RD50

LHCC – 3.June 2015, CERN

RD50 Status Report – June 2015

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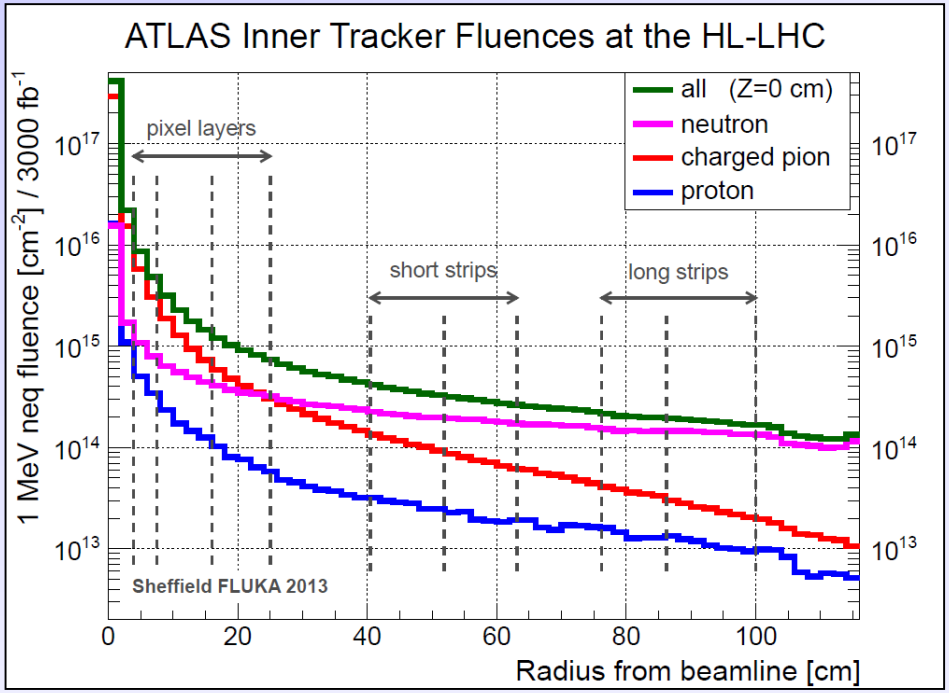
OUTLINE:

- **RD50 Collaboration**
- **Scientific results**
  - **Defect and Material Characterization**
  - **Detector Characterization**
  - **New Detector Structures**
  - **Full Detector Systems**
- **RD50 key results 2014/2015**
- **RD50 Work Program 2015/2016**
- **RD50 achievements**

Motivation and Challenge

- **LHC upgrade** *(and beyond…. FCC)*
  - **upgrade of the LHC to the High Luminosity LHC (HL-LHC)** *after LS3 (~2024)*
  - **expected integrated luminosity: 3000 fb^{-1}** *(x6 nominal)*



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

Silicon detectors will be exposed to hadron fluences equivalent to more than 10^{16} n/cm^2

➔ detectors used now at LHC cannot operate after such irradiation

<u>RD50 mission</u>: development and characterization of silicon sensors for HL-LHC and beyond, analyze and understand radiation damage in silicon detectors

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The RD50 Collaboration

- **RD50:** ***49 institutes and 275 members***

41 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), Ukraine (Kiev), United Kingdom (Glasgow, 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)

- *No changes since last LHCC report in June 2014*

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

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RD50 Organizational Structure

Co-Spokespersons

Gianluigi Casse **and** ***Michael Moll***

(Liverpool University) (CERN PH-DT)

Defect / Material Characterization

Mara Bruzzi
(INFN & Uni Florence)

- **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)

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 Avalance Det.**
- **Slim Edges**
- **HVCMOS**

- 3D (R.Bates)
- LGAD (V.Greco)
- Slim Edges (V.Fadeyev)

Full Detector Systems

Gregor Kramberger
(Ljubljana University)

- **LHC-like tests**
- **Links to HEP**
- **Links electronics R&D**
- **Low rho strips**
- **Sensor readout (Alibava)**
- **Comparison:**
  - **pad-mini-full detectors**
  - **different producers**
- **Radiation Damage in HEP detectors**

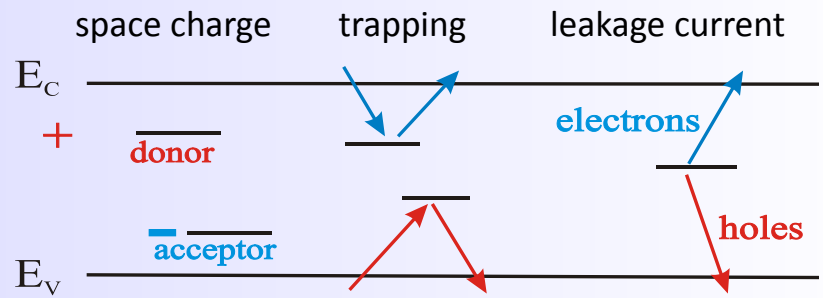
- Test beams (M.Bomben & G.Casse)

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

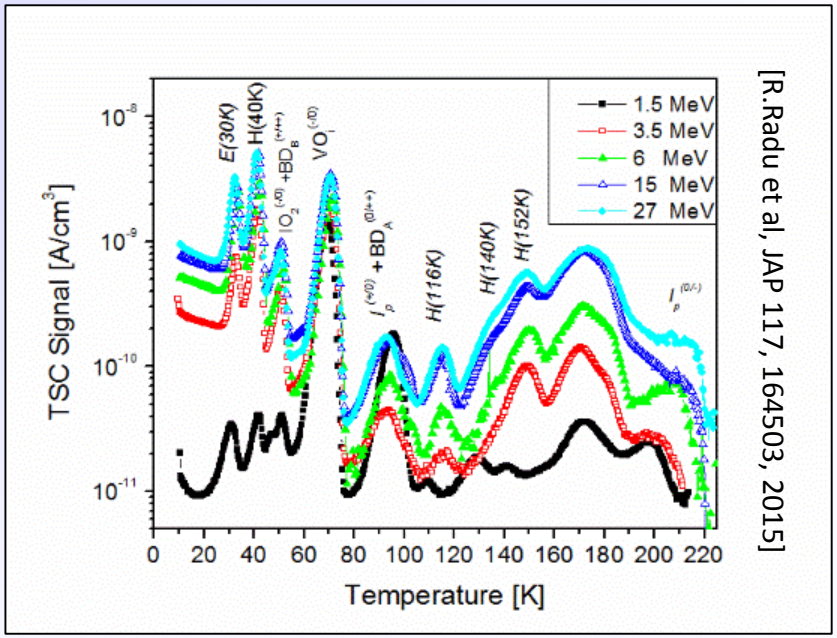
Defect & Material Characterization

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*



Example: TSC measurement on defects produced by electron irradiation (1.5 to 27 MeV)

- **RD50: several hundred samples irradiated with protons, neutrons, electrons and ^{60}Co-γ**

… significant progress on identifying defects responsible for sensor degradation over last 5 years!

Summary on defects with strong impact on device performance after irradiation

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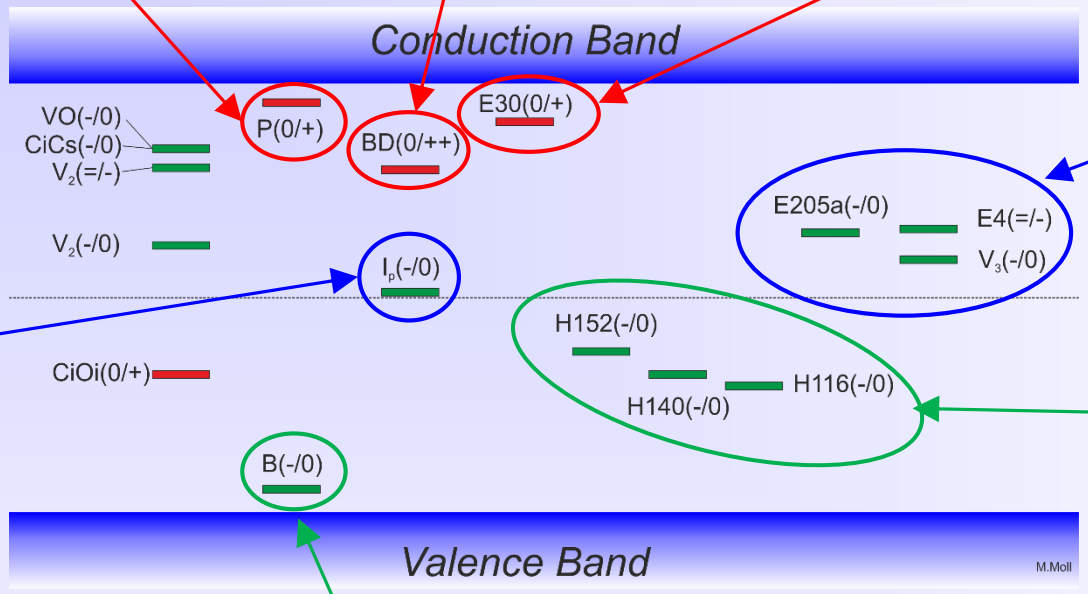
- **Some identified defects**

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)

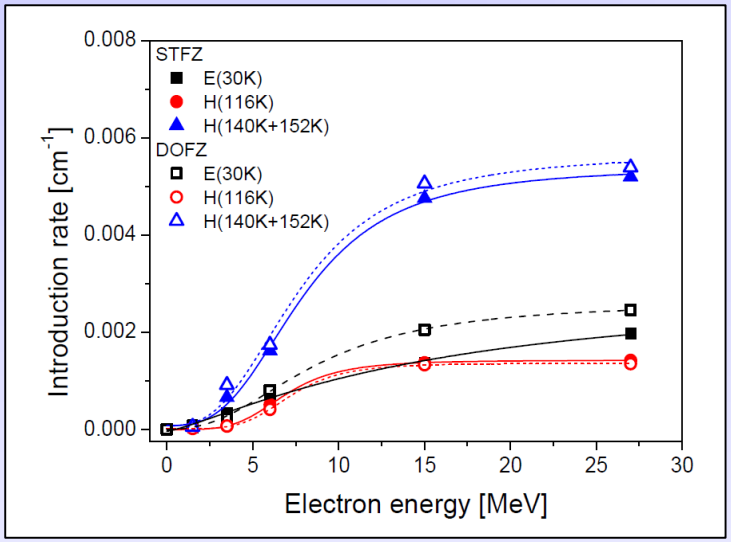
Boron: shallow dopant (negative charge)

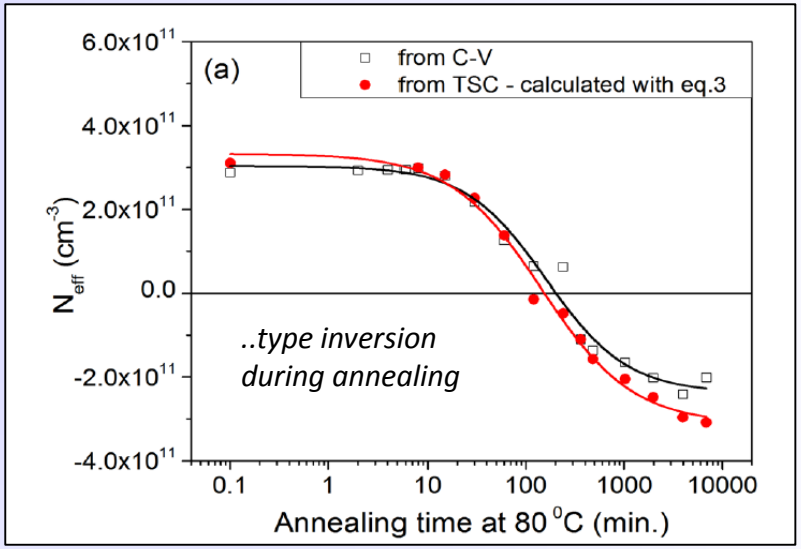
A table with levels and cross sections is given in the spare slides.

- **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!

Electron Damage: Defects & NIEL

- **Study on defects concentrations and damage after electron irradiation (1.5 to 27 MeV)**
  - **Aim: Understand defect generation as function of electron energy ("silicon recoil energy scan")**
  - **What is the threshold for defect cluster formation in terms of PKA (Primary Knock-on Atom) energy?**





Example: 15 MeV e (2.2 x10^{14} e/cm^2), STFZ

- Electrons above ≈ 3 MeV produce "cluster damage"
- Reverse annealing (N_{eff}) observed and matching the observed defect concentrations (H-defects)

- **Observation on the NIEL (Non Ionizing Energy Loss) for electrons below 30 MeV**
  - The leakage current damage factor (alpha) does not scale with the "classical NIEL"
  - We had to use the "effective NIEL" as calculated by Molecular Dynamics (MD) calculations to describe the leakage current and the introduction of cluster related defects correctly

[Effective NIEL: Inguimbert et al., IEEE TNS 57 (2010)1915]

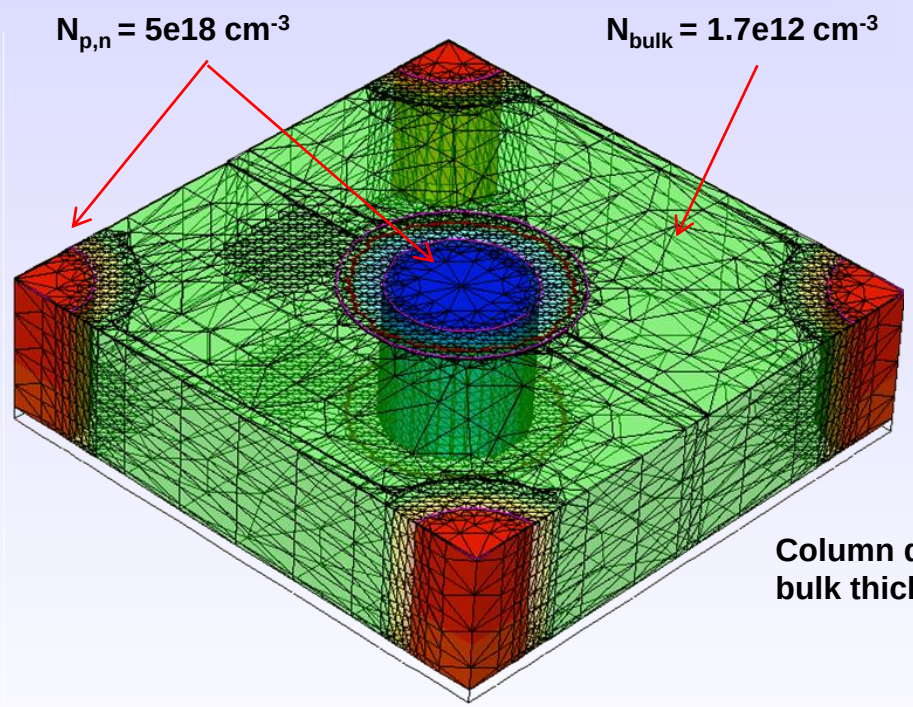
[more details: R.Radu et al, JAP 117, 164503, 2015]

Device Characterization & Simulation

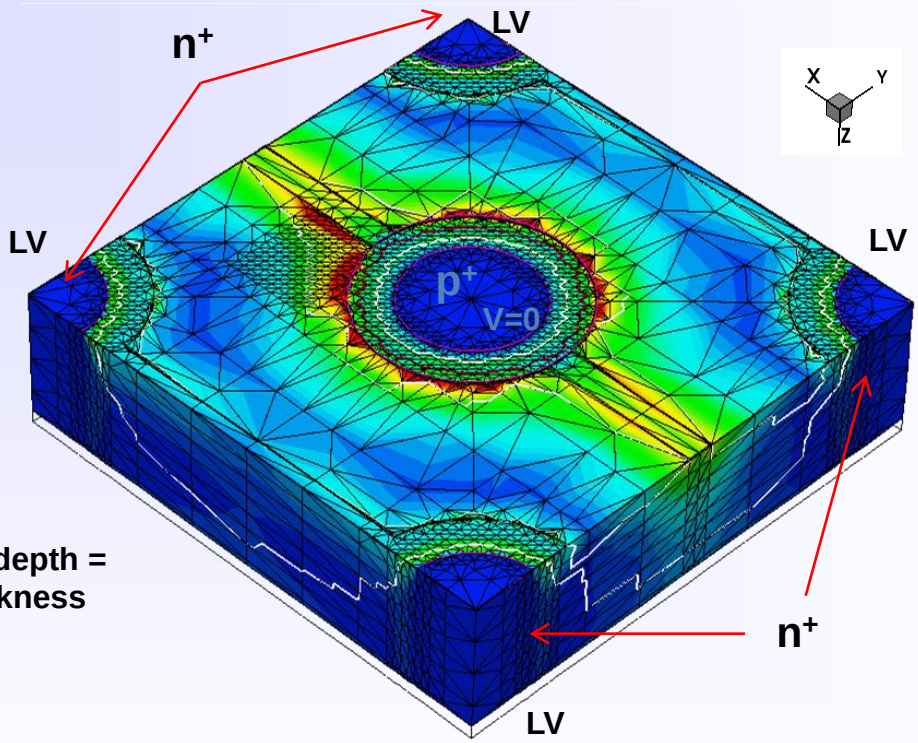
TCAD simulations

- **Why do we need TCAD simulations ?**
  - **Complexity of the problem**
    - Coupled differential equations (semiconductor equations)
    - Impact of defects depending on local charge densities, field-strength, … ("feedback loop")
    - Complex device geometry and complex signal formation in segmented devices ….
    - Interplay of surface and bulk damage
    - *Example: 3D sensors*

Doping profiles



Electric field distribution in 3D detector (Al & oxide layer transparent for clarity)

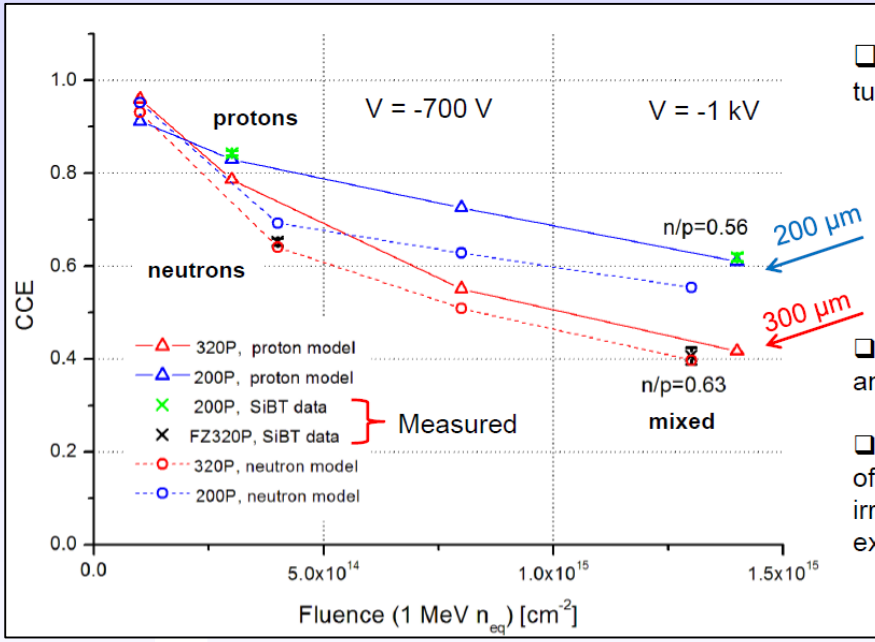


Column depth = bulk thickness

Example of 3D sensor: T.Peltola (HIP, Helsinki): CMS & RD50

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, annealing,…).*
  - Close collaboration with CMS Tracker sensor simulation working group (A.Messineo)
  - **Example of results (simulation vs. measurement):**
    - Comparison between simulation results (Synopsis TCAD) and CMS test beam data (strip sensors)
    - Surface damage included via interface charge layer.



❑ CCE simulations using 2 trap model + tuned Q_f

Fluence [cm^{-2}]	Q_f(neutron) [cm^{-2}]	Q_f(proton) [cm^{-2}]
1e14	6e10	1.4e11
3e14	-	3e11
4e14	9e10	-
8e14	3.25e11	7.1e11
1.3e15	6e11	-
1.4e15	-	1.2e12

❑ Test beam measured CCE of FZ320P and MCz/FZ200P samples is reproduced

❑ Fixed Q_f values used to **predict CCE** of non-measured detectors with equal irradiation type/dose to detectors with experimentally matching CCE

[T.Peltola, Vertex 2015– June 2015]

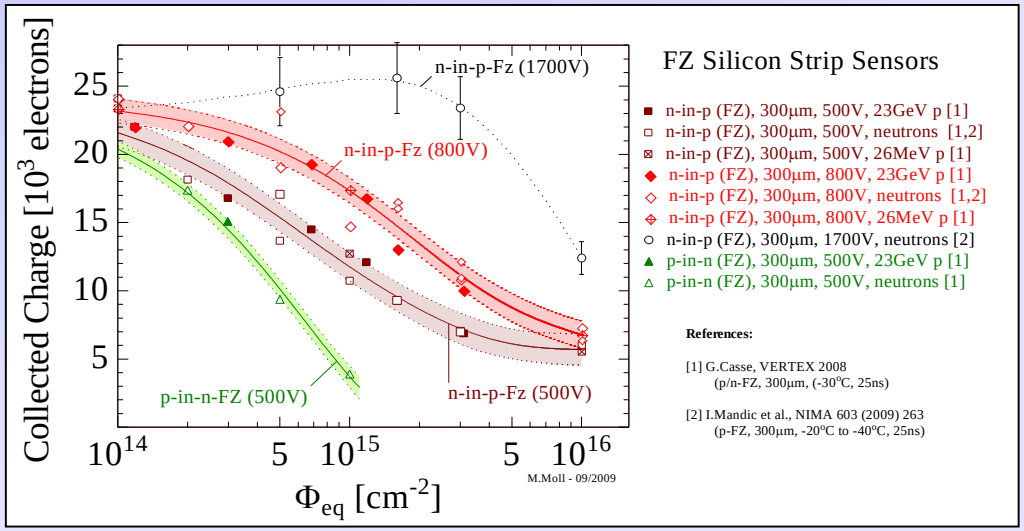
Simulations of irradiated devices in TCAD are getting predictive power!

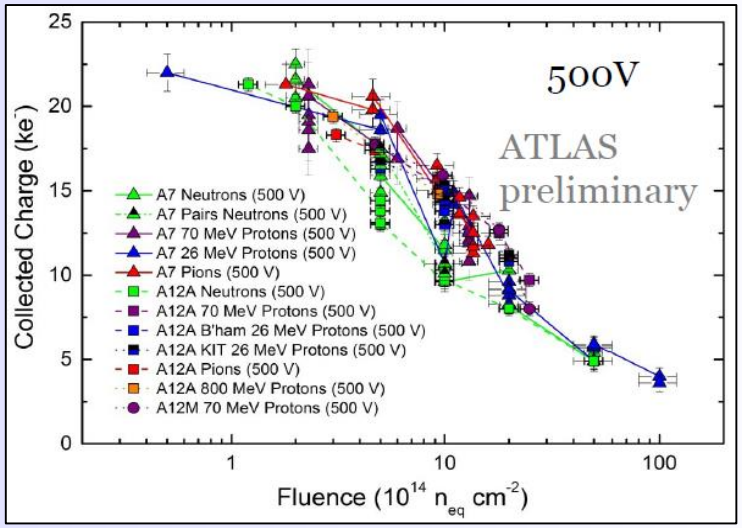
Segmented Sensors with read-out at the n^+ contact

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

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**

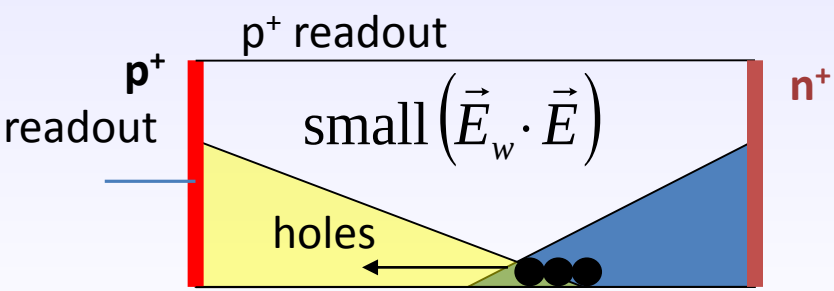


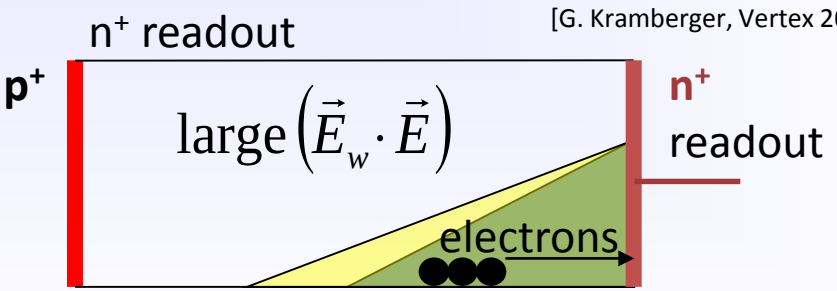


S. Wonsak, 25th RD50 Workshop Nov. 2014

- **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:**

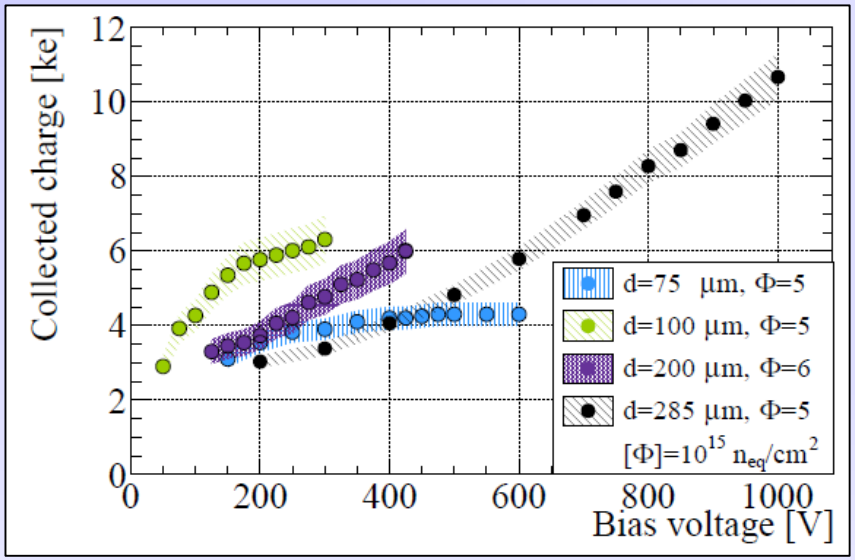
[G. Kramberger, Vertex 2012]

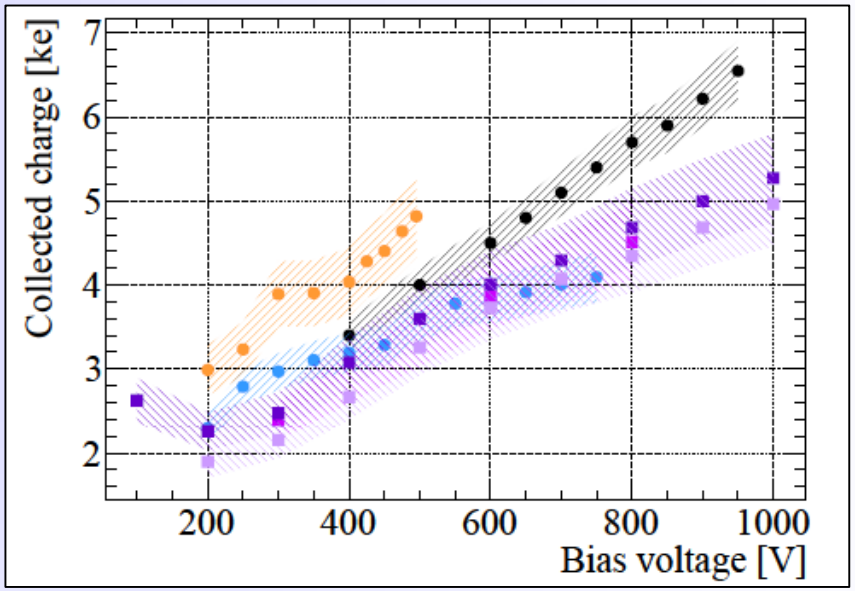




Thin p-type pixel sensors

- **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**

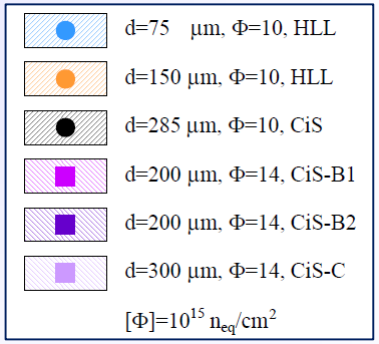




- **Detectors irradiated with 5 10^{15} n_{eq}/cm^2**
- **100μm thick sensors give more charge than 75μm thick sensors, both saturate with voltage**
- **200 μm thick sensors give more charge than 300 μm thick sensors at moderate voltage**
- **Beam tests show 97-99% hit efficiency**

  (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

Slim Edges

Minimize "dead" area of sensors: several techniques

PTI (V. Eremin) & CERN (G. Ruggiero, NIM A604, 2009, 242-245)

SCP slim edges

- Exploits scribe and cleave technique on planar and 3D devices, passivated edge

Laser, XeF_2 etch, DRIE etch, saw cut

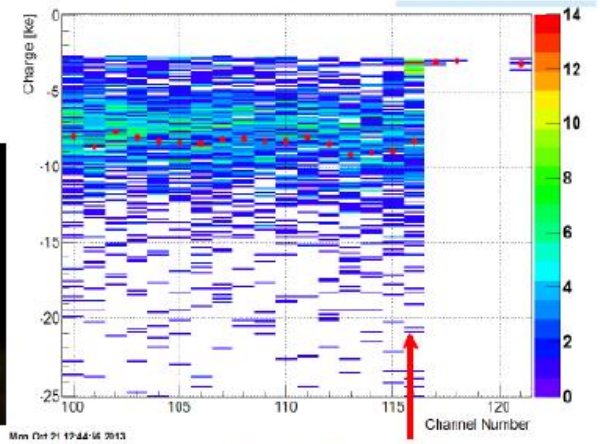
Tweezers, new: Dynatex machine

Native Oxide + Radiation or PECVD (n-type), ALD (p-type)

V. Fadeyev et al, NIM A 731 (2013) 260
V. Fadeyev, 23rd RD50 Workshop Nov. 2013

CIS n-in-p, 285 µm thick, 150 µm slim edge, 800 V bias, $4*10^{15}$ neq/cm^2

Sr90, Alibava, single cluster plot

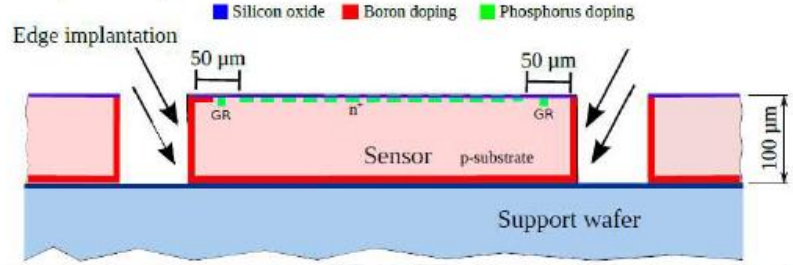


Similar median charge as for other strips

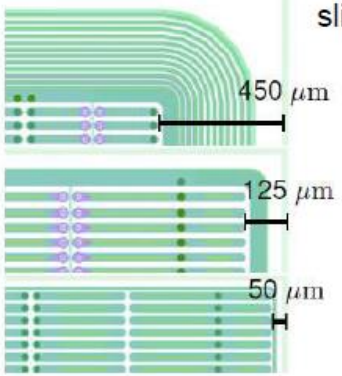
Also under development at HPK

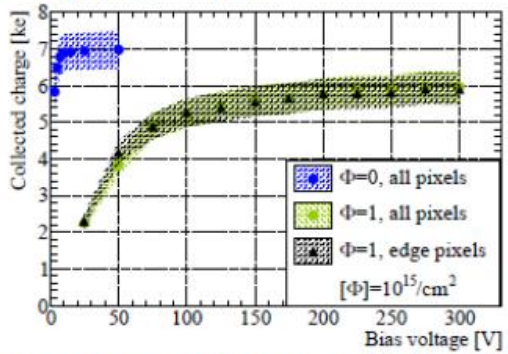
VTT/MPI active edges project

- Pixel sensors with slim edges, trenches doped by four-quadrant implantation



FE-I3 FZ silicon, 100 µm thick, 125 µm slim edge, threshold: 1500 e$^-$





Hit efficiency (98.9+-3)% at 300 V after $5*10^{15}$ neq/cm^2

S. Terzo, 23rd RD50 Workshop Nov. 2013

Overall efficiency, I_{leak} and noise unaffected by edge-cutting

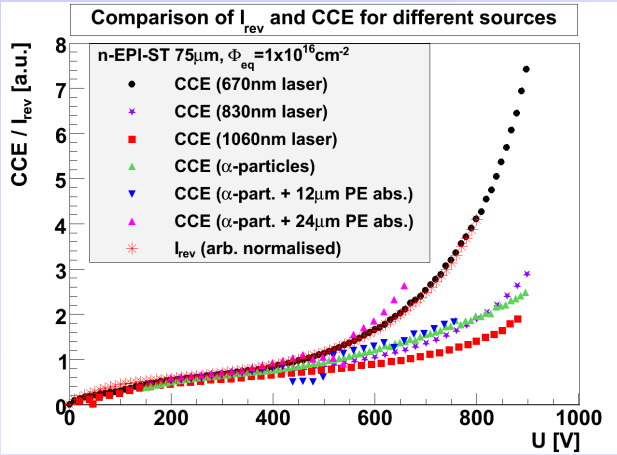
New structures

Charge Multiplication
(Sensors with intrinsic gain)

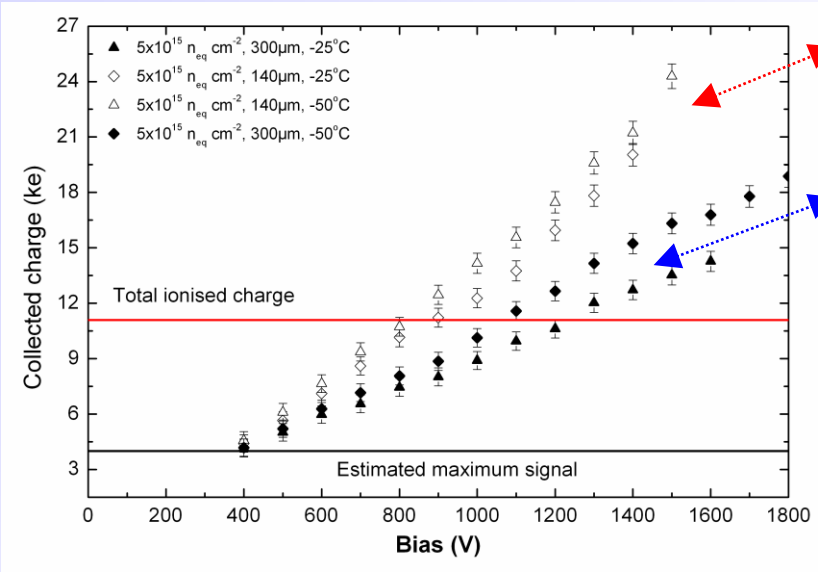
HVCMOS
(towards monolithic sensors)

RD50 Reminder: Charge Multiplication

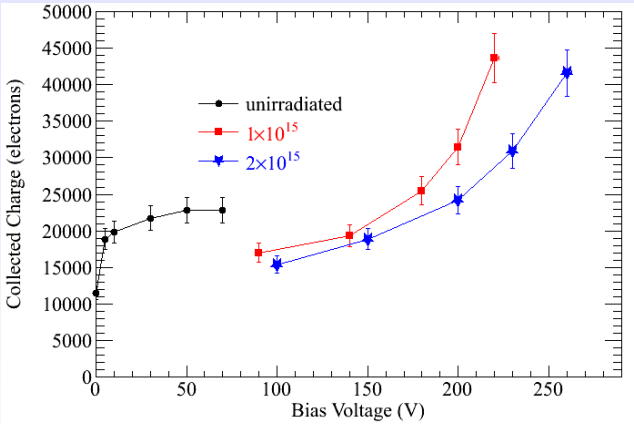
- **Charge Multiplication observed and characterized after high levels of irradiation with different techniques and in several different types of devices**



Diodes ($\Phi_{eq}=10^{16}$ cm^{-2})
Leakage Current & Charge Collection



Strip sensors ($\Phi_{eq}=5\times10^{15}$ cm^{-2}, 26 MeV p)
Charge Collection (Beta source, Alibava)



3D sensors ($\Phi_{eq}=1\text{-}2\times10^{15}$ cm^{-2})
Charge Collection (test beam)

Questions:

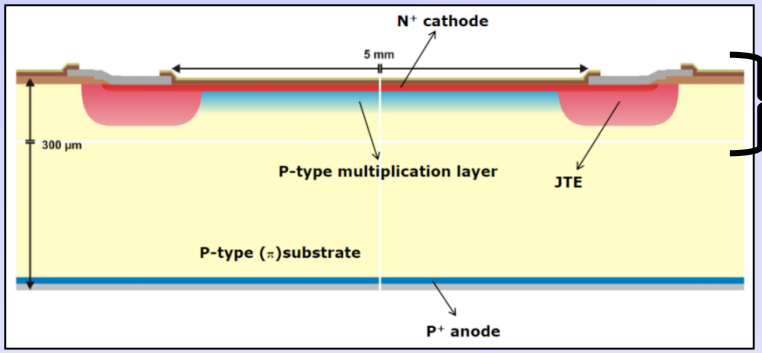
- **Can we simulate and predict charge multiplication ?**
- **Can we better exploit charge multiplication?**

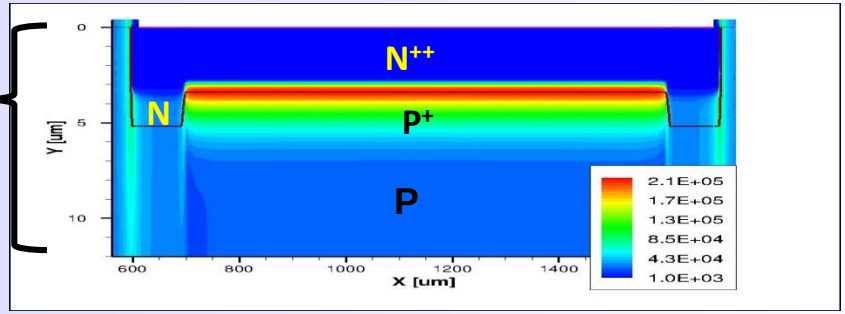
Ref: Diode: J.Lange et al, 16th RD50 Workshop, Barcelona
Strip: G. Casse et al., NIMA 624, 2010, Pages 401-404
3D: M.Koehler et al., 16thRD50 Workshop, Barcelona

RD50 Low Gain Avalanche Detectors (LGAD)

[G.Pellegrini, 9th Hiroshima, 9/2013]

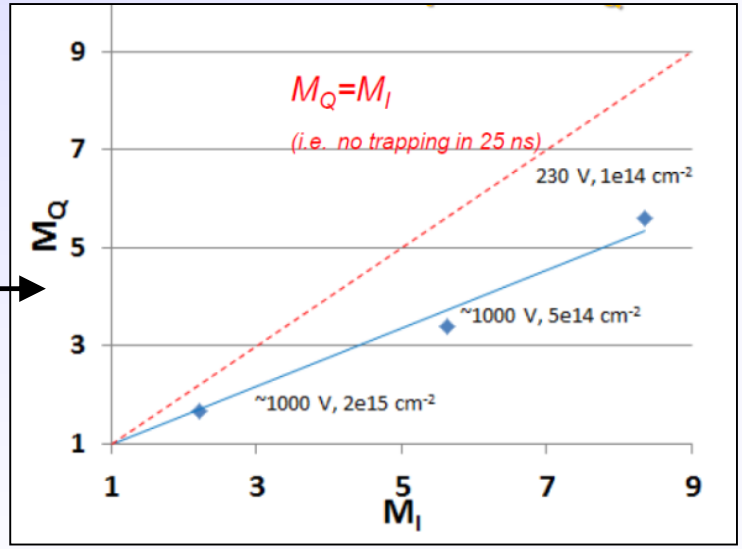
- **Diodes with implemented multiplication layer (deep p+ implant)**
  - **APD concept [n^{++}-p^{+}-p-p^{+} structure] with JET (Junction Edge Termination)**





Simulation of E-Field [V/cm]

  - **Gain of approx. 10-20 before irradiation : linear mode : spectra are Landau spectra (^{90}Sr)**
- **Gain reduces with irradiation**
  - **Dropping to about 1.5 after 2e15 n/cm²**
    - Why? Boron removal in p-type layer?
    - Soon: Test of Gallium implants
  - **Charge (Sr-90) Multiplication versus Current Multiplication (Sr-90)**

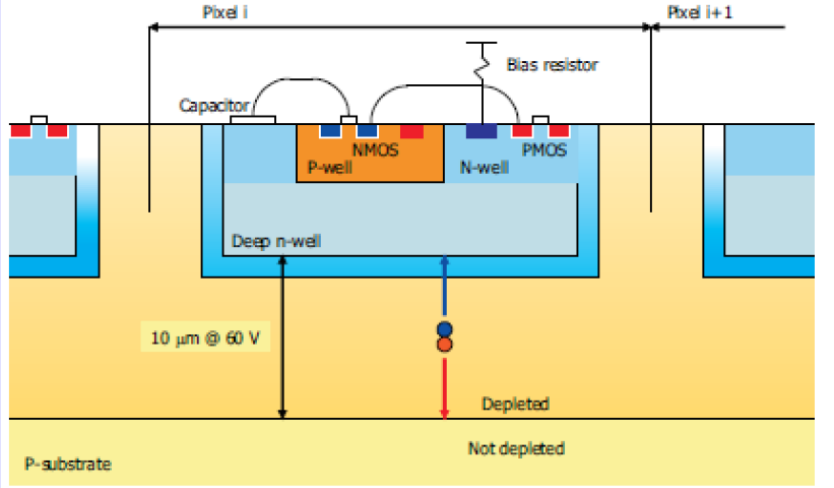


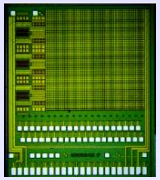
[G.Kramberger, RD50, June 2013]

- **Further work ongoing (strip, pixel, …)**
- **Test of timing capabilities (thin sensors)**
  - **"Ultrafast sensors project"**

HVCMOS & monolithic devices

- **RD50 started to work on HVCMOS device characterization in 2014**
  - close collaboration with ATLAS HVCMOS group
  - RD50 focus on characterizing radiation damage.
- **Typical HVCMOS 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
- **Edge-TCT measurements**





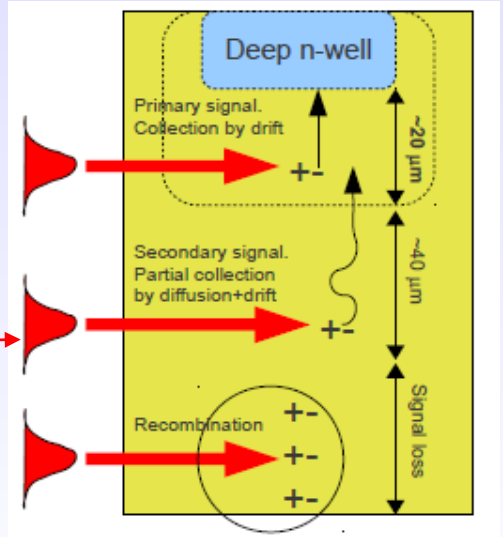
HVCMOSv3

Edge-TCT

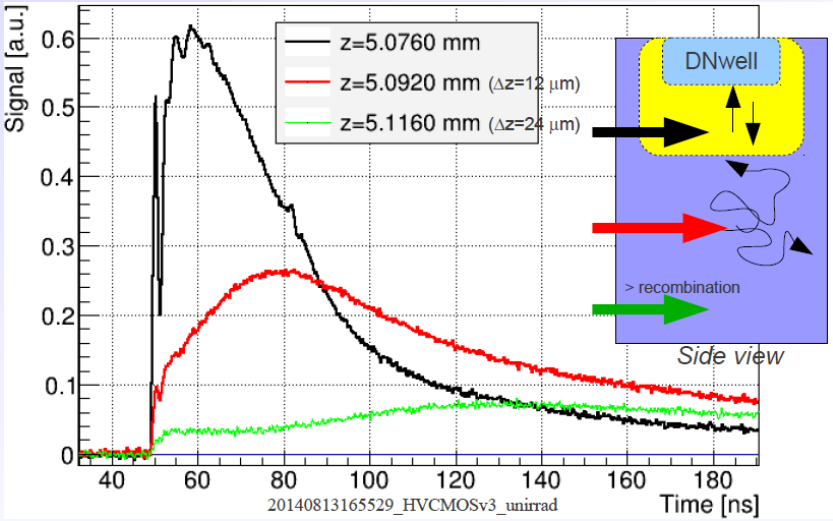
laser light

scan in y

fast readout amplifier



Side view of HVCMOS

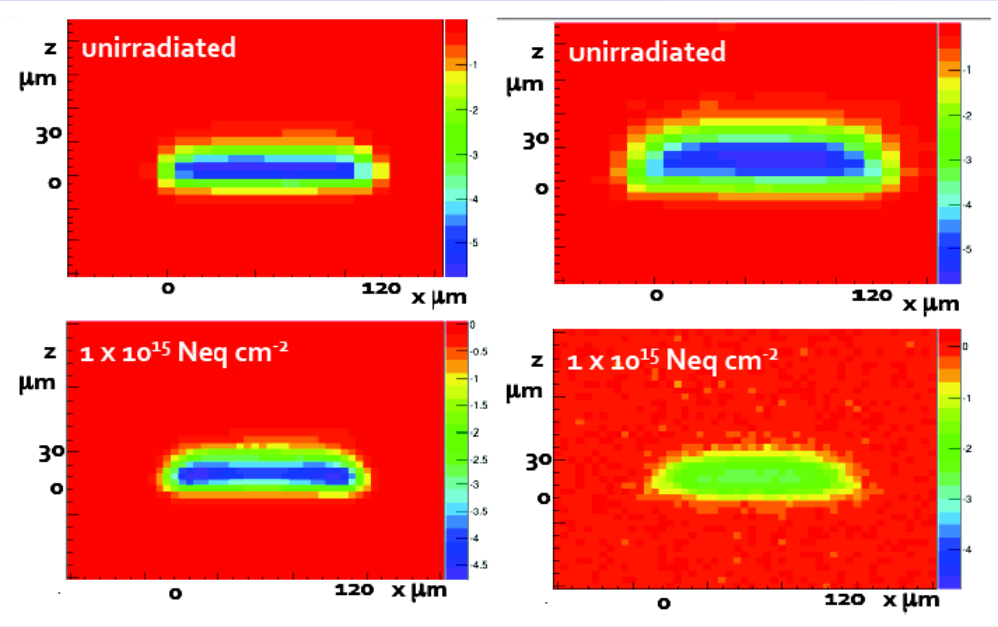


Drift and Diffusion component visible

HVCMOS

- **Several HVCMOS devices tested after neutron irradiation up to $2x10^{16}cm^{-2}$**
  - **Example: HVCMOSv3; investigating 100 μm test structure**
  - **Edge-TCT measurements**

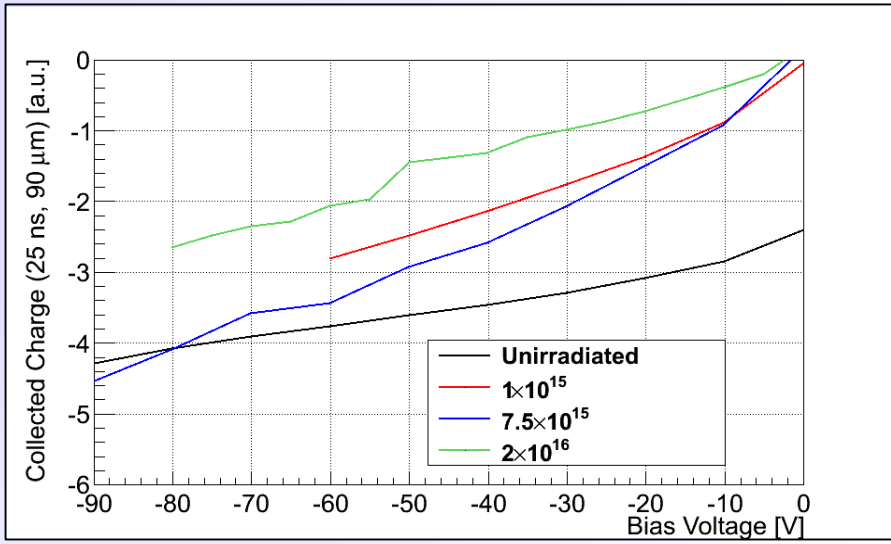
Signal: 3ns integration ; integration: 3-25ns



Drift component t<3ns contributing before and after irradiation

Diffusion component 3ns < t <25ns contributing before and after irradiation

Total collected charge in **25ns**

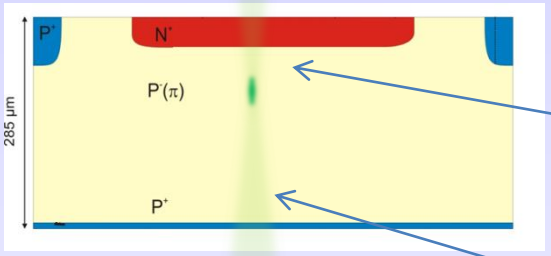


- **For >80V the 10^{15} cm^{-2} irradiated sample gives more charge than non irradiated**
- **After $2x10^{16}$ n_{eq}/cm^2 still ≈50% CCE !**

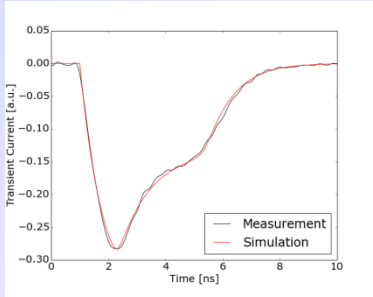
TPA – Two Photon Absorption

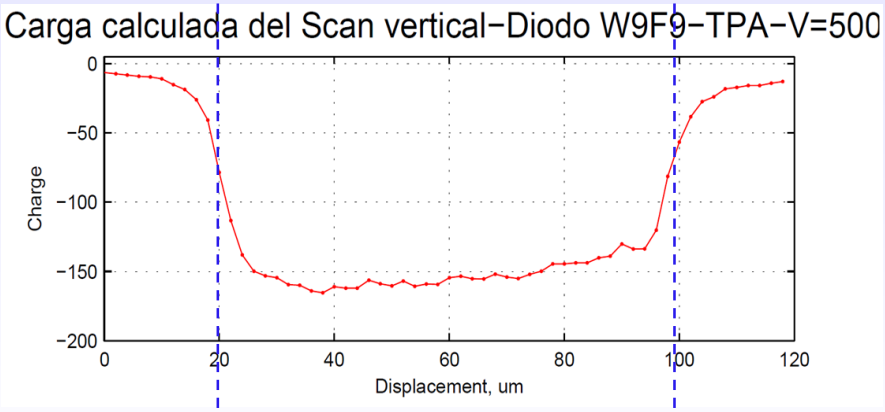
- **Investigation on a new technique for sensor characterization (TPA – TCT)**
  - **Deposition of charge at specific position in detector**
  - **Laser: $\lambda \sim 1300$ nm; P ~ 50-100 pJ; $\Delta T \sim 240$ fs**
  - **Proof of principle achieved:**

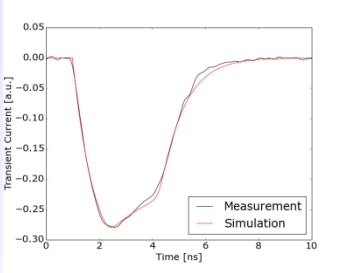
Diode Displacement



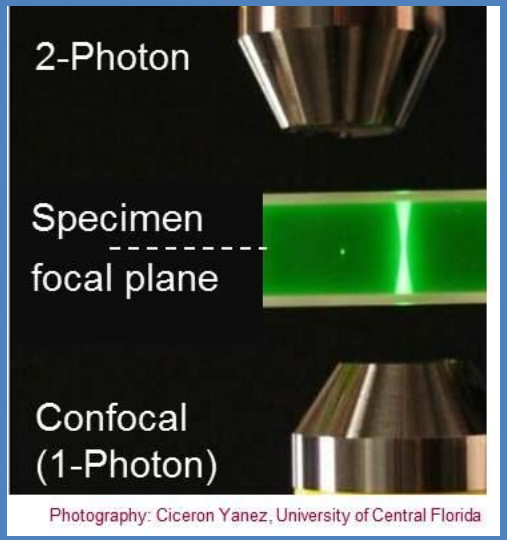
80 x n_{index_Si} ~ 280 um

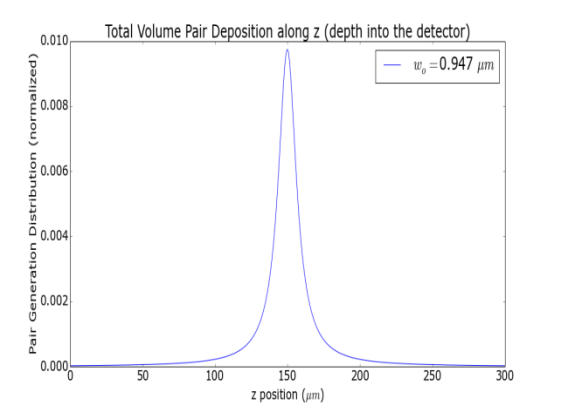






Two Photon absorption:





- **r spot size** → 1σ~0.8 µm & 2σ~3.4 µm
- **z spot size** → 1σ~13 µm & 2σ~60 µm

[I.Vila, 25th RD50 Workshop, CERN, November 2014]

RD50

Workplan for 2015/2016 (1/2)

- **Defect and Material Characterization** *(Convener: M.Bruzzi, INFN and University of Florence, Italy)*
  - 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
  - **Review NIEL approach; Modeling and understanding role of clusters;**
    - Study of electron damage: Implement results into simulations
  - **Characterization of Nitrogen enriched silicon**

- **Detector Characterization** *(Convener: E.Fretwurst, University of Hamburg, Germany)*
  - **TCAD sensor simulations**
    - Cross-calibration of different simulation tools (ongoing)
    - Refine defect parameters used for modeling (**from effective to measured defects**)
    - Extend modeling on charge multiplication processes
  - **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 study on "mixed" irradiations**
  - **Explore fluence range to10^{17}cm^{-2}** (to prepare for future needs in forward physics)

RD50

Workplan for 2015/2016 (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)
    - Understand impact of implant shape and other geometrical parameters on avalanche processes
  - **Evaluate 'low resistance strip' sensors**
  - **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**

RD50

RD50 main achievements & links to LHC Experiments

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 (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,….).
- **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?
- **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.**

RD50

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**
  - Noise issue particularly important for exploitation of this feature in Experiments
  - New dedicated sensors produced to test avalanche effects, sensors working after irradiation
- **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

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**

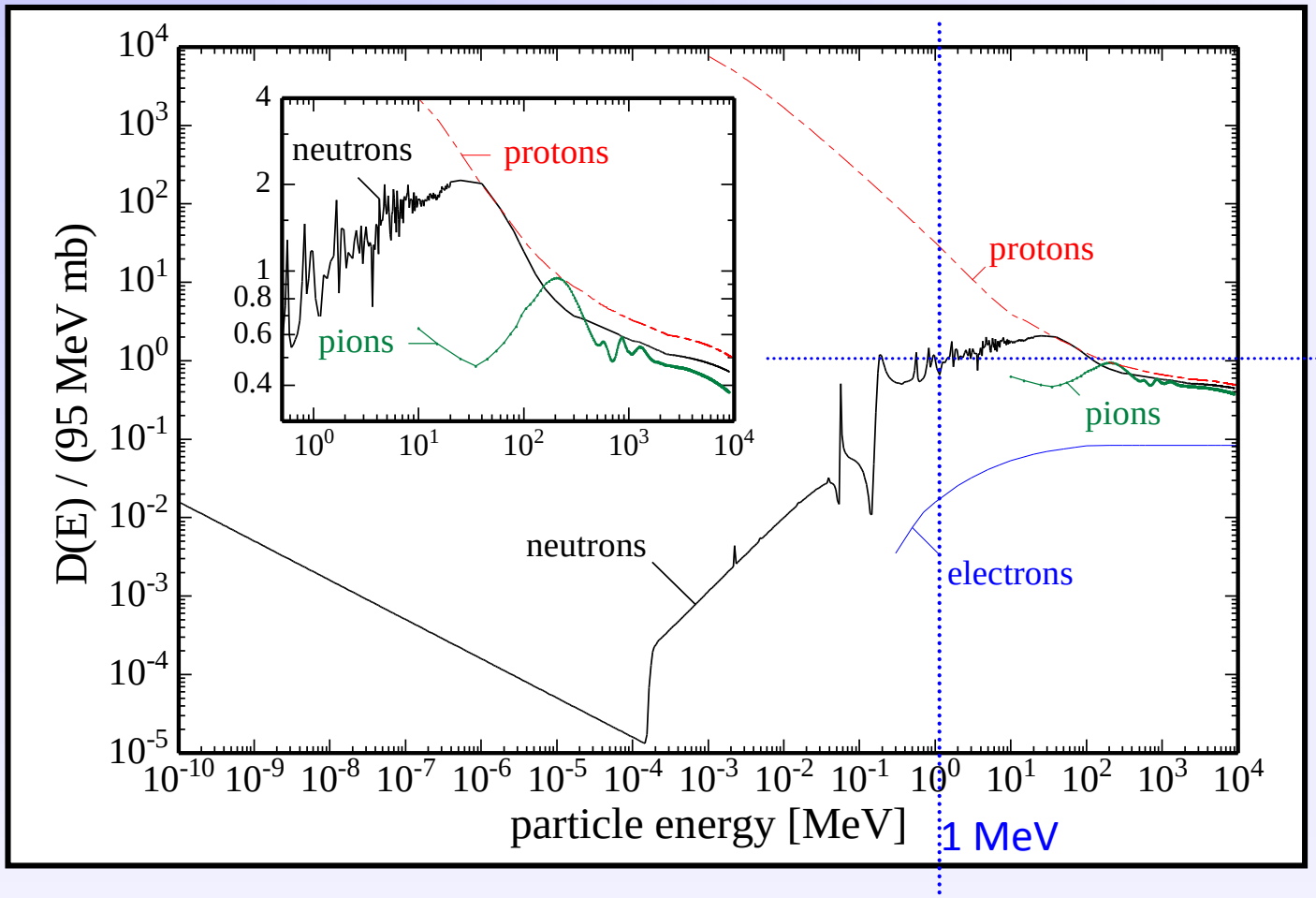
RD50 Summary on defects with strong impact on device performance after irradiation

- **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 $\sigma_n = 2.3x10^{-14}$	- 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}	

Reminder: NIEL – Non Ionizing Energy Loss Displacement damage functions

RD50



1

1 MeV neutron equivalent damage

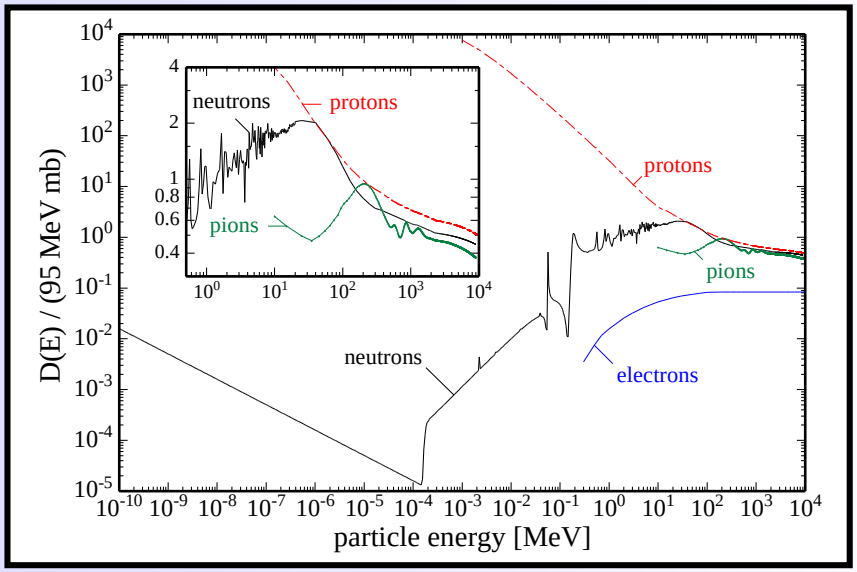
$$\Phi_{eq} = \kappa_x \, \Phi_x$$

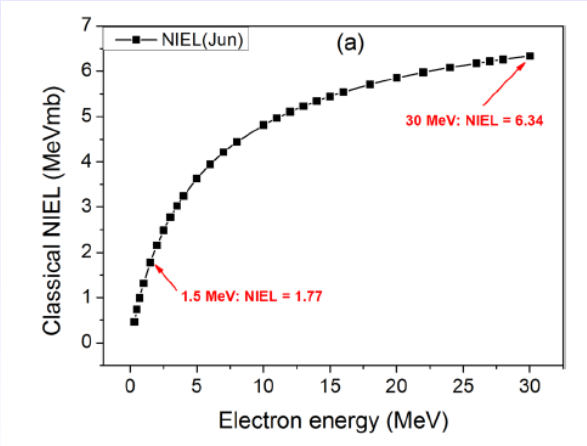
κ_p =0.62 (24 GeV/c protons)
κ_p = 1.85 (26 MeV protons)
κ_π = 1.14 (300 MeV pions)
κ_n = 0.92 (reactor neutrons >100 keV)

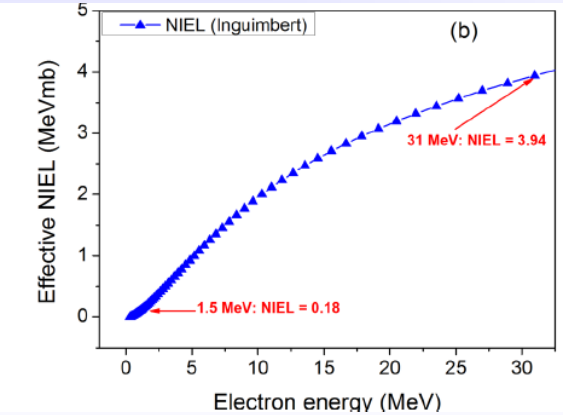
- **Hypothesis: Damage parameters scale with the NIEL**
  - **Be careful, does not hold for all particles & damage parameters (see later)**

NIEL for electron damage

- **Non Ionizing Energy Loss (NIEL)**
  - **Used to calculate effective damage for different particles with different energy.**
  - **Normalization usually to 1 MeV neutron equivalent damage**
  - **Study on the validity of NIEL for electrons in the range of 1.5 MeV to 27 MeV**
  - **Two approaches:**
    - a) **Classical NIEL** (our standard; based on two body elastic collisions between PKAs, 0K)
    - b) **Effective NIEL** (Molecular Dynamics calculations taking into account many body interactions)







[Effective NIEL: Inguimbert et al., IEEE TNS 57 (2010)1915]

[R.Radu et al, JAP 117, 164503, 2015]

Ratio of cluster to point defects

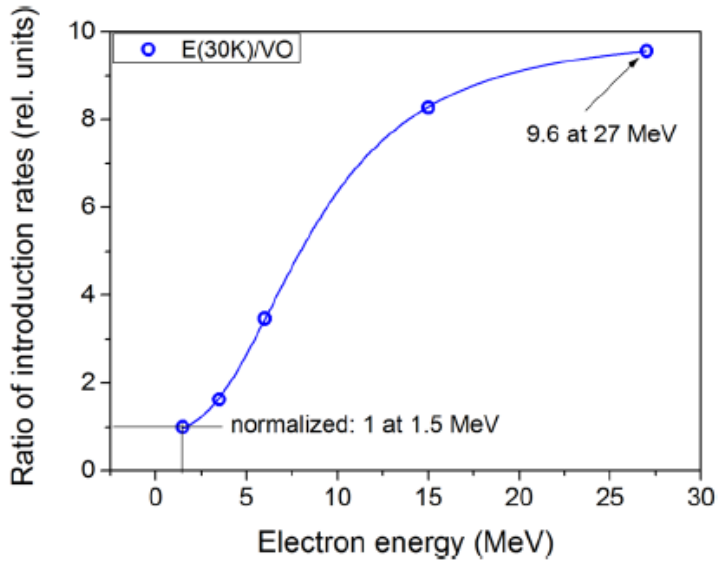
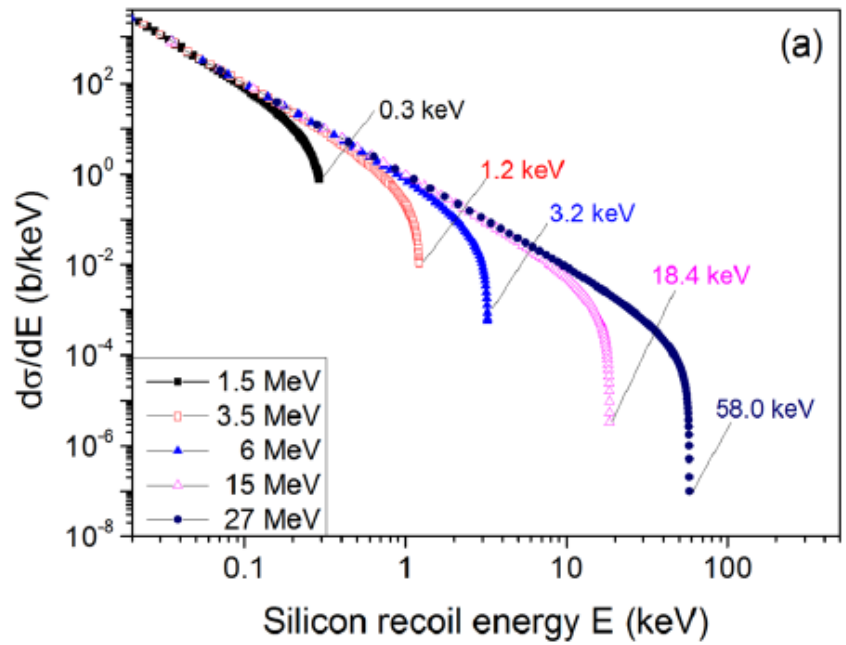


FIG. 17. Normalized ratio of introduction rates for E(30K) (8 min/80 °C) and VO(as irradiated) for DOFZ silicon as function of electron energy.



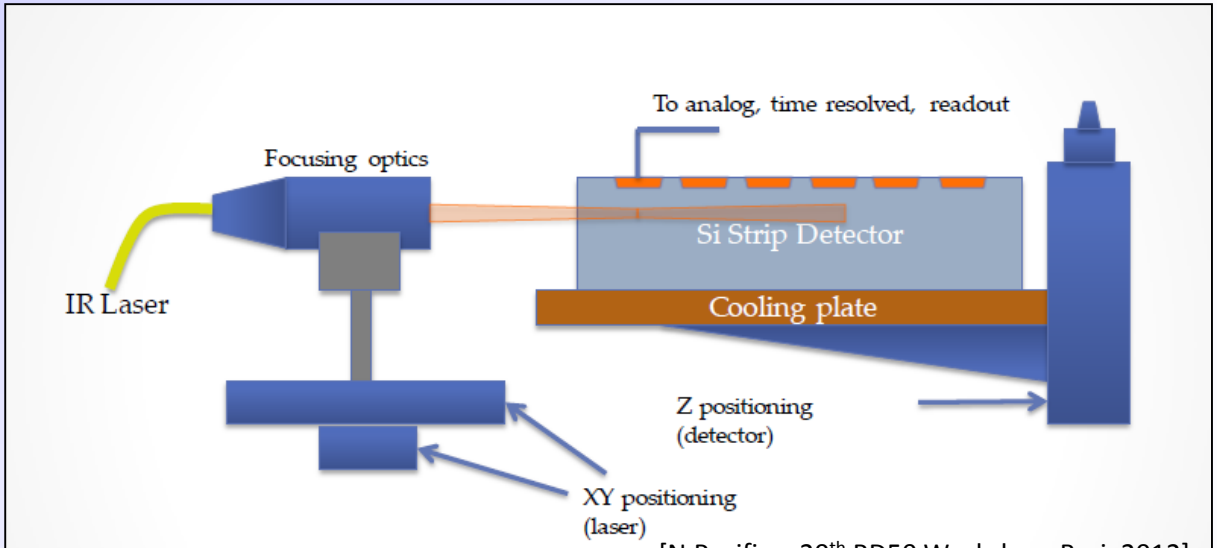
[more details: R.Radu et al, JAP 117, 164503, 2015]

Edge-TCT to Study Fields

[Edge-TCT, G. Kramberger, IEEE TNS, VOL. 57, NO. 4, AUGUST 2010, 2294]

- **Study of Electric field inside silicon sensor very challenging problem**

- **New tool (2010): Edge-TCT (Transient Charge Technique)**
  - **Illuminate segmented sensor from the side with sub-ns infrared laser pulses**
  - **Scan across the detector thickness**
  - **Record current pulses as function of depth**
  - **Extract rise time and collected total charge**
  - **Reconstruct the electric field**



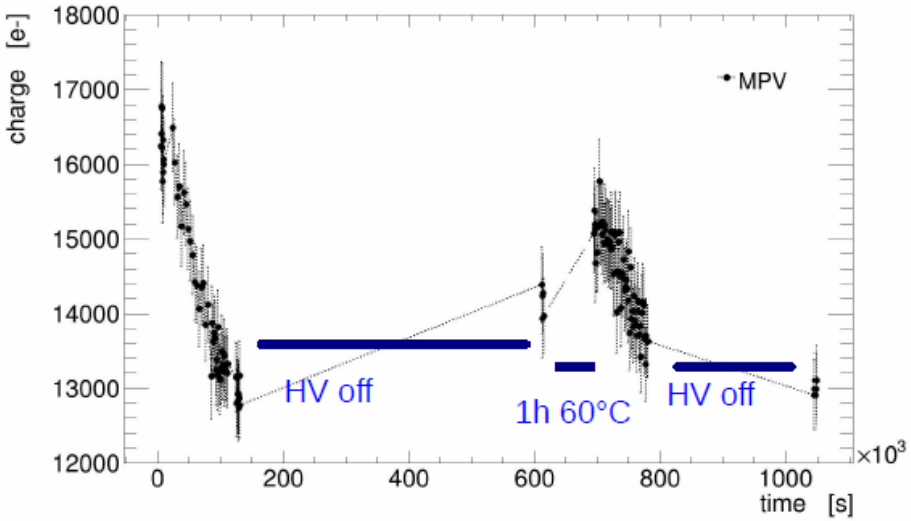
[N.Pacifico, 20th RD50 Workshop, Bari, 2012]

- **Expectations**
  - **Significant electric field only in depleted volume**
  - **Charge generated in 'undepleted' part of detector is lost**

Charge Multiplication

Long term behaviour of multiplication effect:

- HPK strip sensor, mixed irradiated to $2.1*10^{15}$ n_{eq}/cm^2 and annealed 4200min@RT

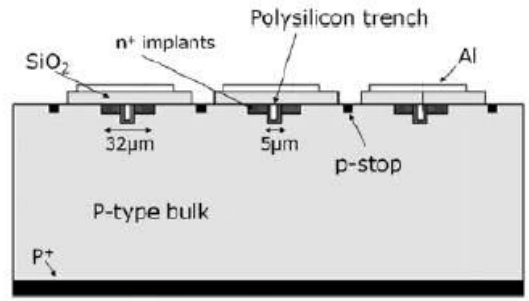


S. Kuehn, 10th Trento Workshop, 2015

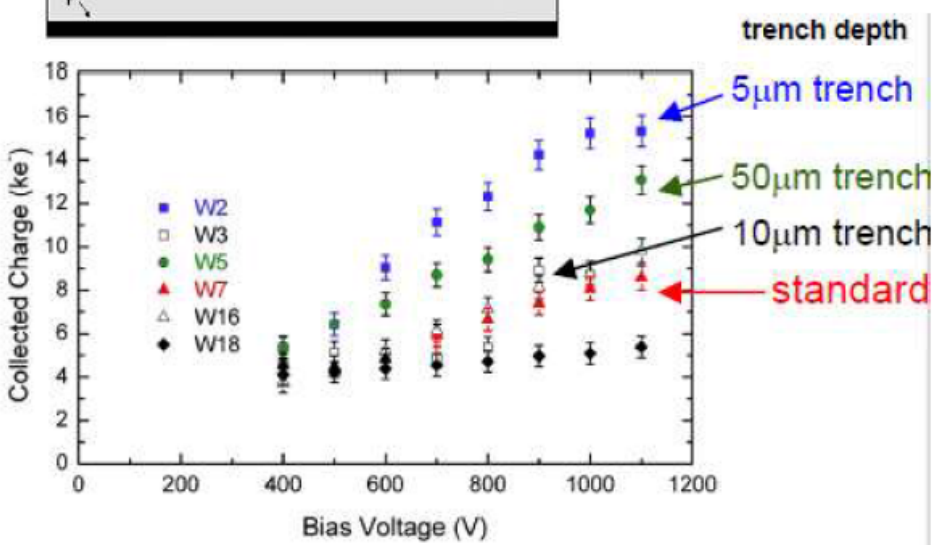
- Charge multiplication observed
- After long term biasing and subsequent CCE measurements drop in charge seen (observed by several groups)
- Partial recovery after 1 day without bias or temperature treatment (1h at 60°C)
- No full recovery of charge

Production of sensors with trenches:

- 5, 10, 50 µm deep, 5 µm wide in center on n+ electrode



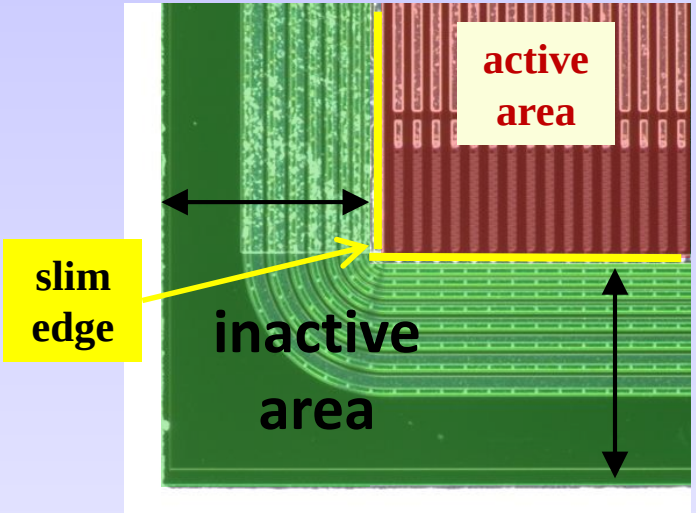
G. Casse, NIM A 669 (2013) 9-13,
P. Fernández-Martínez, NIM A 658 (2011) 98-102

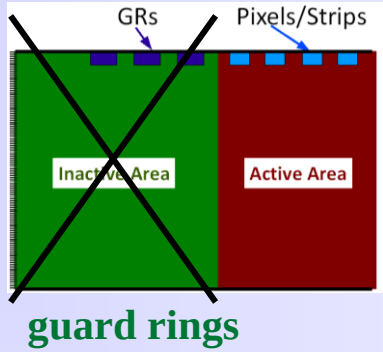


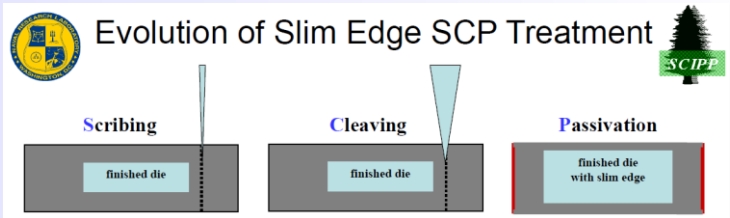
After $5*10^{15}$ neq/cm^2 neutrons, n-in-p sensor 300 µm thick
→ CCE higher for sensors 5 and 50 µm trenches compared to standard sensors

New structures: slim and active edges

- **RD50 slim edges project (reduce dead space around the active sensor)**





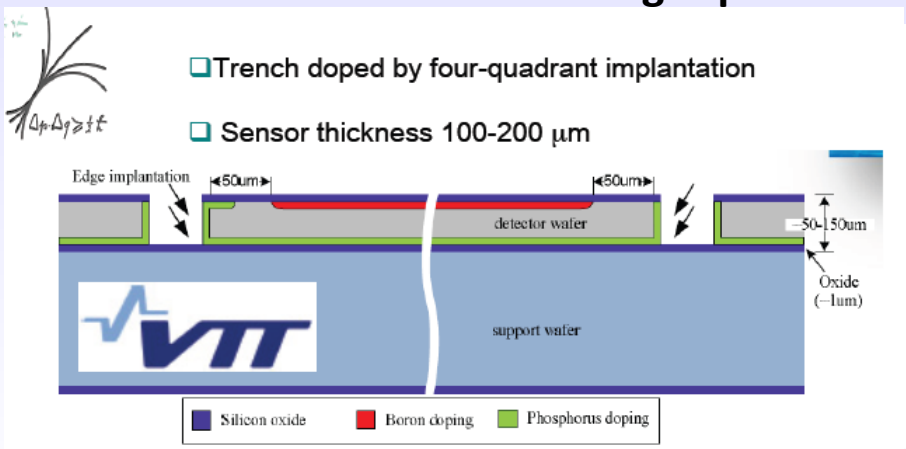


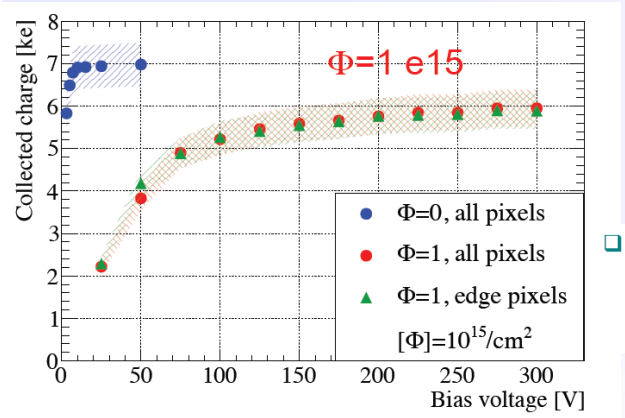
- **Scribe** XeF_2 etch, diamond scribe, DRIE
- **Cleave** automated, manual
- **Passivate** nitride, oxide (n-type) alumina ALD (p-type)

[V. Fadeyev, 22nd RD50 Workshop, Albuquerque, June 2013]

… development picked up by HPK (see Hiroshima Symposium 9/2013)

- **Active edges (VTT & MPI Munich)**
  - **Thin wafers with active edges produced at VTT** [A.Macchiolo, 22nd RD50, Albuquerque, June 2013]





10^{15} p/cm^2

Testbeam:
no difference between edge and other pixel!

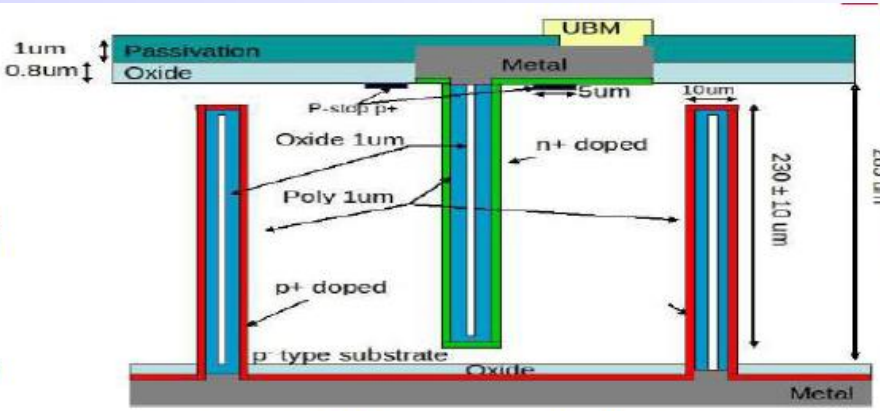
- FE-I3 100 μm thick sensor with 125 μm slim edge, threshold 1500 e- → 87% CCE at 300 V for both all and edge pixels after irradiation at KIT

3D

3D sensors:

- Doped columns double-sided vertical to surface
- Decoupling of depletion voltage and detector thickness (collected charge) but have low-field region
- Allows slim edge
- Intensively studied in RD50 Collaboratio and others

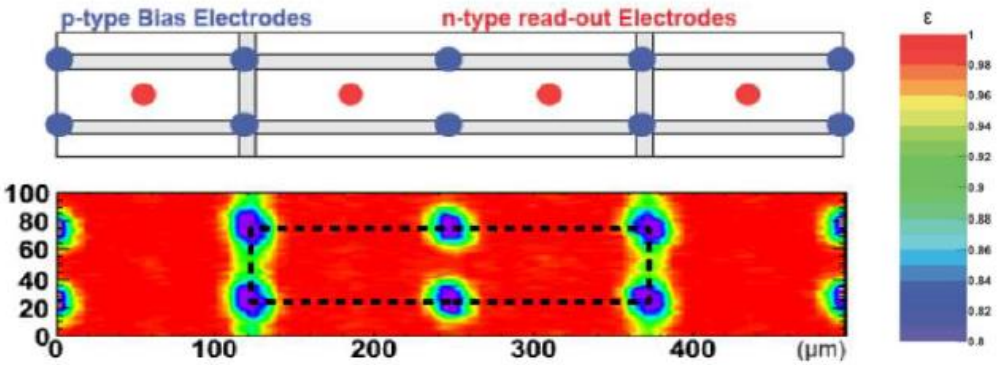
S. Parker et al. NIMA 395 (1997) 328
A. Zoboli et al., IEEE TNS 55(5) (2008) 2775
G. Giacomini, et al., IEEE TNS 60(3) (2013) 2357



G. Pellegrini, NIM A 592 (2008) 38-43

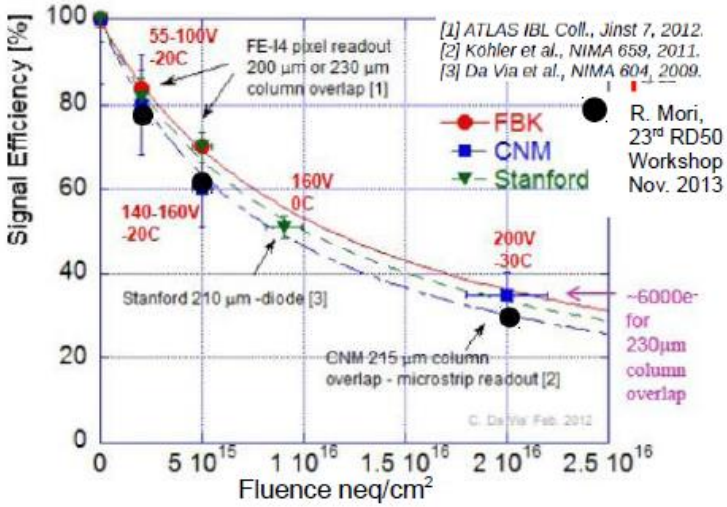
sketch of CNM sensor with filled columns

Efficiency in test beam of CNM sensors: mean 97.5%



ATLAS Collab. JINST 2012, 7 P11010

Signal efficiency vs. fluence



R. Mori, 23rd RD50 Workshop Nov. 2013

→ Well performing and detectors from CNM and FBK installed in ATLAS IBL