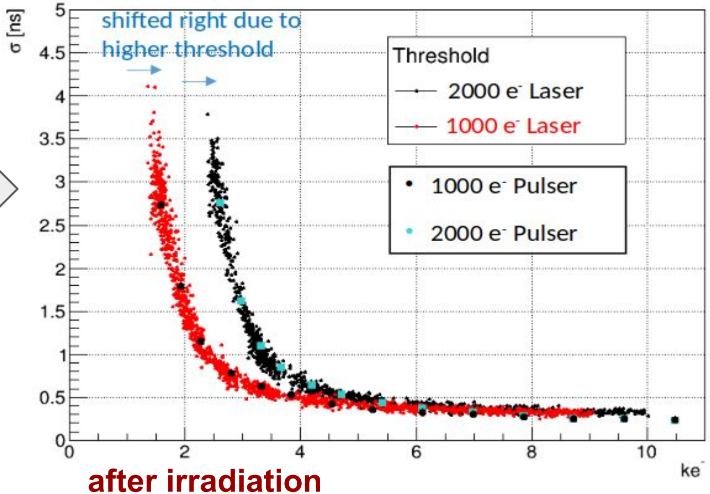
[J. Debevc, JSI]



before irradiation

5e14 neutrons
0.5 Mrad

JSI TRIGA



after irradiation

Timing results of RD50-MPW2

- Tested with IR laser (1064 nm) TCT setup and pulser
- Measurement repeated with $5*10^{14}$ neutron / 0.5 Mrad irradiated sample
- Higher pixel threshold in irradiated sample (samples not tuned)
- No difference at high signals, **asymptotic time resolution: 160 ps**

For more information, see the talk:

Timing properties of the RD50-MPW2 CMOS detector, *Bojan Hiti,* Jozef Stefan Institute (SI)

Disentangling pileup

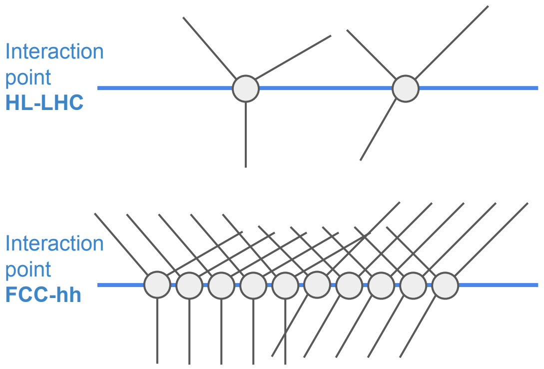
Timing detectors

As pileup increses, so does the necessity for strong timing capabilities

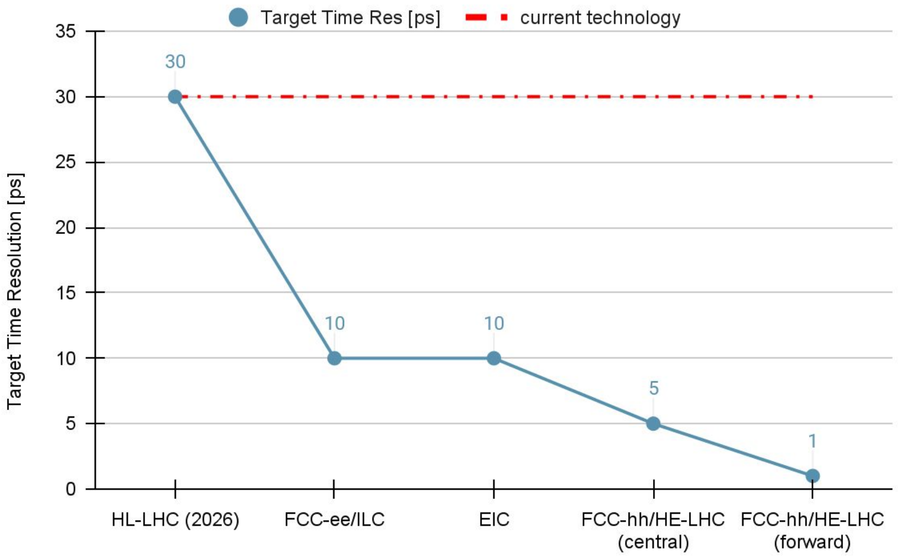
e.g. Average distances between vertices at z=0

- **HL-LHC** (pileup:140) = 1 mm
- **FCC-hh** (pileup:1000) = 125 um

To achieve the same pileup rejection ATLAS and CMS experiments @HL-LHC can obtain with σ_t = 25-30 ps, a FCC-hh detector would need σ_t = 1-5 ps



Required time resolution per detector to achieve HL-LHC-like pileup



Disentangling pileup

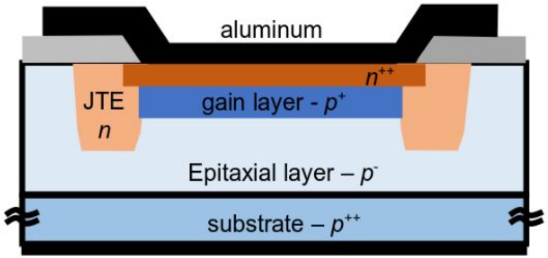
LGAD producers

Origin: Pioneered by RD50 with CNM, Barcelona (and later also FBK, Trento)

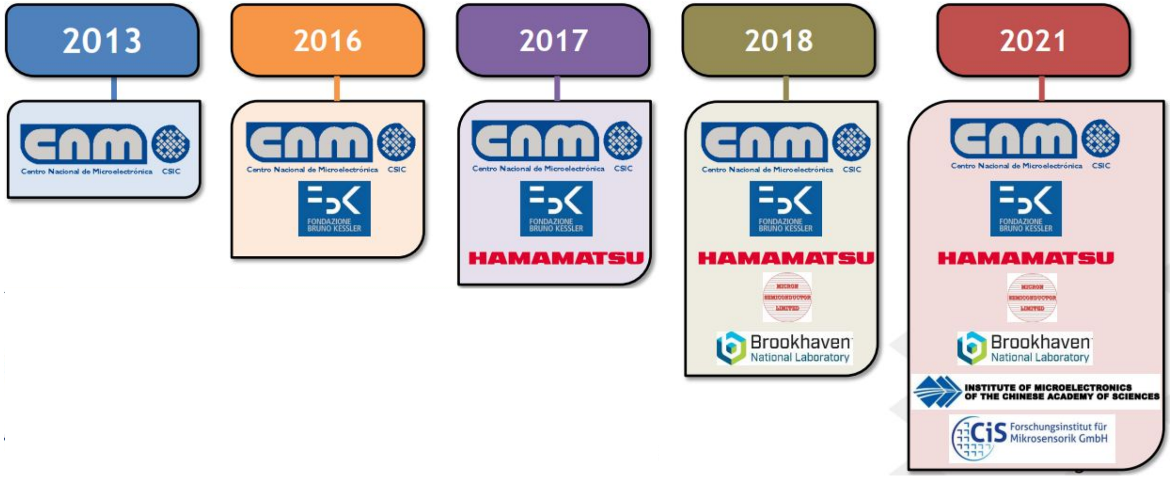
Focused on fast-timing capabilities, embraced by:

- **HEP**: ATLAS (HGTD) and CMS (MTD) timing detectors at the HL-LHC
- **Imaging**, soft X-rays and low-energy electron detection etc.
- Quantum information, Nuclear and forward physics, etc…

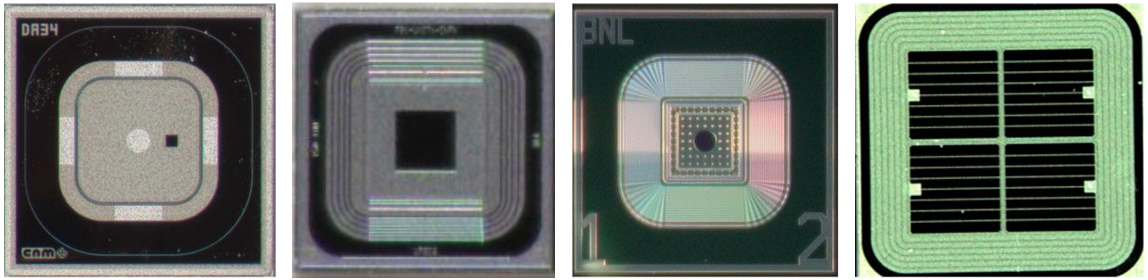
LGAD: highly doped layer of p-implant (Gain layer) near p-n junction creates a high electric field that accelerates electrons enough to start multiplication



Active LGAD producers



…+ more joining!

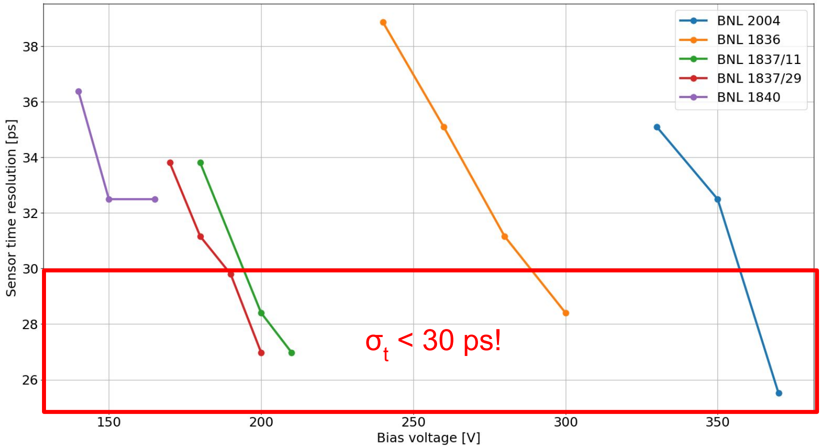


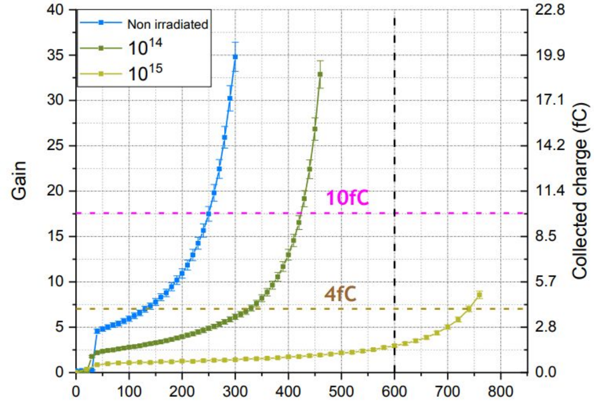
Disentangling pileup

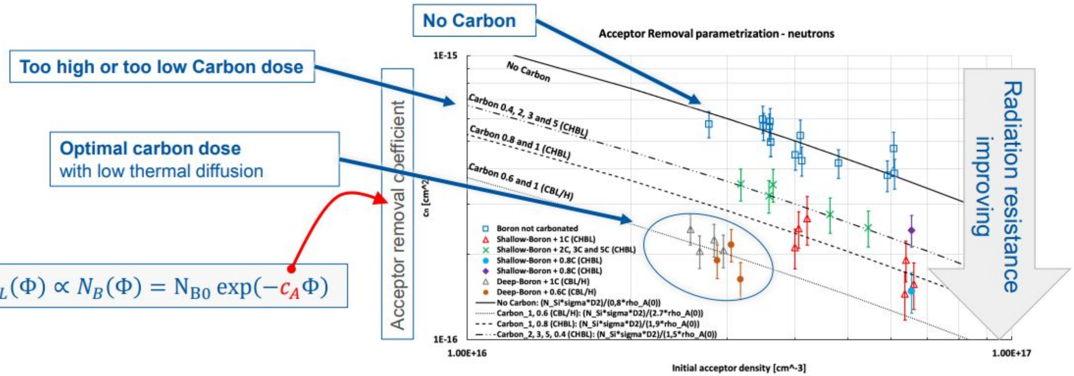
LGAD sensors

LGAD developments @ RD50 (since 2010!)

- **Timing** performance
- **Geometry optimization**: sensor thickness, gain layer profile and signal homogeneity (weighting field)
- **Fill factor** and **signal homogeneity**
- **Mitigation**: New and optimized LGAD concepts investigated
- **Radiation Hardness**
- **Defect Engineering** of gain layer:
  - Ga instead of B or C co-implantation
  - Modification of gain layer profile
- Predictive model for operation performance (radiation, temperature, thickness, annealing, ….)





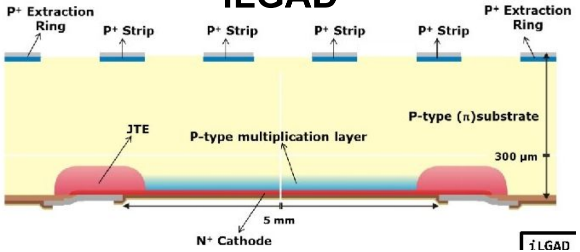


$$V_{GL}(\Phi) \propto N_B(\Phi) = \mathrm{N_{B0}} \exp(-c_A \Phi)$$

Disentangling pileup

Limits of LGAD technology

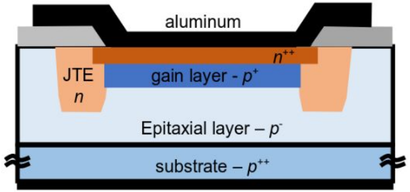
iLGAD



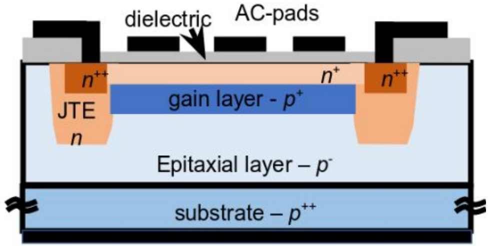
One big issue…

- Dead volume (gain 1) extends outside the JTE and inside the implanted gain layer
- Sensors with small pixels/strips have Fill Factor «100%
- Large pads (~1 mm) are preferred
- Difficult to achieve high-granularity 4D detectors…

LGAD



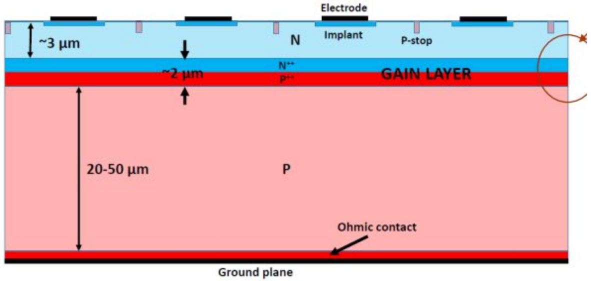
AC-LGAD



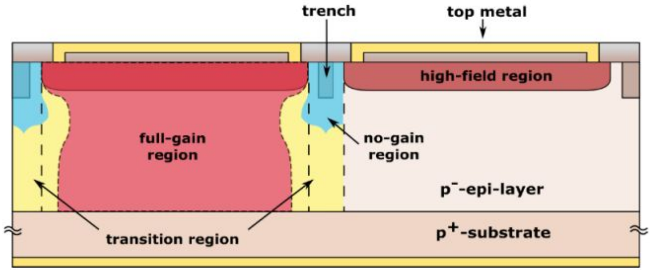
…with multiple solutions!

- **iLGAD** (Inverted LGAD)
- **AC-LGAD/RSD**
- **DJ-LGAD** (Deep-Junction)
- **TI-LGAD** (Trench-Isolated)

DJ-LGAD

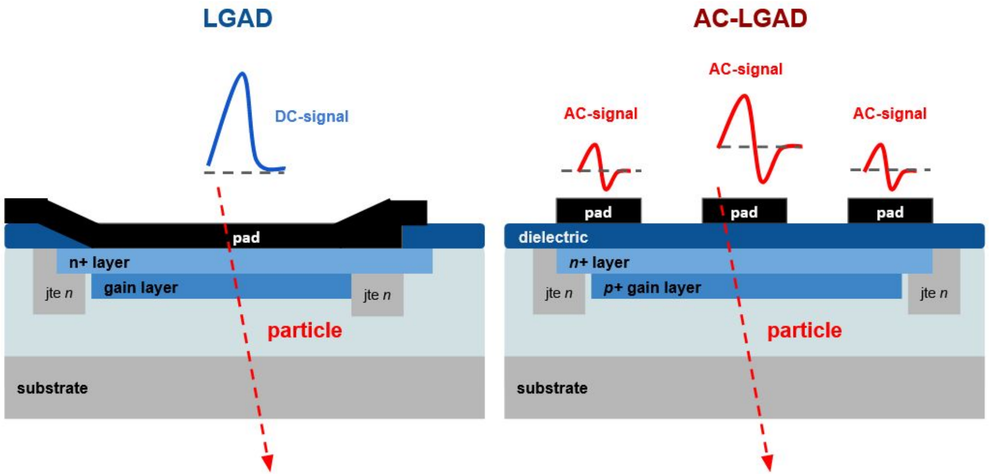


TI-LGAD



Improving resolution

AC-LGAD/RSD



AC-LGAD/RSD: Combining internal **gain** with internal **signal sharing**

- Keep 100% fill factor
- Particle position reconstructed from relative signal shared on multiple pads
- **σ_x < pitch/sqrt(12)** possible! (with ToT/analog info)
- **LGAD-level time resolution** already proven
- Example: **RSD project:** aim for resolution in position < 5mm and in time ~20-30 ps

Producers of LGADs

Producer	LGAD	Resistive readout (RSD)
IMB-CNM (Spain)*+	✓	✓
FBK (Italy)*+	✓	✓
Micron Semiconductors Ltd (UK) °	✓	
HPK (Japan)°	✓	✓
BNL (US)*+	✓	✓
NDL (China)*+	✓	
IME (China)*+	✓	

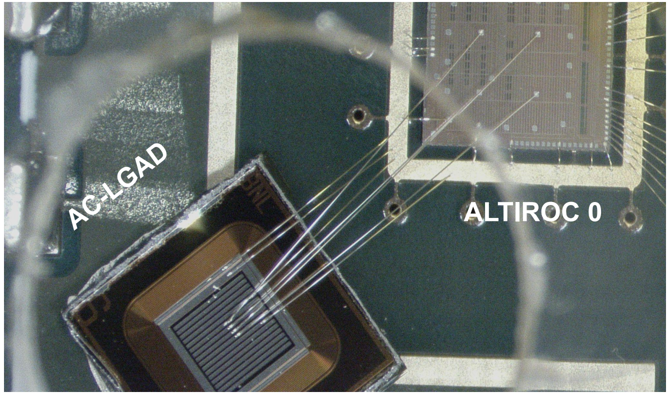
* RD50 member

+ RTO (Research and Technical Organisation)

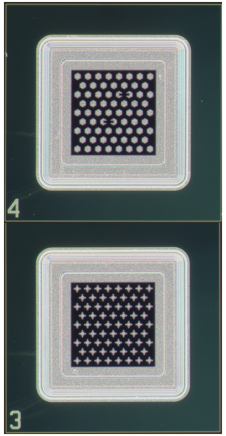
O Commercial manufacturer

Improving resolution

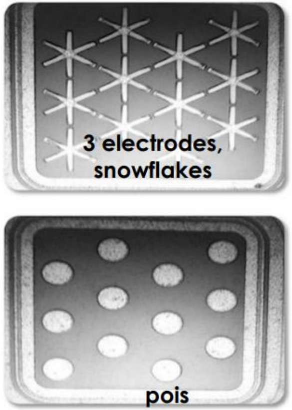
AC-LGAD/RSD



BNL 2020

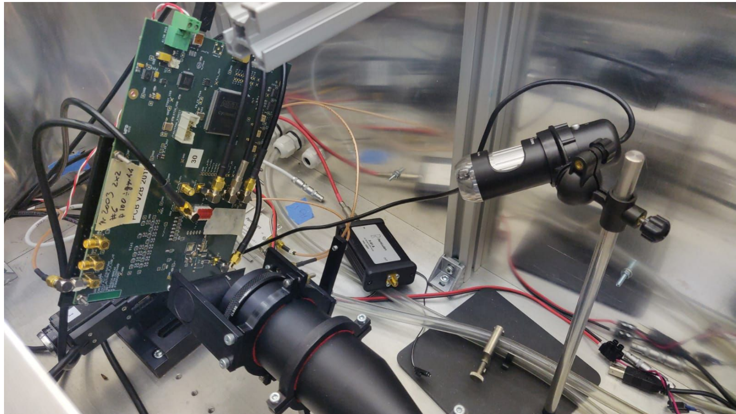


FBK RSD2



AC-LGAD/RSD status

- Variety of designs tested in multiple lab to target custom use-cases
- Tests undergoing to tests performances of **AC-LGADs coupled to readout ASIC** systems
- Information from analog readout used in conjunction to **Machine Learning** to improve spatial resolution
- Response characterization obtained with 120 GeV protons (@FNAL), betas, and IR laser (TCT)



Improving resolution

TPA-TCT

Pulsed laser induced generation of charge carriers inside detector

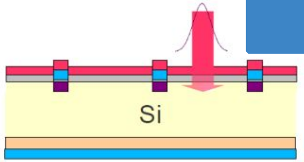
- Study of: electric field in sensor, charge collection efficiency, homogeneity,..
- Benchmark simulation tools, measure physics parameters from mobility to impact ionization

timeline

- 1996 - TCT "invented"
- 2010 - edge-TCT developed within RD50
- 2013 - TCT commercialized
- 2015 - TPA-TCT - proof-of-concept presented by RD50
- 2020 - Table-top TPA-TCT laser commercialized

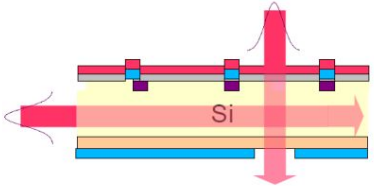
TCT (red laser)

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



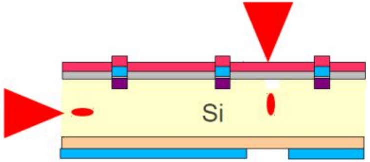
TCT (infrared laser)

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



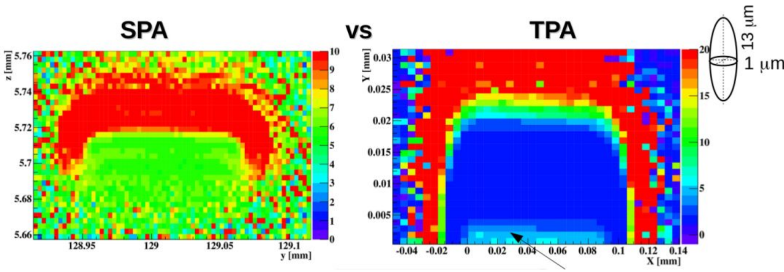
TPA-TCT (far infrared)new!!!

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



e.g. deep n-well in HVCMOS Not resolved in SPA-TCT

Imaged by edge-TCT (left) and TPA-TCT (right|)



Recap & Conclusions

- Many results of the RD50 collaboration presented, but were just a small part of the corpus of RD50 recent achievements
- Developed network of expertise and experience in the various fields of radiation damage and sensor R&D
- **RD50 mission focused on challenges for HL-LHC** in terms of timing, radiation hardness, and much more; Main goals achieved by the collaboration!
- Strong share in the development of p-type sensors, 3D sensors, LGAD sensors, all essential for HL-LHC
- **Important contributions to solid-state physics** landscape of radiation induced defects in silicon materials
- Development of **unique characterization methods** for sensor (TPA-TCT, …) and material analyses
- Next challenge will be an **order of magnitude** (at least) harder: **FCC-hh**
  - Very extreme radiation conditions in the far future (10^17 neq/cm^2) that will require a deeper understanding of material damage, defect characterization, etc.
  - Push for even stronger timing/4D capabilities by means of smarter use of sensor and geometry information

BACKUP