RD50

LHCC – 25.May 2016, CERN

RD50 Status Report – May 2016

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OUTLINE:

- **RD50 Collaboration**
- **Scientific results** (some highlights)
  - **Defect and Material Characterization**
  - **Detector Characterization**
  - **New Detector Structures**
  - **Full Detector Systems**
- **RD50 Work Program 2016/2017**
- **RD50 achievements, common projects and key results 2015/16** (spare slides)

Motivation and Challenge

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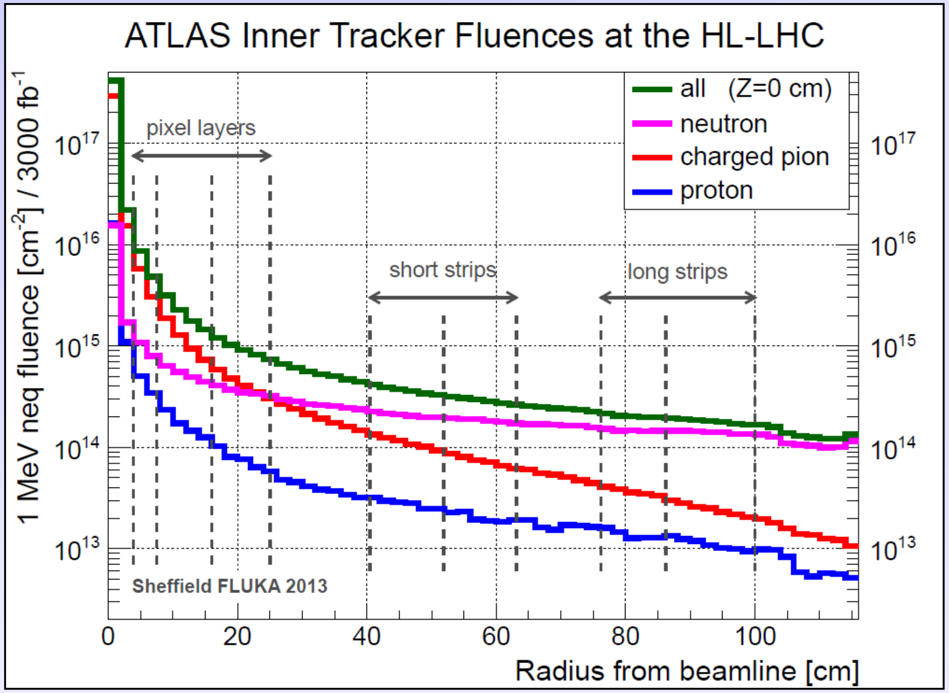
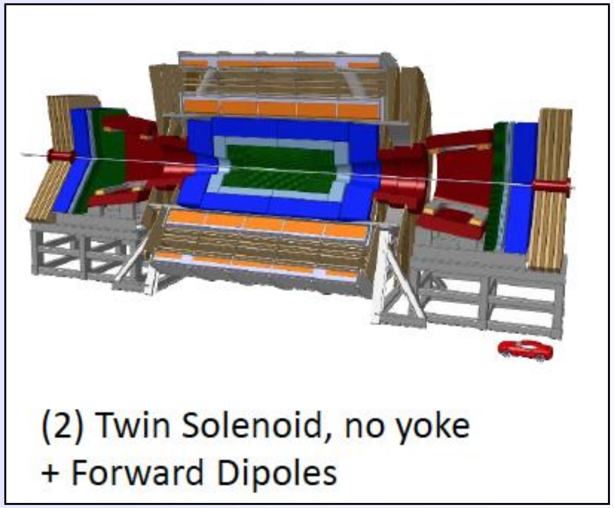
- **LHC upgrade**
  - **LHC upgrade towards High Luminosity LHC (HL-LHC)** *after LS3 (~2024-26); **expect** 3000 fb^{-1} (x6 nominal LHC)*

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



- ***FCC – Future Circular Collider***
  - **….later than 2035**



[W.Riegler, RD50 Workshop, 12/2015]

  - **Radiation levels innermost pixel layer** (30ab^{-1}, without safety factor): **7x10^{17} n$_{eq}$/cm^2, 200MGy**

Semiconductor detectors will be exposed to hadron fluences equivalent to more than 10^{16} n$_{eq}$/cm^2 (HL-LHC) and more than 7x10^{17} n$_{eq}$/cm^2 (FCC)

➔ detectors used now at LHC cannot operate after such irradiation

RD50 : mandate to develop and characterize semiconductor sensors for HL-LHC….. and FCC

RD50 The RD50 Collaboration

- **RD50: 50 *institutes and 282 members***

42 European and Asian institutes

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, Florence, Perugia, Pisa, Torino), Lithuania (Vilnius), Netherlands (NIKHEF), Poland (Krakow, Warsaw(2x)), Romania (Bucharest (2x)), Russia (Moscow, St.Petersburg), Slovenia (Ljubljana), Spain (Barcelona(2x), Santander, Valencia), Switzerland (CERN, PSI), United Kingdom (Birmingham, Glasgow, Lancaster (new), Liverpool)

6 North-American institutes

Canada (Montreal), USA (BNL, Fermilab, New Mexico, Santa Cruz, Syracuse)

1 Middle East institute

Israel (Tel Aviv)

1 Asian institute

India (Delhi)

+ 4 new institutes requested membership

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

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RD50 Organizational Structure

CERN

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)**
- WODEAN: Workshop on Defect Analysis in Silicon Detectors (G.Lindstroem & M.Bruzzi)

Detector Characterization
Eckhart Fretwurst
(Hamburg University)

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

New Structures
Giulio Pellegrini
(CNM Barcelona)

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

Full Detector Systems
Gregor Kramberger
(Ljubljana University)

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

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

Defect & Material Characterization

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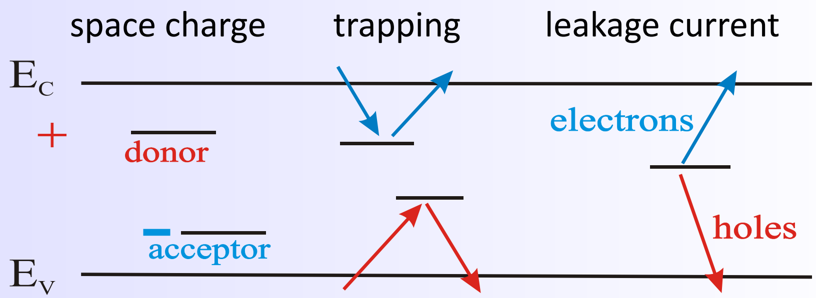
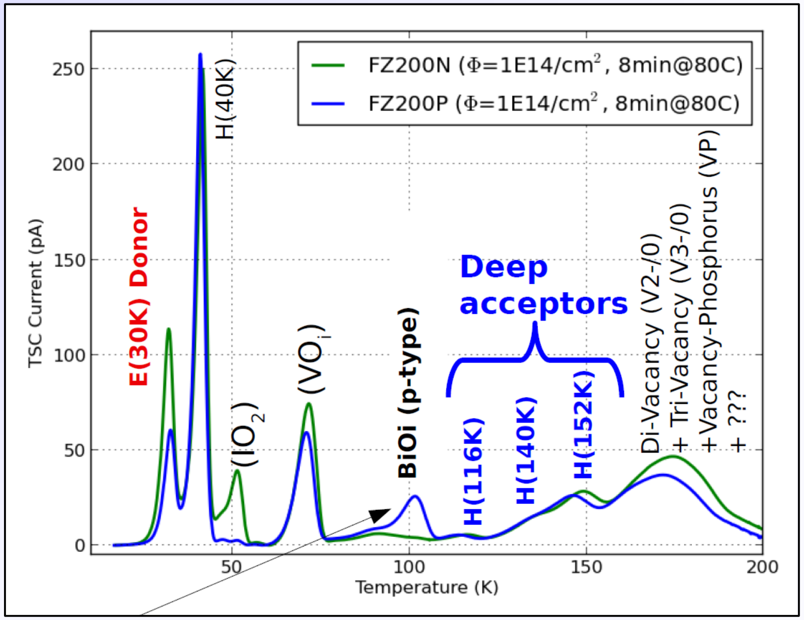
Defect Characterization

- **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)
  - *PC, RL, I-DLTS, TEM,… and simulation*
  - RD50: several hundred samples irradiated with protons, neutrons, electrons and ^{60}Co-γ

… significant progress on identifying defects responsible for sensor degradation over recent years!



Example: TSC measurement on defects produced by 23 MeV protons

[Elena Donegani et al, UniHH, RD50 Workshop, December 2015]

Summary on defects with strong impact on device performance after irradiation

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- **Some identified defects**

Phosphorus: shallow dopant (positive charge)

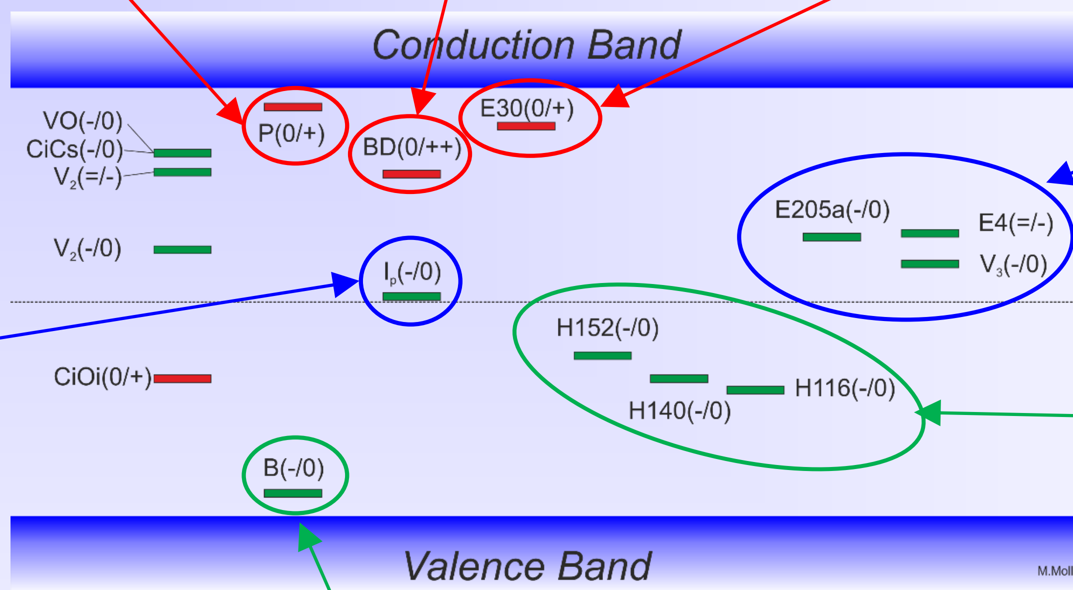
positive charge (higher introduction after proton than after neutron irradiation, oxygen dependent)

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

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!

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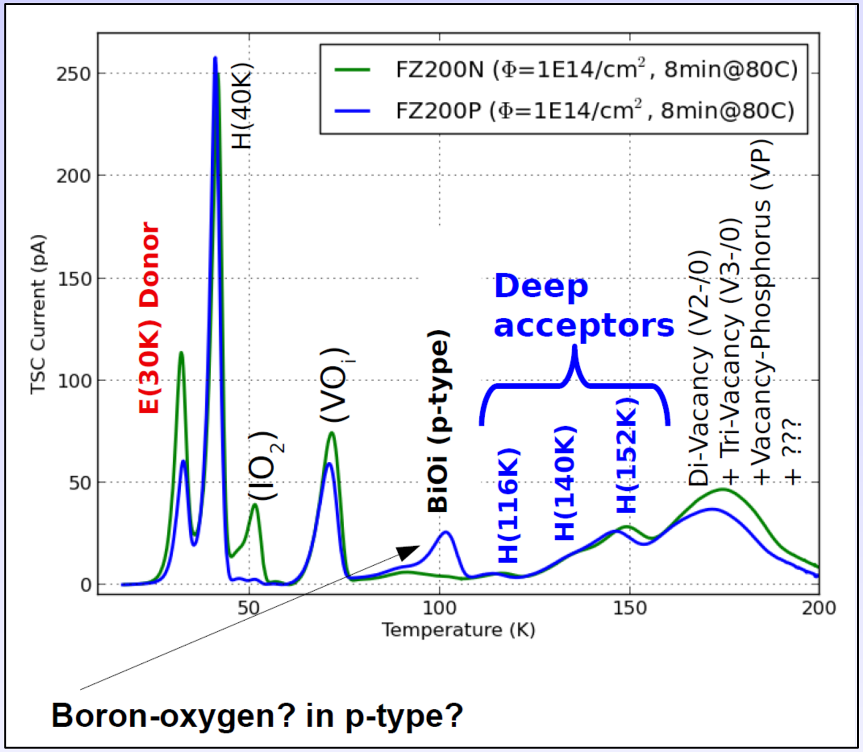
Acceptor removal - Boron related defects?

• Microscopic study of defects

- TSC (Thermally Stimulated Current) comparing n- and p-type sensors



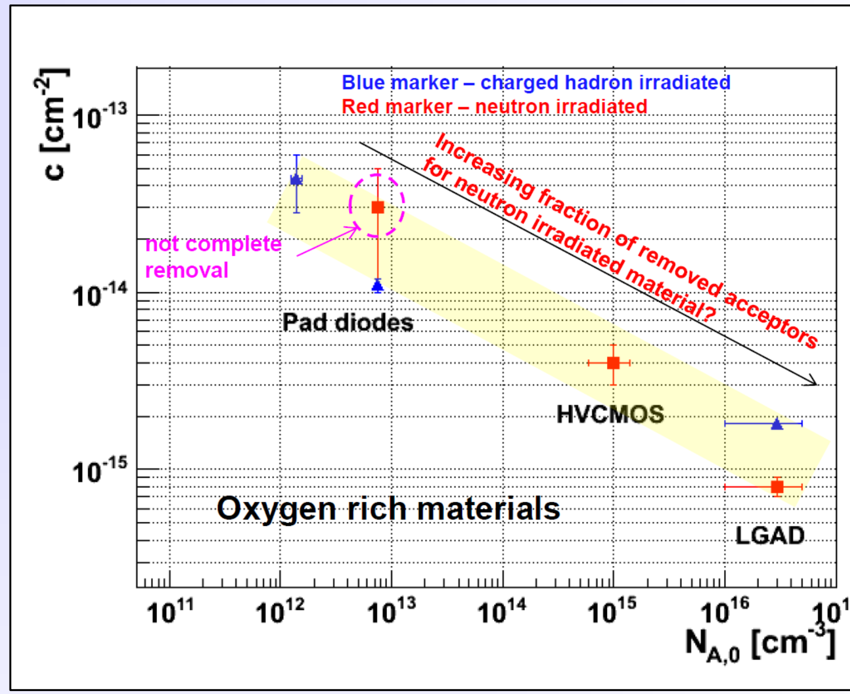
[Elena Donegani et al, UniHH, RD50 Workshop, December 2015]

- Reminder: Deep acceptors (H(116K)..) and shallow donors (E30K) alter space charge
- Some defect only seen in p-type (Boron containing) material; indication for "Boron removal" by defect kinetics (e.g. $B_i \rightarrow B_iO_i$)

• Macroscopic observation (Neff)

- p-type sensors of different resistivity show acceptor removal:

$$\Delta N_{eff} = |N_{Boron}| \cdot exp(-c \cdot \Phi) + \ldots$$ *[simplified]*



[Gregor Kramberger et al, Ljubljana, RD50 Workshop, June 2015]

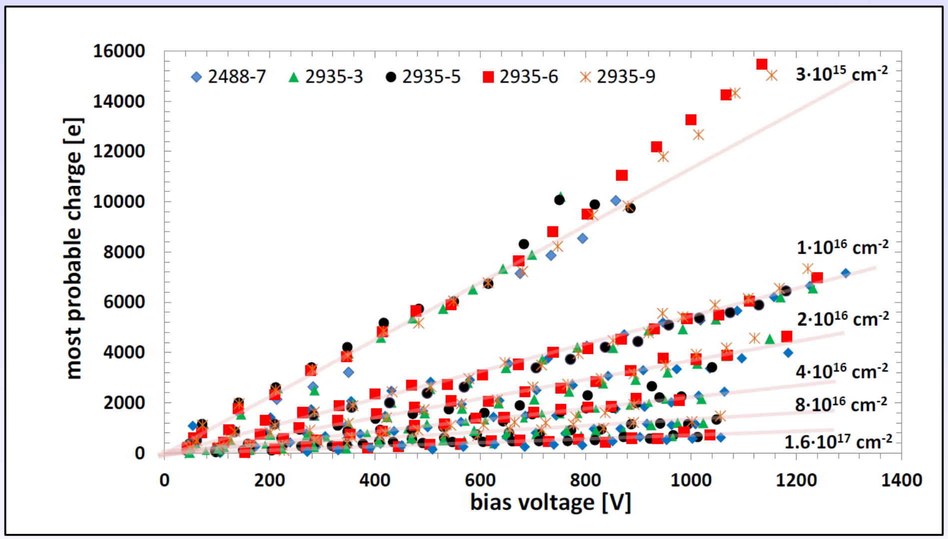
- **So-called *"acceptor removal"* responsible for:**
  - Gain degradation in sensors with intrinsic gain
  - Good performance of low resistivity CMOS sensors after high irradiation.
- **Why not studied more intensively before?**
  - Focus was on high resistivity and on n-type!

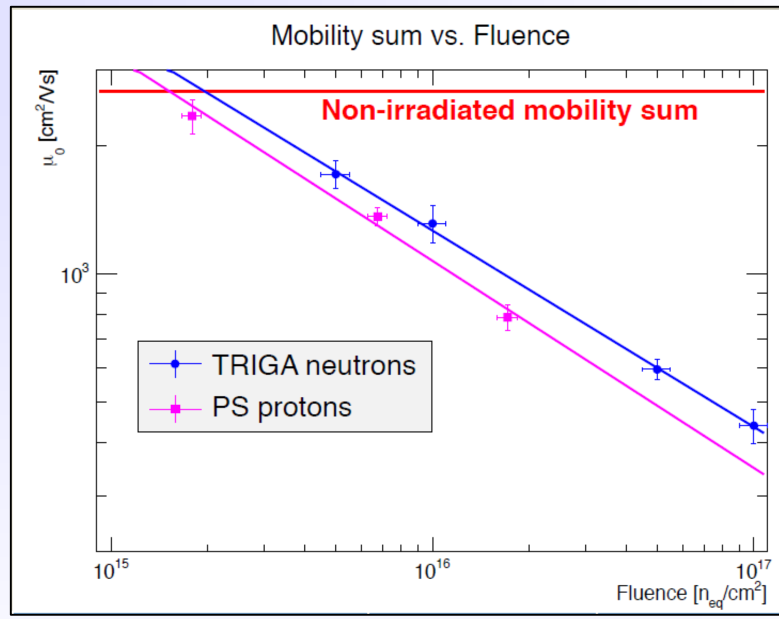
Device Characterization and TCAD simulations

RD50 Investigation on extreme fluences

- **Why?:**
  - Future applications (e.g. forward calorimeters at the LHCC, FCC detectors, …) will face radiation levels in the order of 1×10^{17} n_{eq} cm^{-2} and beyond!
  - Helps to understand limits of our parameterizations and modelling!
- CCE (Sr^{90}) as measured on pad sensors: Surprisingly high charge, low current
  - Linear extrapolation (depletion, leakage, trapping) does not work!
  - Working on new parameterization for Efield, leakage, trapping, charge collection.

[G. Kramberger et al. 2013 JINST 8 P08004]



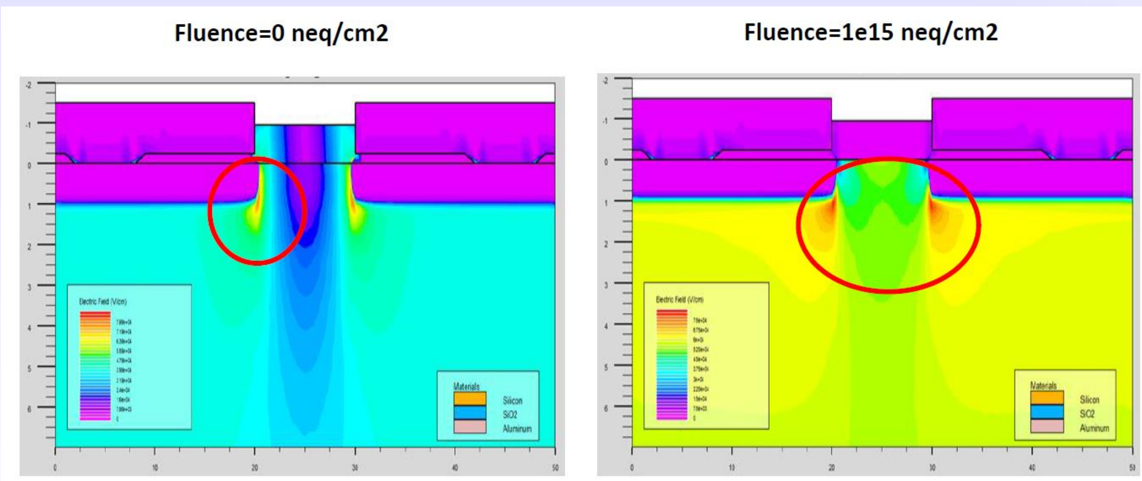


[M.Mikuz, Ljubljana, RD50 Workshop, 12/2015]

- **Collecting 1000 electrons after 10^{17} cm^{-2}**
- **Strong indication that the mobility decreases with fluence (e.g. factor 6 at $10^{17}cm^{-2}$)!**

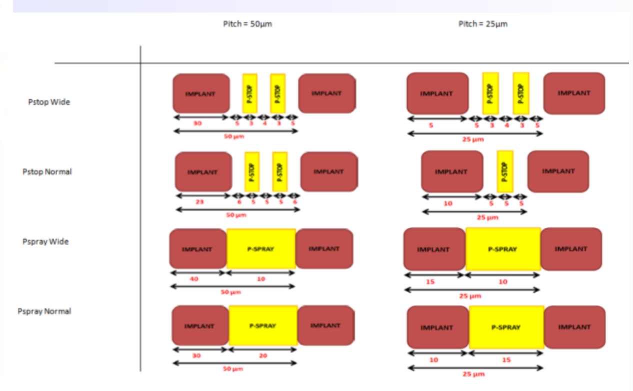
RD50 Simulation working group

- **Aim:** Develop simulations (TCAD input parameters) allowing to simulate performance of irradiated silicon sensors and performance predictions under various conditions *(sensor design and material, irradiation fluence and particle type, annealing,…).*
  - Close collaboration with CMS, AIDA and ATLAS sensor simulation working groups
  - **Challenge for irradiated sensors:**
    - Correct implementation of bulk and surface damage by defect levels
    - Defect concentration is function of fluence, particle type, material, annealing, …. !
- Status:
  - The **defect analysis results** drive the construction of the radiation damage model to be implemented in TCAD packages to be able to simulate of the performance of complex silicon devices after hadron irradiation. The **simulation output is increasingly accurate** in term of IV, CV, CCE inter-electrode resistance and capacitance, break-down voltage prediction etc.
  - Example: CMS phase II pixel design studies [Understanding peak E-Field]



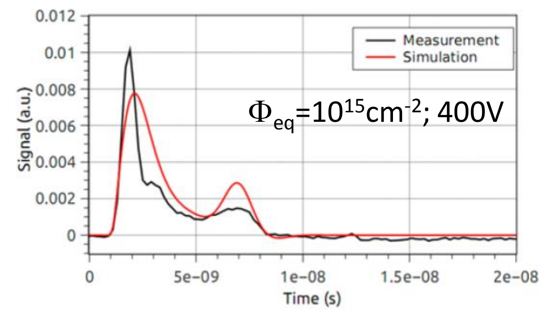
[G.Jain, Delhi, RD50 Workshop 12/2015]

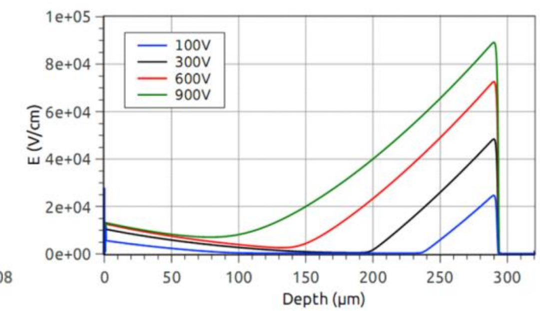
Evaluating different pixel layout designs and production parameters (p-stop, p-spray)

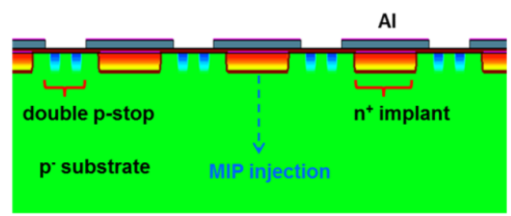


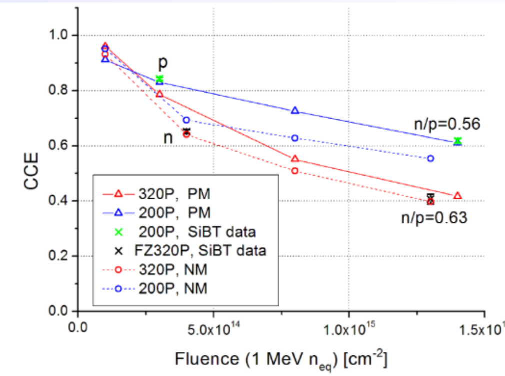
RD50 TCAD Simulations: Status

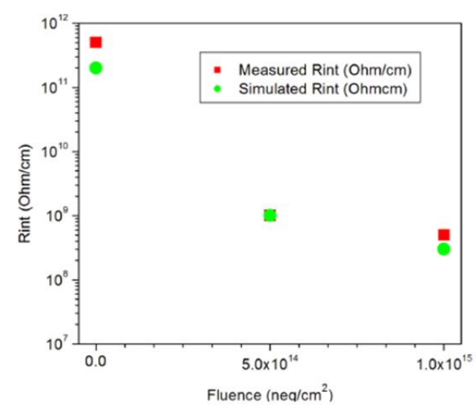
- **Bulk damage studies**
  - **Optimization of TCAD parameters**
  - TCT – Transient Current Technique and other methods used to produce data sets
- **CCE in strip or pixel sensors**
  - **Complex geometries evaluated against test beam data**
  - **Good agreement between data and measurement**
  - **Simulations get predictive power** (taking into account validity range of model!)
- **Surface damage**
  - **SiO_2 charge-up and Si-SiO_2 interface states**
  - **Important role in detector performance:** some properties can only be understood if implementing surface damage in simulation
  - Surface damage properties (e.g. R_{int}) can also only be understood if bulk damage is included!
  - **Figure:** Left: Simulated and measured inter-strip resistance vs. fluence for n-on-p strip sensors with double p-stop isolation at V = 600V. 2 interface traps used and bulk defects. Right: Comparison n-in-p vs. p-in-n
  - **Example:** Random Noise Hits in n-type strip sensors explained by E-Field at surface: One of the arguments for CMS to decide for p-type sensors.

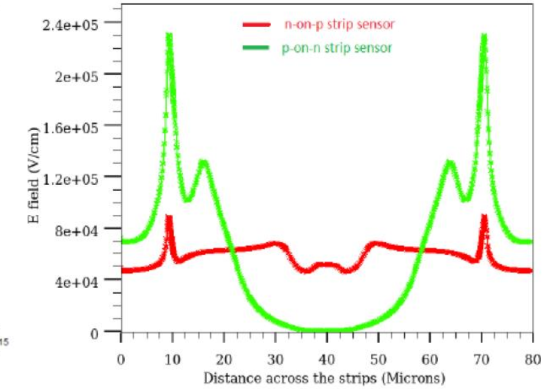












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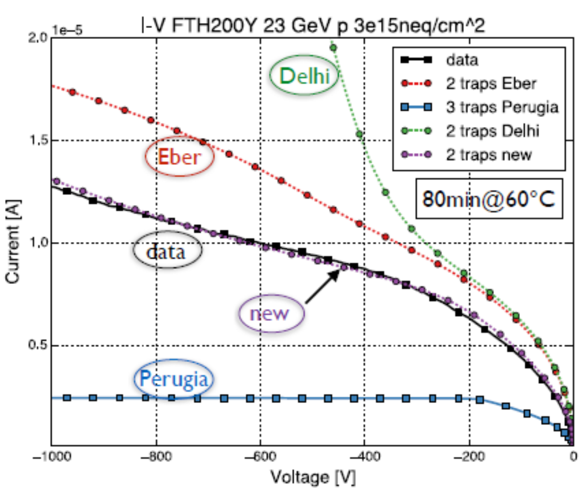
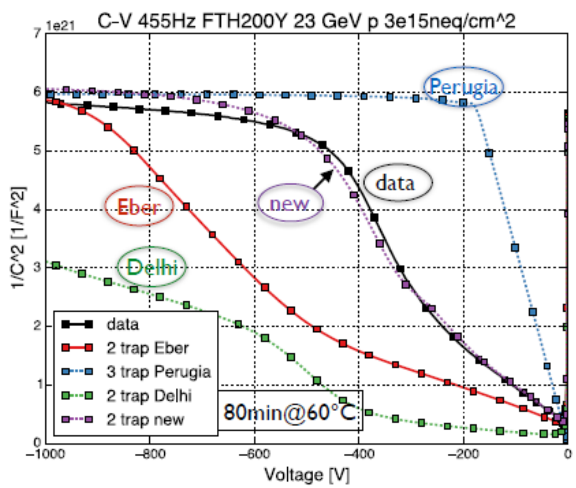
Comparing models and simulators

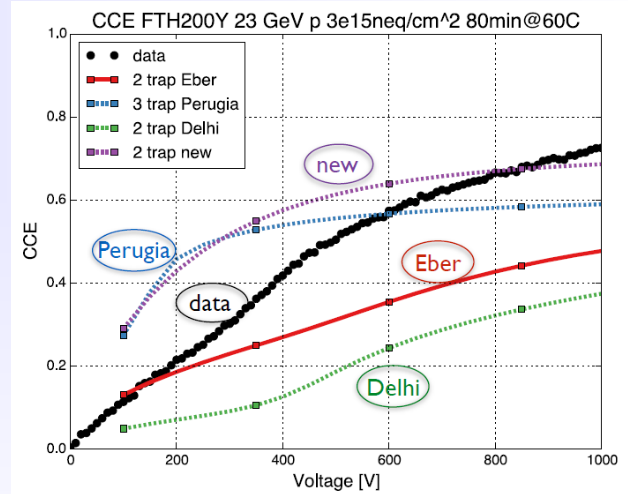
- **Cross checking various models and data fitting within the TCAD simulators**
  - **Many published TCAD models for irradiated sensors**
    - usually optimized for specific data sets with focus on specific parameters (e.g. depletion voltage, reverse current, charge collection)
    - often not applicable to (or not tested for) e.g. different fluence or temperature range !
  - **New RD50 approach:** Understand limits of available models and obtain more consistent parameter set by fitting full data sets (CV,IV, CCE of diodes) within the TCAD simulator.

Minimize difference between measured and simulated IV,CV curves

$$F = w_1 \int_{V_{min}}^{V_{max}} (1 - \frac{I_{sim}}{I_{mes}})^2 \, dV + w_2 \int_{V_{min}}^{V_{max}} (1 - \frac{C_{sim}}{C_{mes}})^2 \, dV$$







Simulation of IV and CV curves & optimization of parameters ("new") → Compare against CCE (1060nm)

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

Segmented Sensors with read-out at the n^+ contact

(n-in-p or n-in-n)

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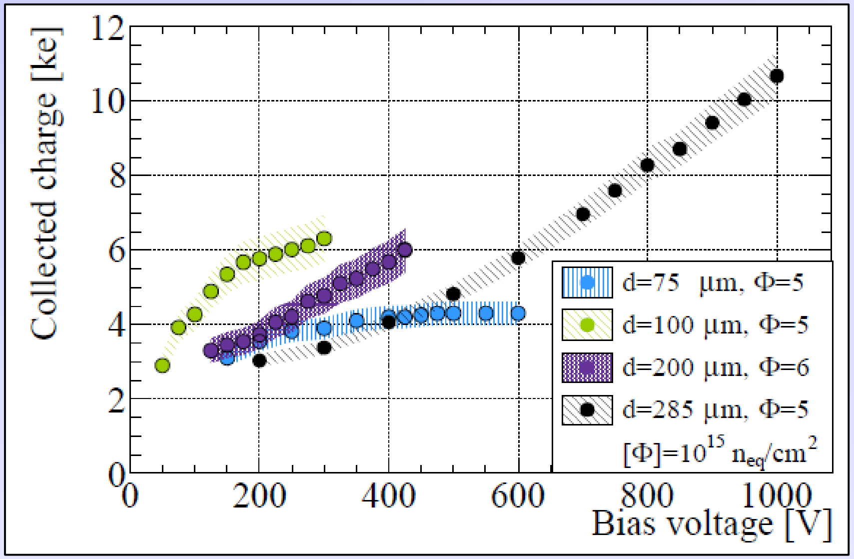
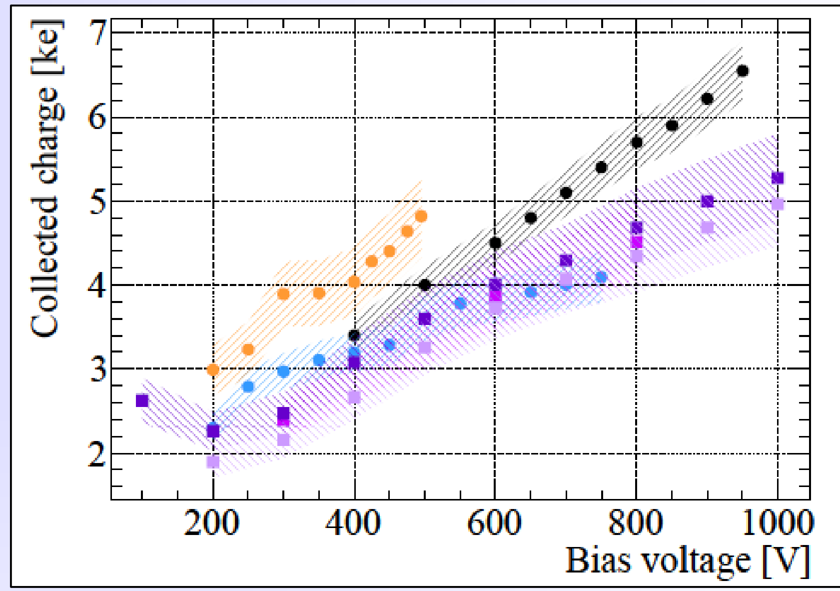
Thin p-type pixel sensors

- **Thin FZ p-type pixel sensors: 75 to 300 μm with 450 μm edge (MPI/CIS/VTT)**
- **ATLAS FEI4, 25 MeV protons, 800 MeV protons, neutrons, data obtained with beta source**

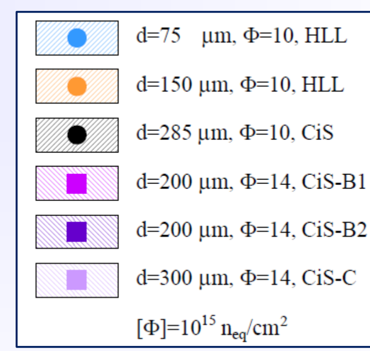




- **Detectors irradiated with 5 10^{15} n_{eq}/cm^2**
- **100μm thick sensors give more charge than 75μm thick sensors, both saturate with voltage**
- **200 μm thick sensors give more charge than 300 μm thick sensors at moderate voltage**
- **Beam tests show 97-99% hit efficiency**

  (thickness tested 100 -200 μm, 500V)

- **Detectors irradiated up to 1.4 10^{16} n_{eq}/cm^2**
- **Sensor modules still functional (even if in homogeneously irradiated)**



B. Paschen, 25th RD50 Workshop Nov. 2014

New structures

..optimizing for

- Radiation hardness
- Time resolution
- Cost effectiveness

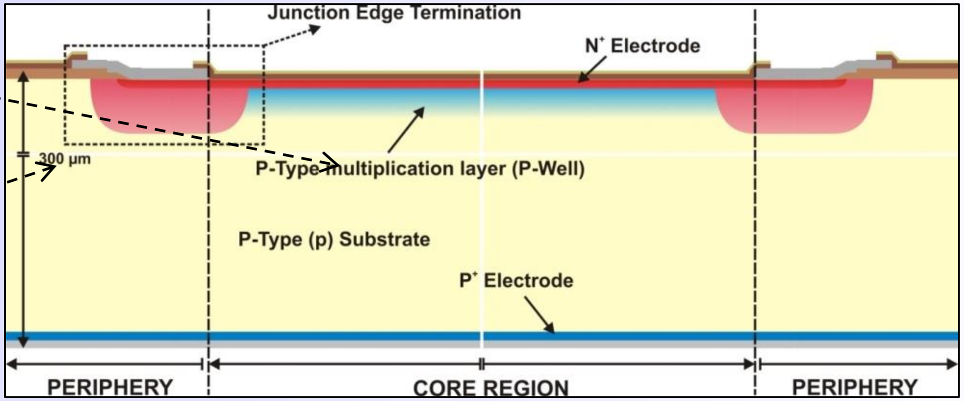
LGAD, APD
(Sensors with intrinsic gain)

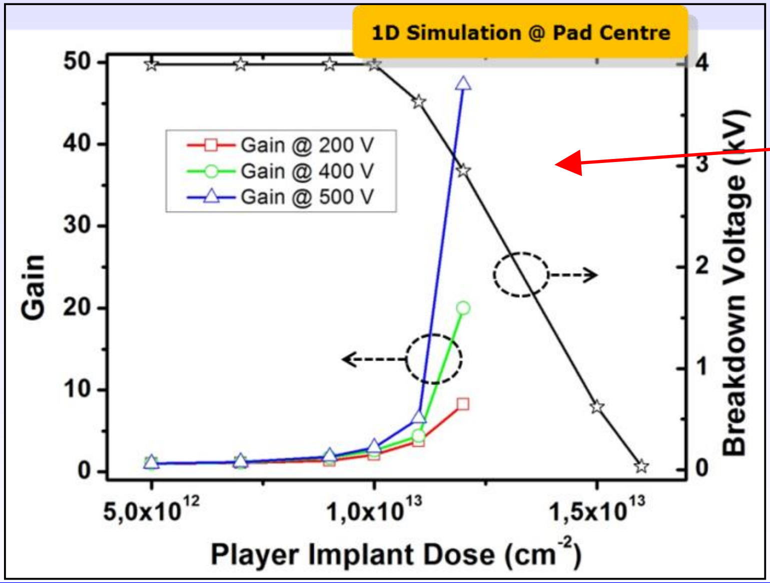
HVCMOS
(towards monolithic sensors)

3D
(sensors with vertical electrodes)

RD50 Sensors with intrinsic gain (LGAD)

- Exploit impact ionization (charge multiplication in high field regions) to achieve faster (→ improve timing performance) and radiation harder (→ mitigate trapping) sensors.
- Main focus: **LGAD** (Low Gain Avalanche Detectors) gain O(10), some work on DD-APD's.
- LGAD structure:
  - **Core Region**: Uniform electric field, high enough to activate impact ionization
  - **Termination**: Confining the high electric field of the core region
  - **Optimization:** TCAD simulations and studies on prototype devices





- Considerations for optimization:
  - **Gain versus $V_{breakdown}$ trade-off**, timing performance
  - Thin detector integration, radiation hardness
  - Proportional Response (linear mode operation)
  - Better S/N ratio (small cell volumes and fast shaping times)
- Since 2010: **18 production runs at CNM** (see spare slides)

[G. Pellegrini et. al., NIM A 765, 2014, 12–16]

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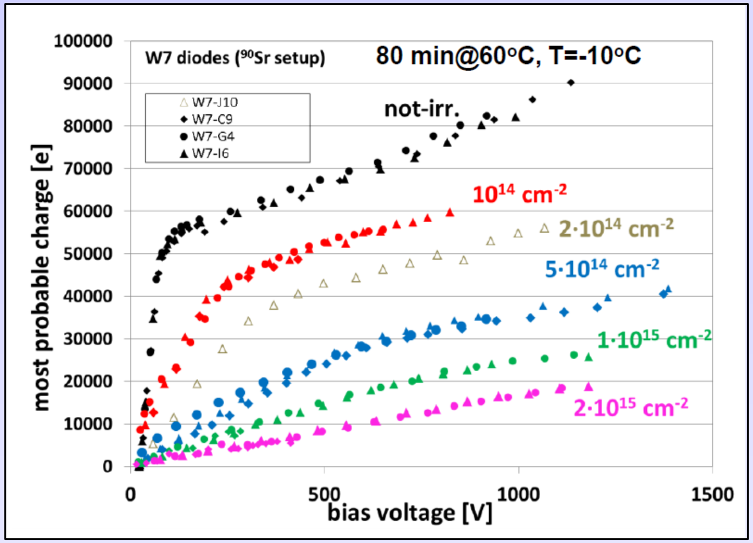
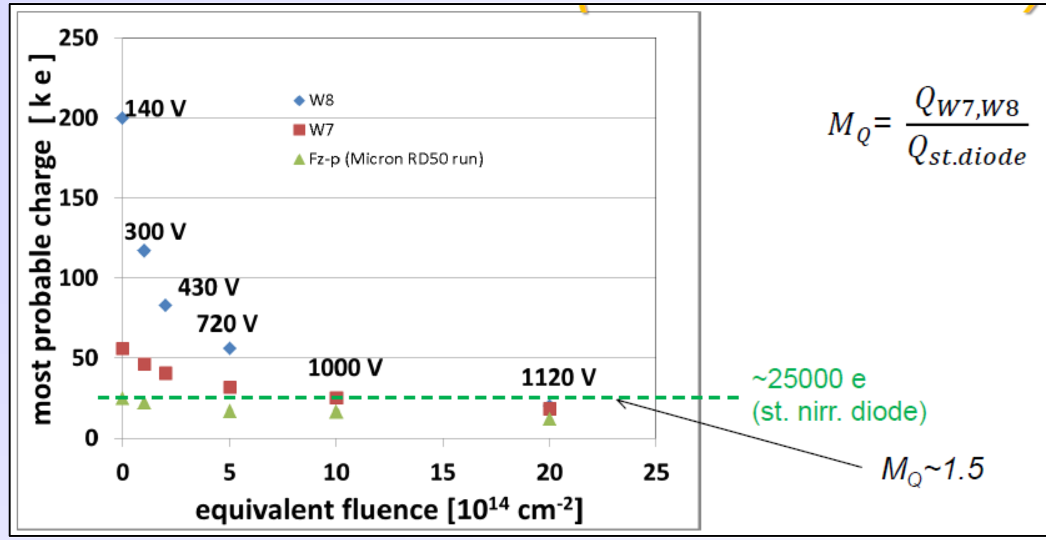
LGAD – Radiation Damage

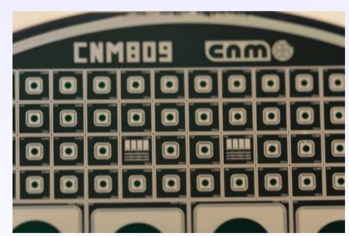
- **Radiation Hardness is limited: “Acceptor removal problem”**
  - **Collected Charge is degrading with fluence** (i.e. we are loosing the “gain”)

[G.Kramberger, RD50 Workshop, June 2014]





- TCAD simulations and CV, e-TCT, TCT measurements point out two mechanisms:
  - Boron removal [Boron bound into defects, i.e. de-activation of shallow dopant]
  - Space charge build-up due to increased hole current from amplification
- Experimental approaches in new production runs:
  - Use **Gallium** instead of Boron to impact on defect kinetics [wafers ready]
  - Use **Carbon** co-implant to “protect” Boron from removal [to be done]



Gallium doped wafer produced, ..to be tested

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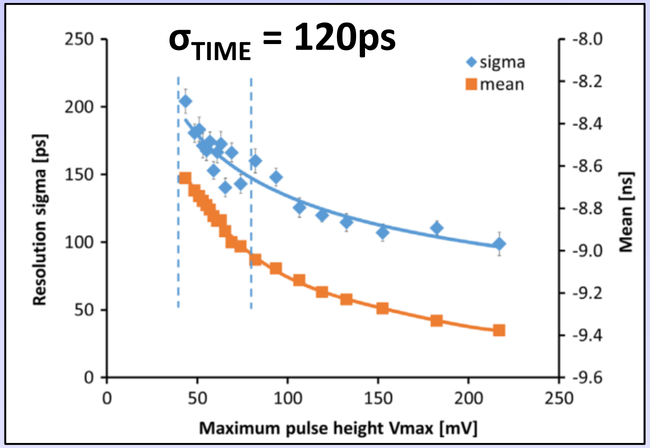
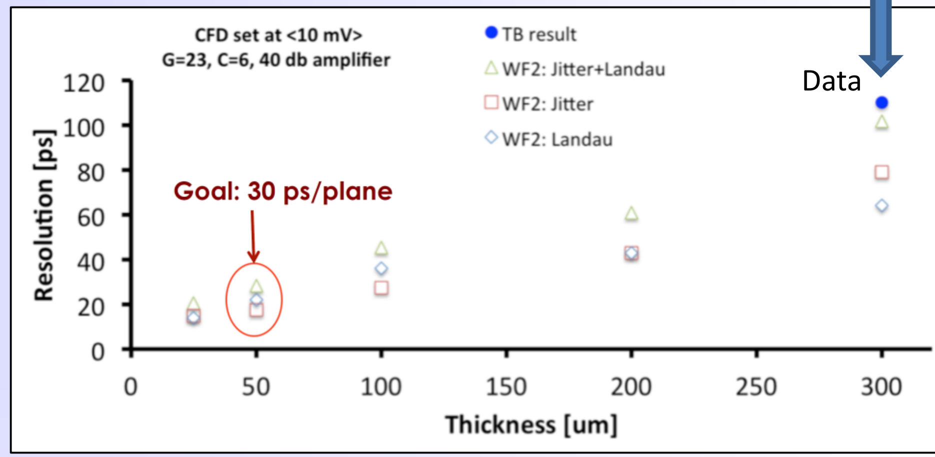
LGAD – Time resolution

[H. Sadrozinski et al. 2016., 10.1016/j.nima.2016.03.093]

- **Test beam data**
  - **300µm LGAD (Gain = 10), 120 GeV π**

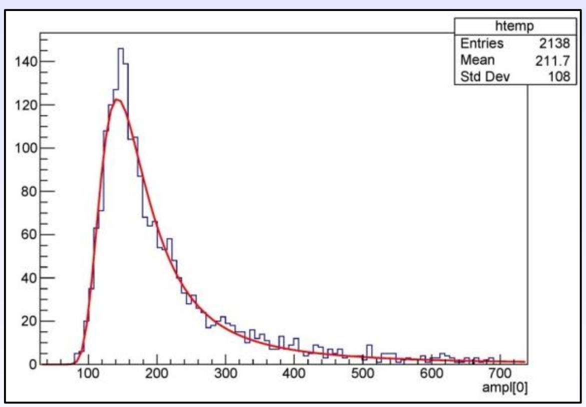


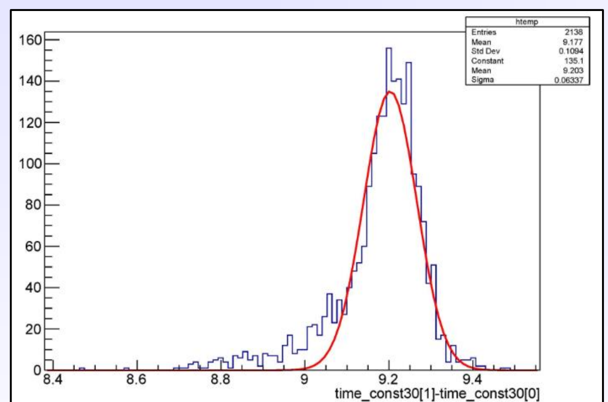
- **Time resolution as predicted by simulations**
  - **Weightfield 2 program**



[N.Cartiglia, RD50 Workshop 12/2015]

- **Beta source; 75µm LGAD (Gain = 5) + Quartz & SiPM trigger**
  - **Time difference between LGAD and trigger : 64ps (Preliminary)** [simulation predicts 50ps]



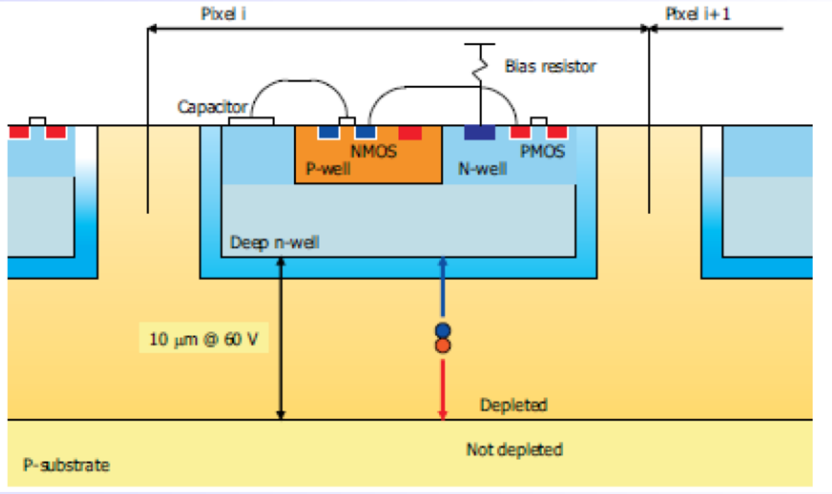


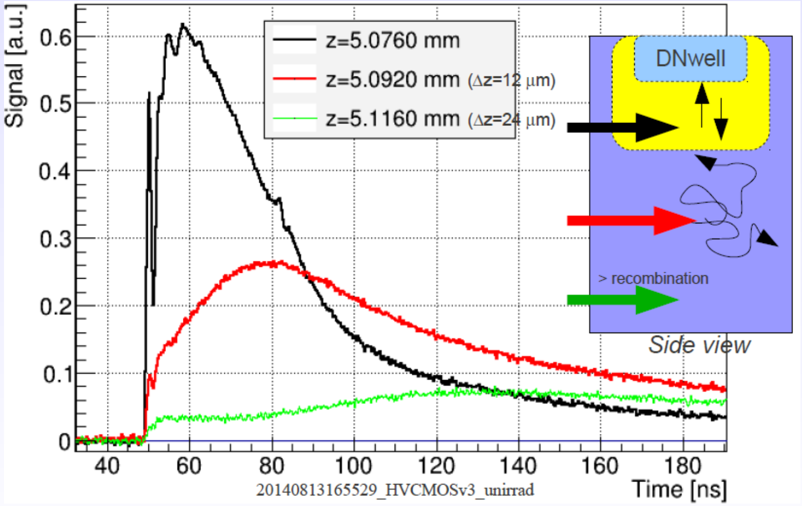
[H.Sadrozinski, May 2016 (preliminary)]

  - **LGAD potential applications: ATLAS HGTD, CTPPS , CMS timing layer in tracker, TOF (medical)**

CMOS & monolithic devices

- **RD50 started to work on HVCMOS device characterization in 2014**
  - close collaboration with ATLAS HVCMOS group and strip CMOS group
  - RD50 focus on characterizing radiation damage.
- **Typical (HV-)CMOS device**
  - Depleted active pixel detectors implemented in CMOS process
  - Sensor element is deep n-well in (usually) low resistivity (~10 Ωcm) p-type substrate
  - Depletion with 60 V ~ 10 μm → charge collection via drift of ~1000 electrons
  - Pixel and strip detectors possible
- **Charcterize e.g. edge-TCT measurements**





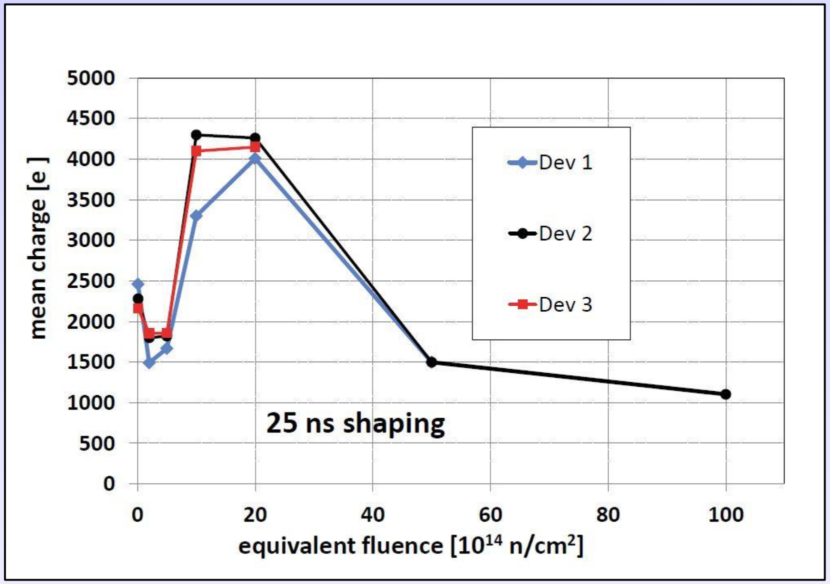
Drift and Diffusion component visible

Diffusion part will quickly disappear with irradiation

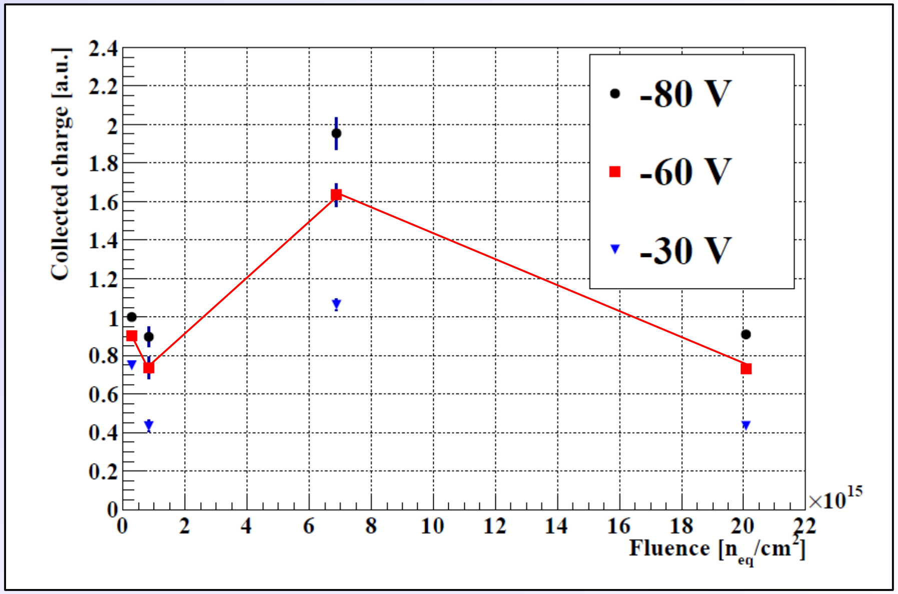
M. Fernandez, 25th RD50 Workshop, Nov. 2014

HVCMOS – CCE as function of fluence

- **350nm – neutron irradiation**
  - AMS, 350nm, CHESS-1, 20 Ωcm ($7 \cdot 10^{14}$cm^{-3})
  - 2mm x 2mm passive sensor (400 pixel)
  - Sr^{90}, 25 ns shaping, 120 V



- **180nm – neutron irradiation**
  - AMS, 180nm, HV2FEI4, 10 Ωcm ($1.4 \cdot 10^{15}$cm^{-3})
  - 100μm x 100 μm passive pixel
  - IR-laser, 5 ns integration



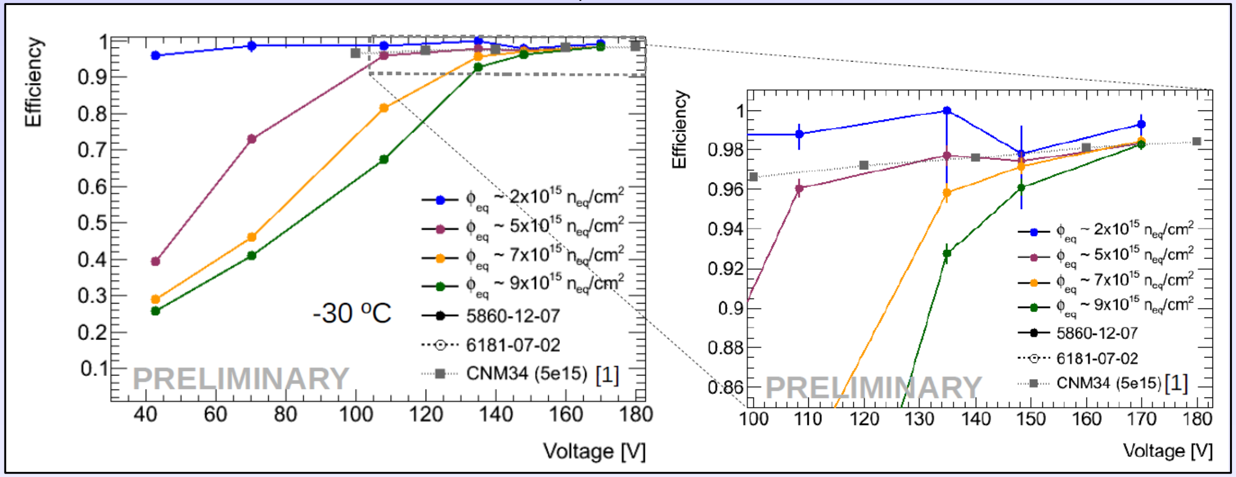
[A.Affolder et al., 2016 JINST 11 P04007, Strip CMOS collaboration]

[M.Fernandez-Garcia et al, 2016 JINST 11 P02016]

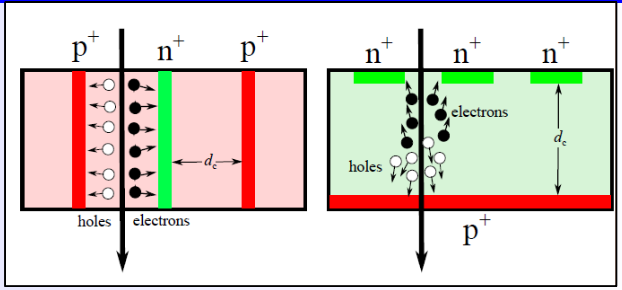
- **CCE rising above initial value for fluences in order of some 10^{15} n_{eq}/cm^2**
  - Up to about 10^{15} n_{eq}/cm^2 CCE decreases [diffusing charge gets trapped]
  - Above about 10^{15} n_{eq}/cm^2 CCE rises above initial value [reduction of N_{eff}, “acceptor removal”]
  - Above some 10^{15} n_{eq}/cm^2 CCE finally degrading [trapping, increase of space charge N_{eff}]

3D detectors

- **Development of 3D silicon sensors for innermost pixel layers at HL-LHC**
  - **Low depletion voltage (low power dissipation)**
  - **Low drift length (reduced trapping)**
- **Testbeam data**
  - Testbeam [ATLAS-ITK; FE-I4 3D modules]
    - 97.5% hit efficiency at $9\times10^{15} n_{eq}/cm^2$

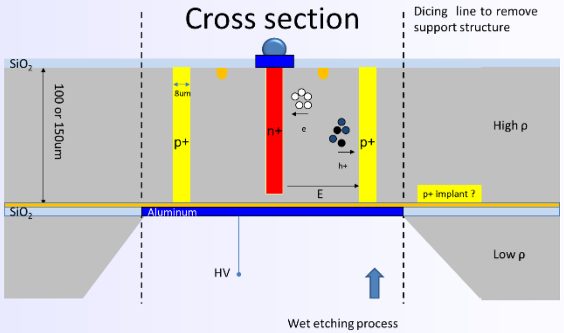


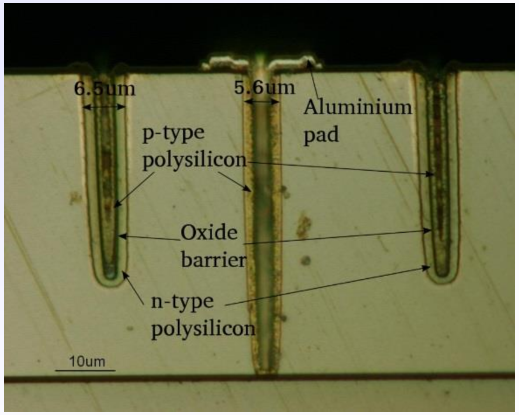
[I.Lopez et al., IFAE,UAB, RD50 Workshop, 12/2015]



3D sensor concept

Implementation as double and single sided (see below) process





[G.Pellegrini, RD50 Workshop, 12/2015]

- **Several recent production runs** [RD50 projects]
  - **joint 3D MPW pixel run with ATLAS, CMS, LHCb**
    - Various layouts, small pitch [μm^2] 50x50, 25x100, 50,125,..
  - **technology studies on SOI wafers**
    - small holes: down to 8um diameter at 230um depth or 5 um in single side 3D on SOI (50, 100 or 150 um layer)
    - temporary metal layers for pixel testing before UBM implemented

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Workplan for 2016/2017 (1/2)

- **Defect and Material Characterization** *(Convener (new) : Ioana Pintilie)*
  - 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
    - Working group on acceptor removal formed!
  - **Characterization of Nitrogen enriched silicon (starting p)**

- **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
    - Surface damage working group (….)
    - CCE and IV versus temperature
  - **Extend experimental capacities on edge-TCT (implement set-up at more RD50 institutions)**
    - Parameterization of electric field (fluence, annealing time, etc.)
    - Studies on charge multiplication processes
  - **Understand potential of Two Photon Absorption for sensor characterization**
  - **Continue parameterization of radiation damage (performance degradation) of LHC like sensors !**
  - **Explore fluence range to10^{17}cm^{-2}and beyond** (to prepare for future needs in forward physics and FCC)

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Workplan for 2016/2017 (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
    - 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?)**
    Continue to evaluate the possibility for application in ATLAS HGTD, CTPPS, CMS timing layers, …
  - **HVCMOS**
    - Continue characterization of existing devices (close collaboration with ATLAS HVCMOS working group)
    - End of year: submission of first RD50 devise in an engineering run on AMS 35 process

- **Full detector systems** *(Convener: G.Kramberger, Ljubljana University, Slovenia)*
  - **Further studies of thin (low mass) segmented silicon devices**
  - **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**

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RD50 common projects

- **RD50 common projects**
  - **Part of the RD50 R&D is performed within "RD50 common projects"**
    - Projects involving several RD50 institutes, one lead institution, evaluated by RD50, co-funded from RD50 fund, well defined time-line and objectives targeting a specific R&D question
  - **Most recent projects**
    - 2014-01 UBM for Avalanche Sensors (Giulio Pellegrini, CNM, Spain)
    - 2014-02 Avalanche PAD sensors (Giulio Pellegrini, CNM, Spain)
    - 2014-03 Sensors with ADVACAM (Anna Macchiolo, MPI, Munich)
    - 2014-04 RD50 common test beam (Marco Bomben, LPHNE, Paris)
    - 2014-05 Investigation of the properties of thin LGAD (Nicolo Cartiglia, Torino, Italy)
    - 2015-02 3D sensors for HL-LHC (Marcos Fernandez Garcia, Santander, Spain)
    - 2015-03 Evaluation of Two Photon Absorption - TPA (Ivan Vila, Santander, Spain)
    - 2015-04 Doping profiling of LGAD and other devices (Hartmut Sadrozinski, SCIPP, USA)
    - 2016-01 NitroSil project: Nitrogen doped silicon (Alexander Dierlamm, Karlsruhe, Germany)
    - 2016-02 Gallium doping (David Flores, CNM, Barcelona)
  - ***Under discussion***
    - *Surface damage simulation (Marco Bomben, LPHNE Paris)*
    - *Carbon enrichment of silicon (Gregor Kramberger, Ljubljana)*
    - *RD50 CMOS submission (Gianluigi Casse, Liverpool, UK / Vitaliy Fadeyev, SCIPP, USA)*
    - *RD50 pion irradiation (Tilman Rohe, PSI, Switzerland)*

RD50 main achievements & links to LHC Experiments

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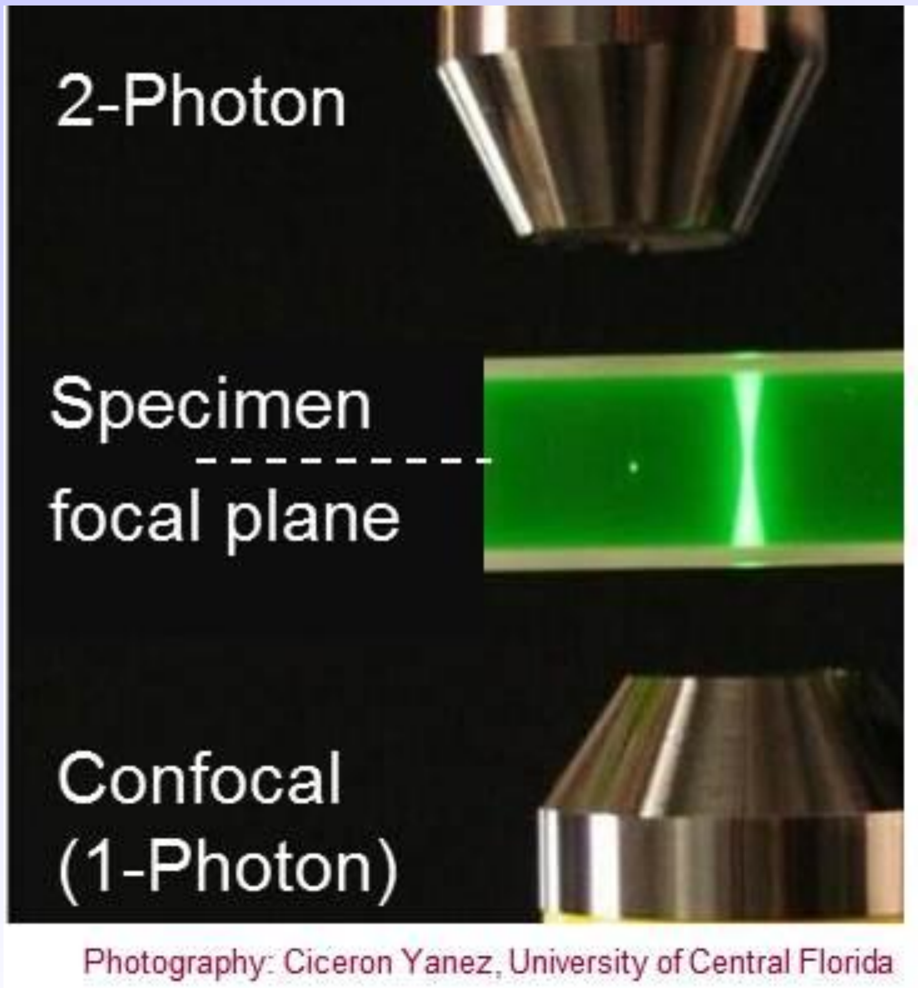
Some important contributions of RD50 towards the LHC upgrade detectors:

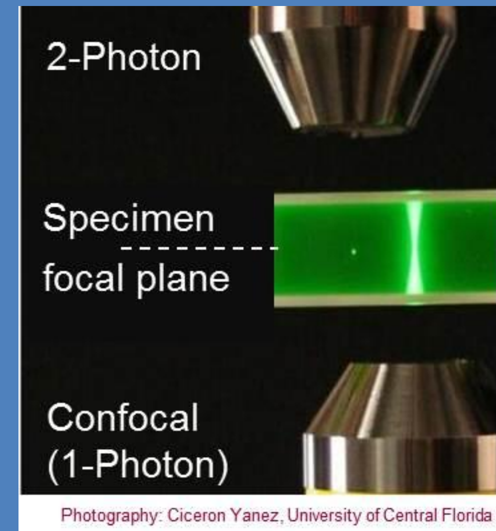
- **p-type silicon** (brought forward by RD50 community) is the base line option for the ATLAS and CMS Strip Tracker upgrades
- n- MCZ and oxygenated Silicon (introduced by RD50 community) might improve performance in mixed fields due to compensation of neutron and proton damage: MCZ is under investigation in ATLAS, CMS and LHCb
- Double column **3D detectors** developed within RD50 with CNM and FBK. Development was picked up by ATLAS and further developed for ATLAS IBL needs.
- RD50 results on very highly irradiated **planar segmented sensors** have shown that these devices are a **feasible option for the LHC upgrade**
- **RD50 data are essential input parameters** for planning the running scenarios for LHC experiments and their upgrades (evolution of leakage current, CCE, power consumption, noise,….) and sensor design (TCAD parameters).
- **Charge multiplication** effect observed for heavily irradiated sensors (diodes, 3D, pixels and strips). Dedicated R&D launched in RD50 to understand underlying multiplication mechanisms, simulate them and optimize the CCE performances. Evaluating possibility to produce fast segmented sensors?
- **New characterization techniques** for the community: Edge-TCT, Alivaba readout, TPA-TCT, … part of them now available through spin-off companies.
- **Close links to the LHC Experiments:**
  - **Many RD50 groups are involved in ATLAS, CMS and LHCb upgrade activities (natural close contact).**
  - **Common projects with Experiments:**
    Irradiation campaigns, test beams, wafer procurement and common sensor projects.
  - **Close collaboration with LHC Experiments on radiation damage issues of present detectors.**

Device Characterization

TPA – Two Photon Absorption



Two Photon absorption:



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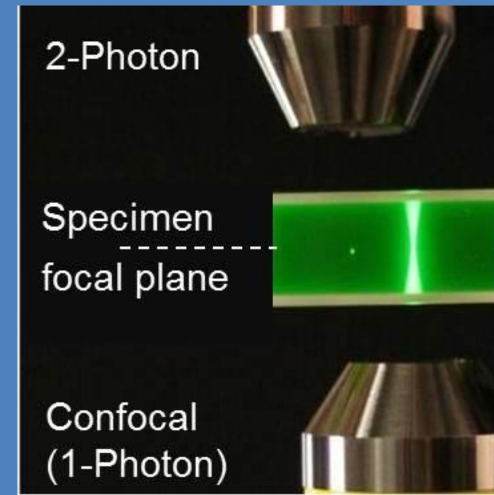
TPA – Two Photon Absorption

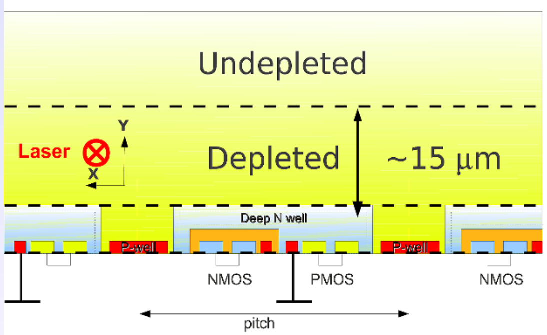
- **Investigation on a new technique for sensor characterization (TPA – TCT)**
  - **Deposition of charge at specific position in detector**
  - **Laser: $\lambda \sim 1300$ nm; P ~ 50-100 pJ; $\Delta T \sim 240$ fs**
  - **Proof of principle presented last LHCC**
  - **Example of application:**
    - HVCMOS sensors (AMS 180nm), 10 ohmcm
    - 100µm x 100 µm passive pixel, measured at 80V, 20°C

Two Photon absorption:

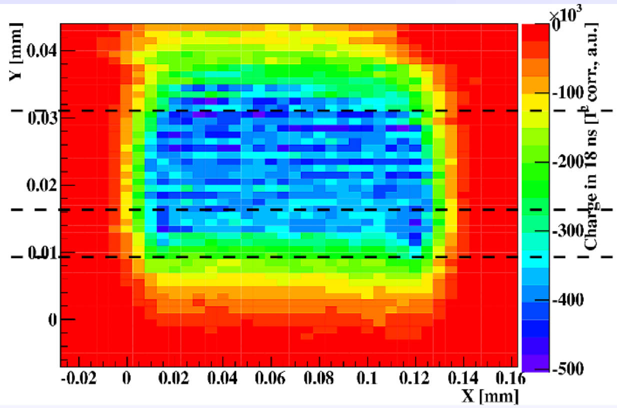


Photography: Ciceron Yanez, University of Central Florida

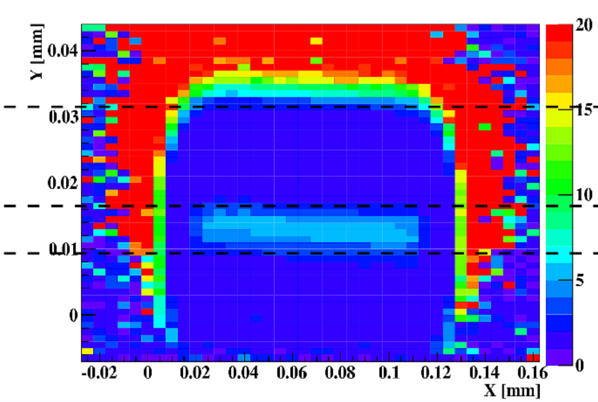
[M.Fernandez-Garcia et al, VCI 2016, Feb.2016]



Sketch of HVCMOS sensor



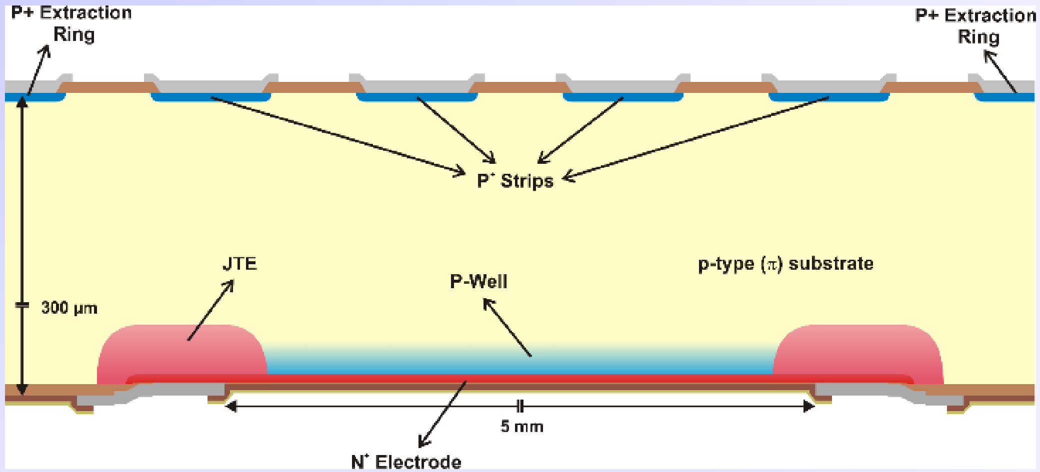
Map of charge collected within 10ns



Map of collection time needed to get 98% of charge

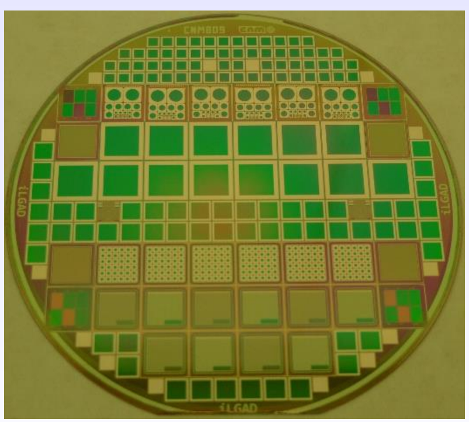
The “inverse LGAD” – iLGAD

- **Decouple multiplication layer from segmented electrodes**
  - **Strip, pixel and pad structures with this configuration produced in 2016**

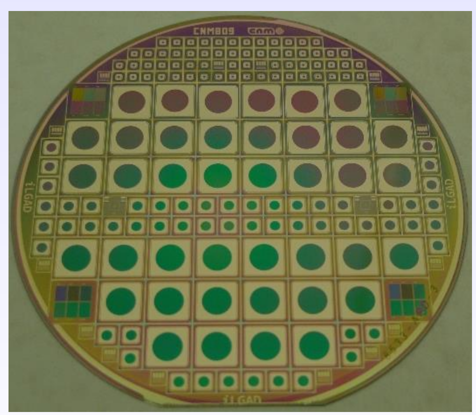


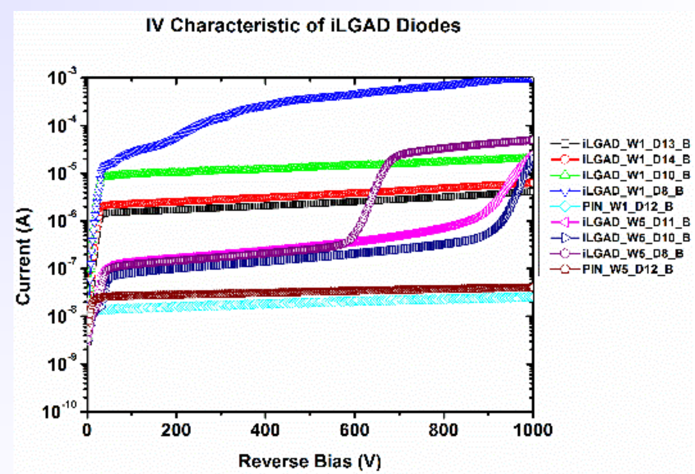
  - First wafers show good electrical performance (CV,IV), intensive testing ahead

Front-Side



Back-Side





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Spare Slides

- Some spare slides

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

  - Most results presented here have been shown on the last RD50 Workshop

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Recent key results

- **Progress in understanding microscopic defects**
  - Defects responsible for positive space charge in DOFZ, MCZ and EPI and defects provoking reverse annealing are characterized!
  - Consistent list of defects produced covering electron, gamma, neutron and proton/pion damage
- **TCAD simulations : Good progress on simulations *[Note: RD50 profiting from strong CMS simulation group]***
  - Commercial TCAD packages well understood and proved to be well adopted to our needs (defect description)
  - Simulations can reproduce pulse shapes, depletion voltage, charge collection and leakage current. Getting predictive capabilities!
- **Systematic analysis of the Charge multiplication mechanism and exploitation as timing detector**
  - Noise issue particularly important for exploitation of this feature in Experiments
  - New dedicated sensors produced to test avalanche effects, working after irradiation up to some 10^{14}, good timing performance
- **Consolidation of data obtained on p-type and thin segmented sensors**
  - Further results on radiation tolerance and further results on long term annealing
  - Thin sensors seem to extend fluence reach of silicon detectors; Optimization: Optimum thickness depends on many parameters !
- **Slim and active edges**
  - Further progresses towards reduction of insensitive area (edges) of detectors
- **New structures based on mixed technologies**
  - Exploitation of DRIE etching: 3D-trench electrode, semi-3D sensors; planar strip with trenched electrodes, active edge planar pixel; Use of deep implantation for controlling avalanches.
- **Use of tools developed in framework of RD50: ALIBAVA & Edge-TCT & Beam telescope**
  - Edge-TCT and TCT systems are now produced centrally and can be procured by interested groups
  - Use of the ALIBAVA readout system in many RD50 institutions

Summary on defects with strong impact on device performance after irradiation

RD50

- **Most important defects** *[for details and references see JAP 117, 164503, 2015]*

Defect	Assignment and particularities	Configuration	Energy levels (eV) cross section (cm^2)	Impact on electrical characteristics of Si diodes at room temperature (RT)
E(30K)	-Not identified extended defect -Donor in tupper part of the bandgap, strongly generated by irradiation with charged particles. [10,29] -Linear fluence dependence. [this work]	$E(30K)^{0/+}$	E_C-0.1 $\sigma_n = 2.3\times10^{-14}$	- Contributes in full concentration with positive space charge to N_{eff}
BD	*Thermal double donor (TDD2)* - point defect - Bistable donor existing in two configurations (A, B) in the upper part of the bandgap, strongly generated in Oxygen rich material. [24, 26, 27]	$BD_A^{0/++}$	E_C - 0.225 σ_n= 2.3 x 10^{-14}	- It contributes twice with its full concentration with positive space charge to N_{eff}, in both of the configurations
		$BD_B^{+/++}$	E_C - 0.15 σ_n= 2.7 x 10^{-12}	
I_p	- Not identified point defect - Suggestions: V_2O or a C related center. [22-24, 10] - Amphoteric defect generated via a second order process (quadratic fluence dependence), strongly generated in Oxygen lean material. [22-24, this work]	$I_p^{+/0}$	E_V + 0.23 σ_p= (0.5-9) x10^{-15}	- No impact
		$I_p^{0/-}$	E_C - 0.545 σ_n=1.7 x10^{-15} σ_p= 9 x 10^{-14}	- Contributes to both N_{eff} and LC
E_{75}	*Tri-vacancy (V3)* - small cluster -Bistable defect existing in two configurations (FFC and PHR) with acceptor energy levels in the upper part of the bandgap. [10, 28, 30-33] -Linear fluence dependence. [this work]	FFC $V_3^{-/0}$	E_C - 0.075eV σ_n = 3.7x10^{-15}	- No impact
E4		PHR $V_3^{=/-}$	E_C - 0.359 σ_n = 2.15x10^{-15}	- No impact
E5		PHR $V_3^{-/0}$	E_C - 0.458 σ_n = 2.4x10^{-15} σ_p = 2.15x10^{-13}	- Contributes to Leakage Current
H(116K)	- Not identified extended defect - Acceptor in lower part of the bandgap. [10, 29] - Linear fluence dependence. [this work]	$H(116K)^{0/-}$	E_V + 0.33 σ_p=4 x 10^{-14}	Contribute in full concentration with negative space charge to Neff **Reverse annealing!**
H(140K)	- Not identified extended defect - Acceptor in the lower part of the bandgap. [10, 29] - Linear fluence dependence. [this work]	$H(140K)^{0/-}$	E_V + 0.36 σ_p=2.5 x 10^{-15}	
H(152K)	- Not identified extended defect - Acceptor in lower part of the bandgap. [10, 29] - Linear fluence dependence. [this work]	$H(152K)^{0/-}$	E_V + 0.42 σ_p=2.3 x 10^{-14}	

Summary of LGAD Activities at IMB-CNM Clean Room

No. Run	Tipo	# Wafers	PiN Waf	Mask Set	P-Well	Drive-in	Implant Mask	Year
5176	1st APD	8	-	CNM 458	3 Doses	Long	Photoresist	2010
5646	2nd APD	9	2	CNM 458	6 Doses	Short	Photoresist	2010
5730	3rh APD	4	2	CNM 458	2 Doses	Short	Oxide	2011
5870/5883	4th APD	4	-	CNM 458	2 Doses	Short	Oxide	2011
5944/5982	5th APD	5	1	CNM 458	3 Doses	Short	Oxide	2011
6474	1st LGAD	11	1	CNM 652	8 Doses	Short	Oxide	2012
6884/6951	2nd LGAD	13	1	CNM 652	3 Doses	Short	Oxide	2013
6984/7062	3th LGAD	7	1	CNM 652	3 Doses	Short	Oxide	2013
7509	4rh LGAD	7	1	CNM 761	3 Doses	Short	Oxide	2014
7735	1st Gallium	3	-	CNM 761	3 Doses	Short	Oxide	2014
7782/8642	1st 200 µm	10	-	CNM 761	5 Doses	Short	Oxide	2014

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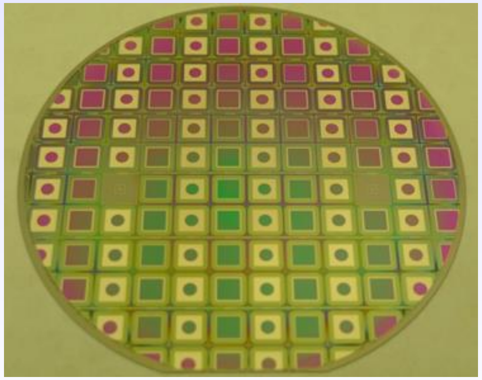
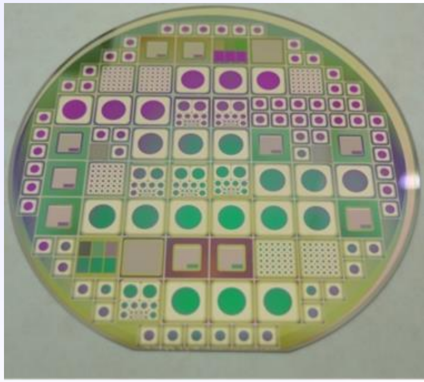
Summary of LGAD Activities at IMB-CNM Clean Room

No. Run	Tipo	# Wafers	PiN Waf	Mask Set	P-Well	Drive-in	Implant Mask	Year
7859	5th LGAD	6	-	CNM 761	3 Doses	Short	Oxide	2015
8373	1st SOI 6”	4	2	CNM 784	1 Dose	Short	Oxide	2015
8533	1st iLGAD	6+3	-	CNM 809	2 Doses	Short	Oxide	2015
8622	6th LGAD	6+3	-	CNM 761	2 Doses	Short	Oxide	2016
9088	1st SOI 50 µm	14	1	CNM 827	3 Doses	Short	Oxide	2016
9089	Ga diodes	15	15	CNM 809	-	Short/Long	Oxide	2016
9254	2nd Epi 50 & 75um	5	-	CNM 827	1 Dose	Short	Oxide	2016

- Good
- Under electrical testing
- In fabrication
- Calibration run

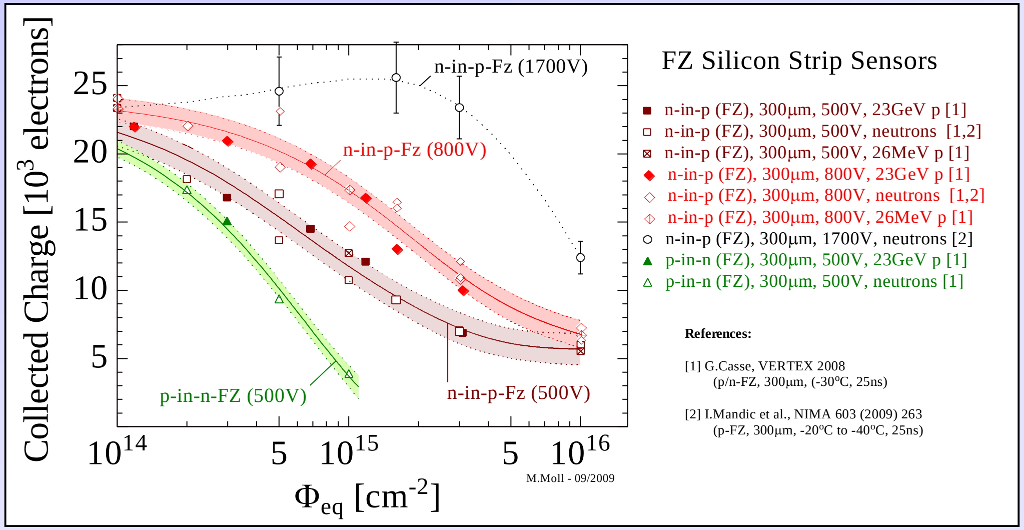


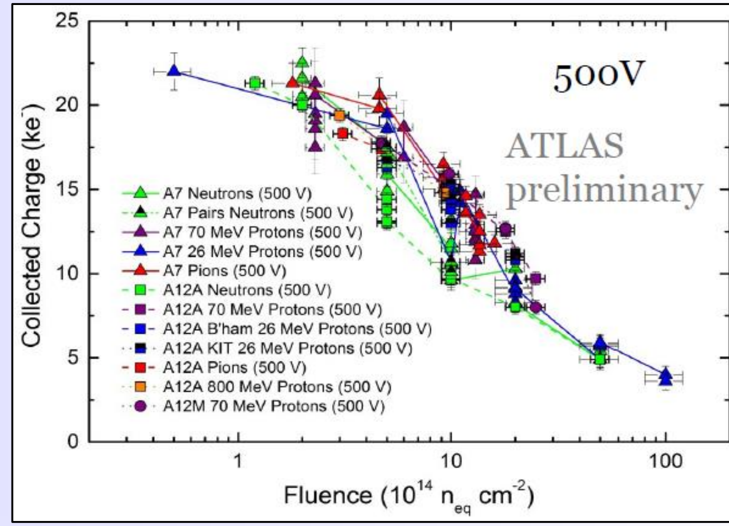


R&D mainly financed by Spanish research project and partially by CERN RD50 collaboration

RD50 Reminder: Segmented sensors: n^+ vs. p^+ readout

- **p-type strip sensors with n^+ readout** *(brought forward by RD50)*
  - **are now the sensor choice for ATLAS and CMS Tracker upgrades**

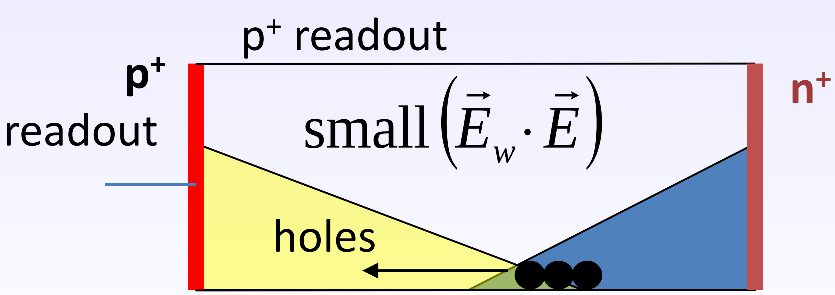


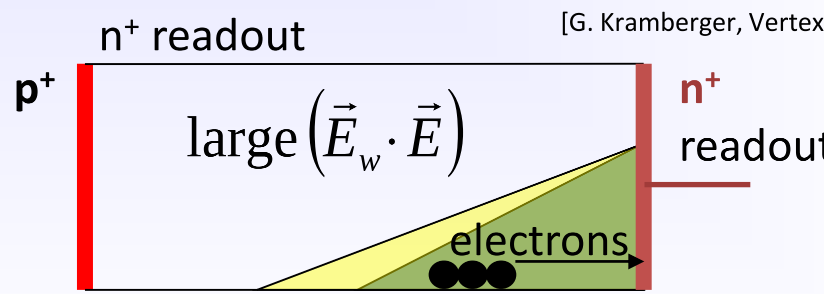


S. Wonsak, 25th RD50 Workshop Nov. 2014

- **n^+-electrode readout ("natural in p-type silicon"):**
  - favorable combination of weighting and electric field in heavily irradiated detector
  - electron collection, multiplication at segmented electrode
- **Situation after high level of irradiation:**

[G. Kramberger, Vertex 2012]





TCAD - Simulations

- **Device simulation of irradiated sensors**
  - **Using: Custom made simulation software and Silvaco & Synopsis TCAD tools**
  - **RD50 simulation working group**
    - Good progress in reproducing experimental results on leakage current, space charge, E-Field, trapping …..
    - However, …. still some work on going to “inter-calibrate” the tools
    - 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

Measured defects ➔ *TCAD input*