LHCC – 30.May 2018, CERN

RD50 Status Report – May 2018

Radiation hard semiconductor devices for very high luminosity colliders

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University of Liverpool, UK
& FBK-CMM, Trento, Italy

Michael Moll

CERN, Geneva, Switzerland

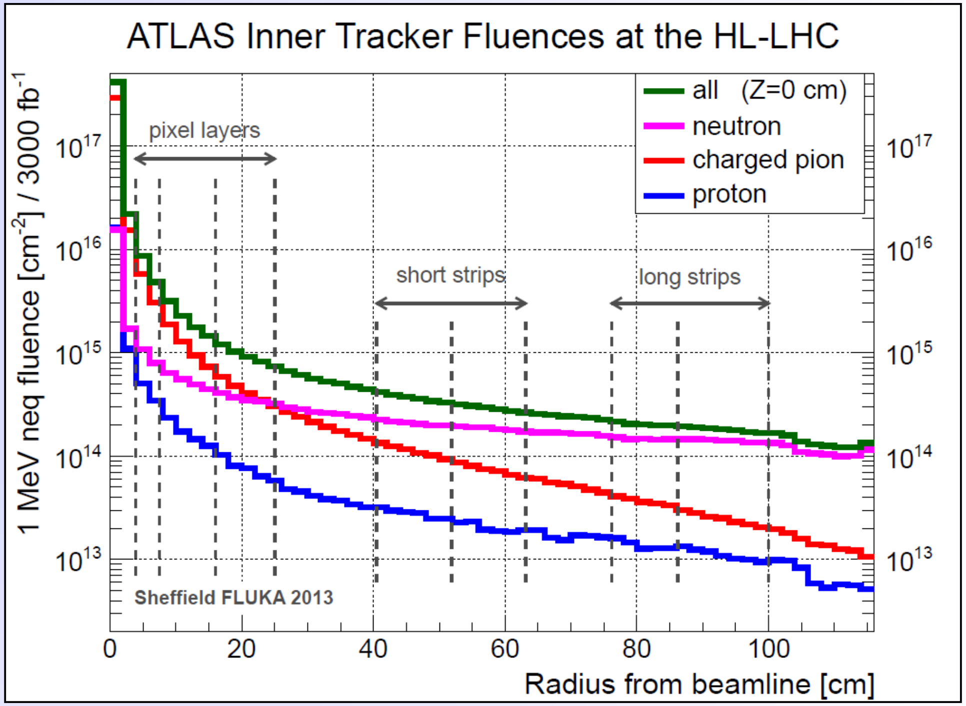
OUTLINE:

- **RD50 Collaboration**
- **Scientific results 2017/18** (some highlights)
  - **Defect and Material Characterization**
  - **Detector Characterization**
  - **New Detector Structures**
  - **Full Detector Systems**
- **Request to LHCC**
- Spare slides
  - RD50 work program, RD50 achievements, additional material

Motivation and Challenge

Detector upgrades (and operation)
- Radiation Hardness –

- **HL-LHC (High Luminosity LHC)**
  - *developments for HL-LHC; after LS3 (~2024-26); **expect 4000 fb^{-1}** (x8 nominal LHC)*
  - *operation of HL-LHC (damage modeling, evaluation, mitigation)*
- **LHC operation**
- **HL-LHC operation & upgrades**
  - *ATLAS Pixel replacement, LHCb upgrade, …*
- **FCC – Future Circular Collider**



[I. Dawson, P. S. Miyagawa, Sheffield University, Atlas Upgrade radiation background simulations]

1. Increasing radiation levels

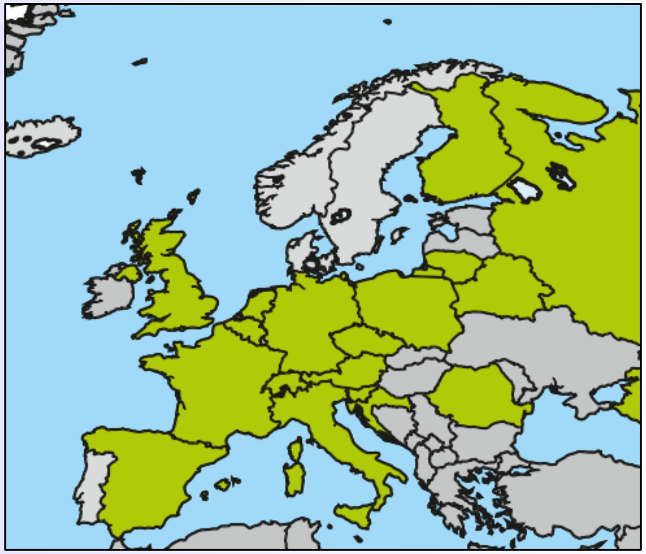
- **Semiconductor detectors will be exposed to hadron fluences equivalent to more than 10^{16} n_{eq}/cm^2 (HL-LHC) and more than 7×10^{17} n_{eq}/cm^2 (FCC)**
  ➔ detectors used now at LHC cannot operate after such irradiation

2. 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

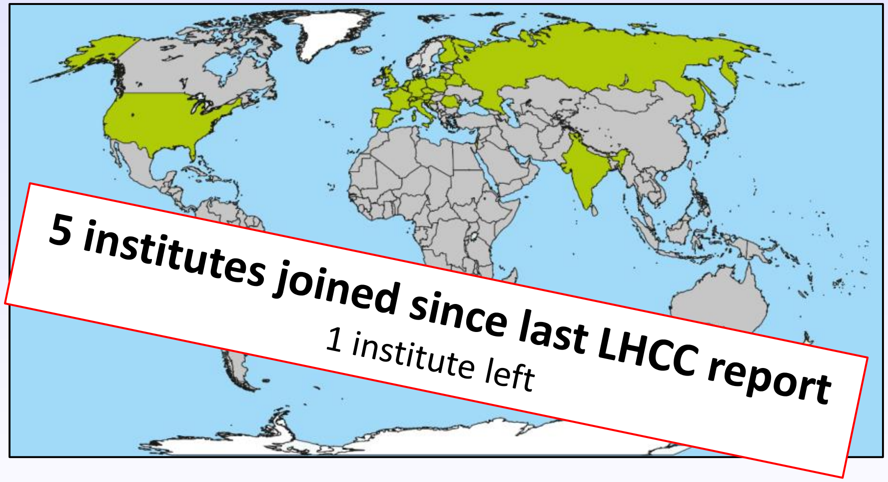
The RD50 Collaboration

- **RD50: 59 *institutes and 345 members***



50 European institutes

Austria (HEPHY), Belarus (Minsk), Belgium (Louvain), Czech Republic (Prague (3x)), Finland (Helsinki, Lappeenranta), France (Paris, Orsay), Germany (Dortmund, Erfurt, Freiburg, Hamburg (2x), Karlsruhe, Munich(2x)), Italy (Bari, Perugia, Pisa, Trento, Torino), Kroatia (Zagreb), Lithuania (Vilnius), Netherlands (NIKHEF), Poland (Krakow, Warsaw(2x)), Romania (Bucharest (2x)), Russia (Moscow, St.Petersburg), Slovenia (Ljubljana), Spain (Barcelona(3x), Santander, Sevilla (2x), Valencia), Switzerland (CERN, PSI, Zurich), United Kingdom (Birmingham, Glasgow, Lancaster, Liverpool, Oxford, RAL)



5 institutes joined since last LHCC report

1 institute left

7 North-American institutes

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

1 Middle East institute

Israel (Tel Aviv)

1 Asian institute

India (Delhi)

Detailed member list: http://cern.ch/rd50

RD50 Organizational Structure

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

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)

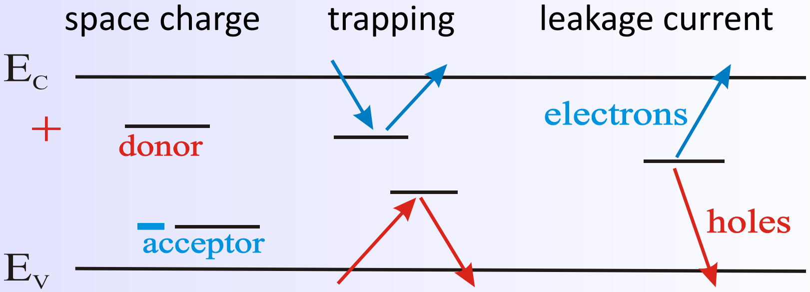
Collaboration Board Chair & Deputy: G.Kramberger (Ljubljana) & J.Vaitkus (Vilnius), Conference committee: U.Parzefall (Freiburg)
CERN contact: M.Moll (EP-DT), Secretary: V.Wedlake (EP-DT), Budget holder & GLIMOS: M.Moll & M.Glaser (EP-DT)

Defect & Material Characterization

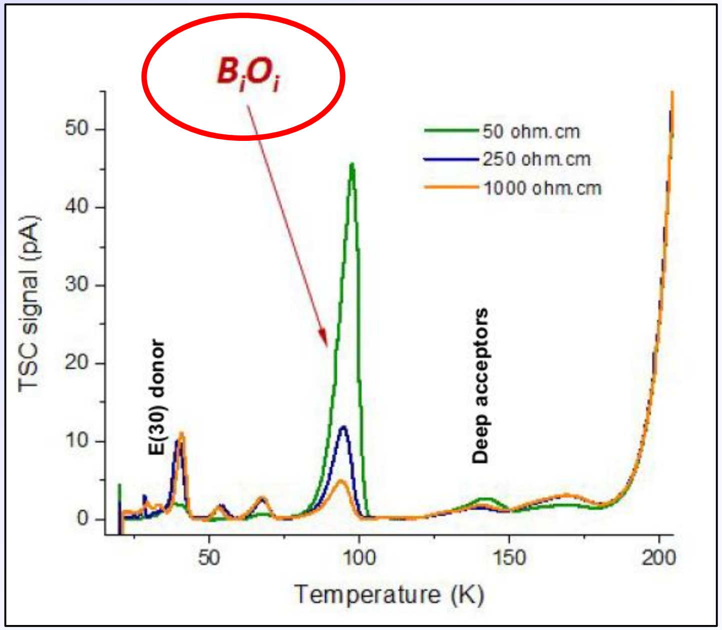
Some highlights (2017/18)

Defect Characterization

- **Aim of defect studies:**
  - **Identify defects responsible for Trapping, Leakage Current, Change of N_{eff}, Change of E-Field**
  - **Understand if this knowledge can be used to mitigate radiation damage (e.g. defect engineering)**
  - **Deliver input for device simulations to predict detector performance under various conditions**



- **Method:** Defect Analysis performed with various tools inside RD50:
  - **C-DLTS** (Capacitance Deep Level Transient Spectroscopy)
  - **TSC** (Thermally Stimulated Currents)
  - **PITS** (Photo Induced Transient Spectroscopy)
  - **FTIR** (Fourier Transform Infrared Spectroscopy)
  - **EPR** (Electron Paramagnetic Resonance)
  - **TCT** (Transient Current Technique)
  - **CV/IV** (Capacitance/Current-Voltage Measurement)
  - **MW-PC** (Microwave Probed Photo Conductivity)
  - *PC, RL, I-DLTS, TEM,… and simulation*
  - **RD50: several hundred samples irradiated with protons, neutrons, electrons and ^{60}Co-γ**



[Pedro Almeida, CERN, Trento Meeting, 2018]

Example: TSC measurement on defects produced by 23 GeV protons in p-type silicon of different resistivity

Summary on defects with strong impact on device performance after irradiation

- **Some identified defects**

Phosphorus: shallow dopant
(positive charge)

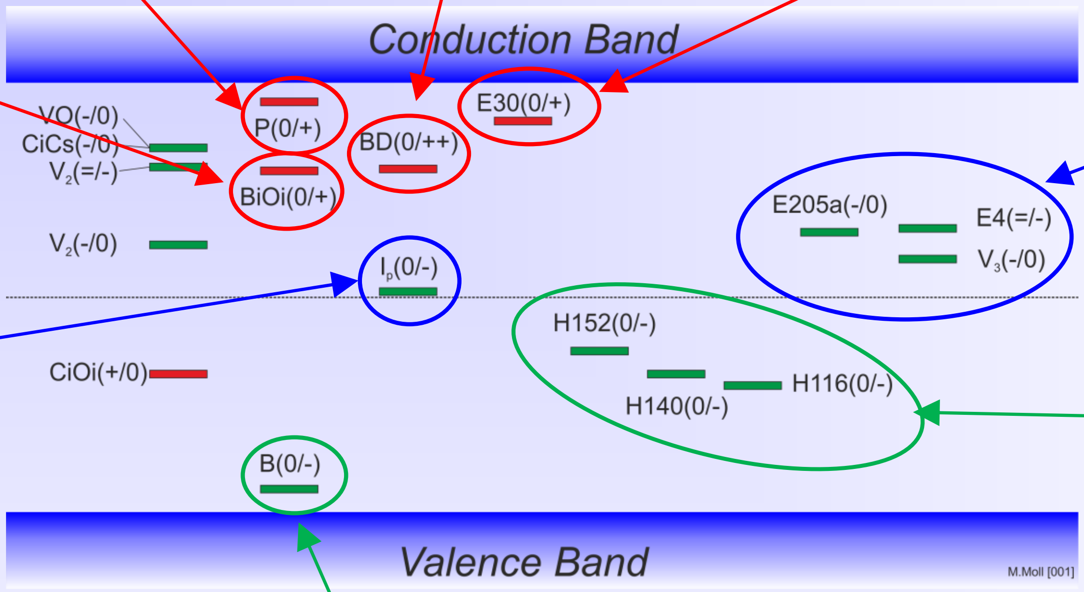
positive charge
(higher introduction after proton than after neutron irradiation, oxygen dependent)

positive charge
(higher introduction after proton irradiation than after neutron irradiation)

BiOi
(positive charge)

Leakage current: V_3

leakage current & neg. charge
current after γ irrad, V_2O (?)



Reverse annealing
(negative charge)

Boron: shallow dopant
(negative charge)

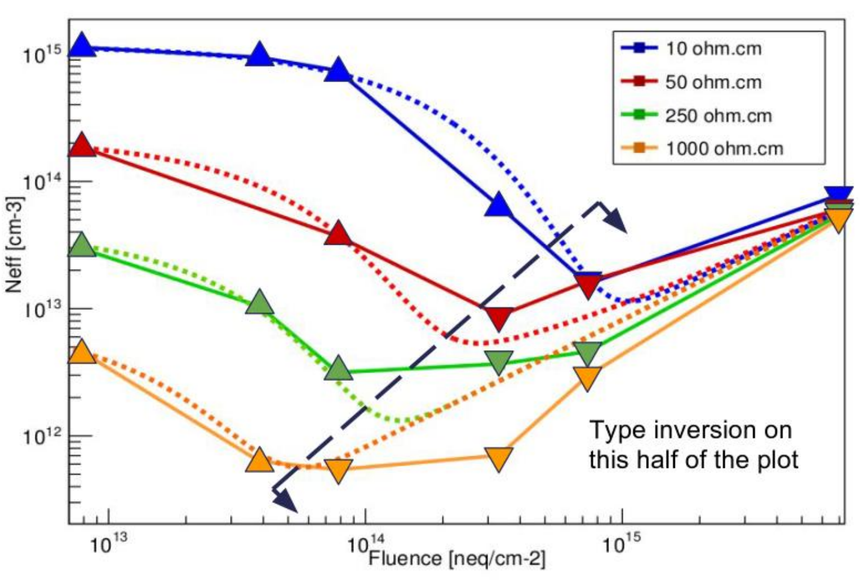
A table with levels and cross sections is given in the spare slides.

- **Trapping: Indications that E205a and H152K are important** (further work needed)
- Converging on consistent set of defects observed after p, π, n, γ and e irradiation.
- Defect introduction rates are depending on particle type and particle energy and (for some) on material!

Acceptor removal - Boron related defects?

"Acceptor removal" macroscopic

- Change of V_{dep} in p-type silicon EPI diodes



[Pedro Almeida, CERN, Trento Meeting, 2018]

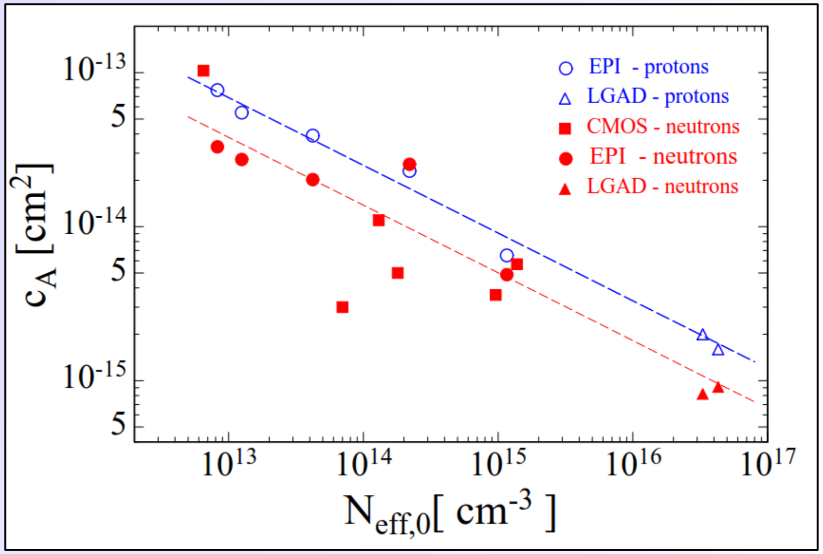
- Change in effective doping ΔN_{eff} is composed of Boron removal and radiation induced defects!

$$\Delta N_{eff} = |N_{Boron}| \times \exp(-c_A \cdot \phi_{eq}) + \ \ldots$$

- **"acceptor removal" responsible for:**
  - Gain degradation in sensors with intrinsic gain
  - Good performance of low resistivity CMOS sensors after high irradiation.

Acceptor removal rate parameter c_A

- p-type sensors of different resistivity (different $N_{eff,0}$) show different rate in acceptor removal (?)



[M.Moll, 2018, https://doi.org/10.1109/TNS.2018.2819506]

"Acceptor removal" microscopic: Origin of effect?

- Boron removal kinetics and/or compensation effects !?
- Need more work on this!

$$I + B_s \rightarrow B_i$$

$$B_i + O_i \rightarrow B_iO_i$$

- **Why not studied more intensively before?**
  - Focus was on high resistivity n-type Silicon and not on low resistivity p-type Silicon!

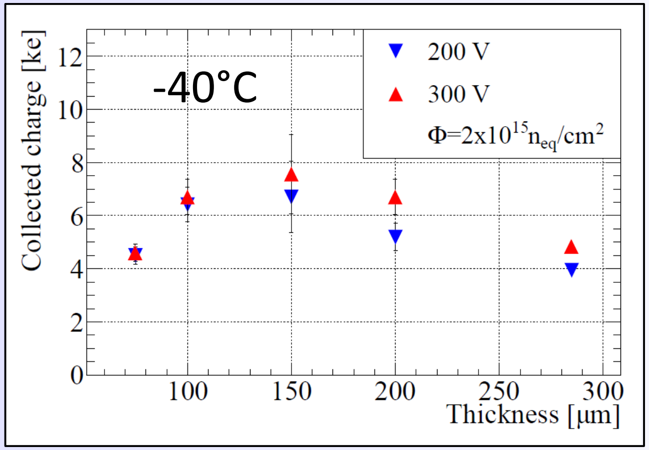
Device Characterization
and
Device Simulations

- selected topics -

Planar Pixel Sensors (p-type, thin)

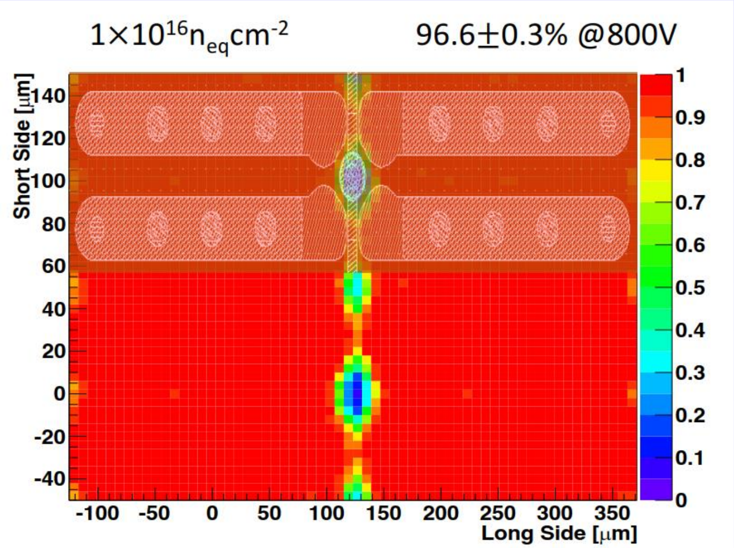
- **Thin planar p-type sensors are baseline for pixel upgrades**
  - **Higher field for same voltage, reduced drift length, less trapping**

- **Thickness was optimized for radiation hardness** (and radiation length)



[76] S. Terzo, L. Andricek, A. Macchiolo, H. G. Moser, R. Nisius, R. H. Richter, and P. Weigell, "Heavily irradiated n-in-p thin planar pixel sensors with and without active edges," *Journal of Instrumentation*, vol. 9, no. 05, p. C05023, 2014.

- **Work on optimization of biasing structures ongoing (test beams & TCAD):**



4x2 pixel efficiency map

Example:

- 100 µm thick sensor
- **97% detection efficiency after $\Phi_{eq} = 10^{16}$ cm^{-2}**
- Both sensor and readout electronics were irradiated
- Biasing structures can play an important role in the efficiency after irradiation
- Loss of efficiency after 13m room temperature annealing observed (to 93%), under investigation

[J.Beyer, RD50 Workshop, Nov.2017]

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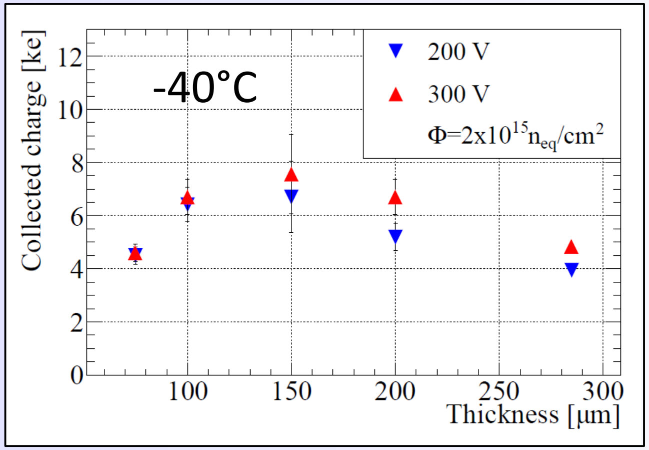

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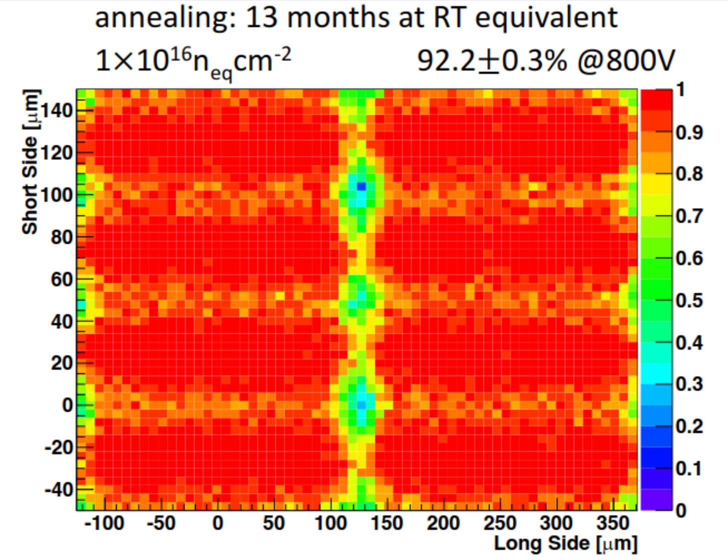


4x2 pixel efficiency map

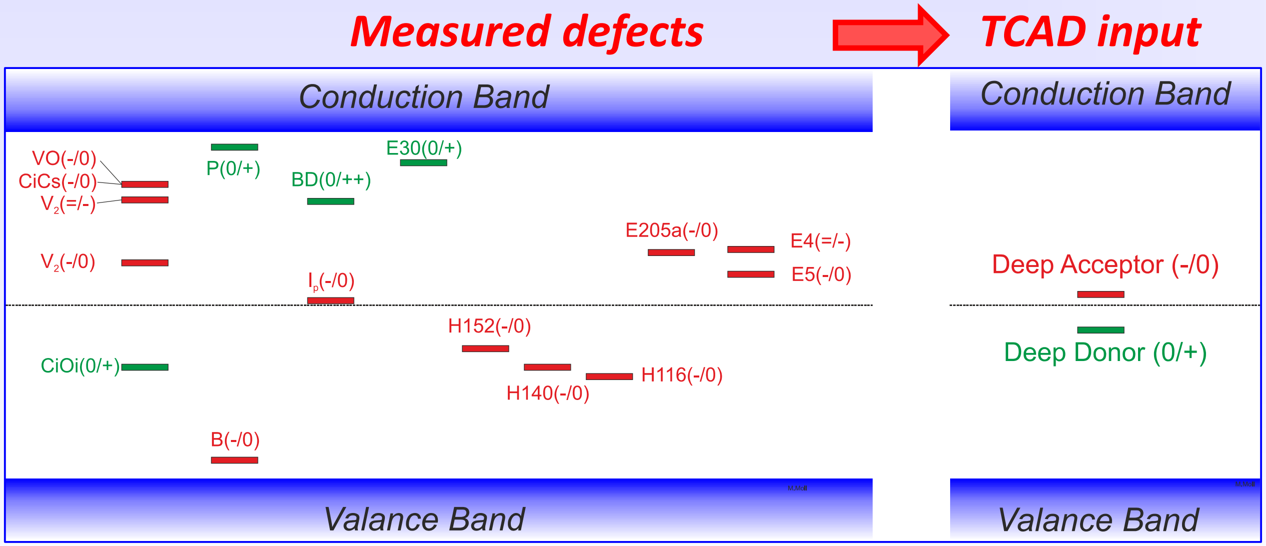
Example:

- 100 μm thick sensor
- **97% detection efficiency after $\Phi_{eq} = 10^{16}$ cm^{-2}**
- Both sensor and readout electronics were irradiated
- Biasing structures can play an important role in the efficiency after irradiation
- Loss of efficiency after 13m room temperature annealing observed (to 93%), under investigation

[J.Beyer, RD50 Workshop, Nov.2017]

TCAD - Simulations

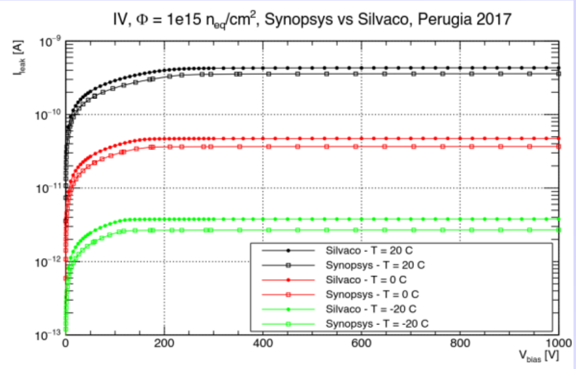
- **Device simulation of irradiated sensors**
  - **Using: Custom made simulation software and Silvaco & Synopsis TCAD tools**
  - **RD50 simulation working group**
    - Progress in reproducing experimental results on leakage current, space charge, E-Field, trapping …..
    - Enormous parameter space ranging from semiconductor physics parameters and models over device parameters towards defect parameters ➔ **Tools ready but need for proper input parameters!**
- **Working with “effective levels” for simulation of irradiated devices**
  - Most often 2, 3 or 4 “effective levels” used to simulate detector behavior
  - Introduction rates and cross sections of defects tuned to match experimental data



A table with TCAD models is given in the spare slides.

TCAD - Simulations

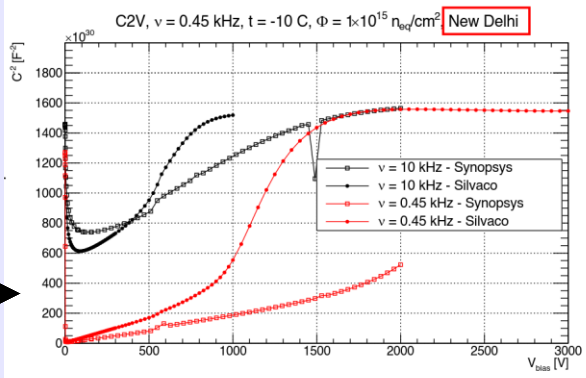
- **Comparison of different simulators performed (Synopsys vs. Silvaco)**
  - Good agreement before “irradiation”, damage model dependent variations “after irradiation”



Irradiated sensors

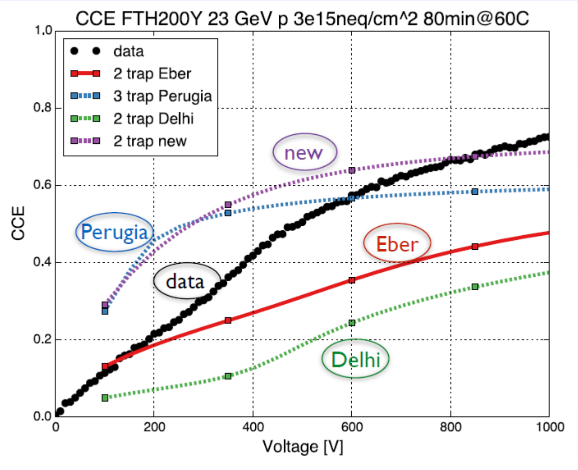
Leakage current
(Perugia 2017 model)

Capacitance-Voltage (V_{dep})
(New Delhi model)

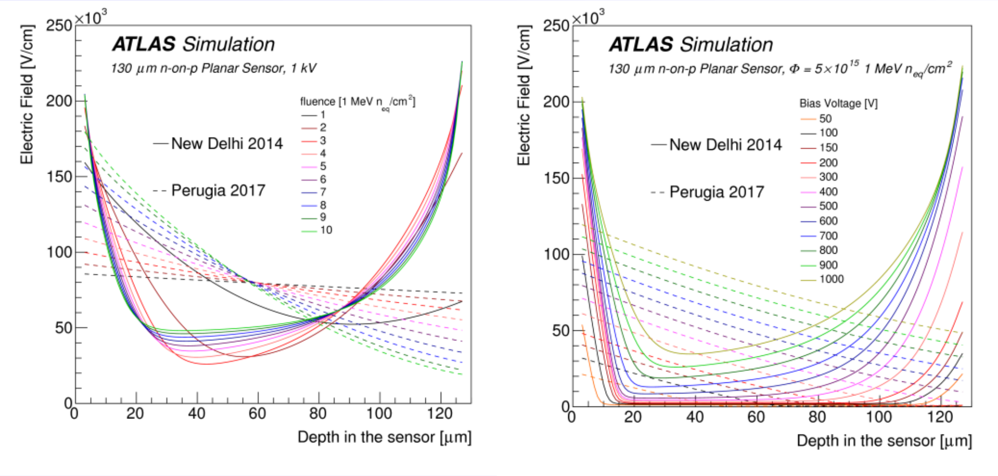


[J.Beyer & M.Bomben, RD50 Workshop, Nov.2017]

- **Comparison of several damage models performed (various models, data)**



[J.Schwandt, RD50 Workshop, 12/2015]



[Technical Design Report for the ATLAS Inner Tracker Pixel Detector; ATLAS-TDR-030]

- **RD50 task: Improve TCAD models**
  - Investigation on increased number of defects for damage model ongoing (more parameters)

needs more work !

New structures

..optimizing for

- Radiation hardness
- Time resolution
- Cost effectiveness

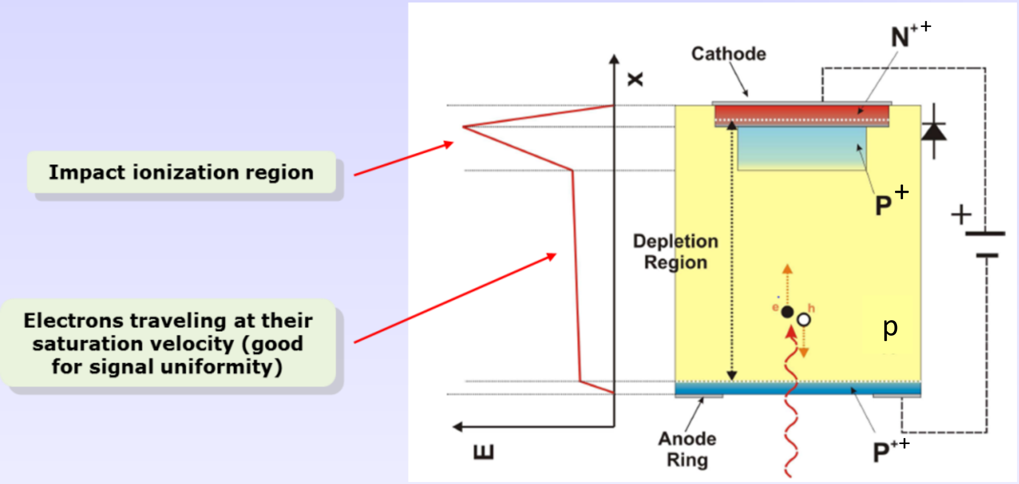
LGAD, APD
(Sensors with intrinsic gain)

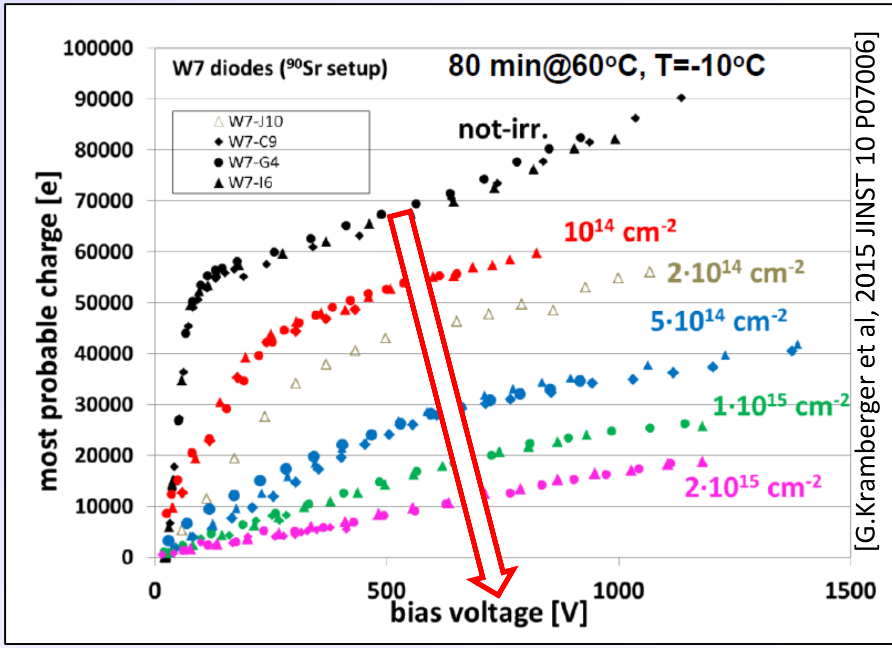
HVCMOS
(towards monolithic sensors)

3D
(sensors with vertical electrodes)

Sensors with intrinsic gain

- **Low Gain Avalanche Detectors (LGAD)**
  - **Concept similar to APD (Avalanche Photo Detector) but lower gain O(10)**
    - Impact ionization in p$^+$-implant (multiplication layer) produces gain
    - Tailored multiplication layer (Boron ~10^{17}cm^{-3})
      optimize: gain vs. breakdown

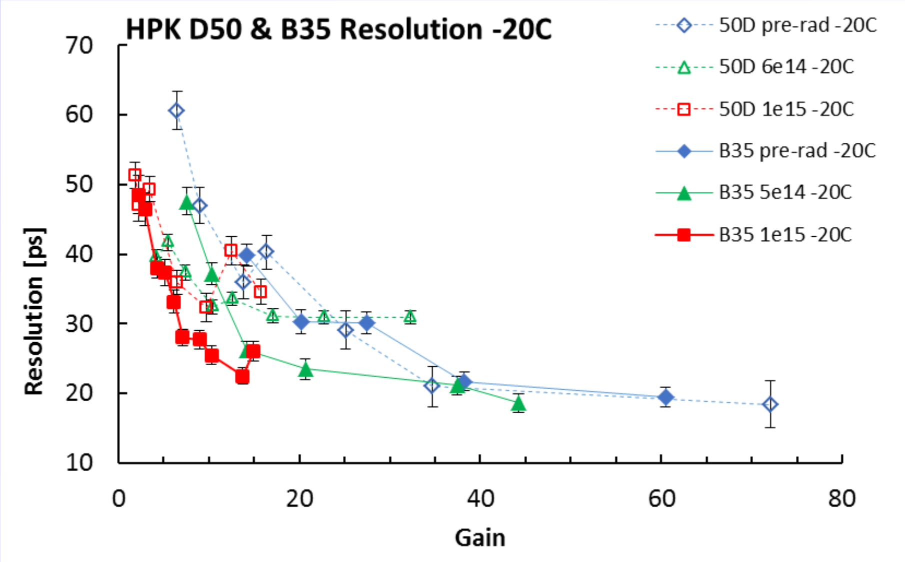




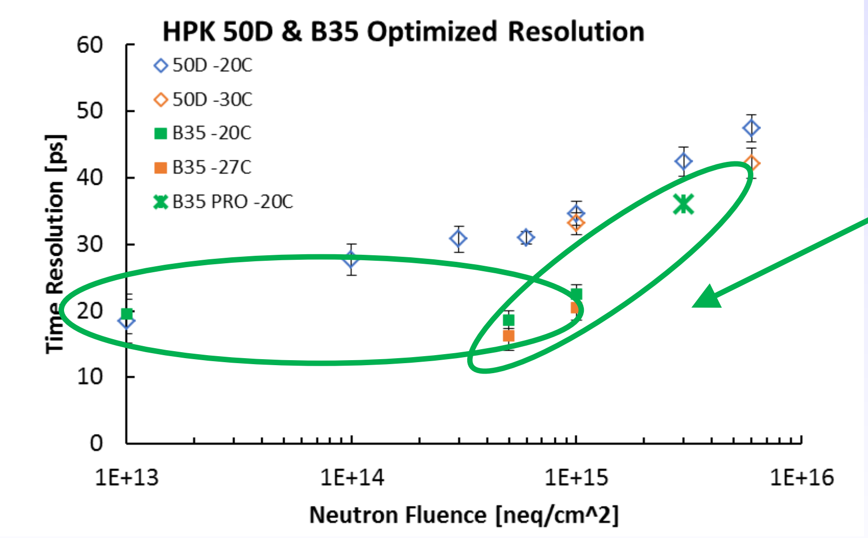
- Radiation Damage: Field in gain layer dropping due to “acceptor removal”
- Defect Engineering mitigation approach being followed
  - Use **Gallium** instead of Boron to impact on defect kinetics
  - Use **Carbon** co-implant to “protect” Boron from removal

LGADs for precision timing

- **LGADs with thickness of 50 or 35 μm**



[H.Sadrozinski,SCIPP, Trento Meeting, 2018]



$$\sigma_t^2 = \sigma_{Jitter}^2 + \sigma_{TimeWalk}^2 + \sigma_{LandauNoise}^2 + \sigma_{Distortion}^2 + \sigma_{TDC}^2$$

- **Typical dimension of active region ≈ 1mm^2**
- **Measurements with charged particles**
- **Readout electronics plays major role in timing applications**

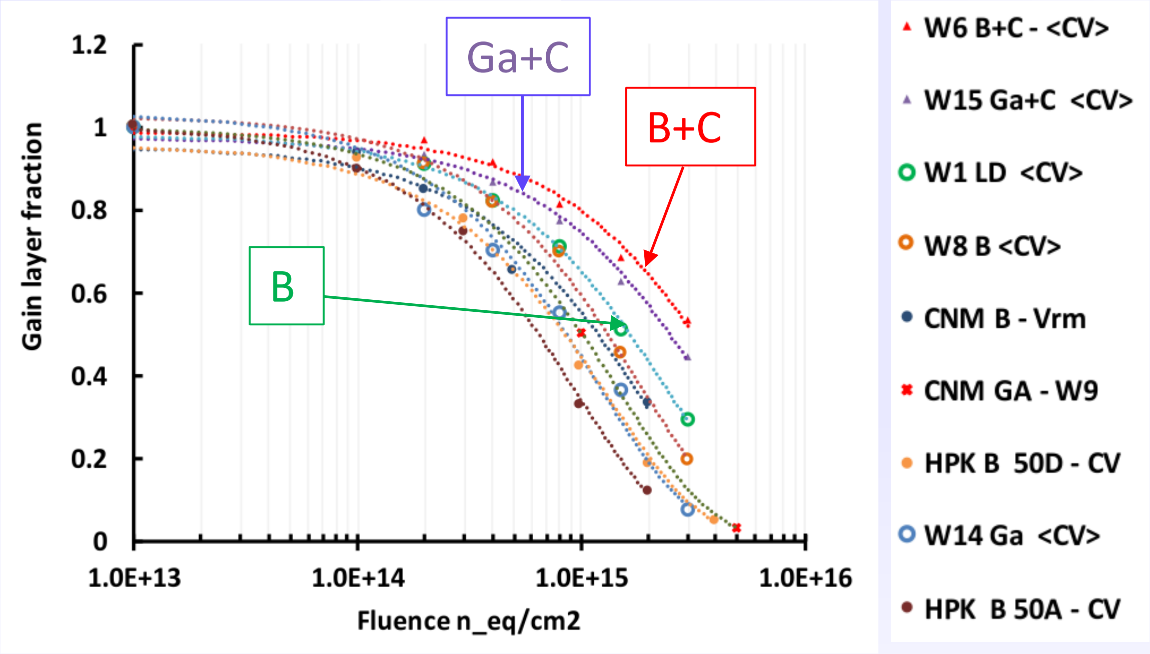
- **35 μm devices (biased up to 500V):**
  - σ_t = 27 ps up to Φ_{eq} =10^{15}cm^{-2}
  - σ_t = 36 ps up to Φ_{eq} =$3{\cdot}10^{15}$cm^{-2}

  - σ_t ≈ 10 ps better than 50μm thick device
  - σ_t ≈ 5 ps better when going from -20 °C to -27 °C

Radiation Hardening of LGADS

- **Problem: Multiplication layer affected by acceptor removal**
  - Go thinner (see previous slide)
  - Modify the multiplication layer (defect engineering)
    - Replace dopant: Use Gallium instead of Boron
    - Protect dopant: Carbon co-implantation to “protect” Boron

[R. Arcidiacono, Tornio, Trento Meeting, 2018]



Increase LGAD Fill Factor

- On going activity in order to increase the LAGD Fill Factor
- Two technological methodology
  - **From Mask Aligner to Stepper**
  - **Introduce new pixel to pixel isolation scheme (trenches, ….)**

outlook

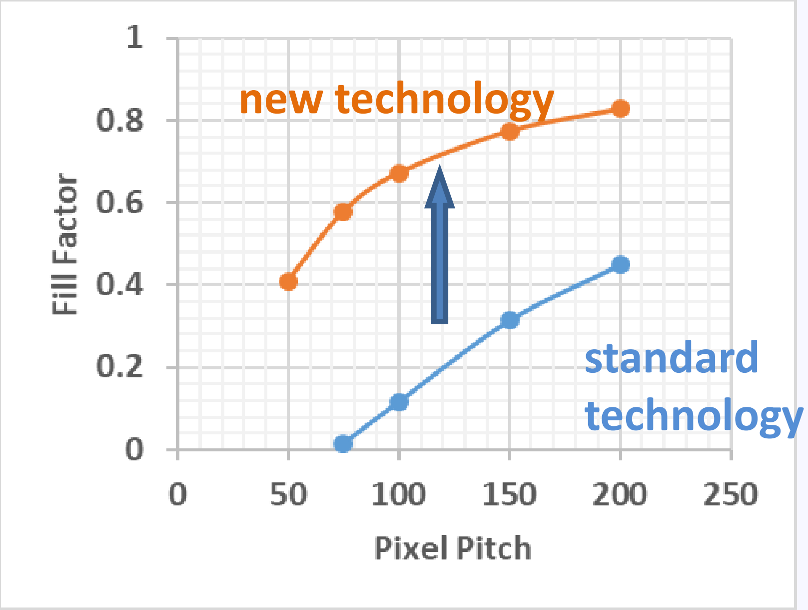
MASK ALIGNER

Resolution=1um.
Critical Size = 2um
Border width = 66um

STEPPER

Resolution = 0.35 um.
Critical Size = 0.5 um

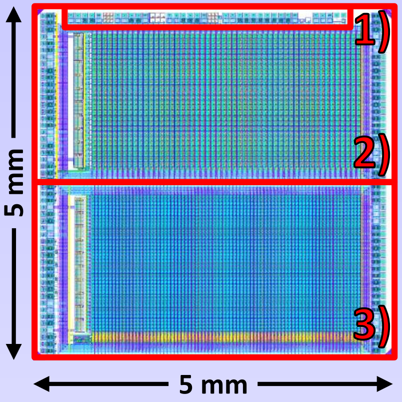
Border width ~ 20 um



Nominal Pixel Fill Factor

- On going: first LGAD batch on stepper technology (results expects in autumn)
- Planned: A second batch to explore new technical solution for pixel isolation

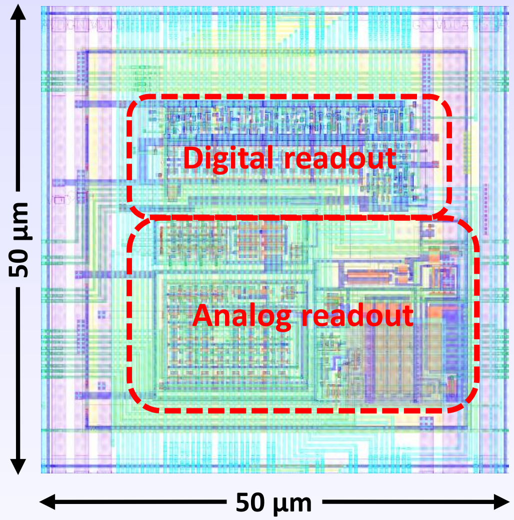
HV-CMOS



RD50-MPW1 → Technical details:

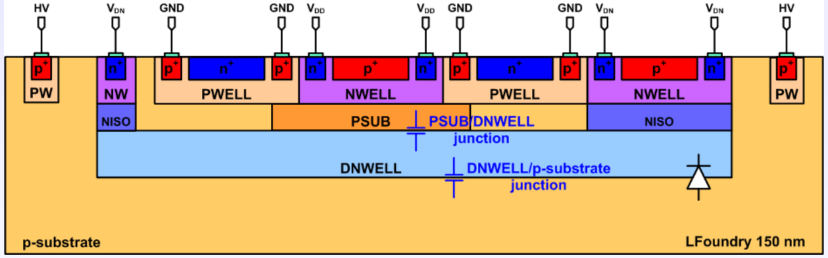
- MPW in 150 nm HV-CMOS from LFoundry
- Manufactured on wafers with different substrate resistivities:
  → 500 Ω·cm (40 samples) and 1.9k Ω·cm (80 samples)
- Fab-in in November 2017, **fab-out in April 2018 (measurements just started)**
- Contents:
  1) Test structures for TCT/e-TCT
  2) Matrix of 26 x 52 HV-MAPS pixels with 16-bits counter
  3) Matrix of 40 x 78 HV-MAPS pixels with FE-I3 style readout
     → pixel area is 50 µm x 50 µm
     → analog and digital readout electronics are embedded inside the pixel area

FE-I3 pixel:



- **Analog readout** → biasing circuit, amplifier, low-pass/high-pass filters and comparator with 4-bit DAC to compensate for offset variations
- **Digital readout** → two 8-bit DRAMs that continuously store leading/trailing edge time stamps (ToT = TE – LE) + one 8-bit ROM to store pixel address (FE-I3 style)

Improved sensor cross-section



- 50 µm x 50 µm
- $C_{PIX} \simeq 200$ fF
- PDK V1.2.0
  (proper verification)

- We expect to test technical design aspects and functionality diodes + electronics, before and after irradiation to high fluences

HV-CMOS

RD50-ENGRUN1 - Aims:

- Improve the current time resolution of HV-CMOS sensors by a factor 10
- Implement new sensor cross-sections
- Study pre-stitching options to increase the device area beyond the reticle size limitation
- Measure the sensors performance after a wide range of fluences

Technology:

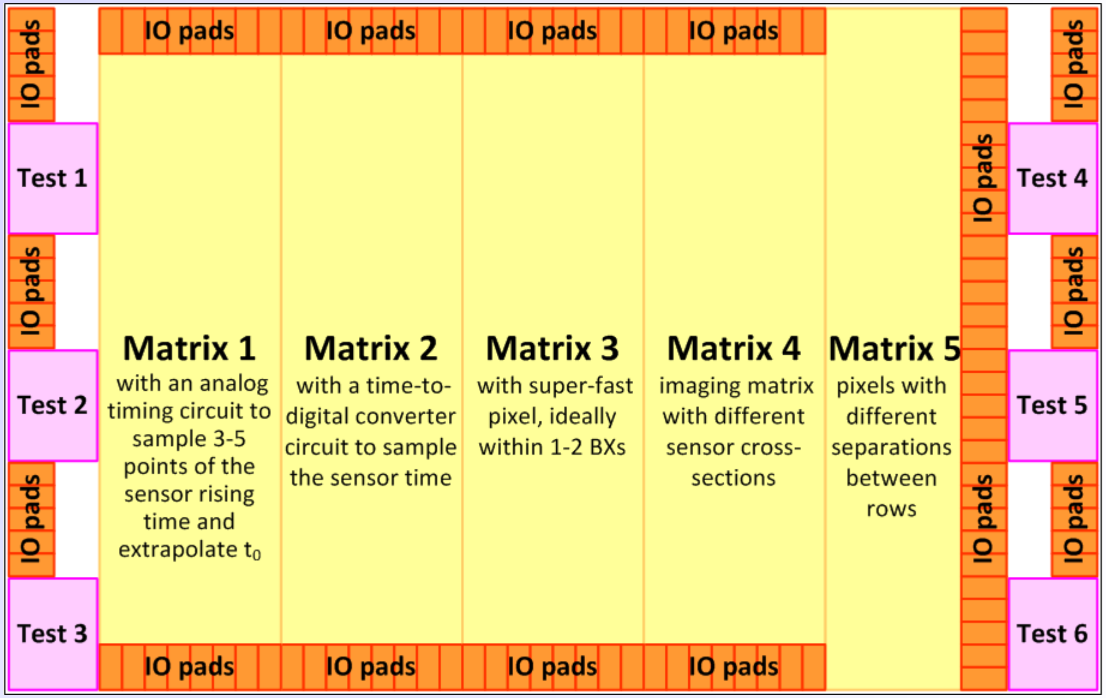
- 150 nm HV-CMOS from LFoundry
- Large area submission (engineering run)

Design effort:

- FBK (N. Massari, M. Perenzoni and C. Zhang)
- IFAE (R. Casanova)
- Uni. Barcelona (O. Alonso, +1)
- Uni. Liverpool (S. Powell, E. Vilella and C. Zhang) + overall coordination
- Uni. Seville (C. Cabrera, F. Muñoz and R. Palomo)

TCAD simulations run in parallel

DAQ development



Matrix 1 with an analog timing circuit to sample 3-5 points of the sensor rising time and extrapolate t_0

Matrix 2 with a time-to-digital converter circuit to sample the sensor time

Matrix 3 with super-fast pixel, ideally within 1-2 BXs

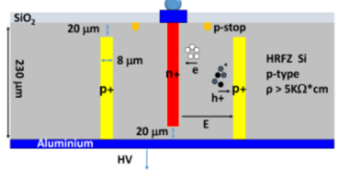
Matrix 4 imaging matrix with different sensor cross-sections

Matrix 5 pixels with different separations between rows

Test structure 1	Simple CMOS capacitors to study oxide thickness
Test structure 2	10 x 10 matrix of very small pixels with passive RO
Test structure 3	10 x 10 matrix of very small pixels with 3T-like RO
Test structure 4	Small matrix of pixels for TCT, e-TCT and TPA-TCT
Test structure 5	Single pixels for sensor capacitance measurements
Test structure 6	…

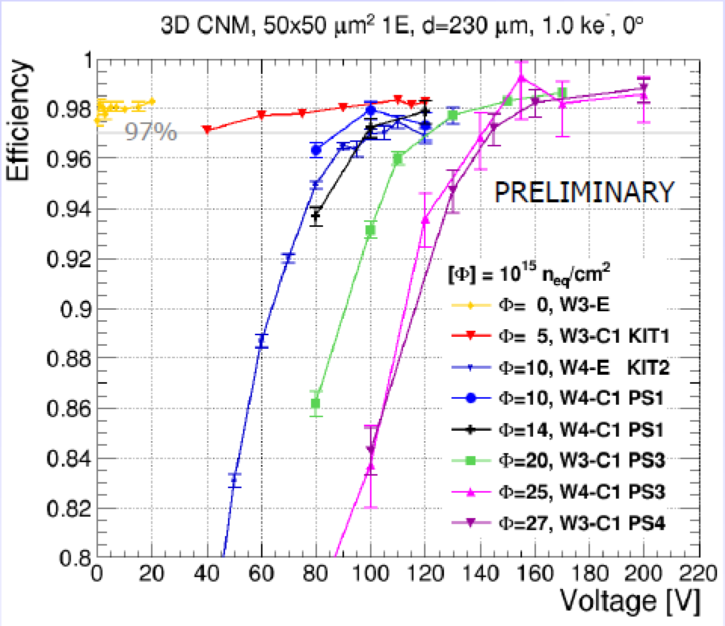
..to be submitted

Radiation–Hard 3D sensor



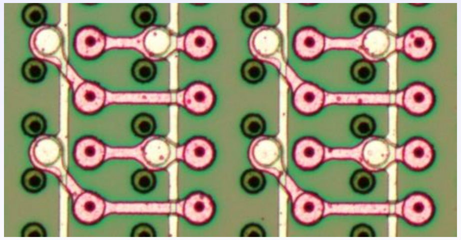
- **Si-3D (50x50µm^2 pixel) after irradiation up to 3×10^{16} n_{eq}/cm^2 show an efficiency > 97%**

Joern Lange et al, "Radiation hardness of 3D pixel sensors up to unprecedented fluences of 3E16 n_{eq}/cm^2", 13th Trento Workshop, Munich 2018

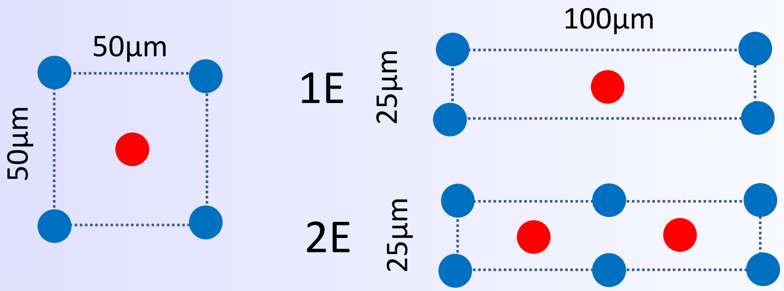


…to be published J.Lange et al. https://arxiv.org/abs/1805.10208

RD53A 25x100 µm^2 (2E) layout is critical for mask aligner lithography !



- **Prototypes of small pitch 3D pixels**
  - **On 150µm active depth silicon wafers**
  - **Pixel size 50x50µm^2 and 25x100µm^2 (1E and 2E)**



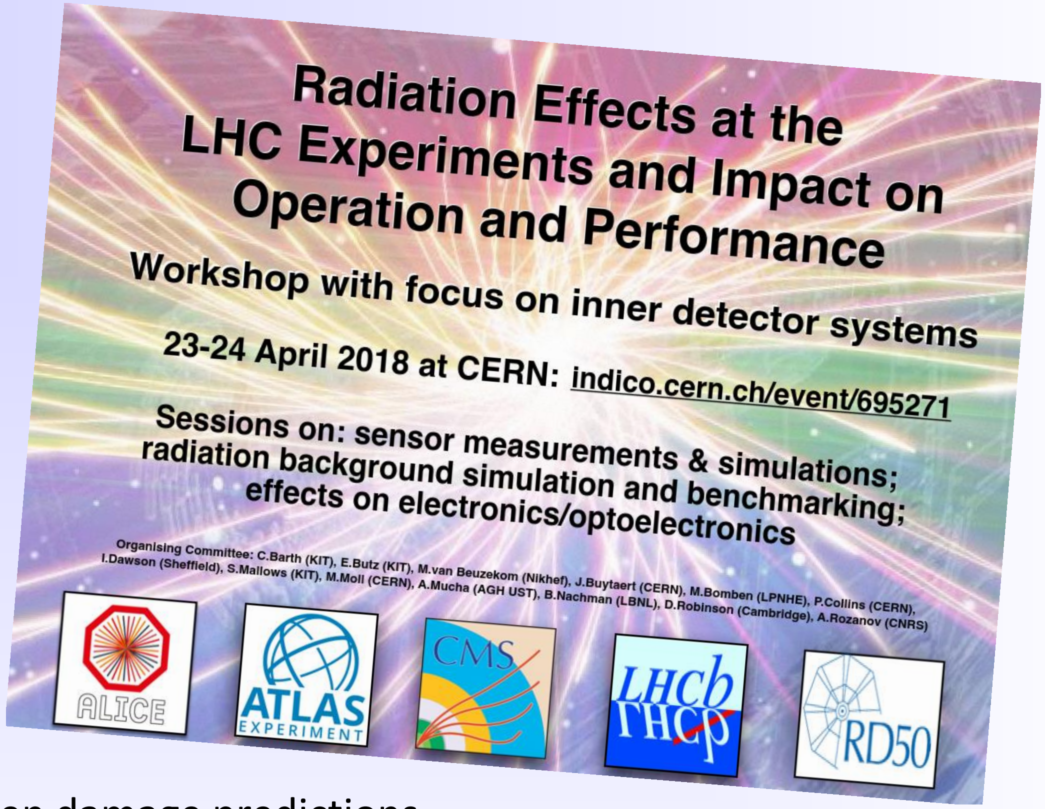
- **CNM**
  - **Realized FE-I4 compatible double sided detectors**
  - **On going realization of RD53A compatible sensors on wafers of different thickness (72-200 µm)**
- **FBK**
  - **Realized FE-I4 and RD53A compatible sensors on 130µm active depth silicon wafers**
  - **On going a design based on stepper technology in order to increase the mask to mask alignment**
    - composition of a big device as a sum of small parts

Full Detector Systems

- selected topics -

Radiation Damage in LHC Experiments

- **Radiation Effects at LHC Experiments and Impact on Operation and Performance**
  - **Common Workshop: (ALICE), ATLAS, CMS, LHCb, RD50** [https://indico.cern.ch/event/695271/]
  - CERN, 23-24 April 2018
  - **4 sessions:**
    - Sensor Measurements
    - Electronics/Optoelectronics
    - Radiation Background Simulation and Monitoring
    - Sensor Simulation
  - **Workshop statistics:**
    - 124 participants
    - 32 talks, discussion sessions



Radiation Effects at the LHC Experiments and Impact on Operation and Performance

Workshop with focus on inner detector systems

23-24 April 2018 at CERN: indico.cern.ch/event/695271

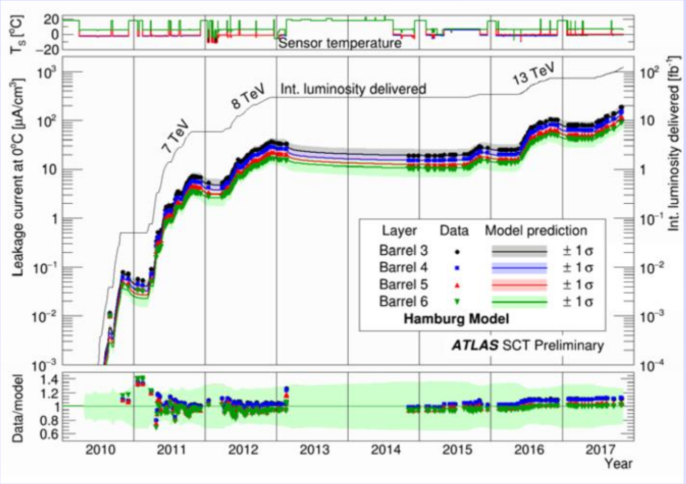
Sessions on: sensor measurements & simulations; radiation background simulation and benchmarking; effects on electronics/optoelectronics

Organising Committee: C.Barth (KIT), E.Butz (KIT), M.van Beuzekom (Nikhef), J.Buytaert (CERN), M.Bomben (LPNHE), P.Collins (CERN), I.Dawson (Sheffield), S.Mallows (KIT), M.Moll (CERN), A.Mucha (AGH UST), B.Nachman (LBNL), D.Robinson (Cambridge), A.Rozanov (CNRS)

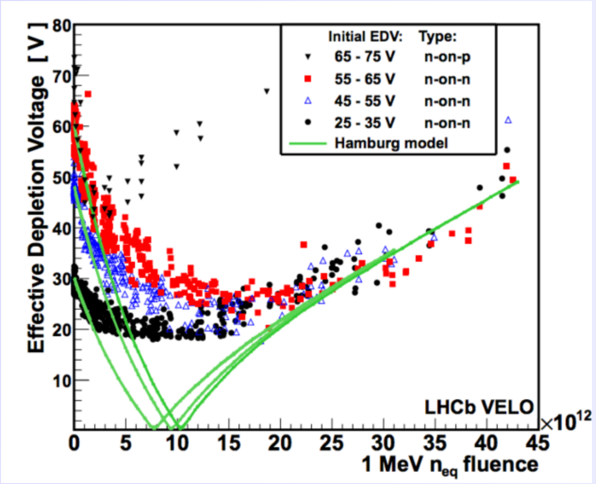
  - **Outcome and follow-up:**
    - Generally: good agreement between damage predictions by RD50 models ("Hamburg model") and radiation damage observed by the experiments.
    - Report under preparation to summarize observations, compare results of different experiments against each other, list open questions and outline further work
    - …follow-up workshop anticipated for early 2019

Radiation Damage in LHC Experiments

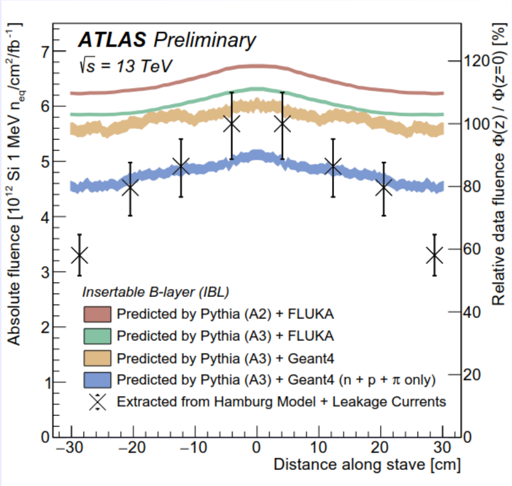
- **Workshop on Radiation Effects at LHC Experiments,** CERN, 23-24 April 2018



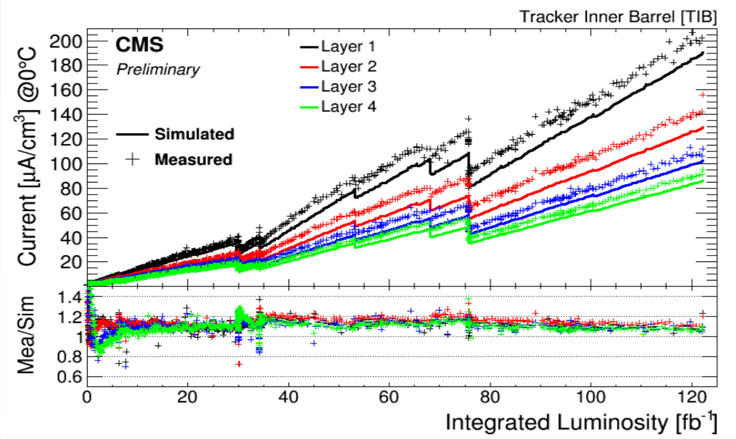
Leakage current in **ATLAS SCT**
and **CMS tracker** and model predictions

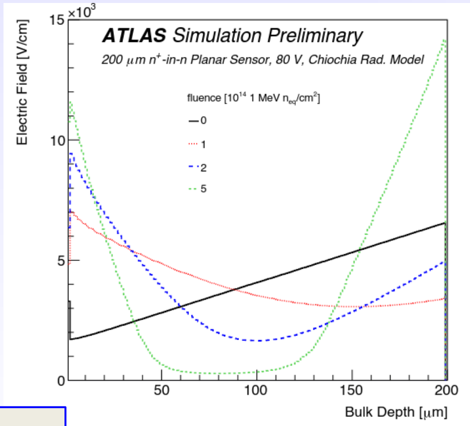


Depletion Voltage in **LHCb Velo**
and model predictions



ATLAS B-layer (data vs. MC&NIEL)
strong z-dependence unexpected
…looking forward to CMS pixel data



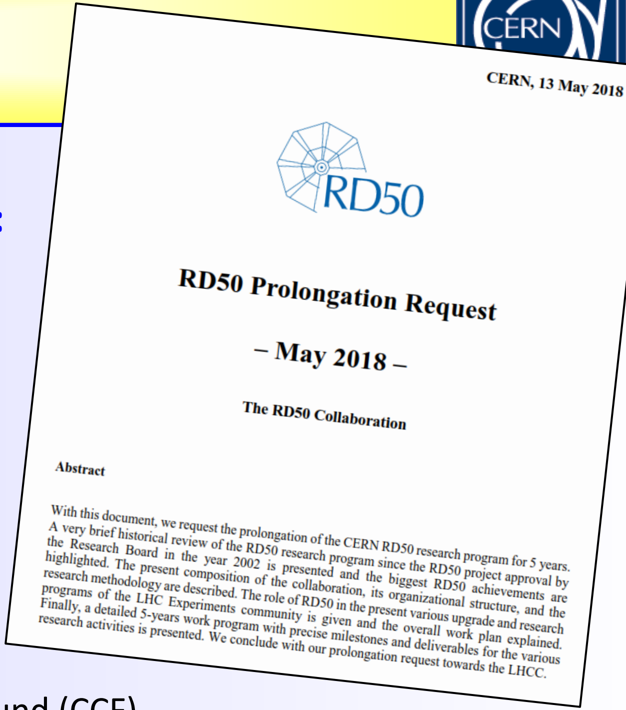


Sensor simulation in Monte Carlo frameworks need reliable E-Field simulations (TCAD)

[Plots: W.Barter(LHCb) J.Hunt (CMS), S.Menke (ATLAS), Ben Nachman (ATLAS),T.Kondo(ATLAS) https://indico.cern.ch/event/695271/]

Request to LHCC

- **RD40 2018/19 work plan outline attached as spare slides below**
- **RD50 has submitted a detailed work snd resource plan to the LHCC:**



CERN, 13 May 2018

RD50

RD50 Prolongation Request

– May 2018 –

The RD50 Collaboration

Abstract

With this document, we request the prolongation of the CERN RD50 research program for 5 years. A very brief historical review of the RD50 research program since the RD50 project approval by the Research Board in the year 2002 is presented and the biggest RD50 achievements are highlighted. The present composition of the collaboration, its organizational structure, and the research methodology are described. The role of RD50 in the present various upgrade and research programs of the LHC Experiments community is given and the overall work plan explained. Finally, a detailed 5-years work program with precise milestones and deliverables for the various research activities is presented. We conclude with our prolongation request towards the LHCC.

- **Workplan**
  - RD50 has submitted a detailed 5 years workplan for approval to the LHCC. (…will become public if approved.)

- **MOU**
  - A new “Memorandum of Understanding” is being prepared and will be submitted for approval to the RB and CERN management, covering as well a time frame of 5 years.

- **Resources:**
  - Every RD50 institution is contributing 2kCHF/year to the RD50 common fund (CCF).
  - The CCF is used to finance common projects and to support common activities of the collaboration, which provide mutual benefits and promote the collaboration.
  - "RD50 common projects" receive a financial contribution from the CCF (within rules defined in the MOU) that allow a sharing of cost between all RD50 institutions participating in the common project.
  - Most RD50 projects are performed as in-kind contributions supported by other funding (national funding agencies, successful competitive funding proposals,….).
  - **RD50 is requesting the approval to continue this funding concept.**

- **Resources from CERN (Host lab)** ***(as previous years)***
  - Access to EP-DT facilities: Irradiation facilities, Bond Lab, Solid State Detector Lab
  - Administrative support at CERN through EP-DT secretariat
  - **Acknowledgement:** The CERN RD50 team is supported through the EP Department

Spare Slides

- Some spare slides
- More details on http://www.cern.ch/rd50/

RD50 … Main Achievements

- Development of the p-type silicon strip and pixel technology
- Double column 3D detectors and first industrialization at CNM and FBK
- Convincing demonstration of the performance of planar segmented sensors to the maximum fluences anticipated for the HL-LHC (3x10^{16} n_{eq} cm^{-2})
- Extensive evaluation of defect engineered Silicon and other semiconductor materials
- Observation and explanation of charge multiplication in highly irradiated sensors operated at high voltage
- Design and production of LGAD (Low Gain Avalanche Detectors) for 4D tracking
- Development of several unique characterization methods and systems for sensor and material analyses: Transient Current Technique (TCT), Edge-TCT, Two Photon Absorption (TPA)-TCT, Alivaba readout system and standardized measurement and analyses procedures, partly now marketed through spin-off companies
- Defect characterization: identification of defects responsible for the degradation of various detectors parameters defining the state of the art in the corresponding solid state community
- Data collection and development of damage parameters/models essential for sensor design (TCAD parameters) and for planning the running scenarios of LHC experiments and their upgrades (evolution of leakage current, CCE, power consumption, noise,….)
- **Close links to the LHC experiments (upgrades** and operation**)**

Workplan for 2018/2019 (1/2)

- **Defect and Material Characterization** *(Convener: Ioana Pintilie, Bucharest)*
  - Consolidate list of defects and their impact on sensor properties (Input to simulation group) including introduction rates & annealing for different type of irradiations and materials
  - **Extend work on p-type silicon including low resistivity material**
    - Understand boron removal in lower resistivity p-type silicon: Performance of MAPS, CMOS sensors, LGAD … adding new macroscopic measurements
  - Study of extended defects and intensifying work on theory of defects and defect kinetics
  - Characterization of **Nitrogen enriched silicon** (starting project, extensive irradiation campaign finished)

- **Detector Characterization** *(Convener: E.Fretwurst, University of Hamburg, Germany)*
  - **TCAD sensor simulations**
    - Cross-calibration of different simulation tools (ongoing) and comparison of “TCAD models”
    - Refine defect parameters used for modeling (**from effective to measured defects**)
    - Extend modeling on charge multiplication processes and surface damage
    - Extend use of signal simulation tools towards fitting of measured data
  - **Extend experimental capacities on e-TCT equipment**
    - Parameterization of electric field (fluence, annealing time, etc.)
  - **Exploit full potential of Two Photon Absorption for sensor characterization; build setup at CERN**
  - **Continue parameterization of radiation damage (performance degradation) of LHC like sensors !**
  - **Explore fluence range to10^{17}cm^{-2}and beyond** (prepare future needs in forward physics and FCC)

Workplan for 2018/2019 (2/2)

- **New structures** *(Convener: Giulio Pellegrini, CNM Barcelona, Spain)*
  - Continue work on thin and 3D sensors (especially in combination with high fluence)
  - **Continue characterization of dedicated avalanche test structures** (LGAD, DD-APD)
    - Understand impact of implant shape and other geometrical parameters on avalanche processes
    - Continue study of Gallium based amplification layers and impact of Carbon co-implantation
  - **LGAD, DD-APD:** intensify evaluation of timing performance and radiation degradation (Where are the limits? How to overcome radiation damage? How much gain is optimum? How to optimize the fill factor?)
  - **HVCMOS**
    - Continue characterization of existing devices (close collaboration with ATLAS HVCMOS group)
    - First RD50 test structures (Lfoundry) received 5/2018; analysis started, submission of an engineering run in 2018

- **Full detector systems** *(Convener: G.Kramberger, Ljubljana University, Slovenia)*
  - Further studies of thin (low mass) segmented silicon devices
  - Continue work in frame of LHC radiation damage working group (RD50, ATLAS, CMS, LHCb)
  - Study performance of thin and avalanche sensors in the time domain (Fast sensors!)
  - Long term annealing of segmented sensors (parameterize temperature scaling)
  - Continue study on “mixed” irradiations (segmented detectors)
  - Continue RD50 program on slim edges, edge passivation and active edges

- **Links with LHC experiments and their upgrade working groups**
  - **Continue collaboration on evaluation of radiation damage in LHC detectors**
  - **Continue common projects with LHC experiments on detector developments**

Defects with strong impact on device performance after irradiation

- **Most relevant defects with impact on device performance**

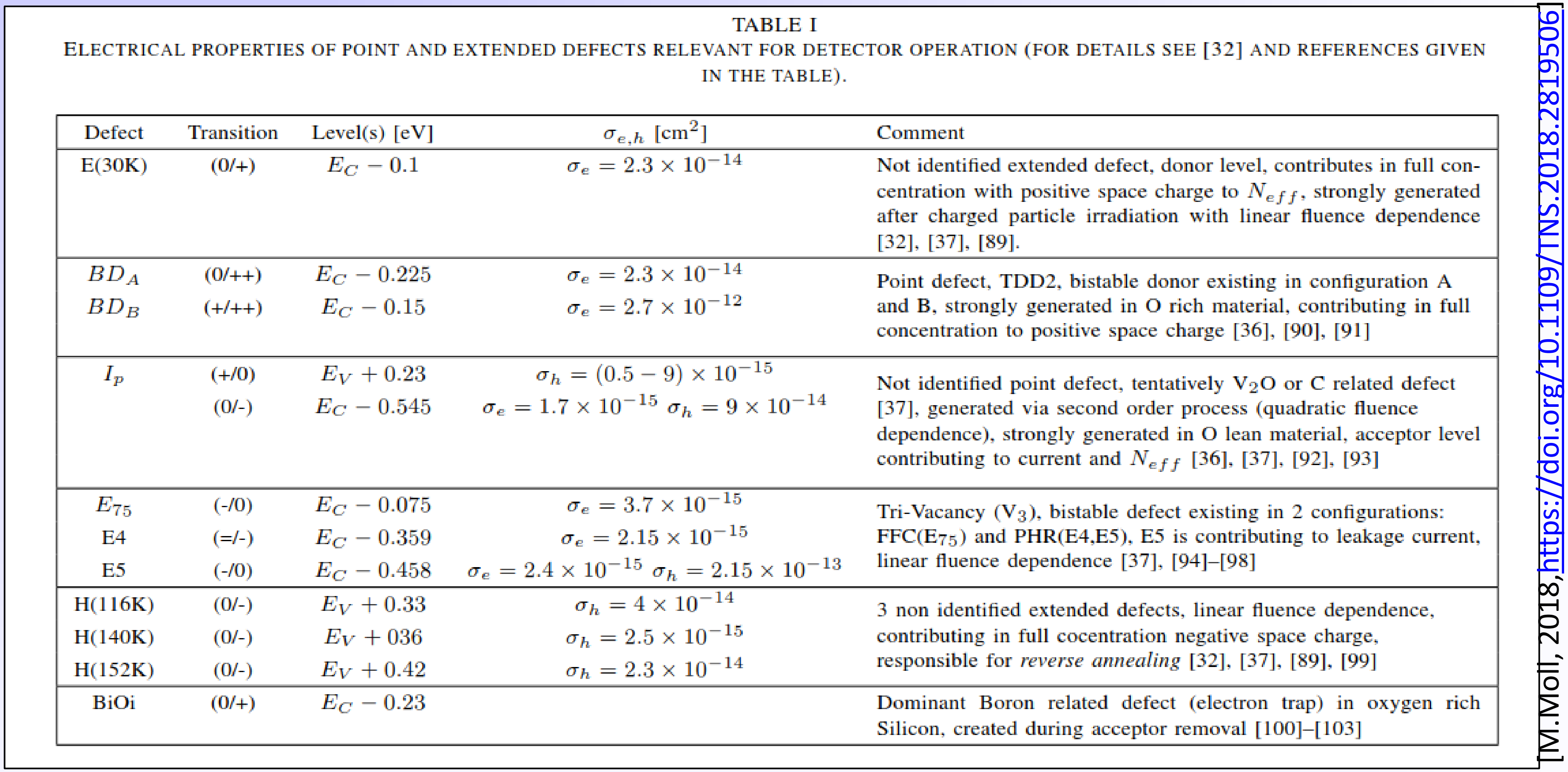
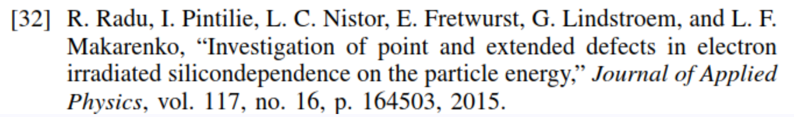


TABLE I

ELECTRICAL PROPERTIES OF POINT AND EXTENDED DEFECTS RELEVANT FOR DETECTOR OPERATION (FOR DETAILS SEE [32] AND REFERENCES GIVEN IN THE TABLE).

Defect	Transition	Level(s) [eV]	$\sigma_{e,h}$ [cm^2]	Comment
E(30K)	(0/+)	$E_C - 0.1$	$\sigma_e = 2.3 \times 10^{-14}$	Not identified extended defect, donor level, contributes in full concentration with positive space charge to N_{eff}, strongly generated after charged particle irradiation with linear fluence dependence [32], [37], [89].
BD_A BD_B	(0/++) (+/++)	$E_C - 0.225$ $E_C - 0.15$	$\sigma_e = 2.3 \times 10^{-14}$ $\sigma_e = 2.7 \times 10^{-12}$	Point defect, TDD2, bistable donor existing in configuration A and B, strongly generated in O rich material, contributing in full concentration to positive space charge [36], [90], [91]
I_p	(+/0) (0/-)	$E_V + 0.23$ $E_C - 0.545$	$\sigma_h = (0.5 - 9) \times 10^{-15}$ $\sigma_e = 1.7 \times 10^{-15}$ $\sigma_h = 9 \times 10^{-14}$	Not identified point defect, tentatively V_2O or C related defect [37], generated via second order process (quadratic fluence dependence), strongly generated in O lean material, acceptor level contributing to current and N_{eff} [36], [37], [92], [93]
E_{75} E4 E5	(-/0) (=/-) (-/0)	$E_C - 0.075$ $E_C - 0.359$ $E_C - 0.458$	$\sigma_e = 3.7 \times 10^{-15}$ $\sigma_e = 2.15 \times 10^{-15}$ $\sigma_e = 2.4 \times 10^{-15}$ $\sigma_h = 2.15 \times 10^{-13}$	Tri-Vacancy (V_3), bistable defect existing in 2 configurations: FFC(E_{75}) and PHR(E4,E5), E5 is contributing to leakage current, linear fluence dependence [37], [94]–[98]
H(116K) H(140K) H(152K)	(0/-) (0/-) (0/-)	$E_V + 0.33$ $E_V + 036$ $E_V + 0.42$	$\sigma_h = 4 \times 10^{-14}$ $\sigma_h = 2.5 \times 10^{-15}$ $\sigma_h = 2.3 \times 10^{-14}$	3 non identified extended defects, linear fluence dependence, contributing in full cocentration negative space charge, responsible for *reverse annealing* [32], [37], [89], [99]
BiOi	(0/+)	$E_C - 0.23$		Dominant Boron related defect (electron trap) in oxygen rich Silicon, created during acceptor removal [100]–[103]

[M.Moll, 2018, https://doi.org/10.1109/TNS.2018.2819506]



[32] R. Radu, I. Pintilie, L. C. Nistor, E. Fretwurst, G. Lindstroem, and L. F. Makarenko, "Investigation of point and extended defects in electron irradiated silicondependence on the particle energy," *Journal of Applied Physics*, vol. 117, no. 16, p. 164503, 2015.

Radiation Damage Models
- Defect Parameters -

- **Several different models and tools are used within RD50 and other communities**

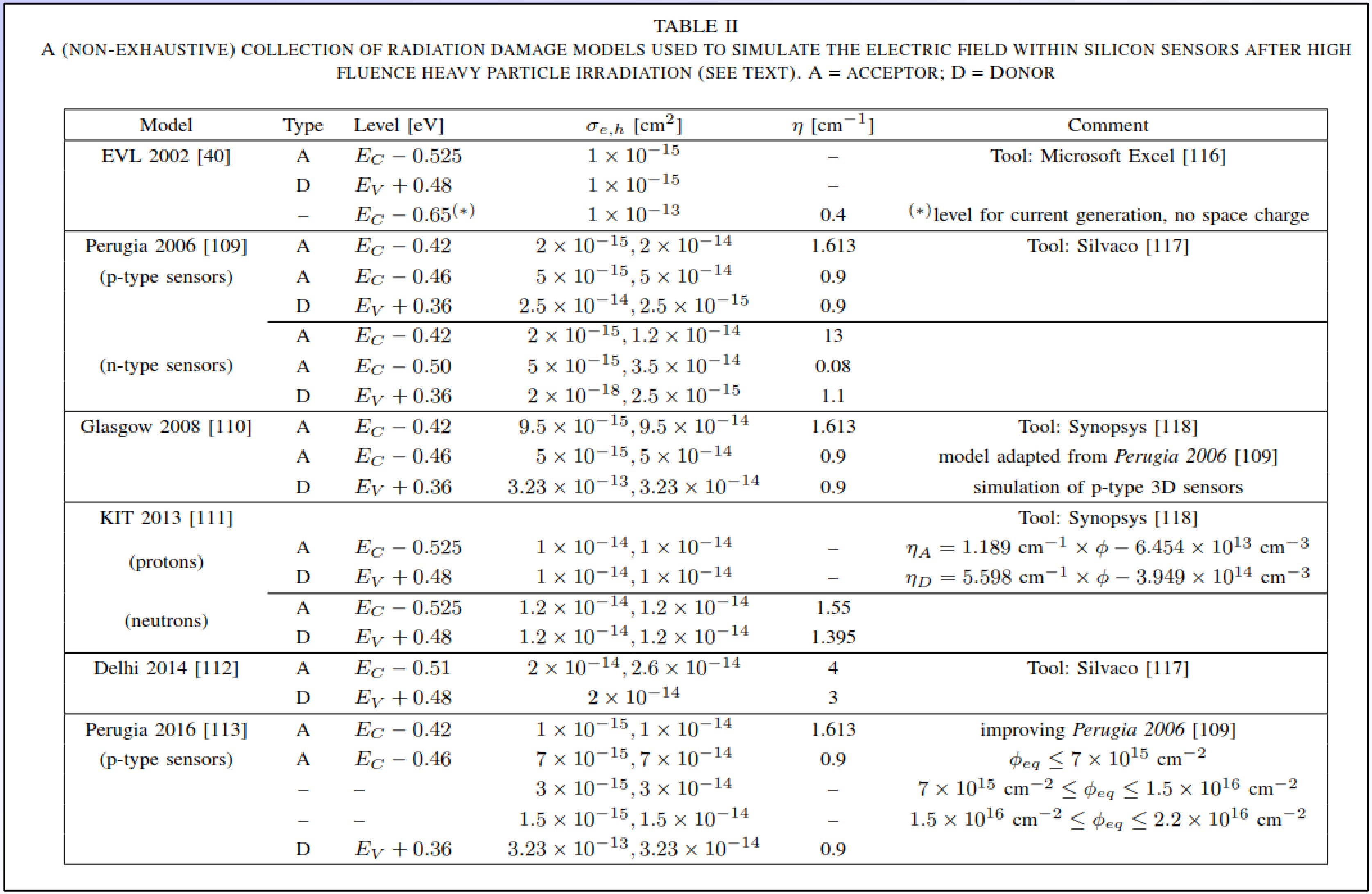


TABLE II

A (NON-EXHAUSTIVE) COLLECTION OF RADIATION DAMAGE MODELS USED TO SIMULATE THE ELECTRIC FIELD WITHIN SILICON SENSORS AFTER HIGH FLUENCE HEAVY PARTICLE IRRADIATION (SEE TEXT). A = ACCEPTOR; D = DONOR

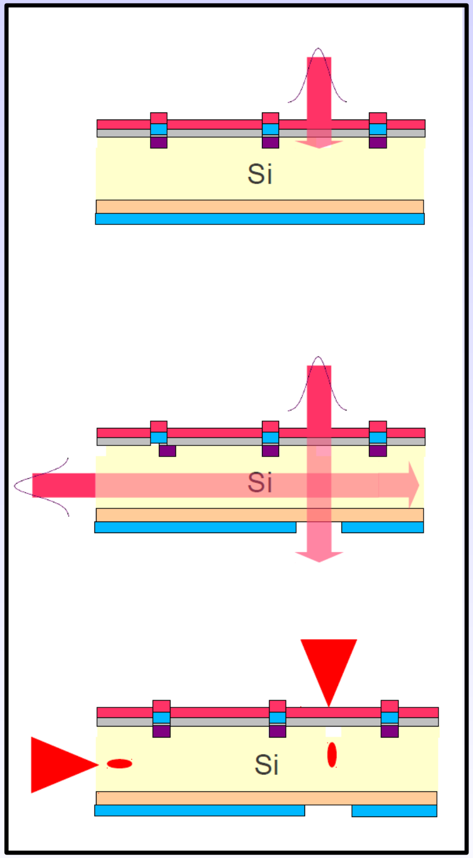
Model	Type	Level [eV]	$\sigma_{e,h}$ [cm^2]	η [cm^{-1}]	Comment
EVL 2002 [40]	A	$E_C - 0.525$	1×10^{-15}	–	Tool: Microsoft Excel [116]
	D	$E_V + 0.48$	1×10^{-15}	–	
	–	$E_C - 0.65^{(*)}$	1×10^{-13}	0.4	$^{(*)}$level for current generation, no space charge
Perugia 2006 [109]	A	$E_C - 0.42$	$2 \times 10^{-15}, 2 \times 10^{-14}$	1.613	Tool: Silvaco [117]
(p-type sensors)	A	$E_C - 0.46$	$5 \times 10^{-15}, 5 \times 10^{-14}$	0.9	
	D	$E_V + 0.36$	$2.5 \times 10^{-14}, 2.5 \times 10^{-15}$	0.9	
	A	$E_C - 0.42$	$2 \times 10^{-15}, 1.2 \times 10^{-14}$	13	
(n-type sensors)	A	$E_C - 0.50$	$5 \times 10^{-15}, 3.5 \times 10^{-14}$	0.08	
	D	$E_V + 0.36$	$2 \times 10^{-18}, 2.5 \times 10^{-15}$	1.1	
Glasgow 2008 [110]	A	$E_C - 0.42$	$9.5 \times 10^{-15}, 9.5 \times 10^{-14}$	1.613	Tool: Synopsys [118]
	A	$E_C - 0.46$	$5 \times 10^{-15}, 5 \times 10^{-14}$	0.9	model adapted from *Perugia 2006* [109]
	D	$E_V + 0.36$	$3.23 \times 10^{-13}, 3.23 \times 10^{-14}$	0.9	simulation of p-type 3D sensors
KIT 2013 [111]					Tool: Synopsys [118]
(protons)	A	$E_C - 0.525$	$1 \times 10^{-14}, 1 \times 10^{-14}$	–	$\eta_A = 1.189$ cm$^{-1} \times \phi - 6.454 \times 10^{13}$ cm^{-3}
	D	$E_V + 0.48$	$1 \times 10^{-14}, 1 \times 10^{-14}$	–	$\eta_D = 5.598$ cm$^{-1} \times \phi - 3.949 \times 10^{14}$ cm^{-3}
(neutrons)	A	$E_C - 0.525$	$1.2 \times 10^{-14}, 1.2 \times 10^{-14}$	1.55	
	D	$E_V + 0.48$	$1.2 \times 10^{-14}, 1.2 \times 10^{-14}$	1.395	
Delhi 2014 [112]	A	$E_C - 0.51$	$2 \times 10^{-14}, 2.6 \times 10^{-14}$	4	Tool: Silvaco [117]
	D	$E_V + 0.48$	2×10^{-14}	3	
Perugia 2016 [113]	A	$E_C - 0.42$	$1 \times 10^{-15}, 1 \times 10^{-14}$	1.613	improving *Perugia 2006* [109]
(p-type sensors)	A	$E_C - 0.46$	$7 \times 10^{-15}, 7 \times 10^{-14}$	0.9	$\phi_{eq} \lesssim 7 \times 10^{15}$ cm^{-2}
	–	–	$3 \times 10^{-15}, 3 \times 10^{-14}$	–	7×10^{15} cm$^{-2} \lesssim \phi_{eq} \lesssim 1.5 \times 10^{16}$ cm^{-2}
	–	–	$1.5 \times 10^{-15}, 1.5 \times 10^{-14}$	–	1.5×10^{16} cm$^{-2} \lesssim \phi_{eq} \lesssim 2.2 \times 10^{16}$ cm^{-2}
	D	$E_V + 0.36$	$3.23 \times 10^{-13}, 3.23 \times 10^{-14}$	0.9	

[M.Moll, 2018,https://doi.org/10.1109/TNS.2018.2819506]

TCT – Transient Current Technique

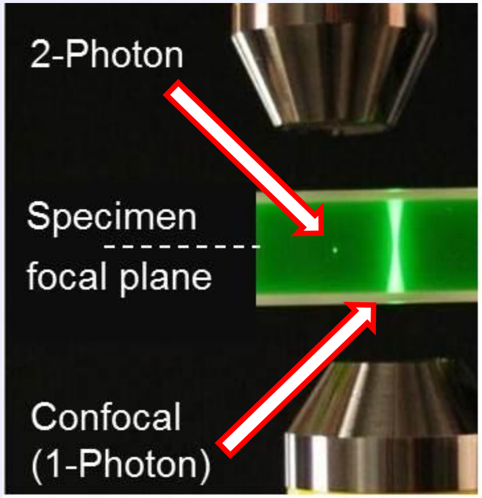
- **TCT: Pulsed laser induced generation of charge carriers in the detector**
  - Study of: electric field in sensor, charge collection efficiency, homogeneity,..
  - Benchmarking of simulation tools, measure physics parameters from mobility to impact ionization

- **New TCT technology: TPA-TCT – Two Photon Absorption TCT**



- **TCT (red)**
  - **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)**
  - **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 x 1 x 10 μm^3)**

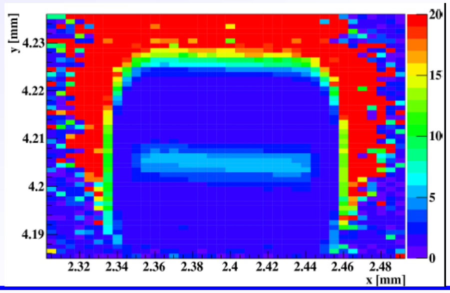
Concept: TPA TCT



Photography: Ciceron Yanez, University of Central Florida

Example: HV-CMOS

100x100 μm^2, 10 μm depleted



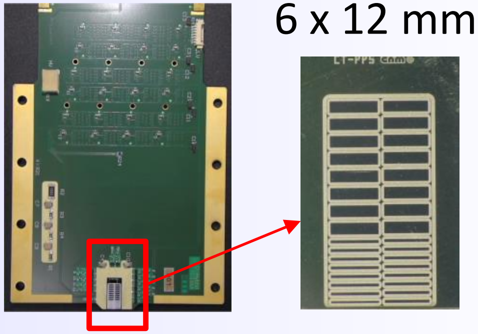
[M.Fernandez, TCT Workshop, Ljubljana, 10/2016]

LGAD for Timing Applications

- **LHC experiments starting to implement/plan on Si based timing detectors with RD50 technology**

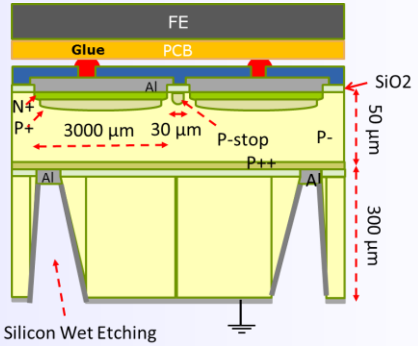
- **CTPPS** – CMS-TOTEM Precision Proton Spectrometer
  - **Installed in 2016 YETS in two Roman pots two planes of segmented LGAD**
  - Time resolution measured by CTPPS (at high voltage!)
    - 45 μm LGAD on SOI – 1.7 mm^2
    - 27ps single device; 16 ps with 3 layers (@ 230 V)
- **ATLAS AFP** - Forward Proton
  - 30 ps up to 3x10^{14} n$_{eq}$/cm^2
  - 57 ps at 10^{15} n$_{eq}$/cm^2 (@ 620 V)
- **ATLAS HGTD** - High Granularity Timing Detector
- **CMS** Timing layer
  - Planning for hermetic timing detector for phase II;
  - CB approved a full coverage eta 0 – 3 timing layer for MIPs, using crystals in the barrel and LGAD as baseline in the endcap;
  - Expect:10^{14} n$_{eq}$/cm^2 to 10^{15}n$_{eq}$/cm$^{2;}$ 9m^2 silicon sensor surface; (tentative: 40-50μm thick , 1x3mm^2 pads, >95% fill factor)

Slide: Summer 2017

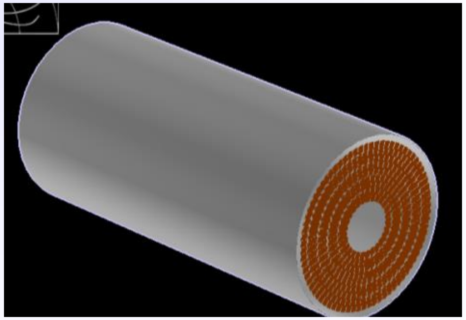


6 x 12 mm^2

CTPPS: 45μm thick LGAD (SOI)



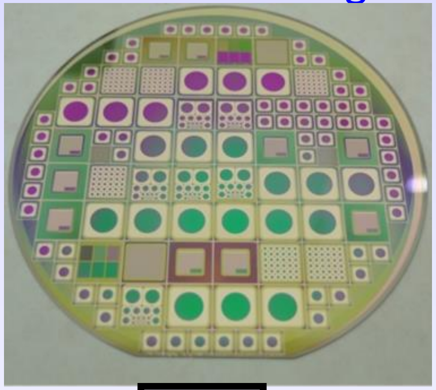
HGTD LGAD on 50 μm SOI



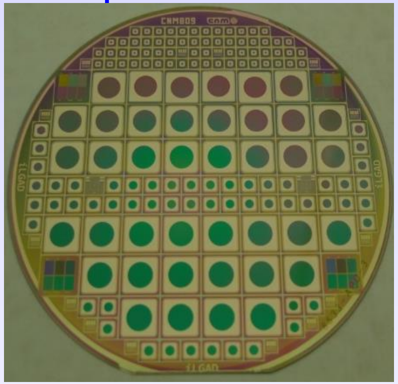
CMS Timing layer

LGAD within RD50 Collaboration

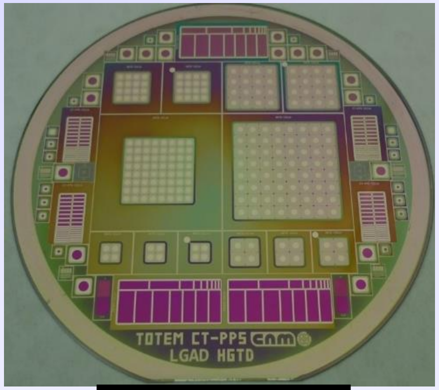
- **2010**: LGAD activities started with CNM project
- **2012**: First **4 inch** wafer, **300 µm** thick, LGAD
- **2014**: First **200 µm** thick LGAD. First Gallium Process
- **2015**: First PiN on **6 inch** wafer. First Inverse LGAD
- **2016**: First **50 µm** thick LGAD for **Timing applications** (ATLAS **HGTD** and CMS **CT-PPS**. SOI and SOS, 4 inch wafer). Gallium and Carbon Processes
- **2017**: First LGAD on **6 inch** wafer
- **25** Fabrication processes. **200** Wafers processed at CNM
- 2018: Working on the optimization of fill factors



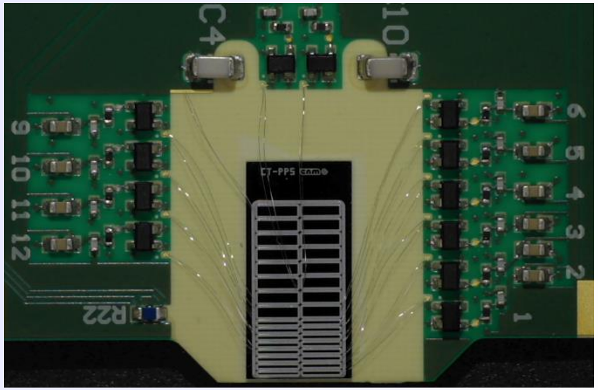
LGAD



iLGAD



HGTD/CTPPS



CTPPS

- FBK, Trento: 1st batch of LGAD in 2016, 2nd in 2017 (processed, being characterized)
  - p-side and n-side segmentation, pixel, strip, AC coupling, … (see Annex)
- Today: CNM Spain, FBK Italy, Mikron UK and HPK Japan produced LGAD's (4 suppliers)

[G. Pellegrini et al., "Low Gain Avalanche Detectors (LGAD)", Vertex 2016

Signal Simulation Tools

- Reduce amount of resources needed compared to TCAD tools (much faster)
- Increase flexibility (source code in hand)

KDetSim
IJS Ljubljana

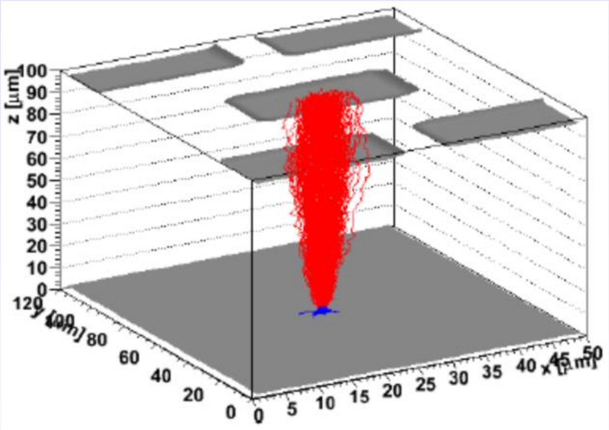
- ROOT shared library
- Scripted
- 3D simulation
- Arbitrary sensor geometry

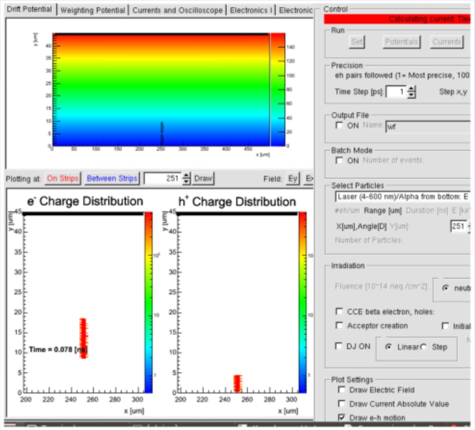
WeightField2
INFN Torino

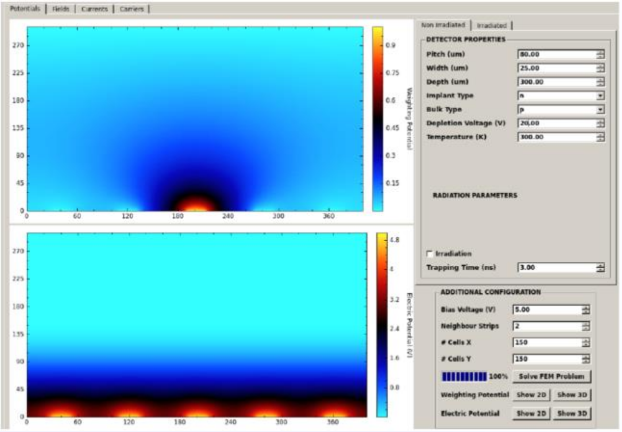
- GUI based
- Build on ROOT
- Diodes and strips
- Accurate description of LGAD

TRACS
IFCA-Santander, CERN

- GUI and CLI available
- Fit of TCT data
- Diodes and strips
- Parallel computing





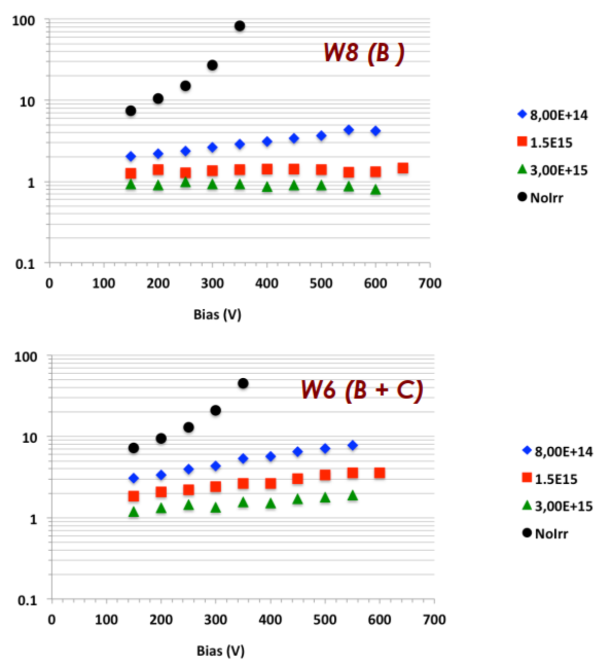


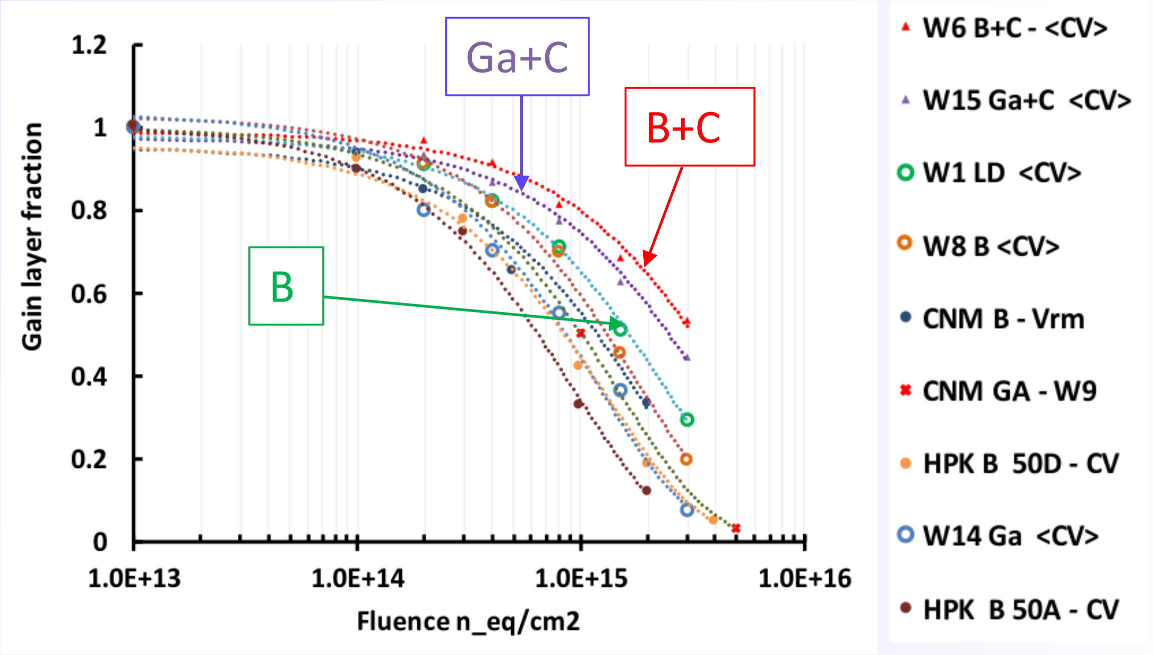
- ATLAS and CMS charge transport software also available: [ATLAS] [CMS]

Radiation Hardening of LGADS

- **Problem: Multiplication layer affected by acceptor removal**
  - Go thinner (see previous slide)
  - Modify the multiplication layer (defect engineering)
    - Replace dopant: Use Gallium instead of Boron
    - Protect dopant: Carbon co-implantation to “protect” Boron

[R. Arcidiacono, Tornio, Trento Meeting, 2018]



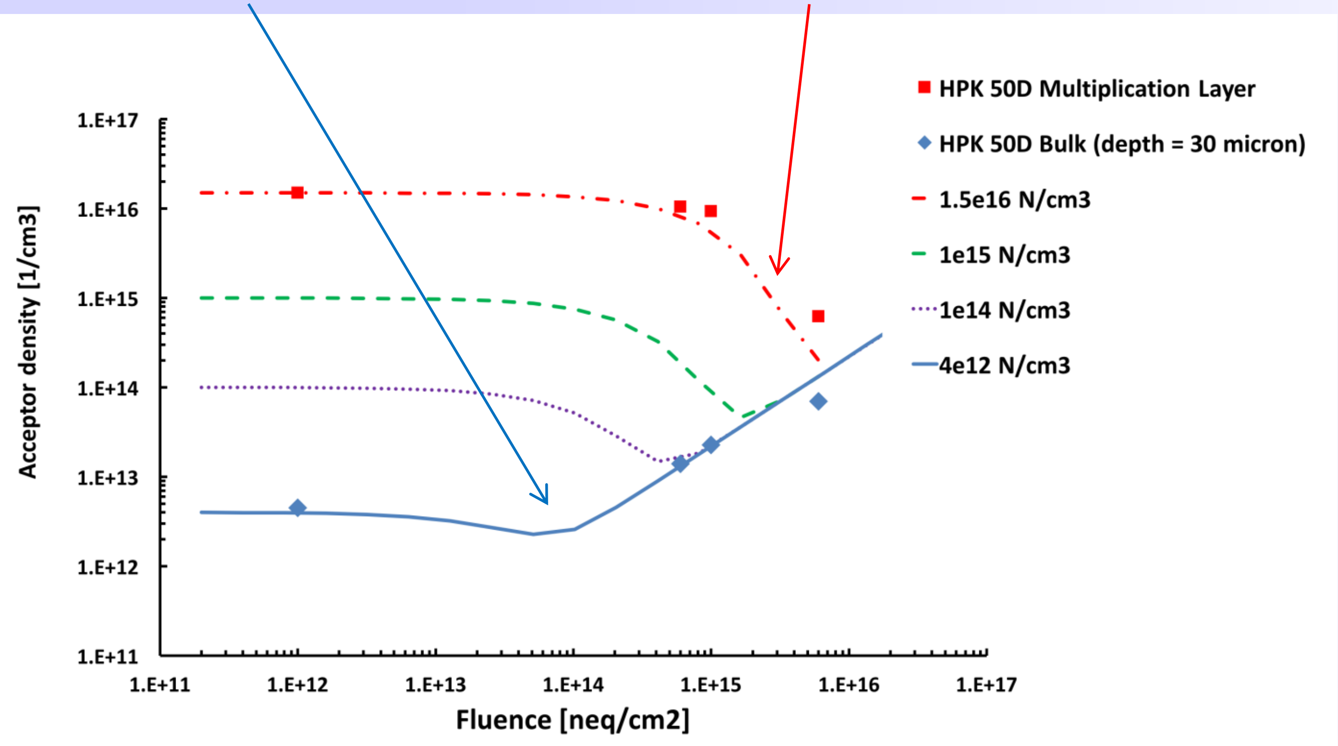


Gain = Q(LGAD)/Q(PiN)

Acceptor Removal & Creation

- **All silicon sensors: creation of acceptors proportional to fluence**
- **LGAD specific: gain decrease due to acceptor removal in the gain layer**

Acceptor density vs. fluence:
Increases in low density bulk, decrease in high density gain layer.



[H.Sadrozinski,SCIPP, Trento Meeting, 2018]

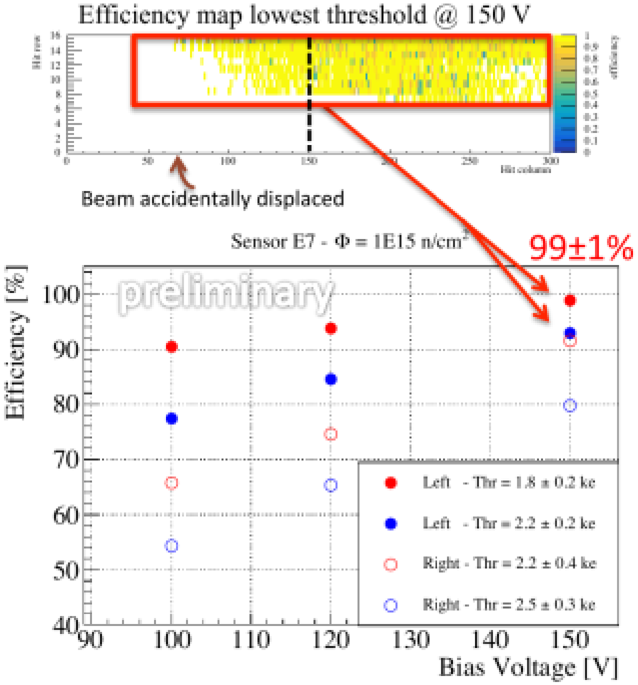
[Z. Galloway et al, arXiv:1707.04961 ; Data from C-V scans on HPK 50D Simulation from Weightfield 2 (WF2) incorporating G. Kramberger's work]

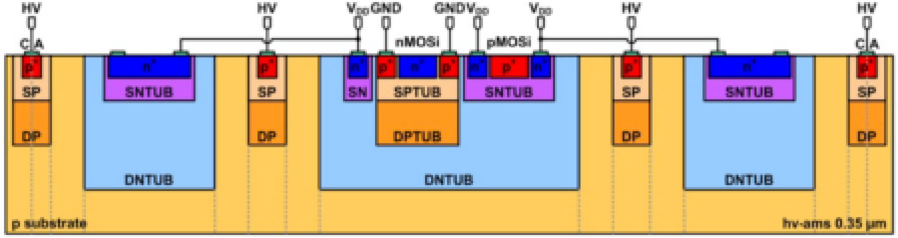
CMOS Pixel Detectors: HV-CMOS

[S. Terzo, "Trento" workshop 2018]

1e15 $n_{eq}cm^{-2}$

Depleted region of ≈60-70 µm at 120-150 V (from E-TCTs)





- HV-CMOS is an industry standard process that allows to apply high voltages to the substrate
- Improved depleted region, charge collection, and radiation tolerance wrt standard CMOS
- 99 ± 1% detection efficiency after $\Phi_{eq} = 10^{15}\,\mathrm{cm}^{-2}$
- Readout performed using the electronics on the die (No readout ASIC needed)