RD50

LHCC – 12.June 2013, CERN

RD50 Status Report – June 2013

Gianluigi Casse
University of Liverpool, UK

Michael Moll
CERN, Geneva, Switzerland

OUTLINE:

- **RD50 Collaboration**
- **Scientific results**
  - **Defect and Material Characterization**
  - **Detector Characterization**
  - **New Detector Structures**
  - **Full Detector Systems**
- **RD50 key results 2012/2013**
- **RD50 Work Program 2013/2014**
- **RD50 achievements**

RD50

The RD50 Collaboration

- **RD50: *48 institutes and 270 members***

38 European and Asian institutes

Belarus (Minsk), Belgium (Louvain), Czech Republic (Prague (3x)), Finland (Helsinki, Lappeenranta), France (Paris), Germany (Dortmund, Erfurt, Freiburg, Hamburg (2x), Karlsruhe, Munich), Italy (Bari, Florence, Padova, Perugia, Pisa, Trento), 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)

7 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)

Joined 2012/13

- Desy, Hamburg, Germany (Doris Eckstein)
- IPNHE, Paris, France (Giovanni Calderini)

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

RD50

RD50 Organizational Structure

CERN

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)
- **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)
- Slim Edges
- 3D (R.Bates)
- Semi 3D (Z.Li)
- Slim Edges (H.Sadrozinski)

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 (G.Casse)

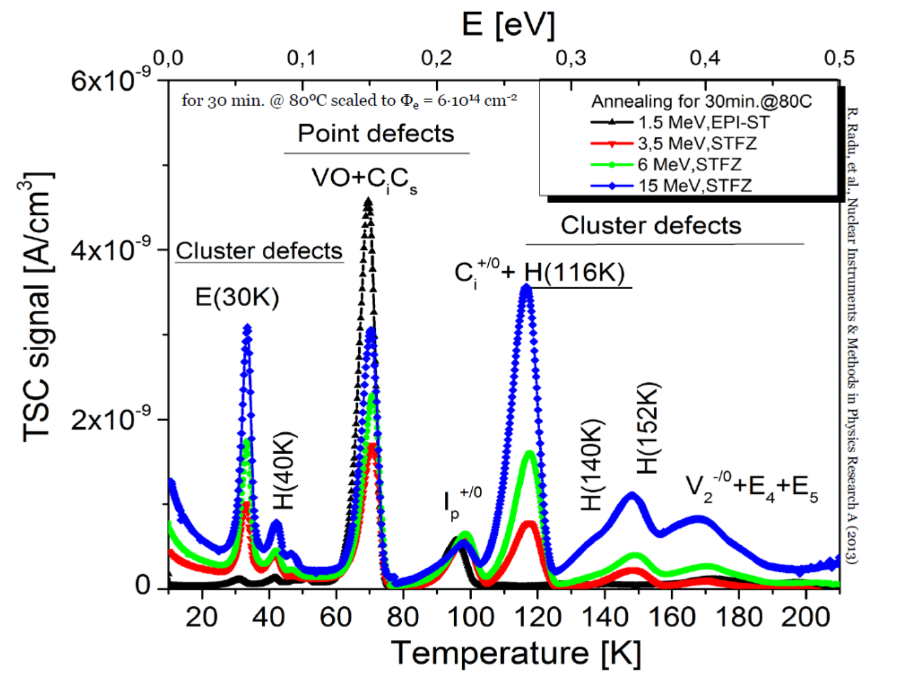
Collaboration Board Chair & Deputy: G.Kramberger (Ljubljana) & J.Vaitkus (Vilnius), Conference committee: U.Parzefall (Freiburg)
CERN contact: M.Moll (PH-DT), Secretary: V.Wedlake (PH-DT), Budget holder & GLIMOS: M.Glaser (PH-DT)

RD50 # Defect Characterization - WODEAN

- **WODEAN project** (since 2005; 10 RD50 institutes, guided by G.Lindstroem and M.Bruzzi)
  - **Aim: Identify defects responsible for Trapping, Leakage Current, Change of N_{eff}**
  - **Method: Defect Analysis on identical samples performed with the various tools available inside the RD50 network:**
    - **C-DLTS** (Capacitance Deep Level Transient Spectroscopy)
    - **I-DLTS** (Current Deep Level Transient Spectroscopy)
    - **TSC** (Thermally Stimulated Currents)
    - **PITS** (Photo Induced Transient Spectroscopy)
    - **FTIR** (Fourier Transform Infrared Spectroscopy)
    - **RL** (Recombination Lifetime Measurements)
    - **PC** (Photo Conductivity Measurements)
    - **EPR** (Electron Paramagnetic Resonance)
    - **TCT** (Transient Charge Technique)
    - **CV/IV**
  - **> 240 samples irradiated with protons, neutrons and electrons**
  - **most important results published in Applied Physics Letters**

… significant impact of RD50 results on silicon solid state physics – defect identification

[R.Radu, 22nd RD50 Workshop, 3-5 June 2013]

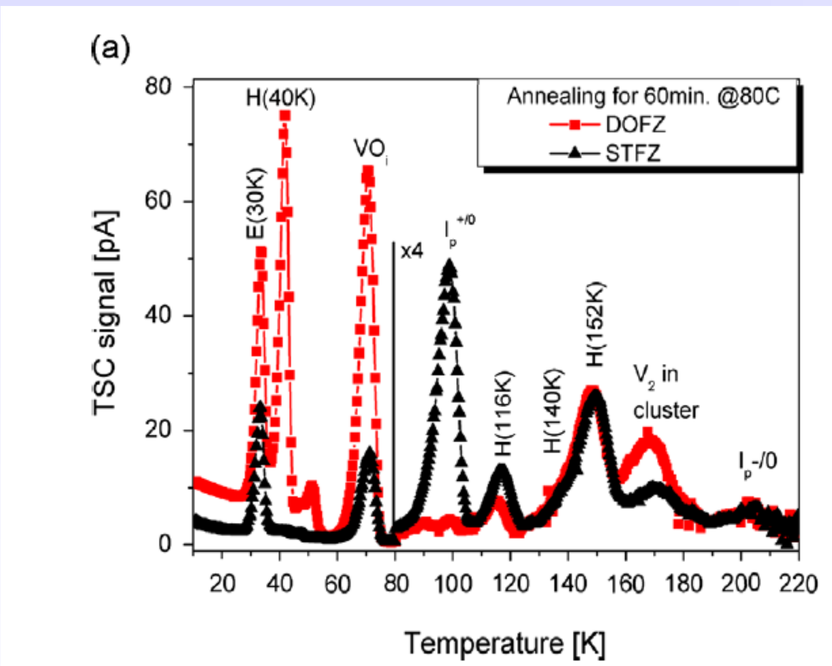


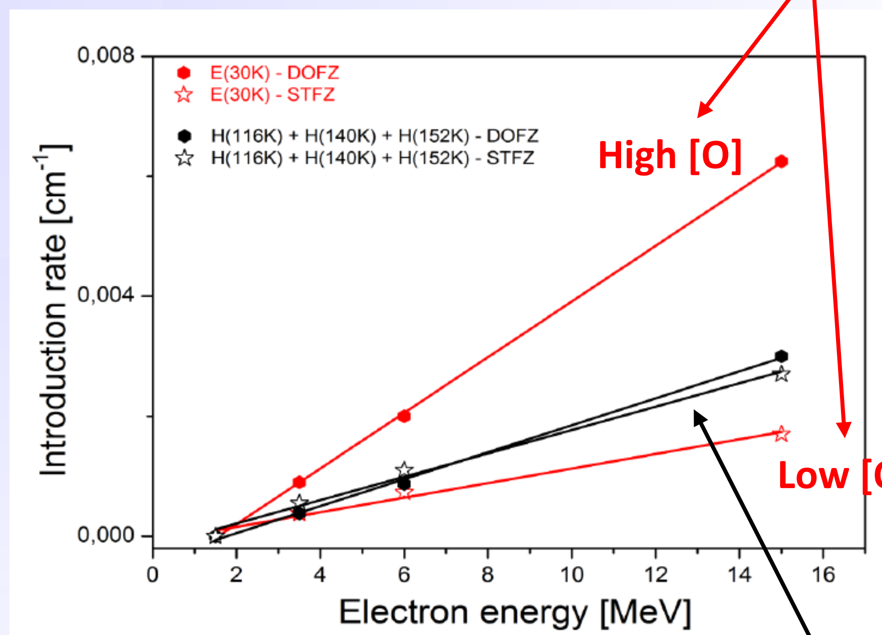
Example: TSC measurement on defects produced by electron irradiation (1.5 to 15 MeV)

Microscopic Defects

- **Defects concentrations after electron irradiation (1.5 to 15 MeV)**
  - **Impact of oxygen content on defect formation**
    - STFZ – Standard Floating Zone Silicon $[O]=10^{16}cm^{-2}$
    - DOFZ – Diffusion Oxygenated Floating Zone Silicon $[O]=10^{17}cm^{-2}$

6 MeV electrons; 10^{15} e/cm^2; 60 min 80°C





Defect introducing positive space charge (depending on Oxygen content)

Defect responsible for reverse annealing (not depending on Oxygen content)

[R.Radu, 22nd RD50 Workshop, 3-5 June 2013; accepted for publication in NIMA]

RD50

Microscopic Defects

CERN

- **Some defects observed after electron irradiation (1.5 to 15 MeV)**

Defects	σ_n [cm²]	σ_p [cm²]	E_A [eV]	Assignment/References	Impact on the diodes electrical characteristics at room temperature
E(30K)	2.3 x 10^{-14}		E_C - 0.1	Electron trap with a donor level in the upper half of the Si bandgap /[11]	On the N_{eff} by introducing positive space charge
H(40K)		1.7 x 10^{-15}	E_V + 0.09	Hole trap/[11]	
$VO_i^{-/0}$	1.44 x 10^{-14}		E_C - 0.176	$VO_i^{-/0}$ / [40]	
$C_iC_s^{-/0}$	1.4 x 10^{-14}		E_C - 0.171	$C_iC_s^{A-/0}$ / [41, 42]	
$I_p^{+/0}$	1.7 x 10^{-15}		E_V + 0.23	Donor level of V_2O or of a still unkown C related defect/[11 ,30]	
$I_p^{0/-}$	1.7 x 10^{-15}	9 x 10^{-14}	E_C - 0.55	Acceptor level of V_2O or of a still unkown C related defect/[11 ,30]	On the N_{eff} by introducing negative space charge and on LC
$C_i^{+/0}$	1.11 x 10^{-15}	4.28 x 10^{-15}	E_V + 0.284	$C_i^{+/0}$/ [21]	
$V_2^{-/0}$	2.1 x 10^{-15}		E_C - 0.424	$V_2^{-/0}$ /[21]	
E_4	1 x 10^{-15}		E_C - 0.38	$V_3^{=/-}$ / [38]	On LC
E_5	7.8 x 10^{-15}		E_C - 0.46	$V_3^{-/0}$ /[38]	On LC
H(116K)		4 x 10^{-14}	E_V + 0.33	Hole trap with an acceptor level in the lower part of the Si bandgap - Extended defect (cluster of vacancies and/or interstitials) /[10,11]	On the N_{eff} by introducing negative space charge
H(140K)		2.5 x 10^{-15}	E_V + 0.36	Hole trap with an acceptor level in the lower part of the Si bandgap - Extended defects (clusters of vacancies and/or interstitials)/[10,11]	On the N_{eff} by introducing negative space charge
H(152K)		2.3 x 10^{-14}	E_V + 0.42	Hole trap with an acceptor level in the lower part of the Si bandgap - Extended defects (clusters of vacancies and/or interstitials)/[10,11]	On the N_{eff} by introducing negative space charge
H(87K)		0.3 x 10^{-15}	E_V + 0.193	$V_3^{0/+}$ /[37]	
H(98K)		1.2 x 10^{-15}	E_V + 0.234	$V_2O^{0/}$ + $V_3O^{0/+}$ /[37]	

Results consistent with previous RD50 works on hadron damage

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

leakage current + neg. charge
(current after γ irradiation)

Reverse annealing
(neg. charge)

- **Converging on consistent set of defects observed after proton, pion, neutron, gamma and electron irradiations by various techniques** (Introduction rates depend of course strongly on the type of irradiation and for some of the defects on the material.)

[R.Radu, 22nd RD50 Workshop, 3-5 June 2013]

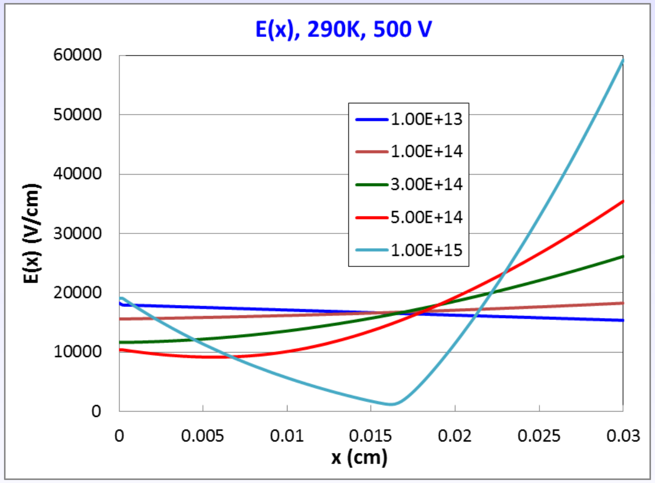
RD50 Simulation working group

- **Device simulation working group formed in 2012** *(10 institutes guided by V.Eremin, Ioffe)*
  - **Aim:** Produce TCAD input parameters that allow to simulate the performance of irradiated silicon sensors and eventually allow for performance predictions under various conditions (sensor material, irradiation fluence and particle, annealing).
  - **Tools**: Commercial TCAD software (Synopsis & Silvaco) and custom made software
  - **First steps:** Inter-calibration of the different tools using a predefined set of defect levels and physics parameters:

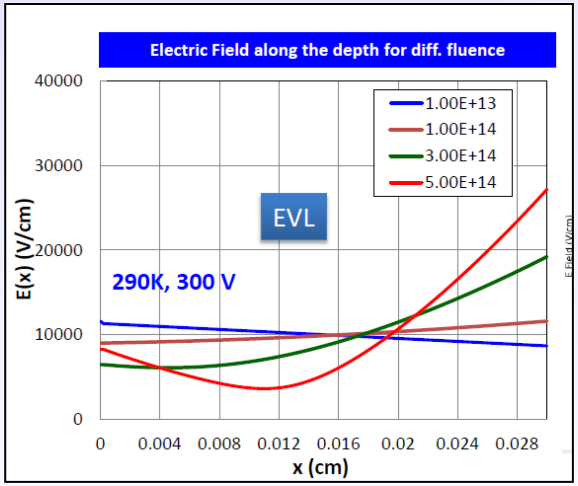
    All tools were able to reproduce the double-junction effect with a two level defect model. However, further tuning of defect and physics parameters is needed.

Two level model:

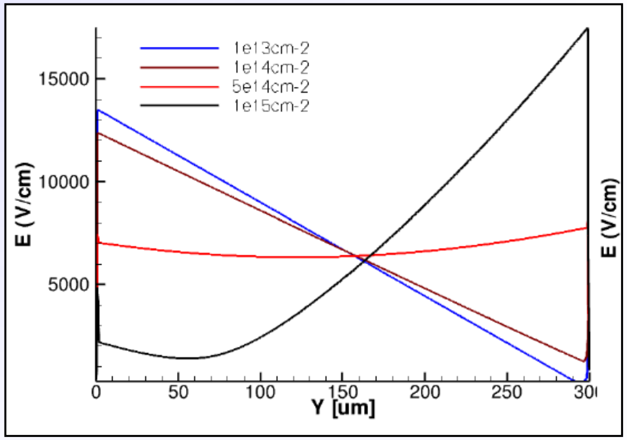
Type	Level[eV]	σ_n [cm^2]	σ_n [cm^2]
Acceptor	E_V+0.595	1x10^{-15}	1x10^{-15}
Donor	E_V+0.480	1x10^{-15}	1x10^{-15}



Ioffe Institute (custom made software)



Delhi University (Silvaco TCAD)



Karlsruhe University (Synopsis TCAD)

RD50

RD50 Simulation working group

- **TCAD simulations can reproduce TCT data, leakage current, depletion voltage and (partly) charge trapping of irradiated sensors with one parameter set!**
  - Example: Input parameter set tuned to match TCT measurements (R.Eber, Uni.Karlsruhe)

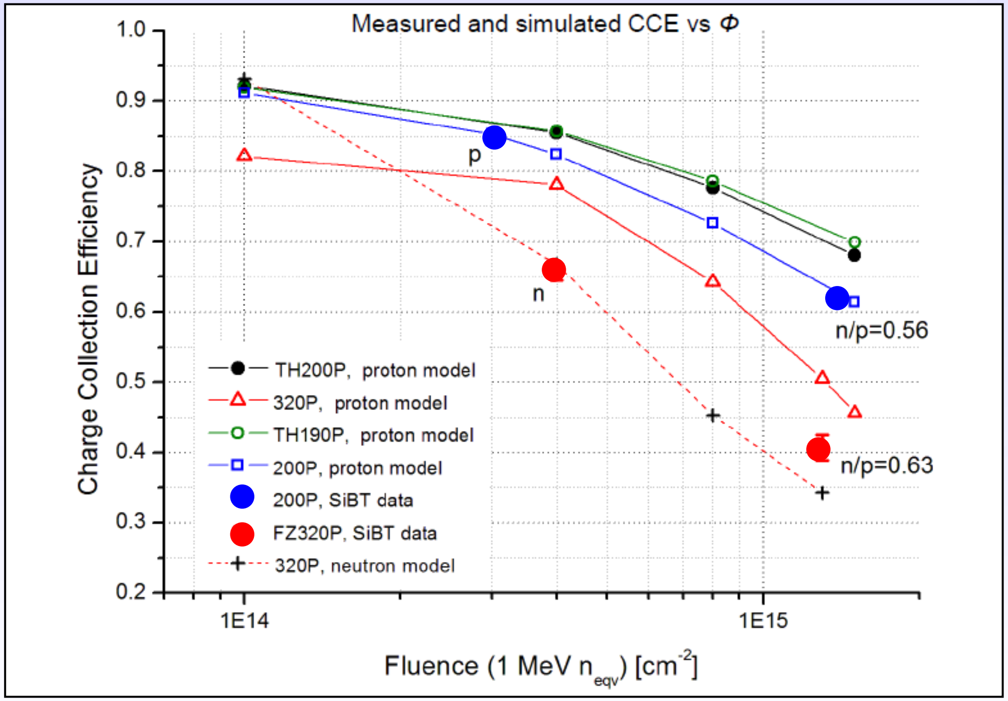
Proton model

Type of defect	Level [eV]	σ_e [cm^2]	σ_h [cm^2]	Concentration [cm^{-3}]
Deep acceptor	E_C - 0.525	1e-14	1e-14	1.189*F + 6.454e13
Deep donor	E_V + 0.48	1e-14	1e-14	5.598*F - 3.959e14

Neutron model

Type of defect	Level [eV]	σ_e [cm^2]	σ_h [cm^2]	Concentration [cm^{-3}]
Deep acceptor	E_C - 0.525	1.2e-14	1.2e-14	1.55*F
Deep donor	E_V + 0.48	1.2e-14	1.2e-14	1.395*F

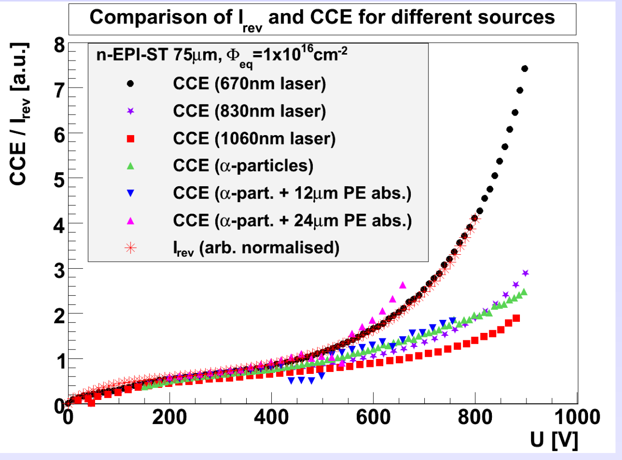
  - Same set of data used to simulate CCE measurements taken in a test beam (T.Peltola HIP)



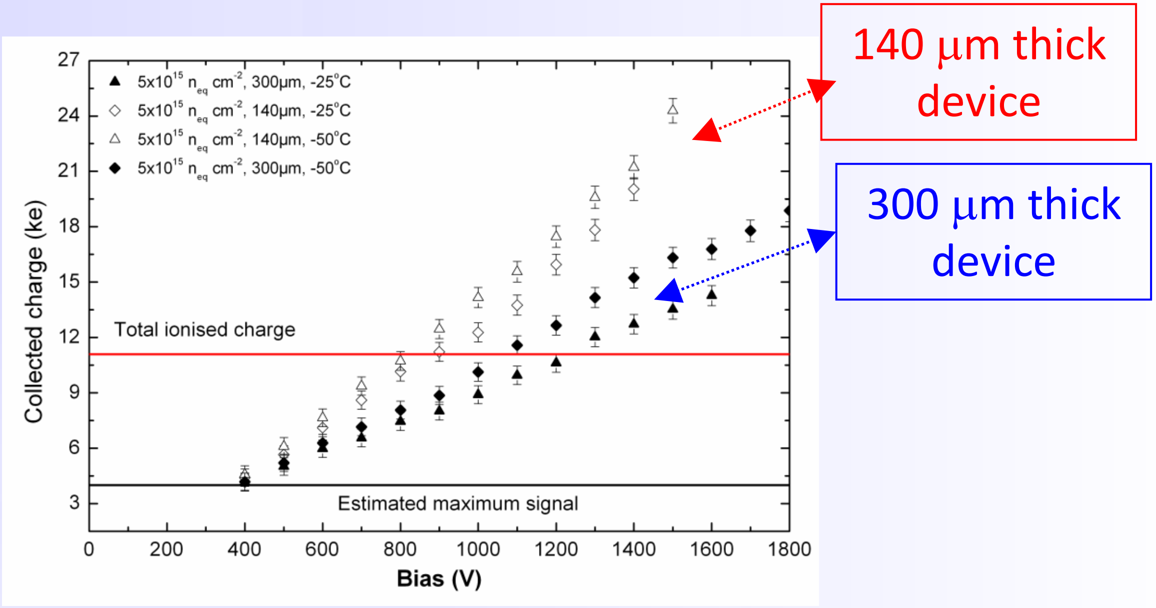
- Simulation predicts leakage current correctly (not shown)
- Simulation predicts CCE for proton and neutron irradiated samples of different thickness within 20%
- **Simulations start to get predictive power**; still the phase space of input parameters is huge and input (defect) parameters have to be tuned and adopted to measured defect parameters.

Charge Multiplication

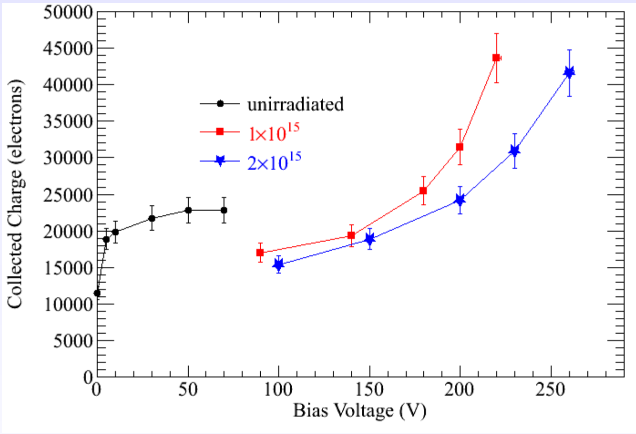
- **Charge Multiplication observed and characterized after high levels of irradiation with different techniques and in several different types of devices**



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)

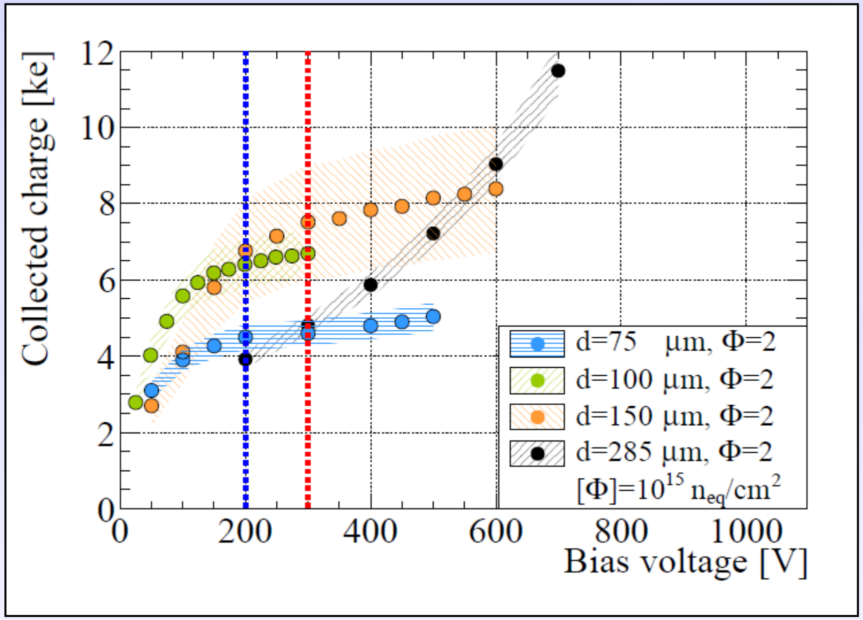
Questions:

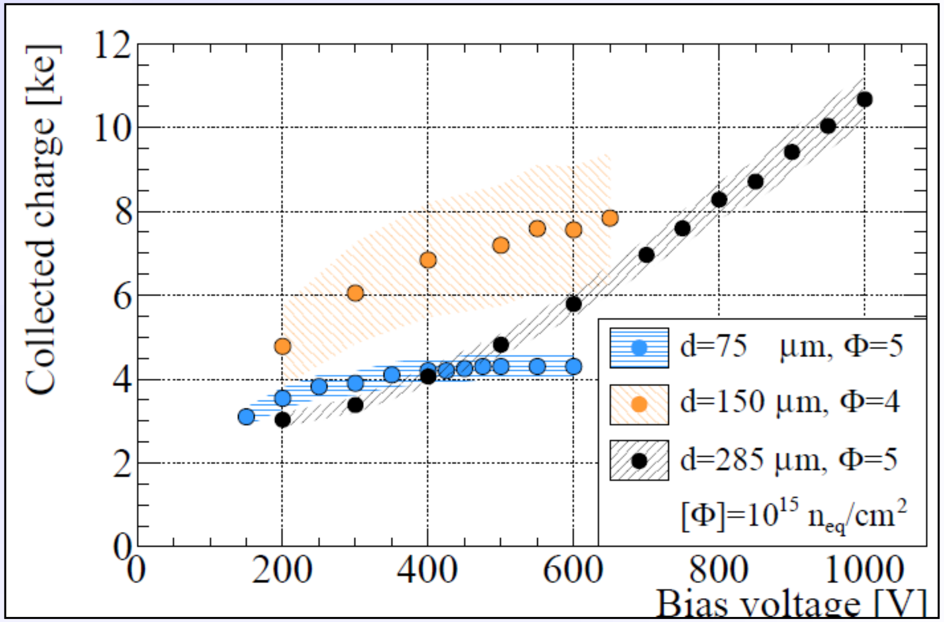
- **Can we simulate and predict charge multiplication ?**
- **Can we better exploit charge multiplication?**

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

Thin p-type pixel sensors

- **Optimizing the sensor thickness**
- **Measurement of thin FZ p-type pixel sensors: 75, 100, 150 and 285 μm (CIS)**
  - **ATLAS FEI4; 25 MeV protons; ^{90}Sr source**



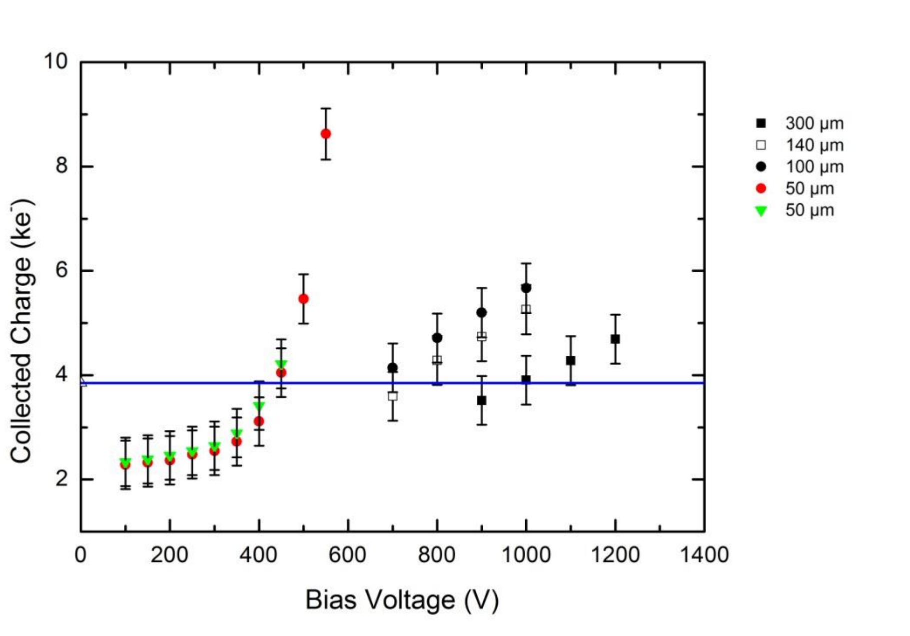


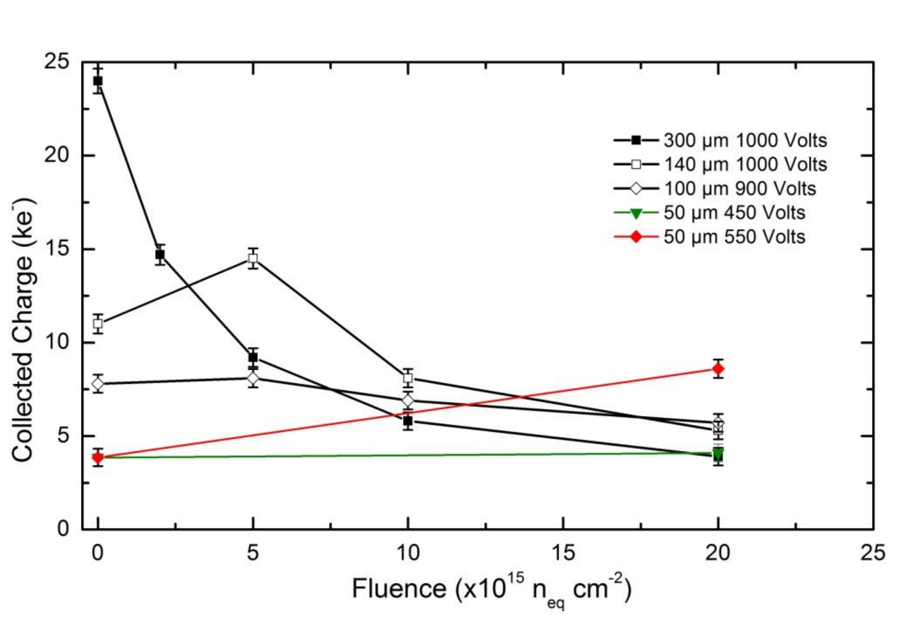
- **150 μm thick devices give higher signal than 75μm and 300 μm thick devices for fluences > 1×10^{15} n$_{eq}$/cm^2**

Thin p-type strip sensors

RD50

- **Measurement of thin p-type strip sensors: 50, 100, 140 and 300 μm**
  - **MPV (mip illumination, 40MHz electronics) of sensors of various thicknesses irradiated with neutrons up to 2×10^{16} n_{eq} cm^{-2}.**





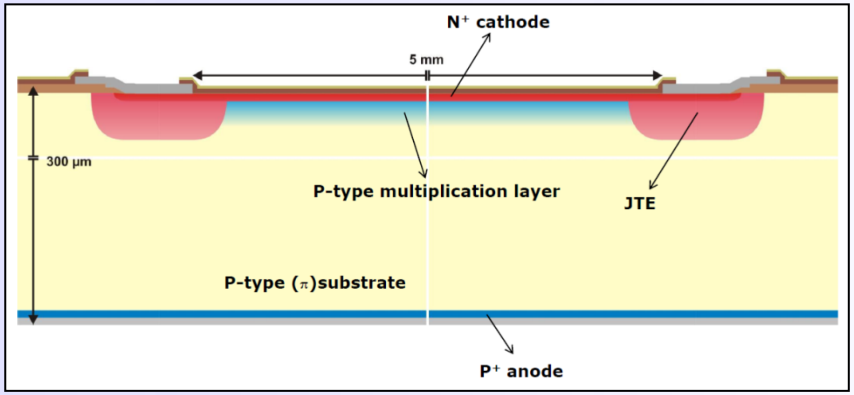
  - **140 μm show good results(highest signal for > 2×10^{15} n_{eq}/cm^2)**
  - **50 and 100 μm show stable performance over all fluence range**

[G.Casse, Liverpool, VCI, 2013]

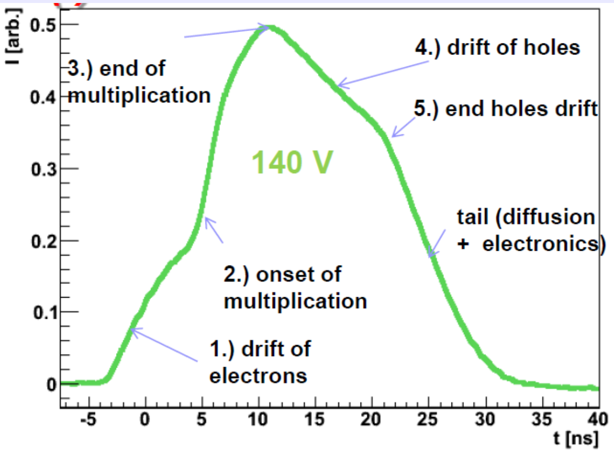
RD50 First production of low gain diodes

- **Diodes with implemented multiplication layer (deep p+ implant)**
  - **Following APD concept**

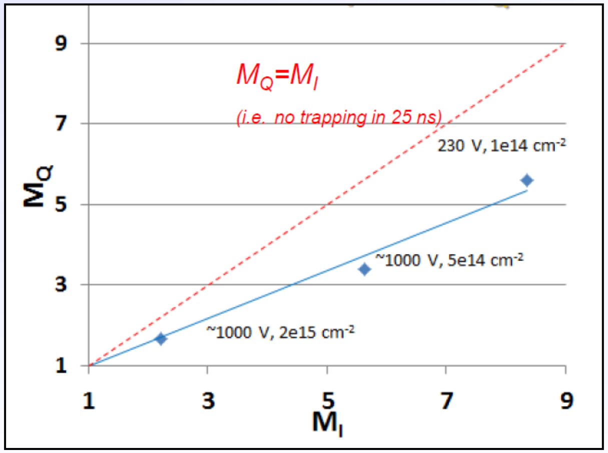
n++ - p+ - p – p+ stucture



- **Gain of ~10 before irradiation**
  - **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?**
  - **Current and noise scale as expected with multiplication**
  - **Characterization with alpha's (Am-241)**

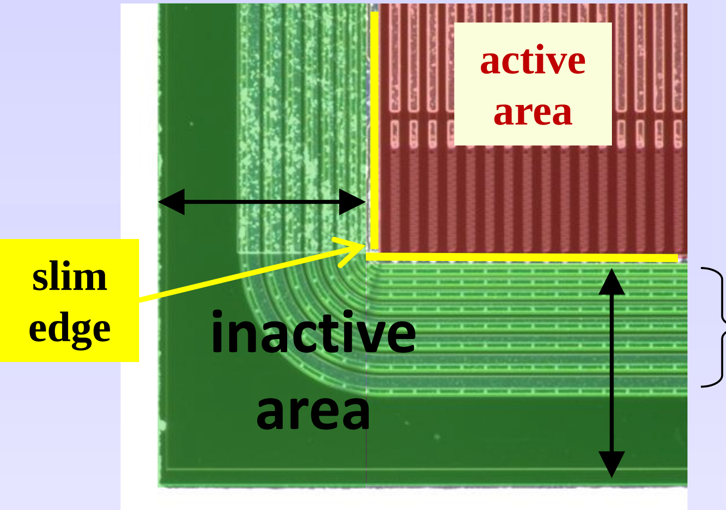


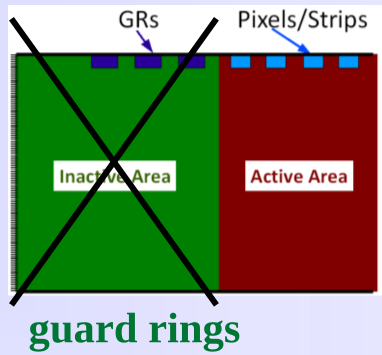
Charge/Current Multiplication (Sr-90)

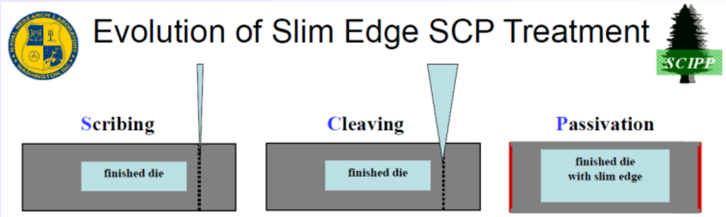


New structures: slim and active edges

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



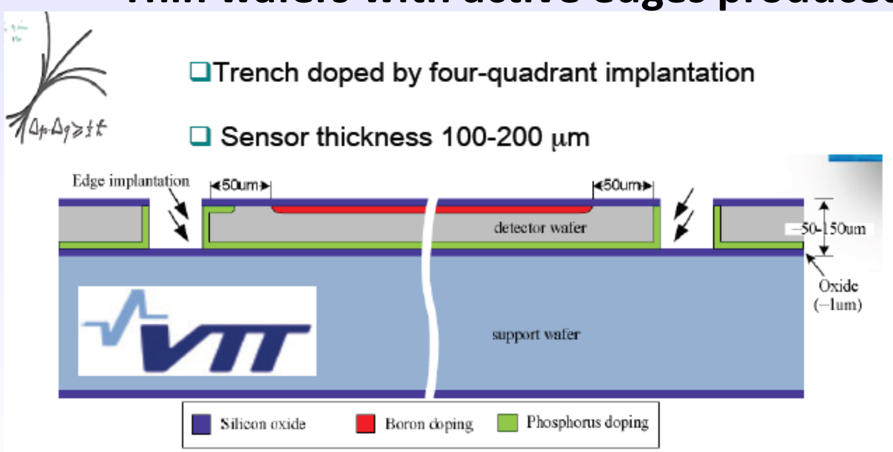


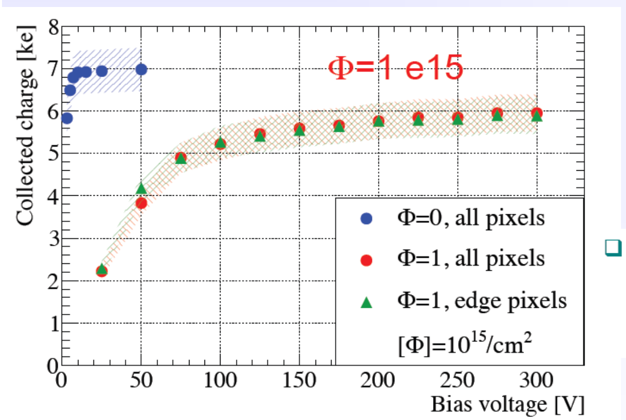


- **Scribe** present: XeF_2 etch)
- **Cleave** present: automated)
- **Passivate** oxide (n-type)
  alumina ALD (p-type)

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

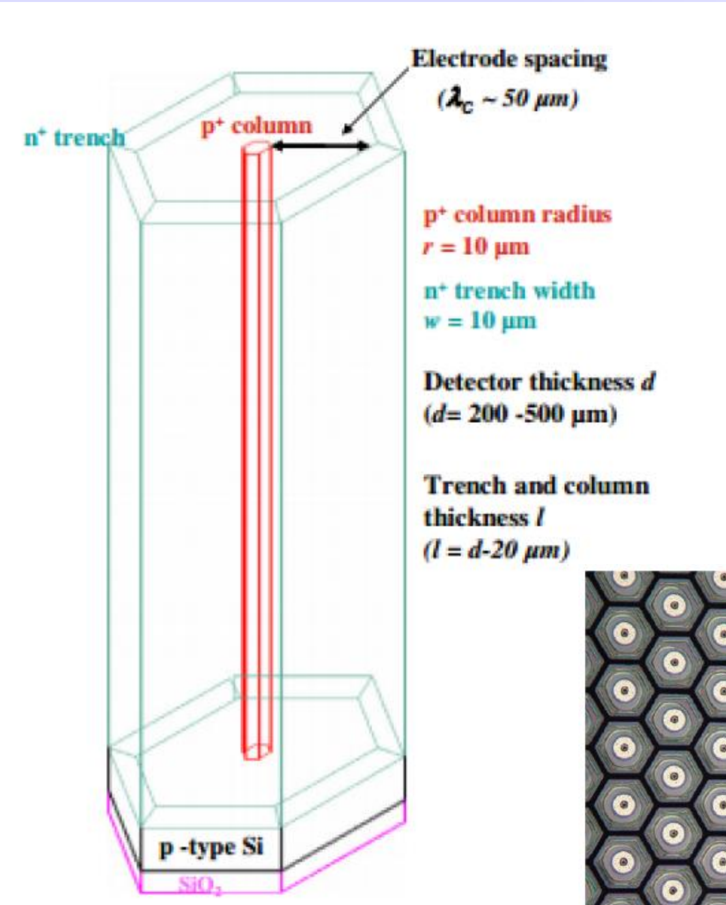
Testbeam:
no difference between edge and other pixel!

- 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

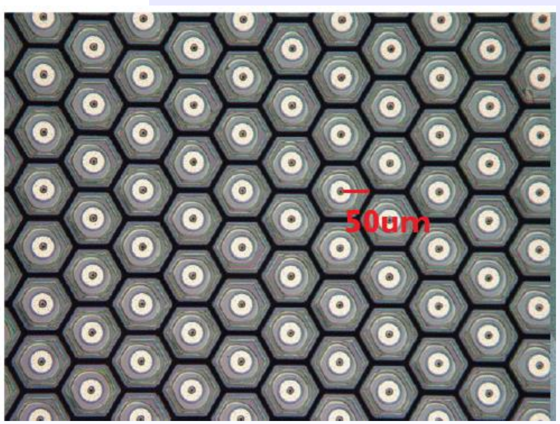
Ongoing technology studies: 3D Trench electrodes & 3D Stripixels

RD50

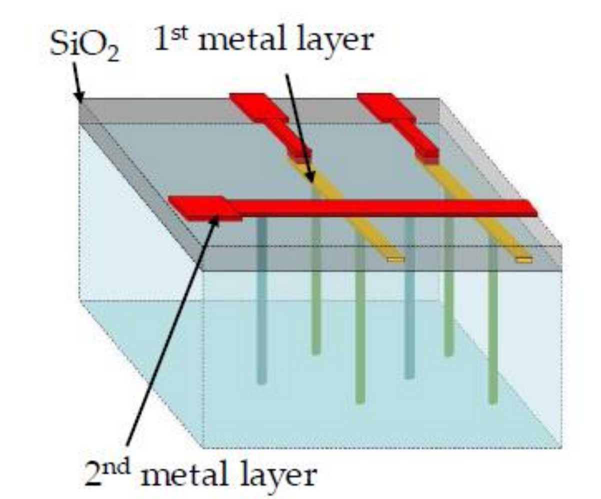
- **Exploring the possibilities of DRIE etching (BNL & CNM)**
  - **3D sensors (well known, installed in ATLAS IBL)**
  - **3D Trench Electrode Detectors**

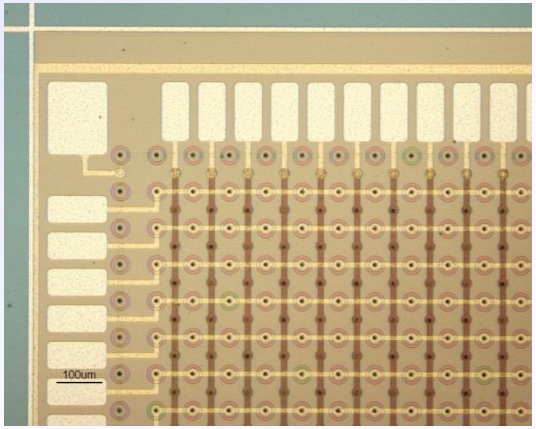


- **Aim**: Function as 3D but with a more homogeneous field (no saddle point)
- First prototypes produced
- CV/IV measured up to 100V
- Next: CCE measurements



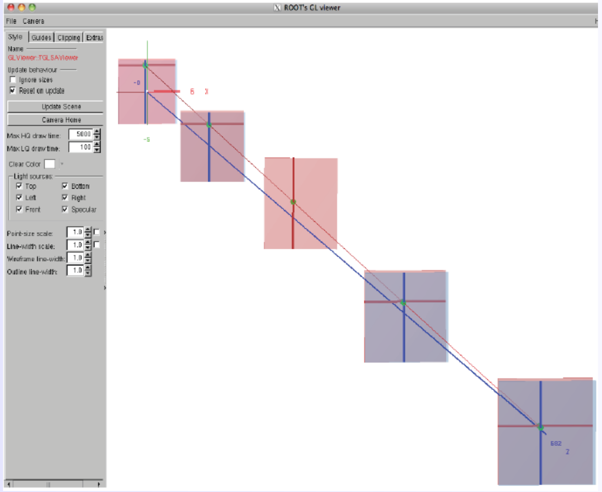
- **3D stripixel**
  (A single-side double strip detector)

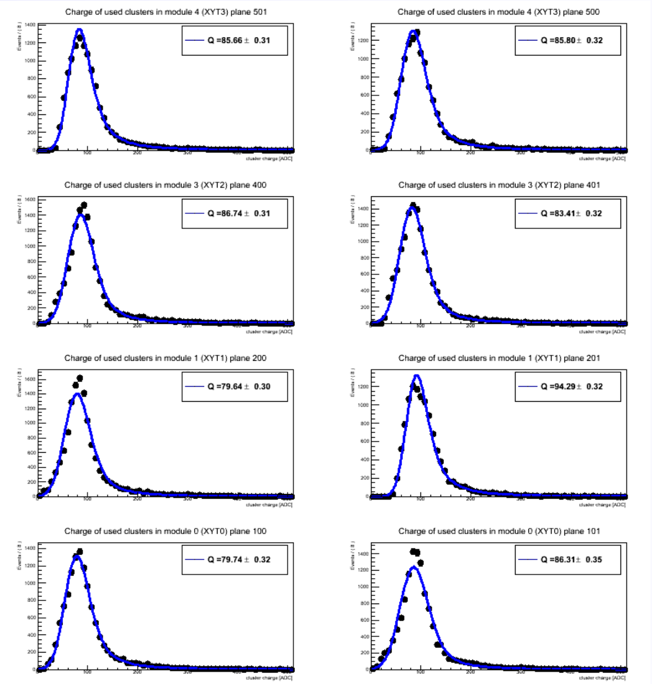


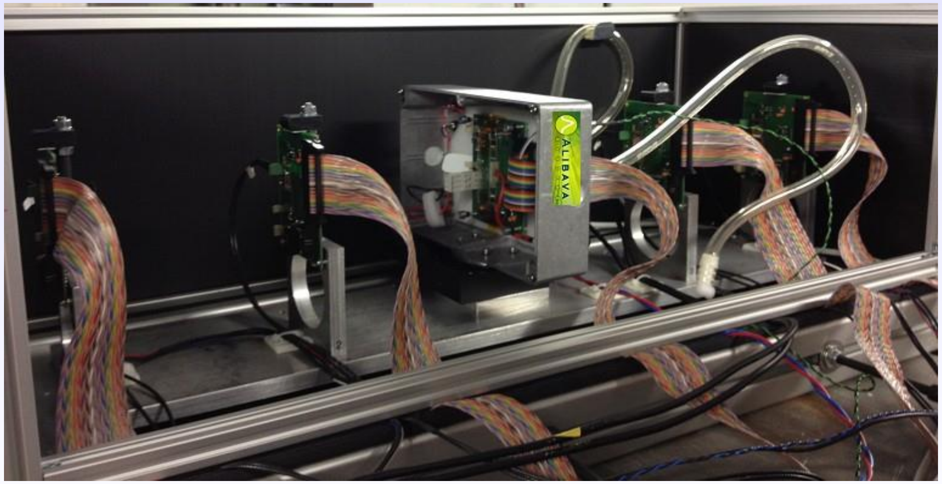


RD50 – ALIBAVA Telescope (AT)

- **RD50 telescope**
  - Alibava based test beam telescope
  - Optimised for easy set-up
  - Fully integrated Alibava readout
    - telescope and DUT have same readout
  - Alignment, tracking and analysis to be standardised. Characteristics of detectors before and after irradiation, as a function of bias voltage or other variables (temperature, influence of magnetic field, etc.) can be studied in real operation conditions.
  - Results from DESY test beam available
  - Note: RD50 has access to other test beams performed in collaboration with e.g. CMS (HIP group)







RD50

Some key results (in 2012/2013)

- **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**
  - 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 the fluence reach of silicon detectors
- **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; Telescope commissioned

RD50

Workplan for 2013/2014 (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**
    - New RD50 common project: Production of test structures on p-type silicon
  - **Review NIEL approach; Modeling and understanding role of clusters;**

- **Detector Characterization** *(Convener: E.Fretwurst, University of Hamburg, Germany)*
  - **RD50 Simulation Working Group** (Leader: V.Eremin, Ioffe, St.Petersburg, Russia)
    - 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
  - **Continue study on "mixed" irradiations**
  - **Extend irradiation program using charged hadrons of different energy**

RD50

Workplan for 2013/2014 (2/2)

- **New structures** *(Convener: Giulio Pellegrini, CNM Barcelona, Spain)*
  - **Continue edge-TCT studies on 3D sensors**
  - **Evaluate Stripixel sensors**
  - **Characterization of dedicated avalanche test structures** (devices have been produced)
    - Understand impact of implant shape and other geometrical parameters on avalanche processes
    - Combine results with edge-TCT data and simulations to get deeper understanding
  - **Evaluate 'low resistance strip' sensors**

- **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 RD50 test beam program and RD50 beam telescope**
  - **Cold irradiations and irradiations under bias** (segmented detectors)
  - **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 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 now considered to be the base line option for the ATLAS Strip Tracker upgrade
- **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.**

Spare Slides

- Some spare slides

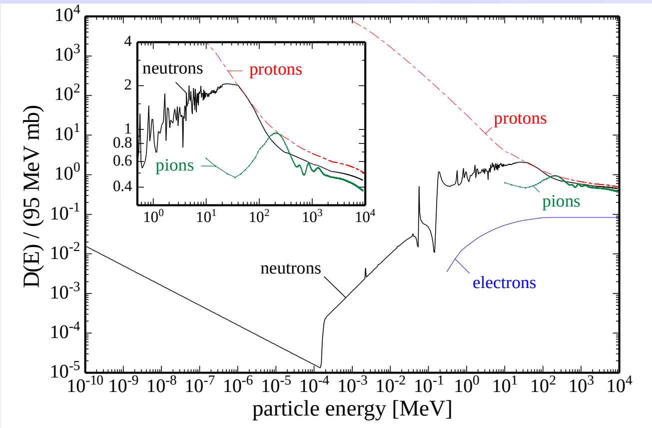
- More details on http://www.cern.ch/rd50/

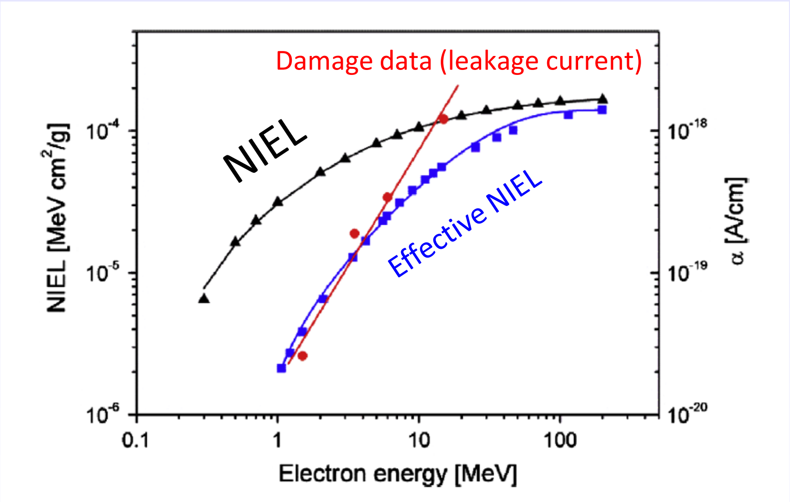
  - Most results presented here have been shown on the 21st or 22nd RD50 Workshop

Microscopic Defects & NIEL

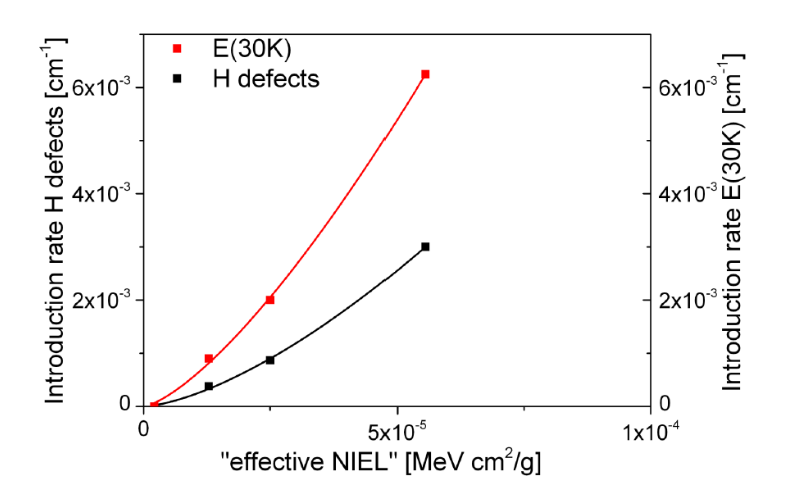
- **Defects concentrations after electron irradiation (1.5 to 15 MeV)**
  - **Do the defect concentrations scale with NIEL (Non Ionizing Energy Loss)?**
    - Data taken with DOFZ – Diffusion Oxygenated Floating Zone Silicon

NIEL





- Defect concentrations vs. effective NIEL



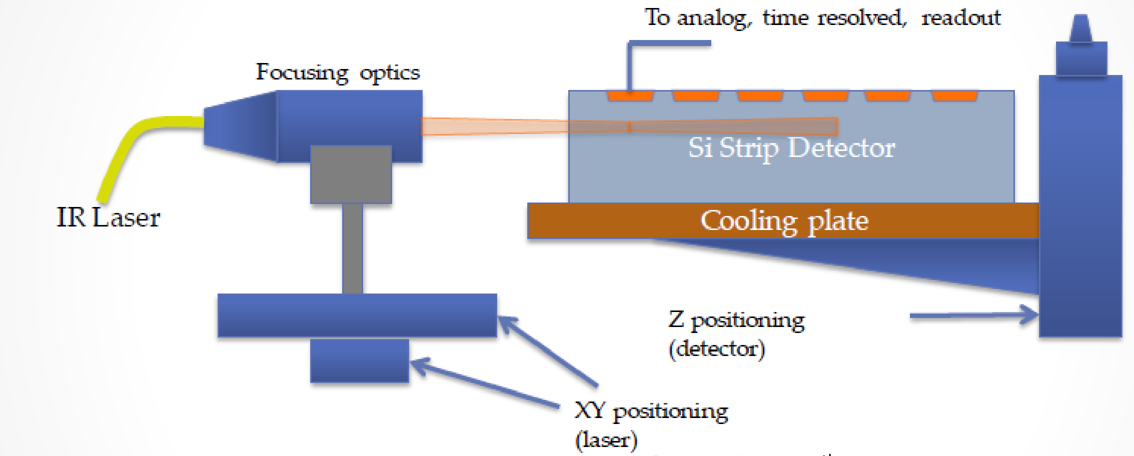
- NIEL scaling (classical and effective) violated for electrons
- Next step:
  Can we improve the NIEL scaling for hadrons by considering an effective NIEL?

RD50

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]

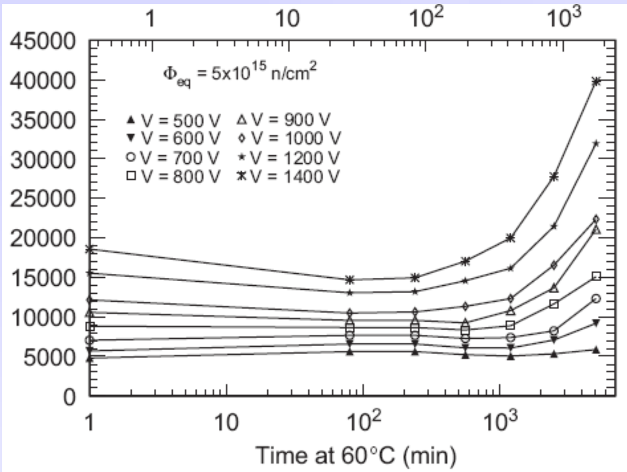
- **Expectations**
  - Significant electric field only in depleted volume
  - Charge generated in ‘undepleted’ part of detector is lost

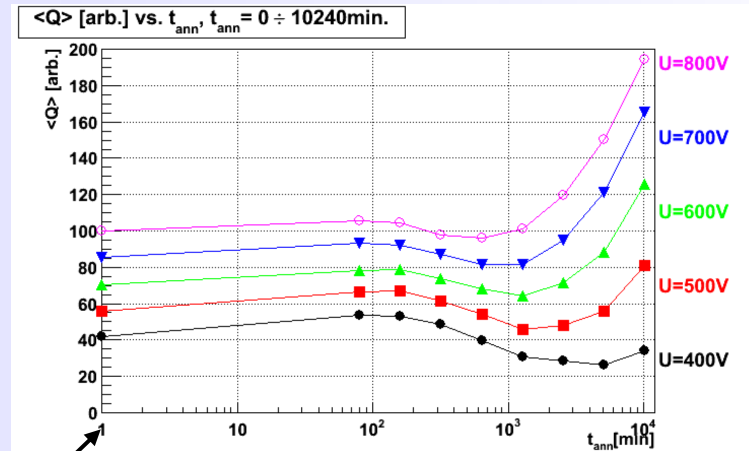
RD50 Characterizing Charge Multiplication

- **Long term annealing of strip sensors** (HPK, 320μm thick, 75μm pitch, FZ, n-in-p)
  - **CCE with SCT 128A (40MHz)**

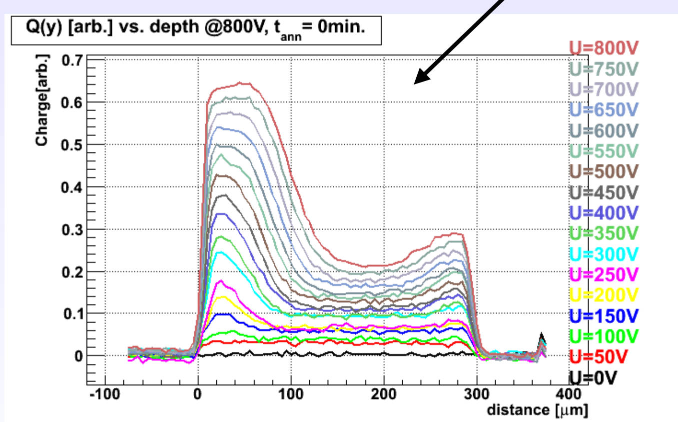
Collected Charge from edge-TCT

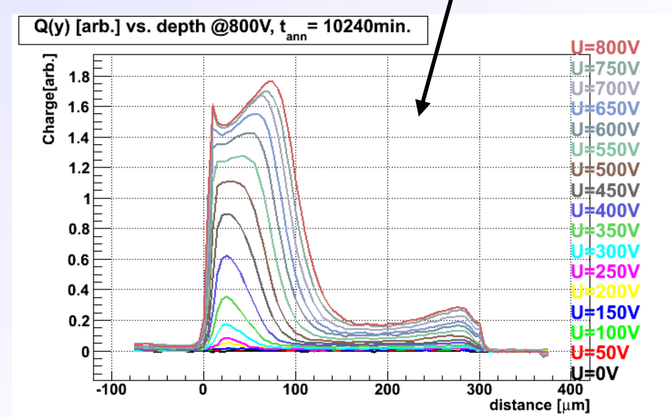
[I.Mandic, 17th RD50 Workshop, CERN, Nov. 2010]





- **Charge multiplication observed after long annealing times for high voltages**
- **Edge-TCT**
  - Shows CM and gives indication from which depth region charge is collected and multiplied



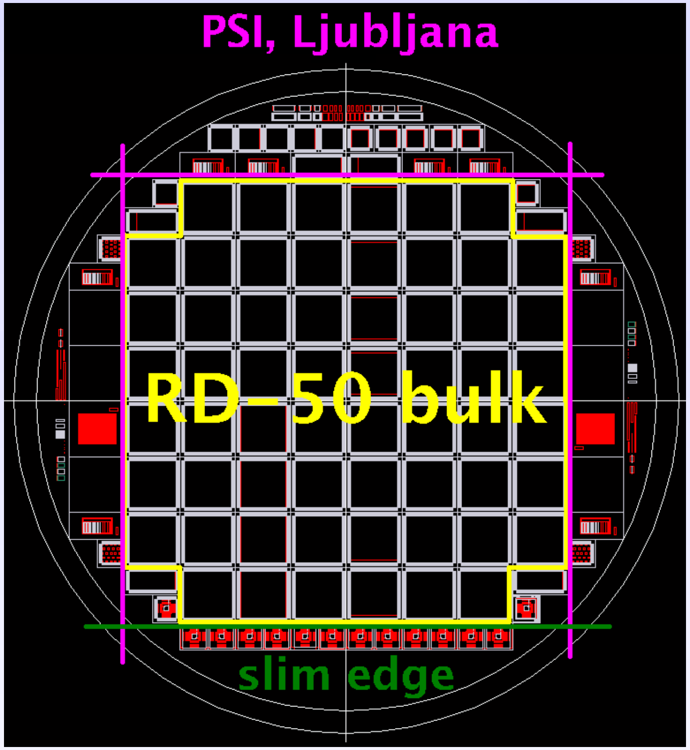


[M. Milovanović, 19th RD50 Workshop, Nov.2011]

Understanding Charge Multiplication

RD50

- **Exploring the effect of implant geometries**
  - ratio of strip implant to pitch
  - effect of intermediate strips
  - effect of deeper junction



- **Status: Detectors produced, irradiated, measurements about to start.**

Label	Strip pitch (μm)	Implant width (μm)	Intermediate strip width (μm)
I8N	80	25	10
I8W	80	25	35
I10N	100	33	33
I10W	100	33	15
I5N	50	15	15
I5W	50	15	6

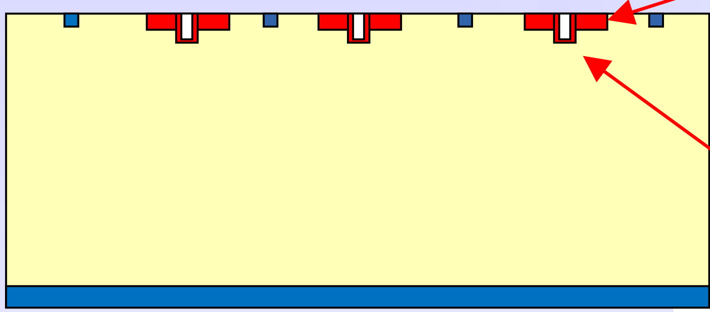
Label	Strip pitch (μm)	Implant width (μm)
NI8W	80	60
NI8M	80	25
NI8N	80	6
NI10W	100	70
NI10M	100	33
NI10N	100	10
NI4W	40	27
NI4M	40	15
NI4N	40	6

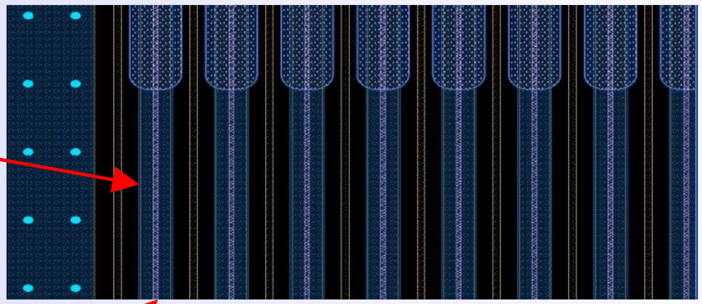
Enhancing Charge Multiplication

RD50

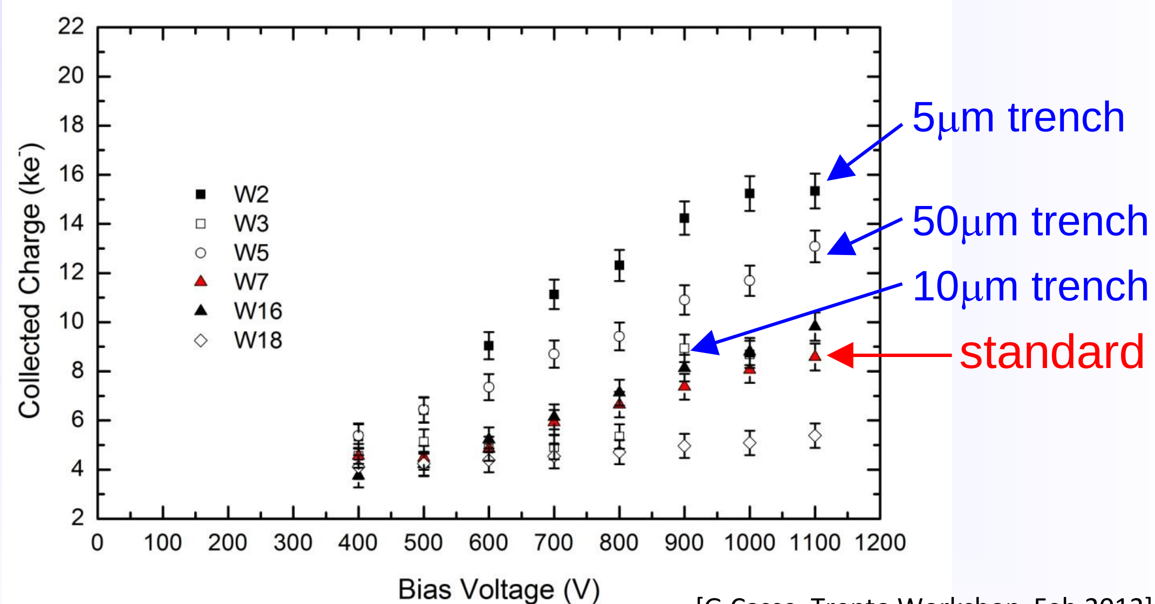
- **Strip detector Design with trenches**
  - **5, 10, 50 μm deep trenches**
  - **5 μm wide in center of n^+ electrode**

[D.Forshaw, 19th RD50 Workshop, Nov.2011]





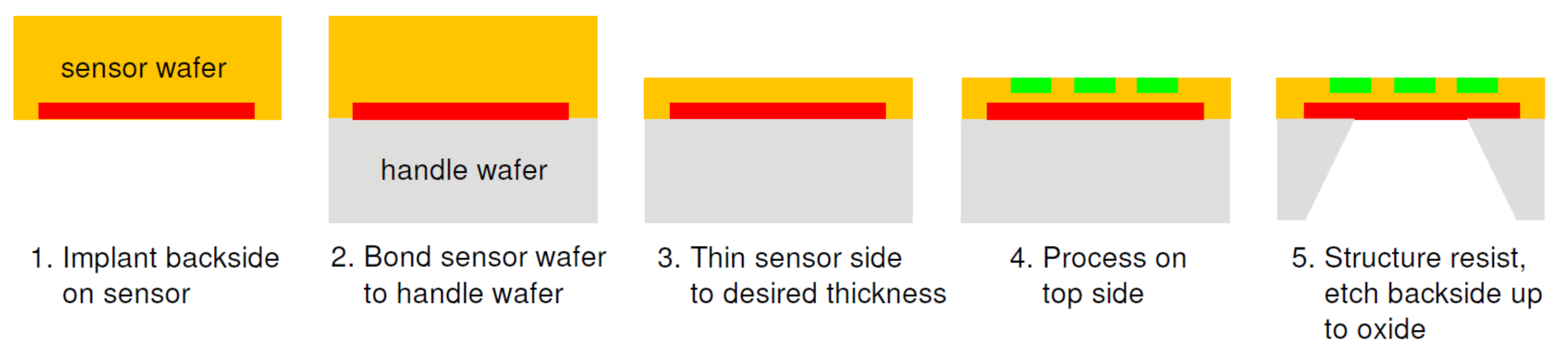
- **Sizeable effect on Charge Multiplication**
  - **Significant difference in CCE between standard and trenched detectors**
  - **Irradiation: 5×10^{15} $n_{eq}cm^{-2}$ (neutrons)**

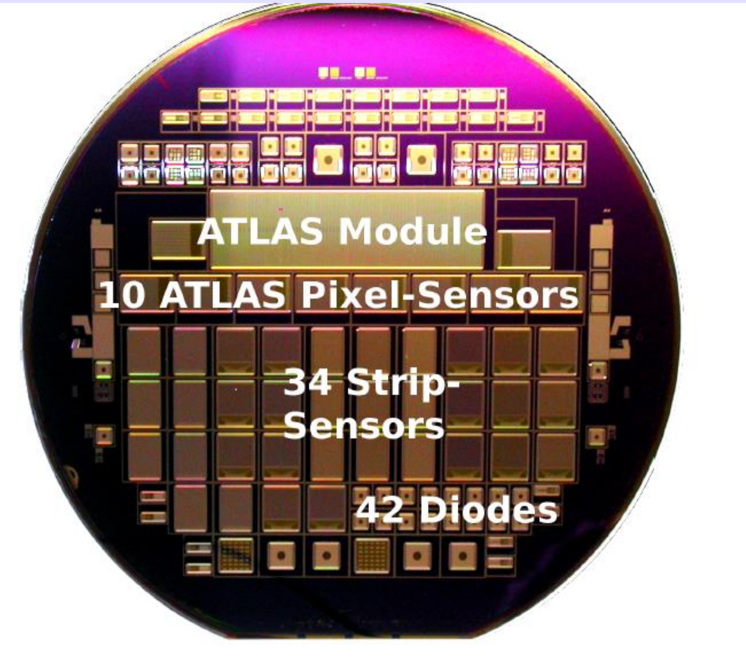


[G.Casse, Trento Workshop, Feb.2012]

Thin pixel sensors

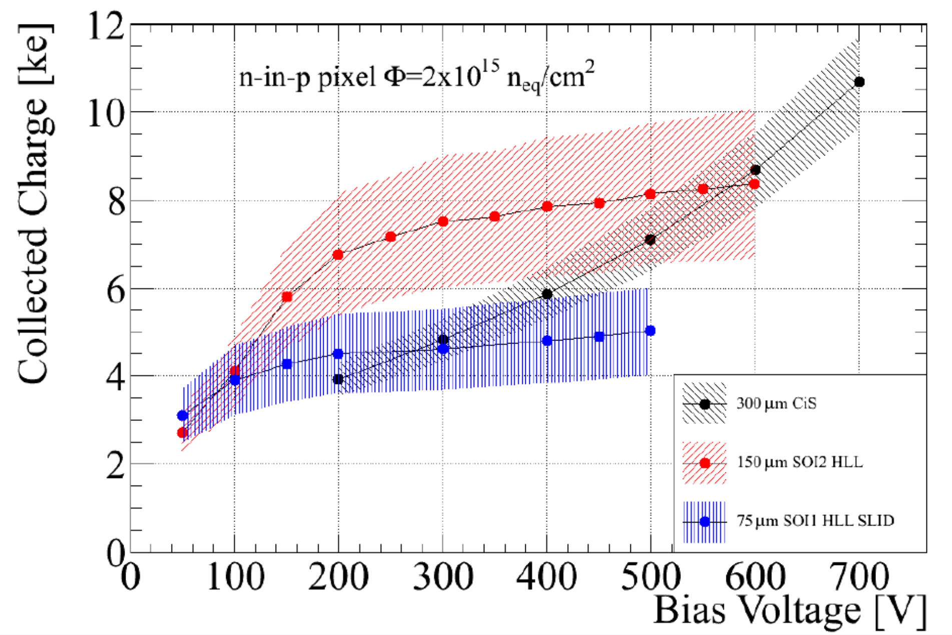
- **Thin pixel sensors produced: 75 and 150 μm thickness [MPI Munich]**





[A.Macchiolo, 20th RD50 Workshop, Bari, May 2012]

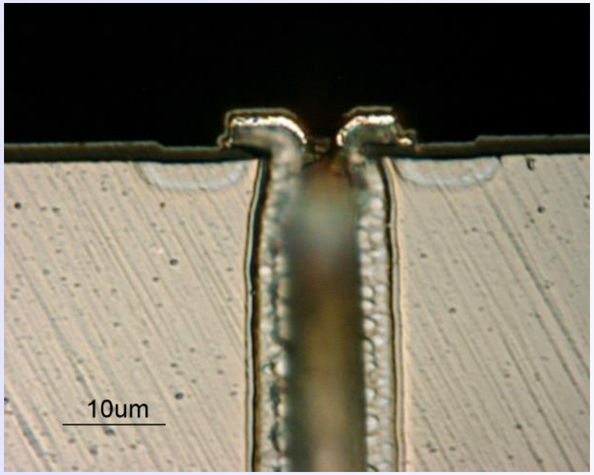
- **n-in-p pixel sensors**
  - **Interconnect: Bump bonding and SLID tested**



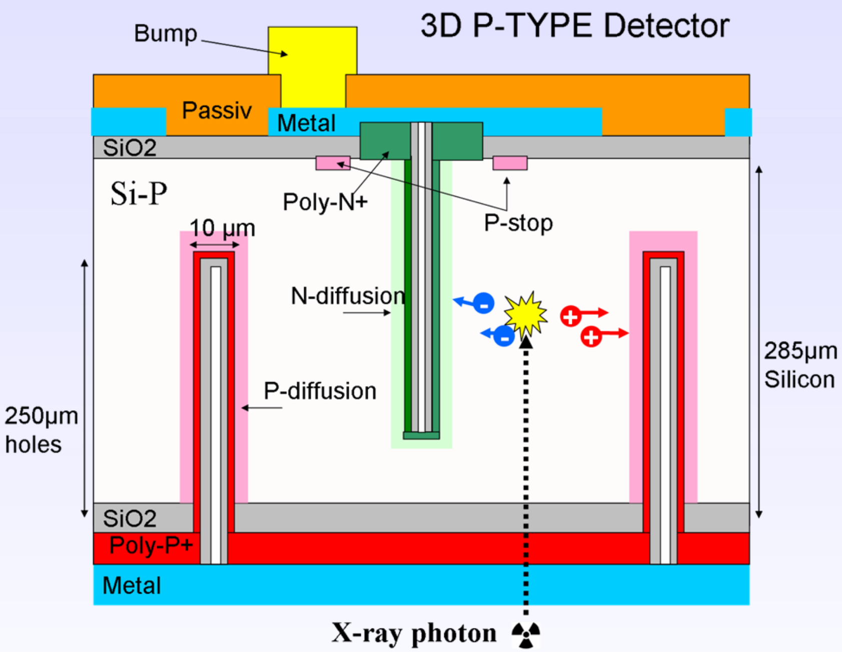
RD50

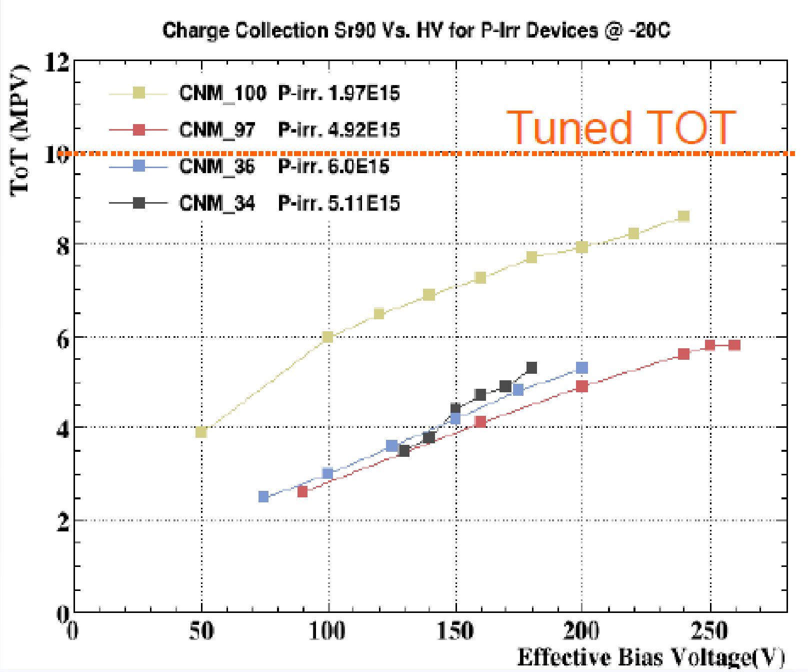
New structures: 3D sensors

- **3D sensors: Mastering the technology (CNM-Barcelona, FBK-Trento)**
  - **Reproducible, reliable results before and after irradiation**



Double sided 3D





[A.Harb (IFAE Barcelona), 19th RD50 Workshop, Nov. 2011]