RD50


VERTEX 2013, Lake Starnberg, Germany, 16-20 September 2013

Development of radiation tolerant Silicon Sensors

- A Status Report of the RD50 Collaboration -

Michael Moll
CERN, Geneva, Switzerland
On behalf of the RD50 collaboration

OUTLINE:

- Introduction
- The RD50 Collaboration
- RD50 scientific results (a selection)
    - Defects and their impact on detector performance
    - Detector Simulation using TCAD
    - Detector Characterization: Study of the Electric Field
    - Charge multiplication
    - Material dependence and sensor thickness, …
- Conclusion and Outlook

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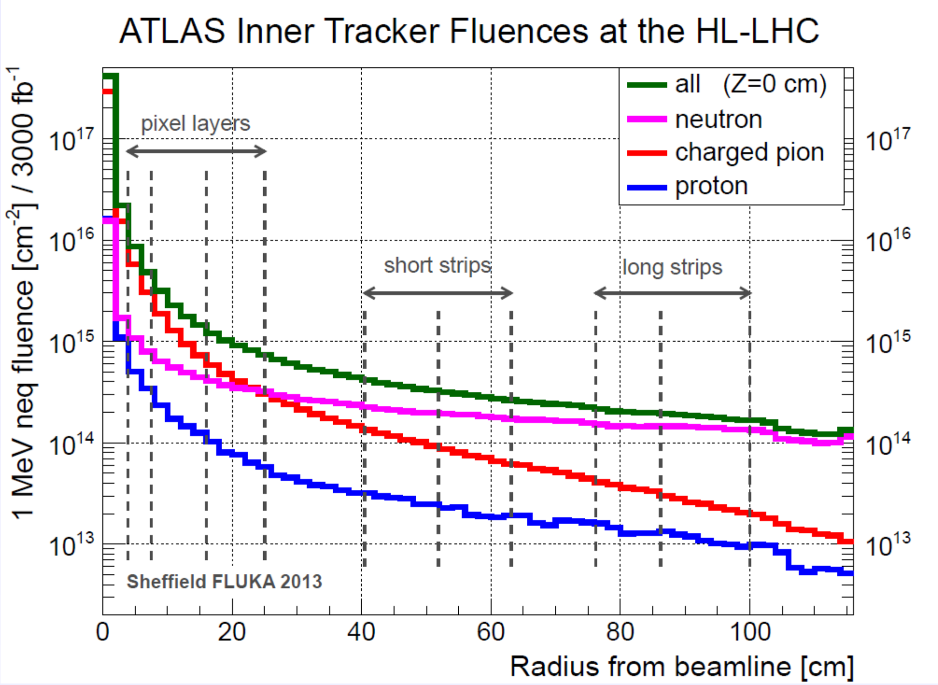
Motivation

- **LHC upgrade** *(and beyond…. HE-LHC, VHE-LHC)*
  - **upgrade of the LHC to the High Luminosity LHC (HL-LHC) after LS3 (2022)**
  - **expected integrated luminosity: 3000 fb^{-1}**



[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

RD50 mission: development of silicon sensors for HL-LHC

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The RD50 Collaboration

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

40 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)

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)

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)**
- **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)

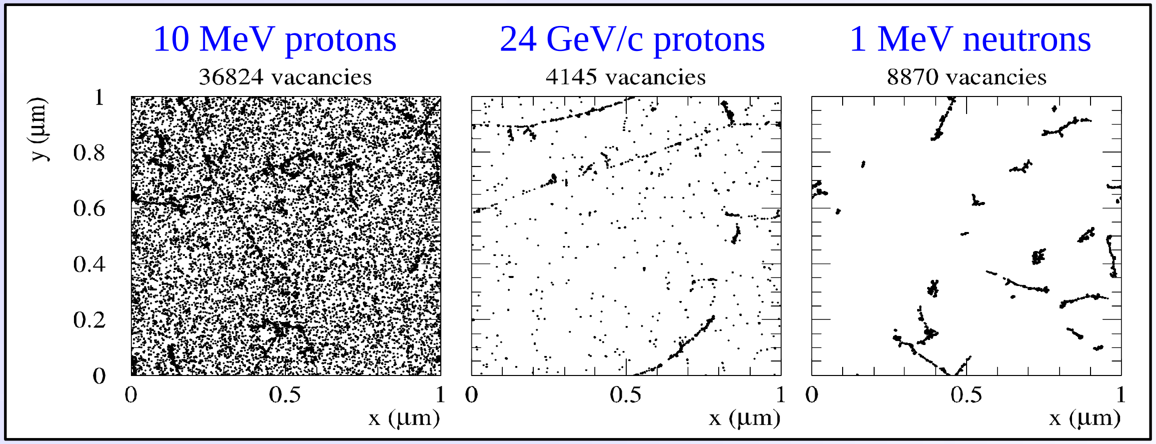
Collaboration Board Chair & Deputy: G.Kramberger (Ljubljana) & J.Vaitkus (Vilnius), Conference committee: U.Parzefall (Freiburg)
CERN contact: M.Moll (PH-DT), Secretary: V.Wedlake (PH-DT), Budget holder & GLIMOS: M.Glaser (PH-DT)

Defects (Reminder)

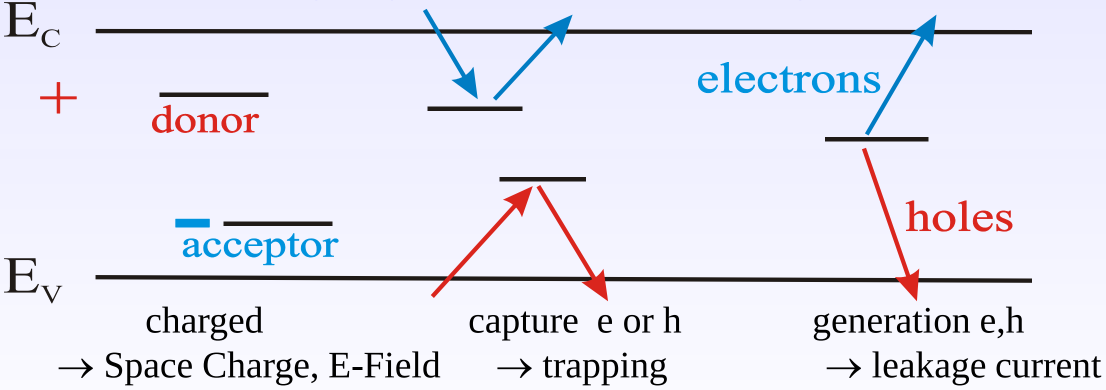
- **Defects are the reason for the radiation induced degradation of the devices**
- **Generation of defects is depending on impinging particle type and energy**
  - Damage usually scaled by NIEL Hypothesis (Non-Ionizing Energy Loss)
    - Not necessary true!

Simulation:
Initial distribution of vacancies in (1µm)^3 after 10^{14} particles/cm^2

[Mika Huhtinen NIMA 491(2002) 194]



- **Defect generation can depend on material (remember: oxygenated silicon)**
- **Electronic defect properties rule the impact on the device**



Defect parameters:

$\sigma_{n,p}$: cross sections
ΔE : ionization energy
N_t : concentration
type : acceptor, donor,…

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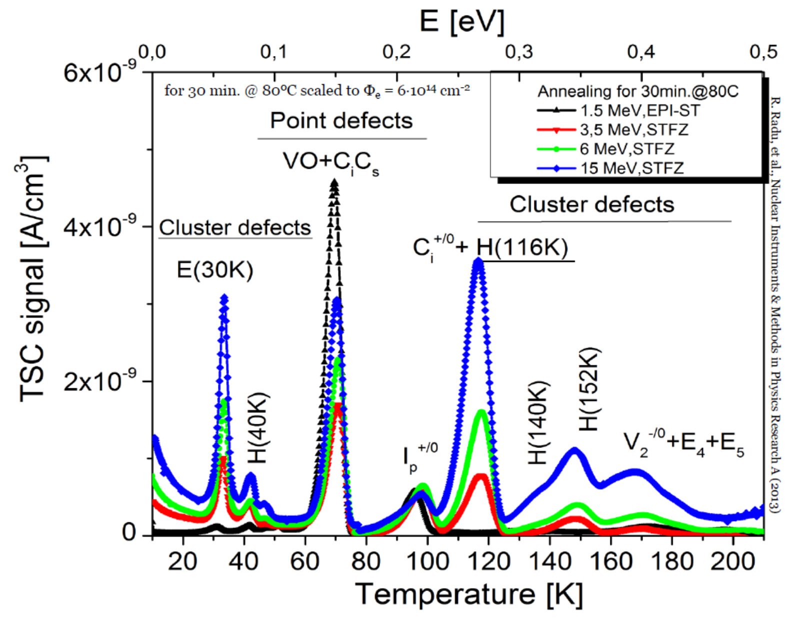
Defect Characterization

- **Defect characterization project**
  - **Aim:**
    - 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 on identical samples performed with various tools inside RD50:**
    - **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 Current Technique)
    - **CV/IV** (Capacitance/Current-Voltage Measurement)
  - **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!

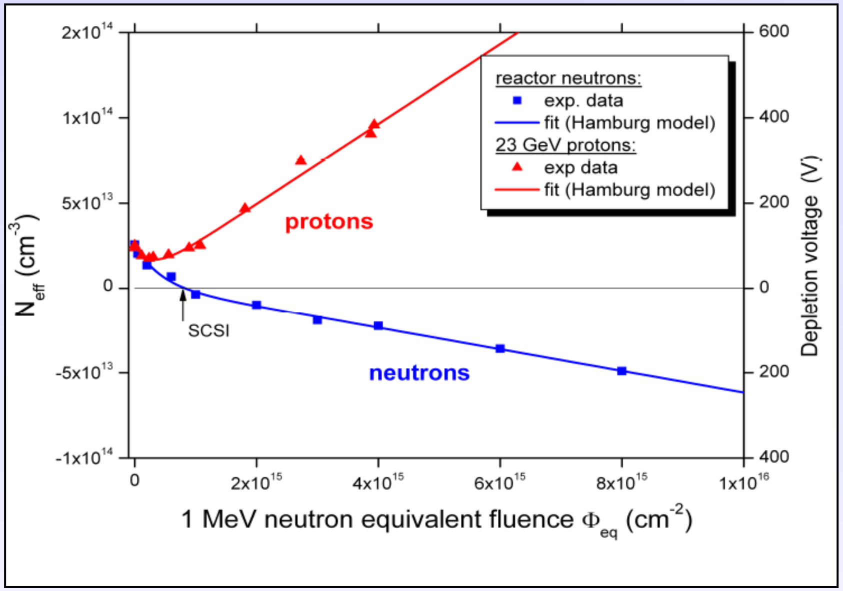


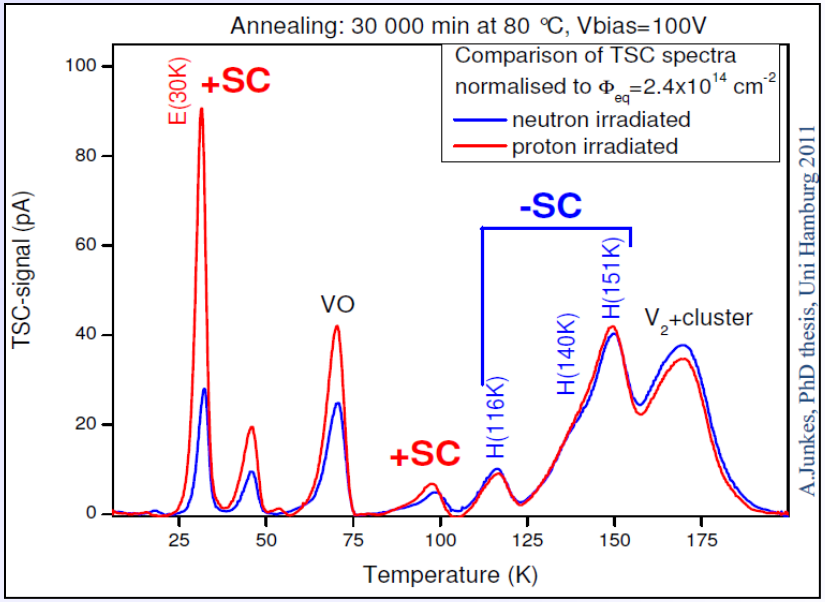
[R.Radu, 22nd RD50 Workshop, 3-5 June 2013]

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

RD50 Defects: Impact on N_{eff} (particle type)

- **Macroscopic observation: Dependence on particle type (protons vs. neutrons)**
  - *In several oxygen rich silicon materials neutron irradiation leads to build-up of net negative space charge ("type inversion") while charged hadron irradiation leads to build up of net positive space charge. Note: Violation of NIEL (Non Ionizing Energy Loss) Hypothesis!*
- *Example:* Epi silicon (EPI-DO, 72µm,170Ωcm) irradiated with **23 GeV protons** or **reactor neutrons**





A.Junkes, PhD thesis, Uni Hamburg 2011

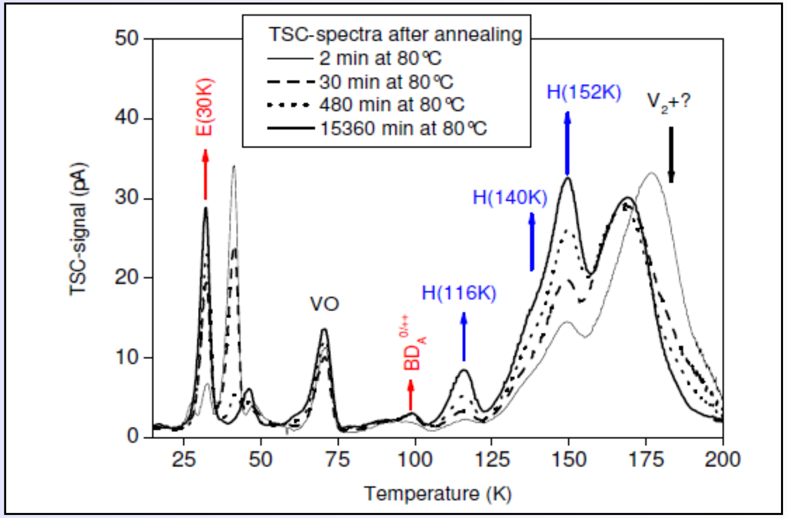
- **Microscopic observation**
  - *The **Donor E(30K)** is introducing the additional positive space charge after proton irradiation*
  - *Defects related to build-up of negative space charge not influenced (follow the NIEL scaling)*

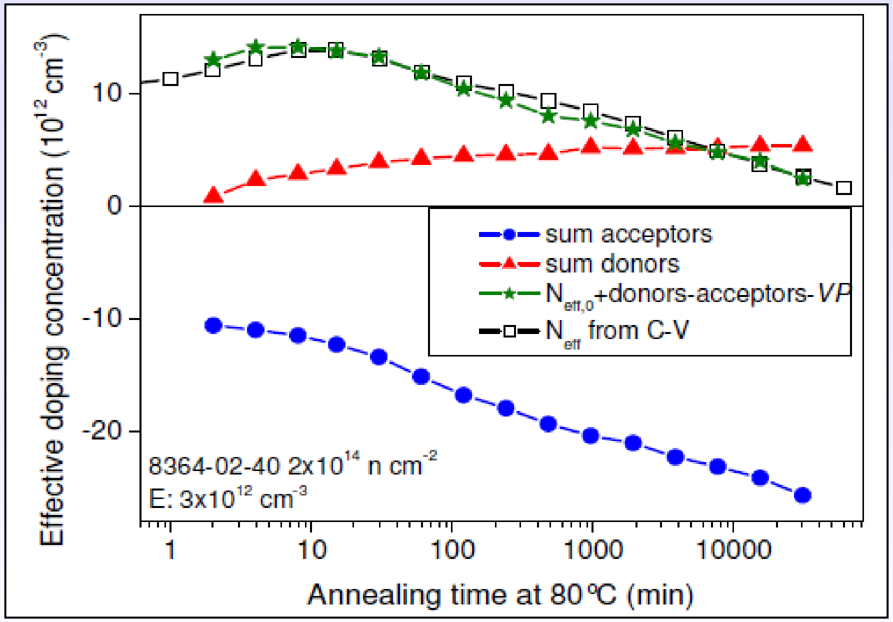
[I.Pintilie et al., NIMA 611 (2009)52-68]

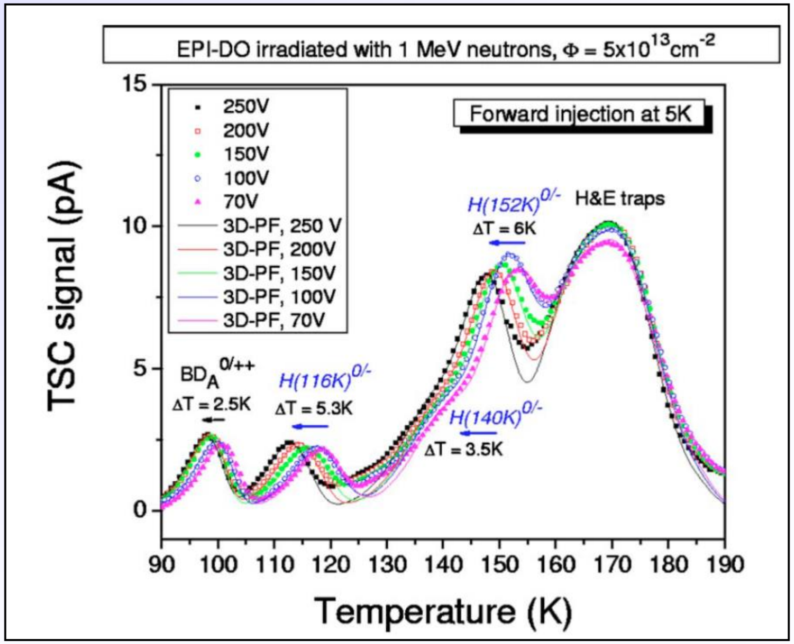
Defects: N_{eff} impact (reverse annealing)

- **Macroscopic observation:**
  - Irradiated silicon sensor show "reverse annealing" (negative space charge increasing with time)
- Example: Neutron irradiated epitaxial silicon
  - Identification of hole traps that grow with reverse annealing and are deep acceptors *(labelled: **H(116K),H(140K),H(152K)**)*
  - Absolute correlation of defect concentration to increase of $|N_{eff}|$ (reverse annealing)

2×10^{14} n/cm^2, Epi-St 75µm





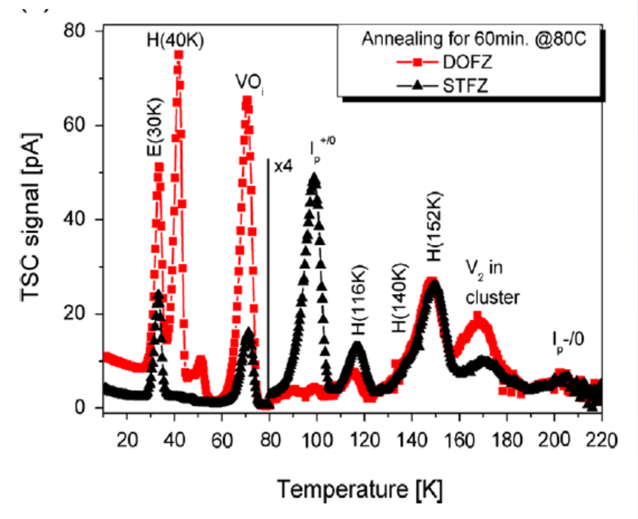


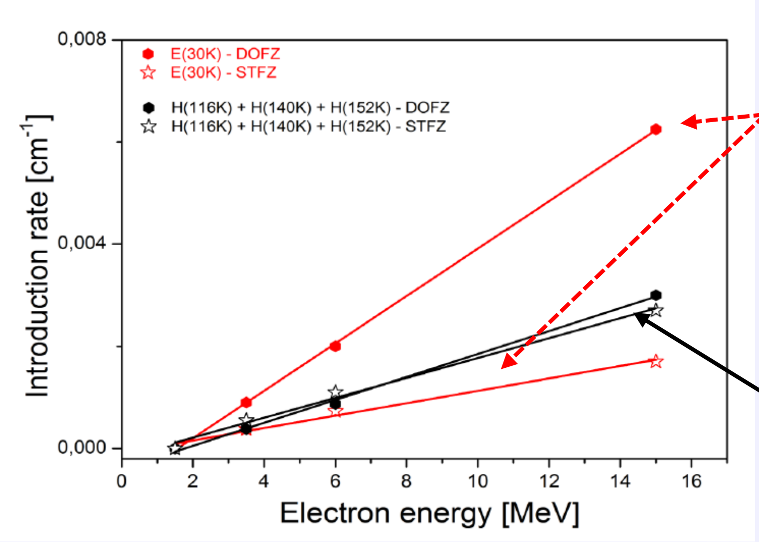
[A.Junkes PoS(Vertex 2011) 035; I.Pintilie, APL 92,024101 (2008); Junkes PhD thesis]

Defects: Impact on N_{eff} (material)

- **Macroscopic observation: Dependence on material type (oxygenated vs. standard)**
  - *In general: Less build up of net negative space charge in oxygen enriched silicon after charged hadron irradiation. (-->LHC pixel detectors build from oxygenated silicon)*
  - *In several cases oxygenated materials (EPI, MCZ) have shown no "type inversion" at all after charged hadron irradiation.*
- Example: **Electron irradiation** (1.5 to 15 MeV) of STFZ ([O]=10^{16}cm^{-2}) and DOFZ ([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)

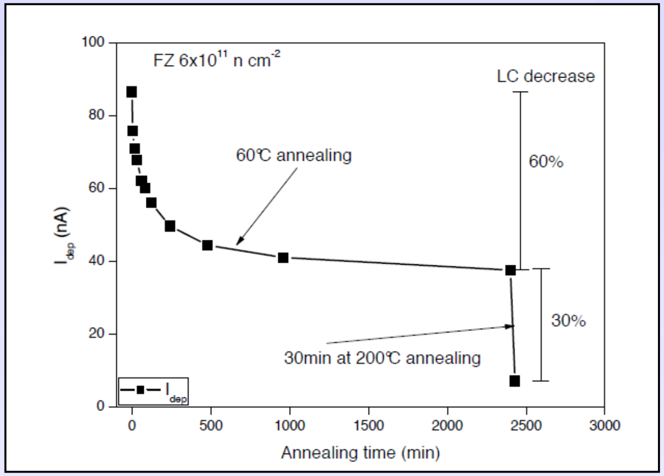
[R.Radu et al., RD50 Workshop June 2013, NIMA, DOI: 10.1016/j.nima.2013.04.080]

- **Microscopic observation**
  - *The* ***Donor E(30K)*** *is introducing more positive space charge in oxygen rich silicon with a particle type and energy dependent rate.*
  - *Defects related to negative space charge (reverse annealing) not influenced by oxygen content*

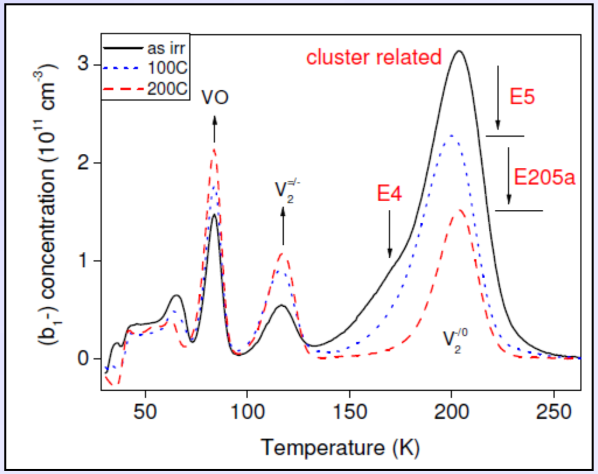
RD50 Defects: Impact on leakage current

- **Macroscopic observation: Leakage current build-up following NIEL (for hadrons)**
  - *Leakage current scaling (almost) with NIEL and independent of silicon material (not for gammas!)*
  - *Leakage current is annealing in time and with temperature.*

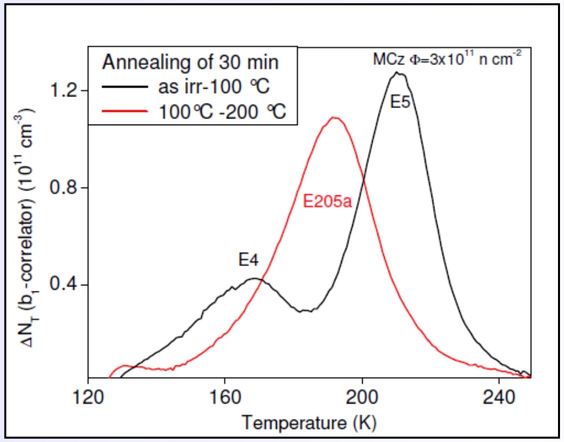
- **Example:** Annealing study on a FZ sample (6x10^{11} n/cm^2)



Leakage Current

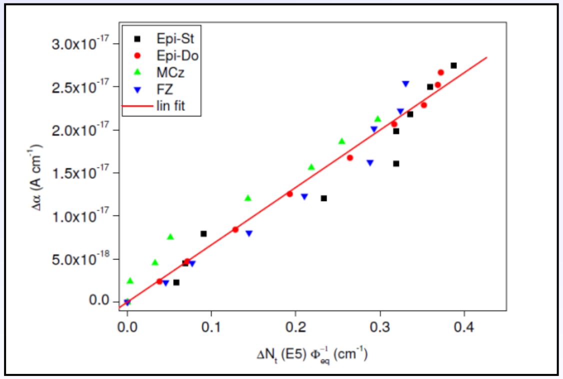


DLTS spectra



DLTS difference spectra (disappearing peaks)

- **Microscopic observation**
  - *The defects **E4/E5** (annealing at 60°C)and **E205a** (annealing at 200C) are contributing to the leakage current with 60% and 30 % respectively.*



ΔN_t(E5) vs. $\Delta\alpha$
Correlation found for many materials after neutron irradiation

[A.Junkes, PhD thesis 2011 & Vertex 2011 Proceedings]

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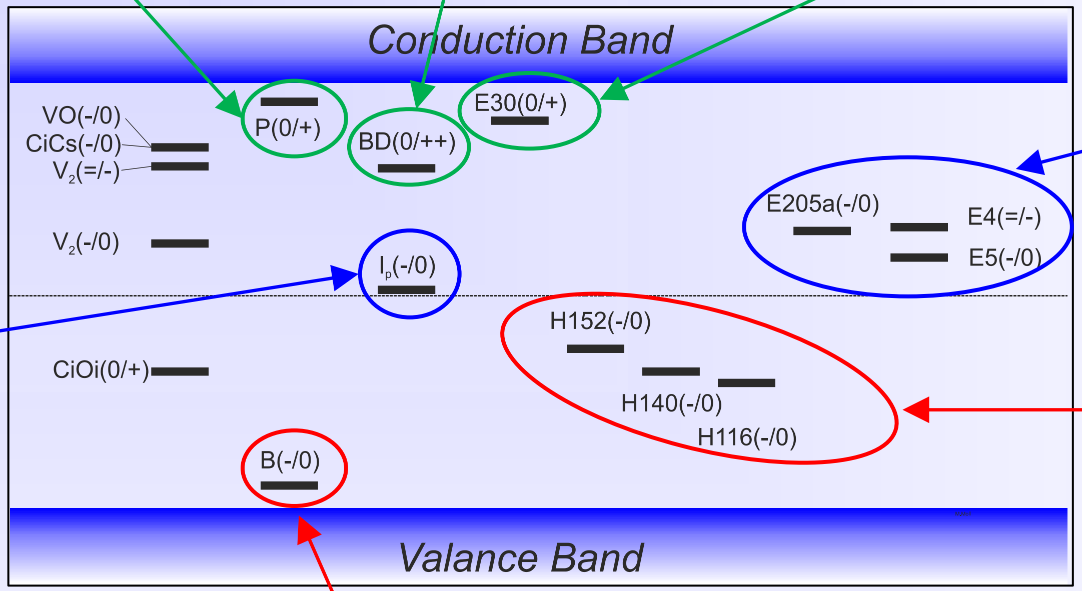
Summary on defects with strong impact on device performance after irradiation

- **Some identified defects**

Phosphorus: shallow dopant (positive charge)

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

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



Leakage current

E4/E5: 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 Annex (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!

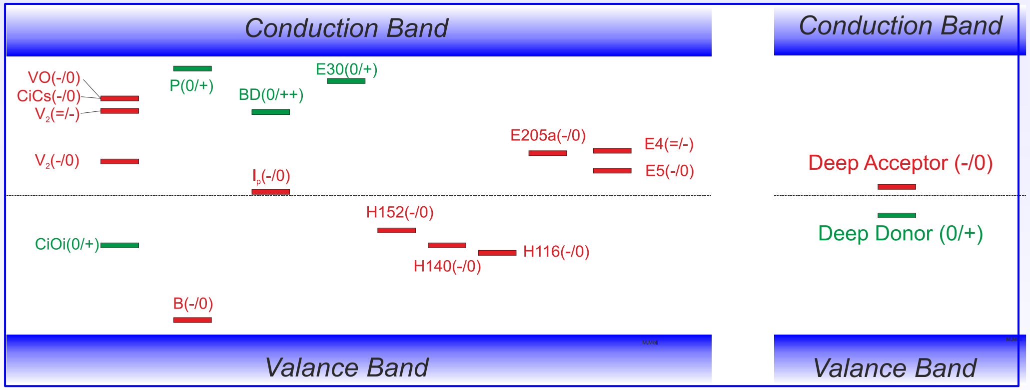
TCAD - Simulations

- **Device simulation of irradiated sensors**

[VERTEX 2013: see also "TCAD Simulations" M.Benoit]

  - **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***

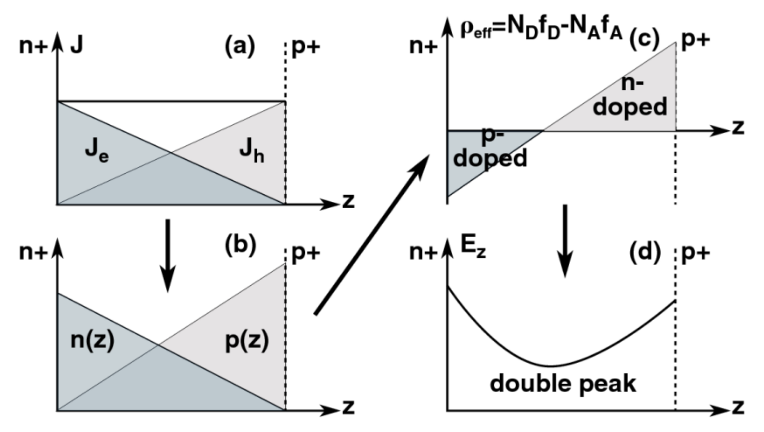


TCAD simulation: Double Junction

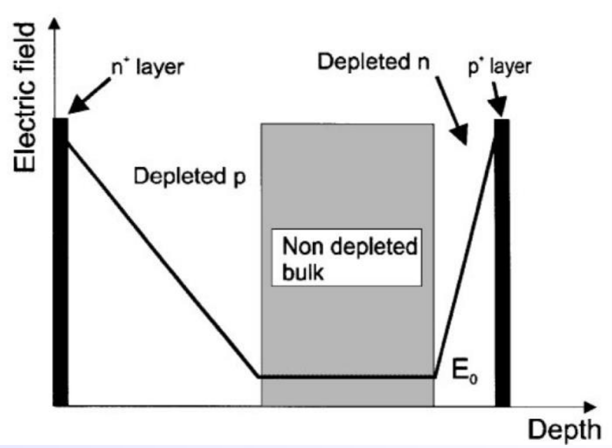
- **Why do do we need TCAD simulations? ➔ Complexity of the problem!**
  - **Example: The double junction effect after high levels of irradiation**

Current density **Space Charge**

[V.Eremin et al., NIMA 476 (2002) 556]

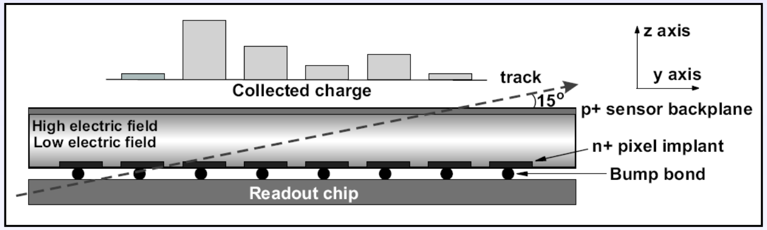


Free carrier density **E-Field**

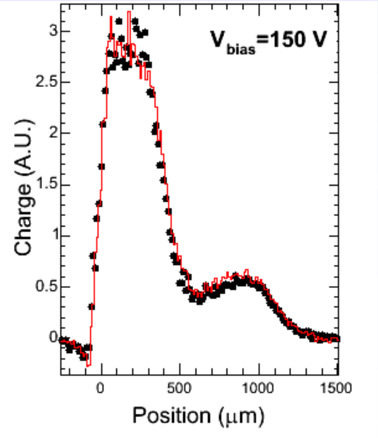


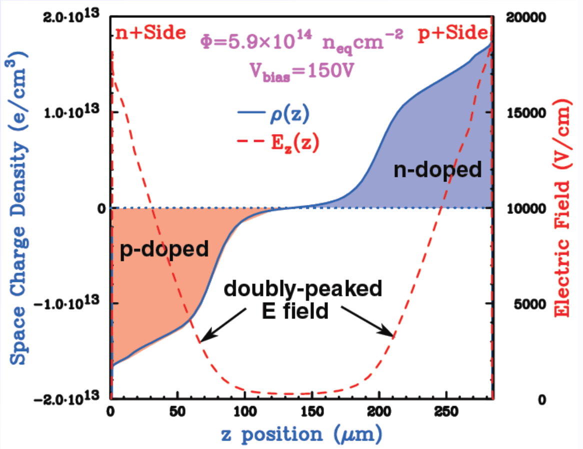
  - **Example: Measurement & TCAD simulation of the double junction**

CMS test beam – grazing angle technique



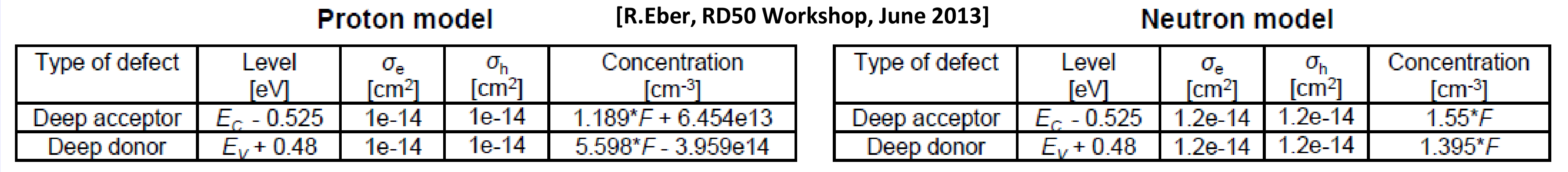
[Chiochia et al., IEEE Trans. Nucl. Sci. Vol. 52(4), 2005, p. 2294.]





TCAD simulation: Trapping

- **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

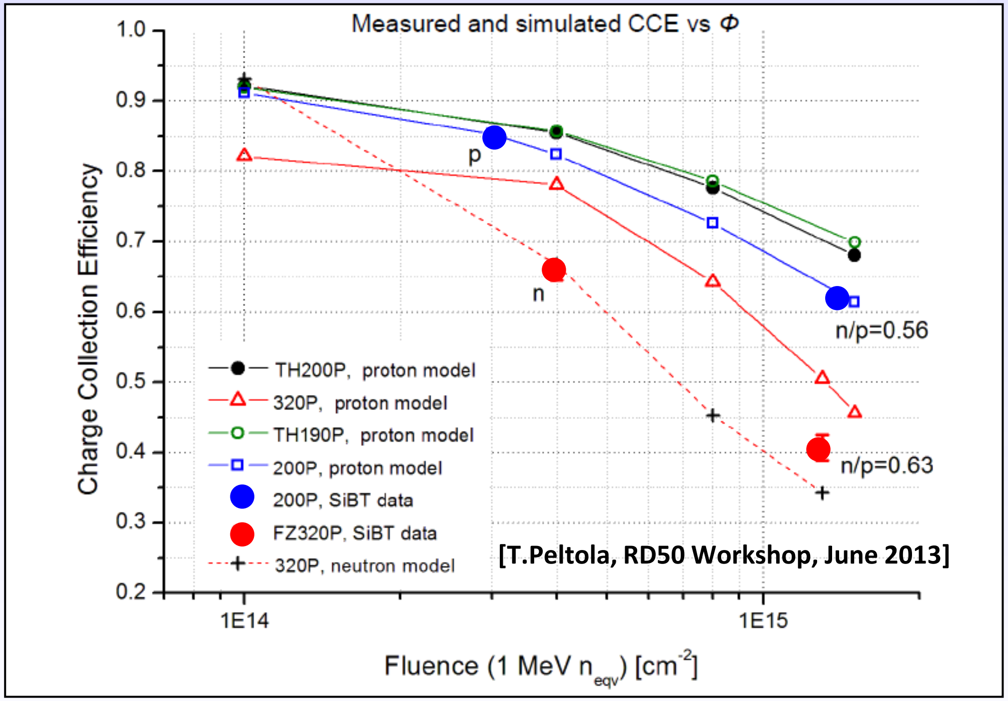
[R.Eber, RD50 Workshop, June 2013]

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 CMS test beam



[T.Peltola, RD50 Workshop, June 2013]

- 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.

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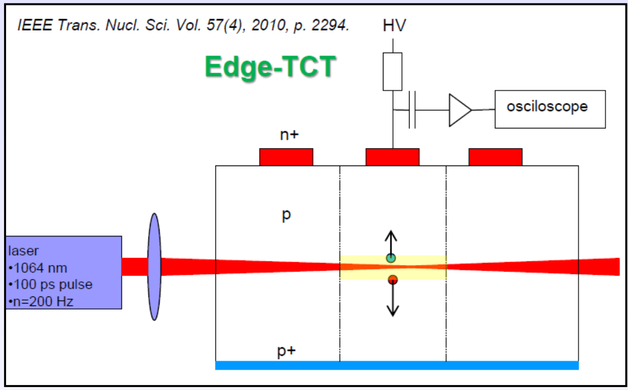
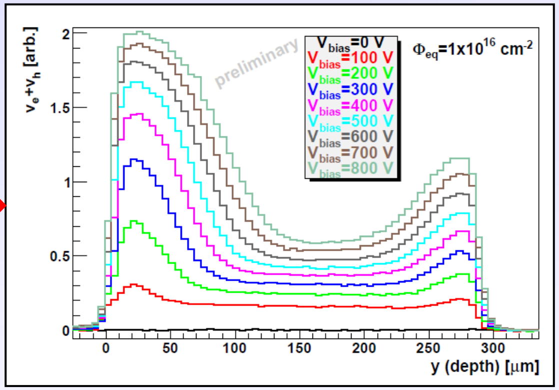
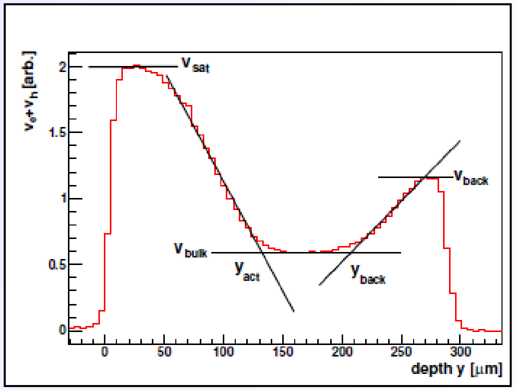
Simulation vs. Parameterization

- **Parameterization known as e.g. “Hamburg model”**
  - **Leakage current (from IV), Neff (from CV), Trapping times (from TCT)**
  - **Does not include the electric field respectively the double junction effect!**
- **TCAD simulations**
  - **Quite complex and no parameter set that is covering full phase space … reliable?** (silicon materials, different particles, full fluence range, annealing)
- **Parameterization of electric field instead**?
  - Edge-TCT: Extract E-field (more precisely the drift velocity) profile and parameterize it

[G.Kramberger et al., PoS (Vertex 2012) 022]





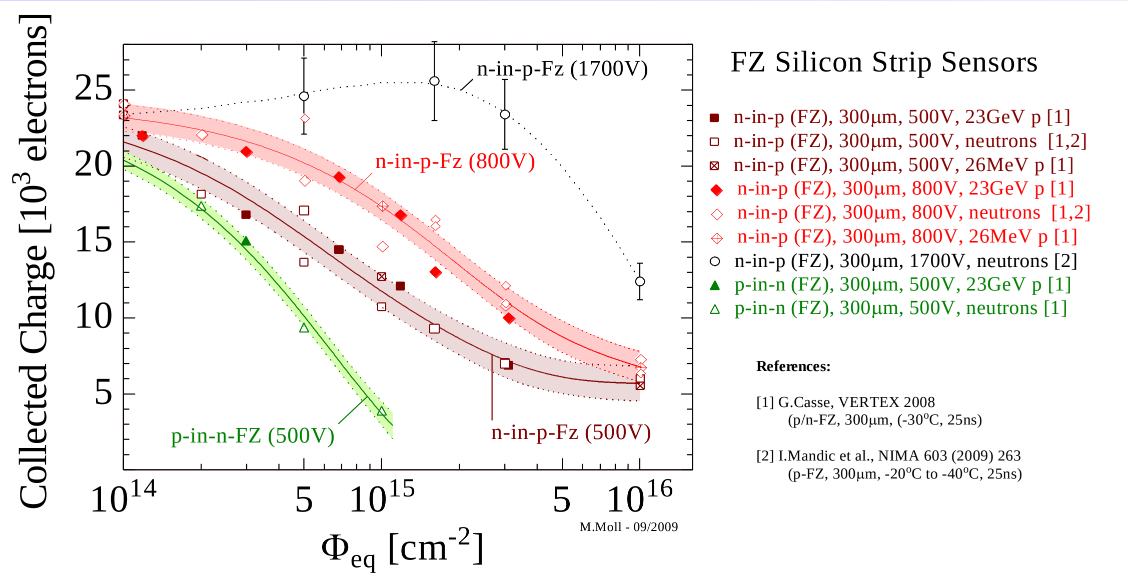


Edge-TCT → Drift velocity profile (v_e+v_h) → fit to extract parameters

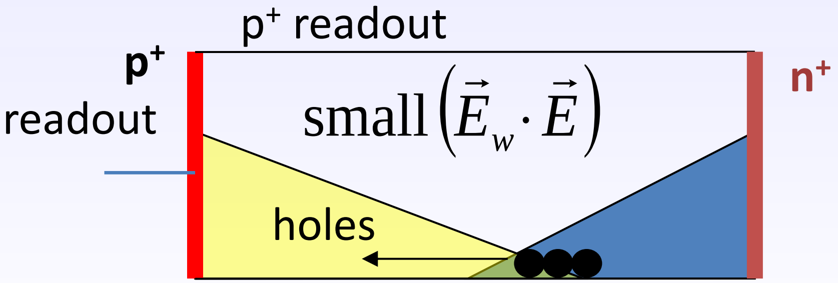
Segmented sensors: n^+ vs. p^+ readout

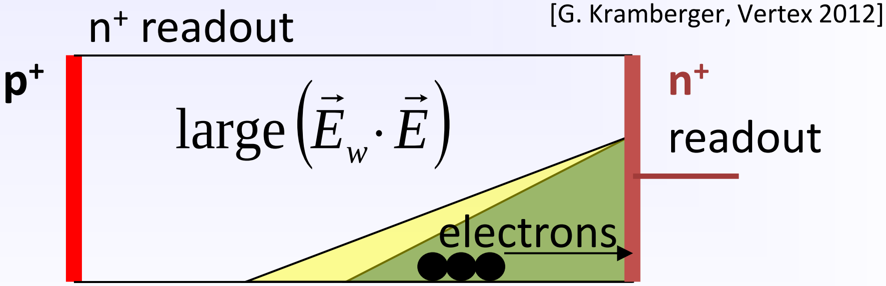
[VERTEX 2013: see also "Planar Sensors" A.Dierlamm]

- **p-type silicon** (brought forward by RD50) **Baseline for ATLAS and CMS Tracker upgrades**



- **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:**



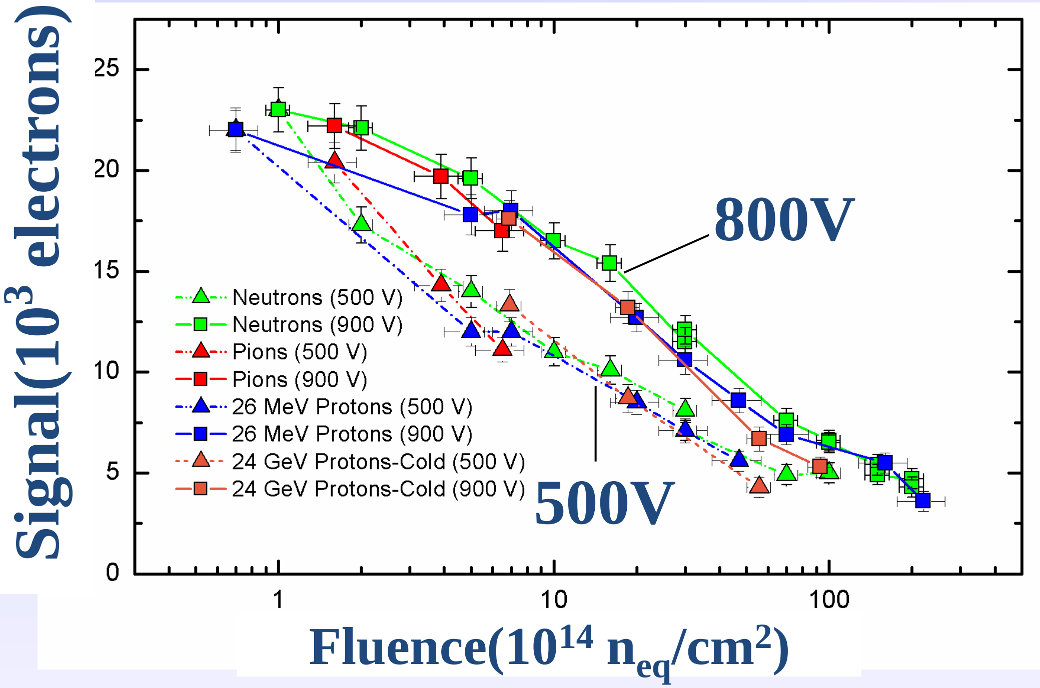


[G. Kramberger, Vertex 2012]

FZ n-in-p microstrip detectors (n, p, p - irrad)

- **n-in-p microstrip p-type FZ detectors** (Micron, 280 or 300μm thick, 80μm pitch, 18μm implant)
- **Detectors read-out with 40MHz** (SCT 128A)

[A.Affolder, Liverpool, NIMA 623, 2010, 177–179]



- **CCE: ~7300e (~30%)**
  after ~ 1×10^{16}cm^{-2} 800V
- **n-in-p sensors are baseline for ATLAS and CMS Tracker upgrades** (previously p-in-n used)

FZ n-in-p microstrip detectors (n, p, π – irrad)

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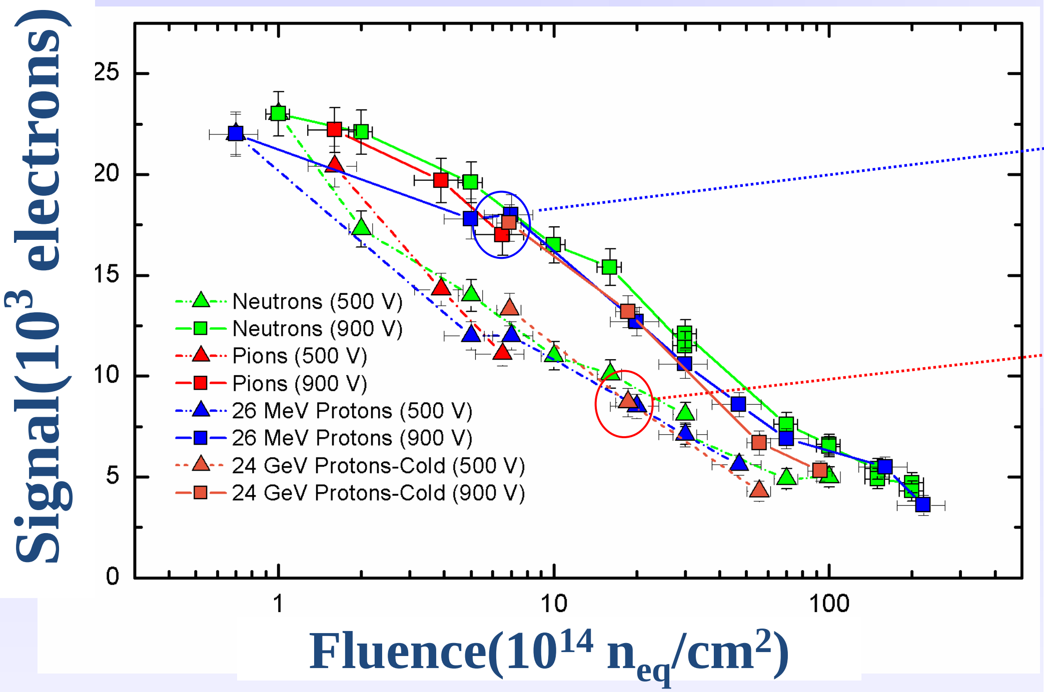

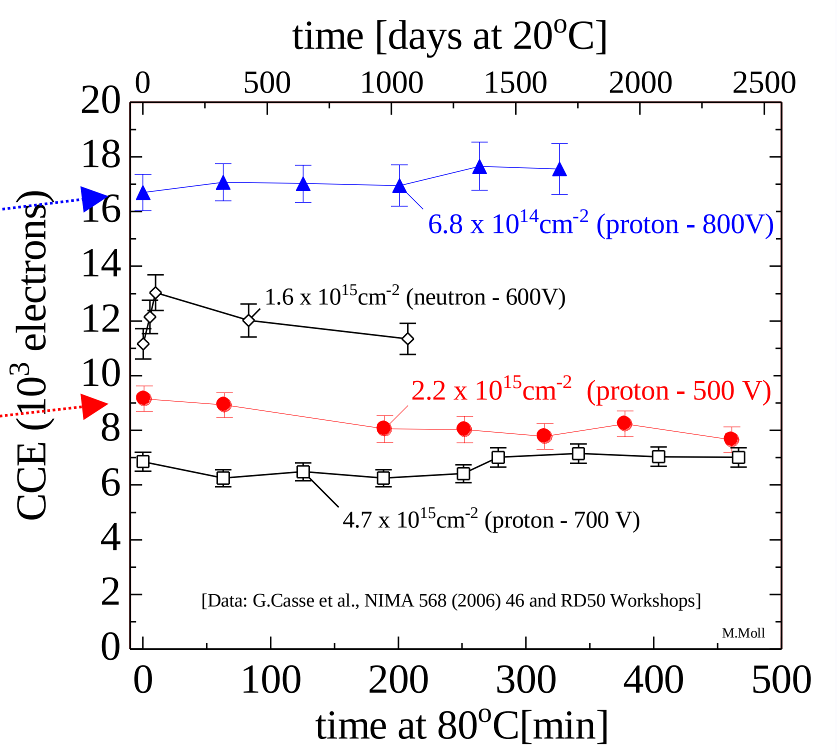

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  after ~ 1×10^{16}cm^{-2} 800V
- **n-in-p sensors are baseline for ATLAS and CMS Tracker upgrades** (previously p-in-n used)

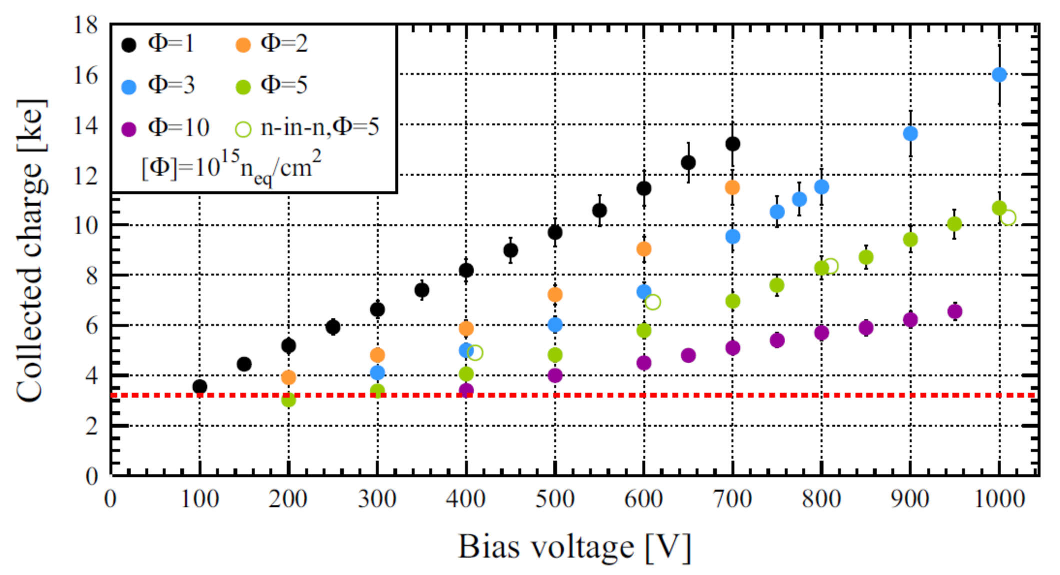
- **no reverse annealing in CCE measurements for neutron and proton irradiated detectors**

P-type pixel sensors

- **Planar segmented detectors n-in-p or n-in-n**
  - **results on highly irradiated planar segmented sensors have shown that these devices are a feasible option for the innermost layers of LHC upgrade**

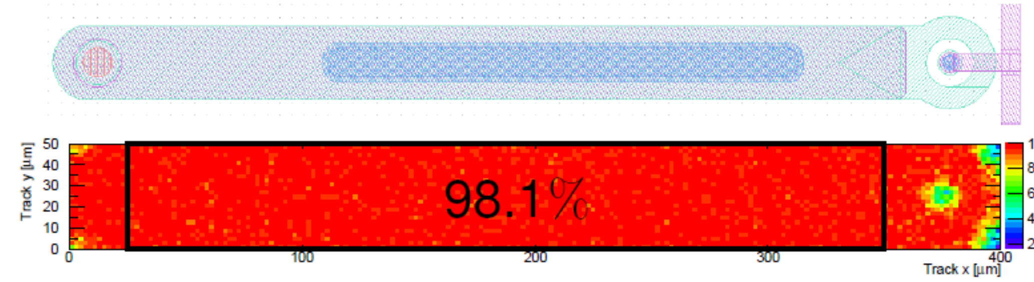
Example:

- 285 µm thick n-in-p FZ pixels
- FE-I3 readout
- sufficient charge also at $\Phi_{eq} = 1 \cdot 10^{16}\ \mathrm{n/cm^2}$



$\Phi_{eq} = 1 \cdot 10^{16}\ \mathrm{n/cm^2}$

- test beam, EUDET Telescope CERN SPS, 120 GeV pions:
- perpendicular beam incidence
- bias voltage: 600V
- threshold: 2000 el



[S. Terzo, 21th RD50 Workshop, CERN, 2012]
[D.Forshaw, NIMA 2013, to be published]

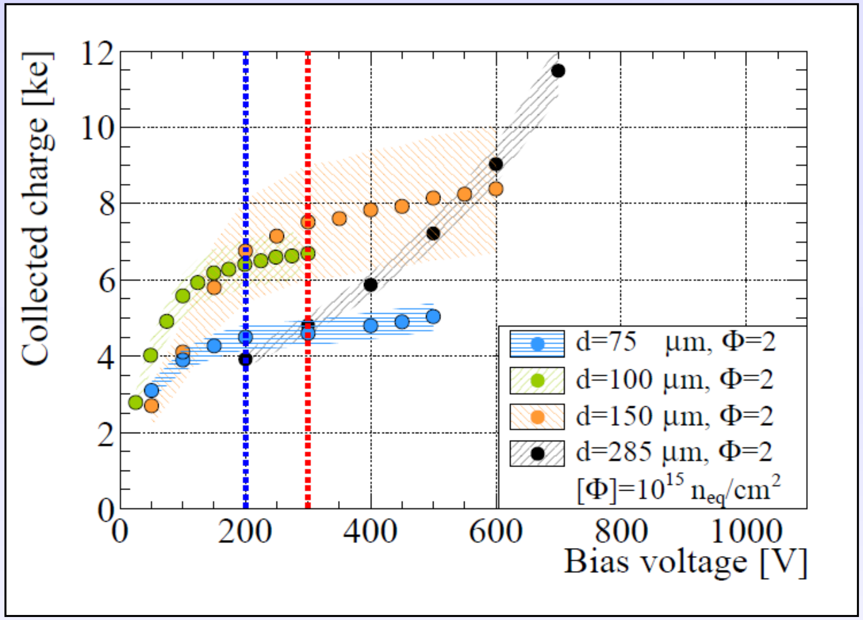
➔ 97.2% hit efficiency (98.1% in the central region)

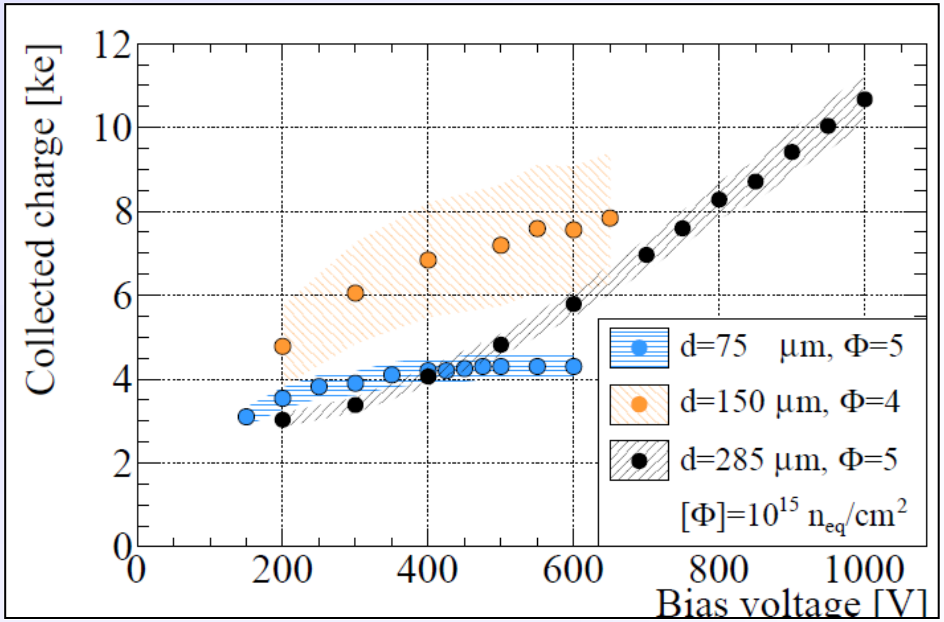
RD50

Thin p-type pixel sensors

[S. Terzo (MPI), 22nd RD50 Workshop, Albuquerque, 2013]

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





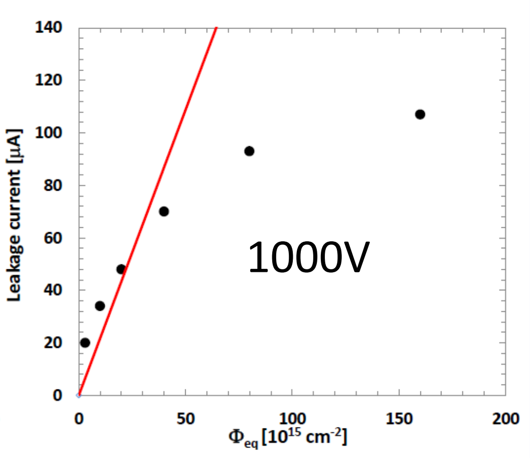
- **150 μm thick devices give higher signal than 75μm and 300 μm thick devices below 600V for fluences > 1×10^{15} n$_{eq}$/cm^2**

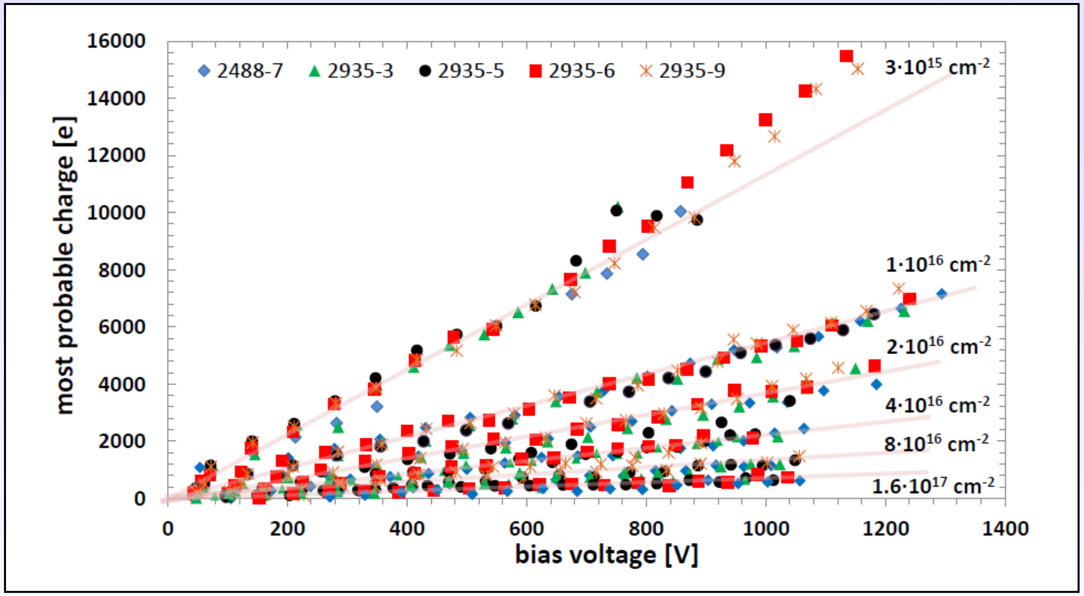
[VERTEX 2013: see also "Planar Sensors" A.Dierlamm]

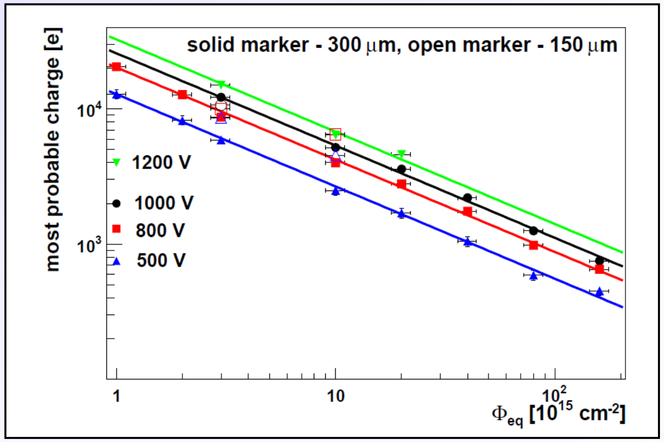
[Stefano Terzo (MPI), 22nd RD50 Workshop, Albuquerque, June 2013]

Going to extreme fluences

- **Irradiation Experiment on spaghetti diodes**
  - **4x4mm^2 p-type sensor (300 μm); DC coupled; strip geometry 80μm pitch,20μm width; all strips connected together**
  - **Produced by Micron** (in framework of RD50 project)
  - **Irradiated in steps with neutrons up to 1.6×10^{17} n/cm^2**
    - 80min 60°C after each step
  - **Measurement at -25°C, Sr^{90} source, 25ns shaping**



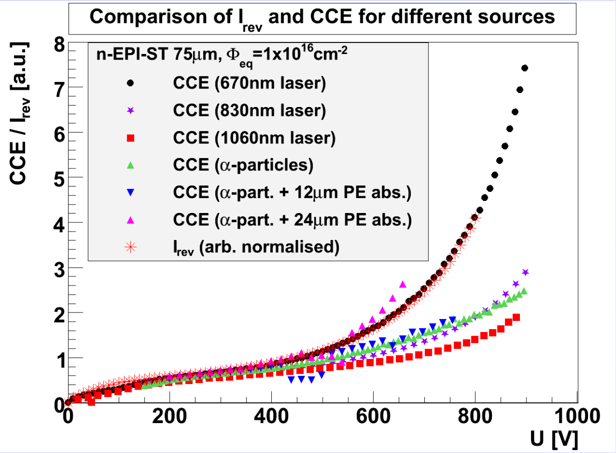




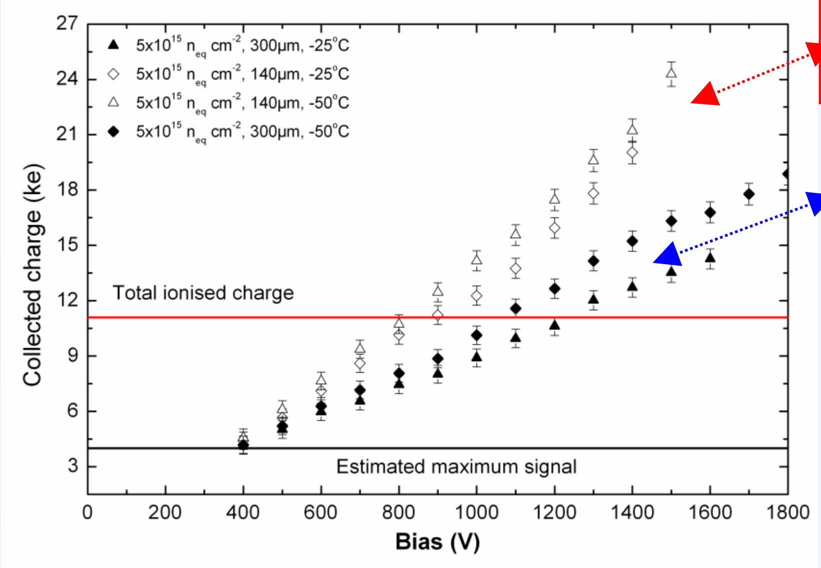
[G. Kramberger et al, JINST 2013 8 P08004]

Charge Multiplication

- <u>Charge Multiplication</u> observed and characterized after high levels of irradiation with different techniques and in several different types of devices



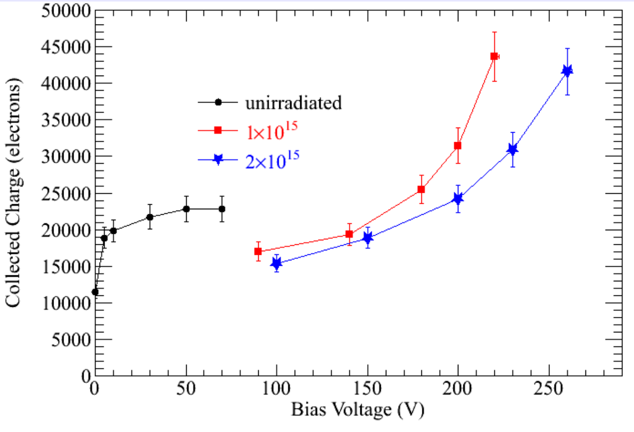
Diodes ($\Phi_{eq}=10^{16}$ cm^{-2})
Leakage Current & Charge Collection



140 μm thick device

300 μm thick device

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)

<u>Questions:</u>

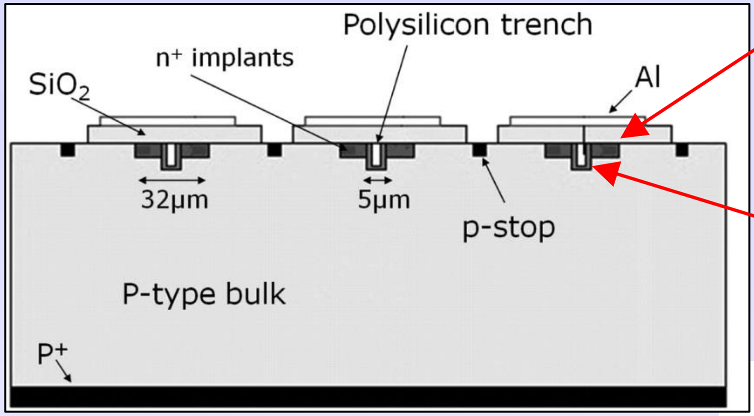
- **Can we simulate and predict charge multiplication ?**
- **Can we better exploit charge multiplication?**

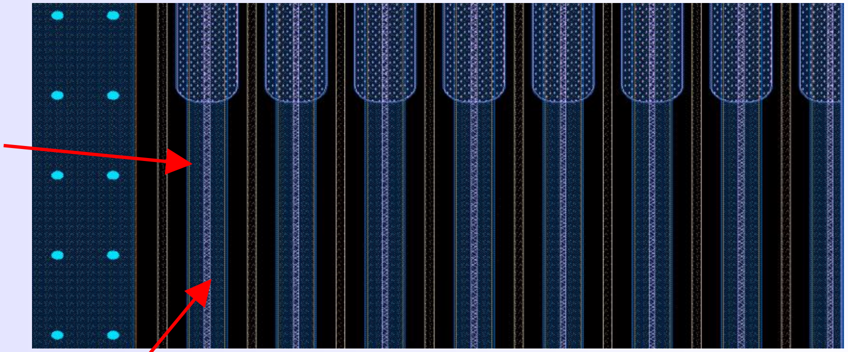
Ref: Diode: J.Lange et al, 16th RD50 Workshop, Barcelona
Strip: G. Casse et al., NIMA 624, 2010, Pages 401-404
3D: M.Koehler et al., 16th RD50 Workshop, Barcelona

Enhancing Charge Multiplication

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

[G.Casse et al., NIMA 669 (2013) 9-13]

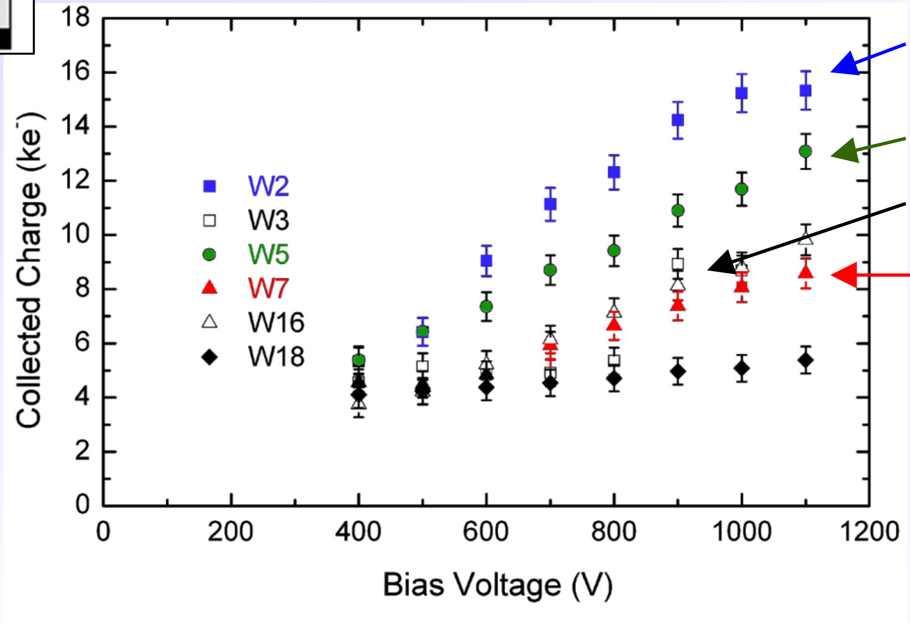




Implant

Poly trench
n-doped

- **Sizeable effect on Charge Multiplication**
  - **Irradiation: $5\times10^{15}\ n_{eq}cm^{-2}$ (neutrons)**
  - **Significant difference in CCE between standard and trenched detectors** (-25°C)
  - **However, not evident how gain relates to depth of trench**



trench depth

5μm trench

50μm trench

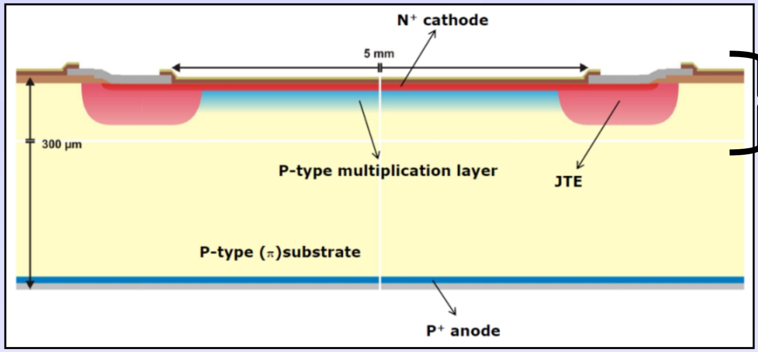
10μm trench

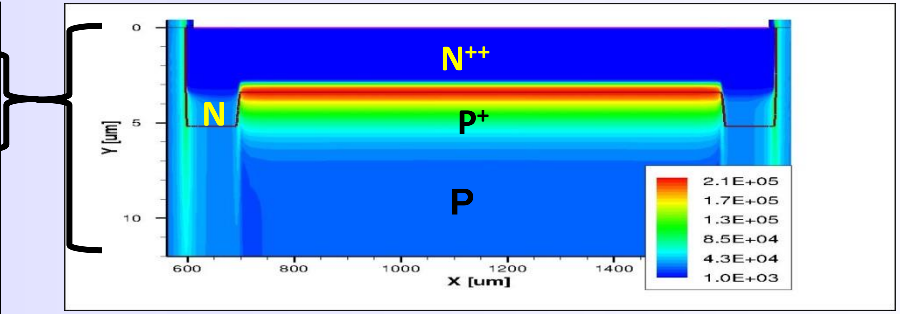
standard

RD50 Low Gain Avalanche Detectors (LGAD)

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

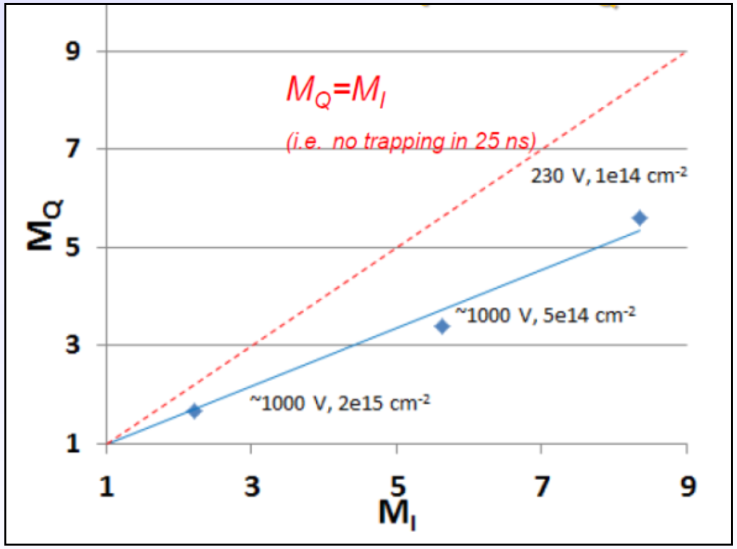
- **Diodes with implemented multiplication layer (deep p+ implant)**
  - **APD concept [n^{++}-p^{+}-p-p^{+} structure] with JET (Junction Edge Termination)**





Simulation of E-Field [V/cm]

  - **Gain of approx. 10 before irradiation : linear mode : spectra are Landau spectra (^{90}Sr)**
- **Gain reduces with irradiation**
  - **Dropping to about 1.5 after 2e15 n/cm^2**
    - Why? Boron removal in p-type layer?
  - **Current and noise scale as expected with multiplication**
  - **Charge (Sr-90) Multiplication versus Current Multiplication (Sr-90)**



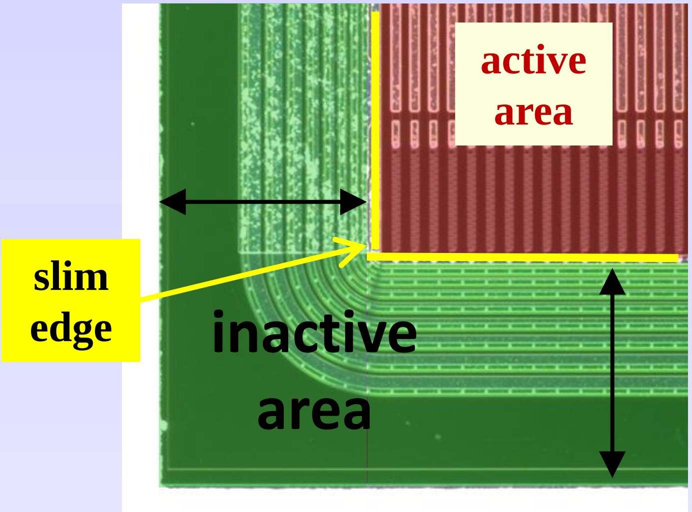
[G.Kramberger, RD50, June 2013]

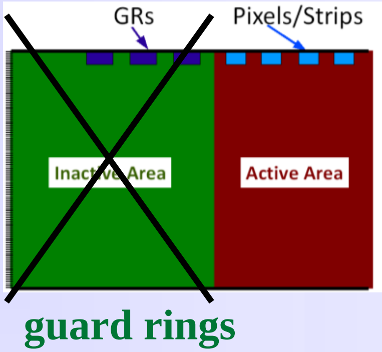
- **Further work ongoing (strip, pixel, …)**

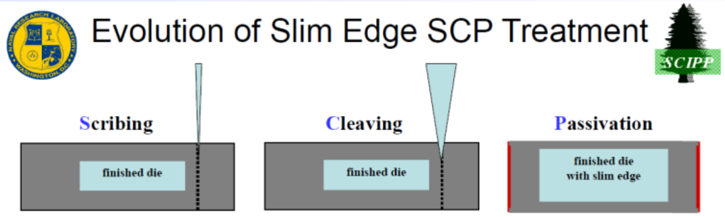
[G.Kramberger, 22nd RD50 Workshop, Albuquerque, June 2013]

New structures: slim and active edges

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







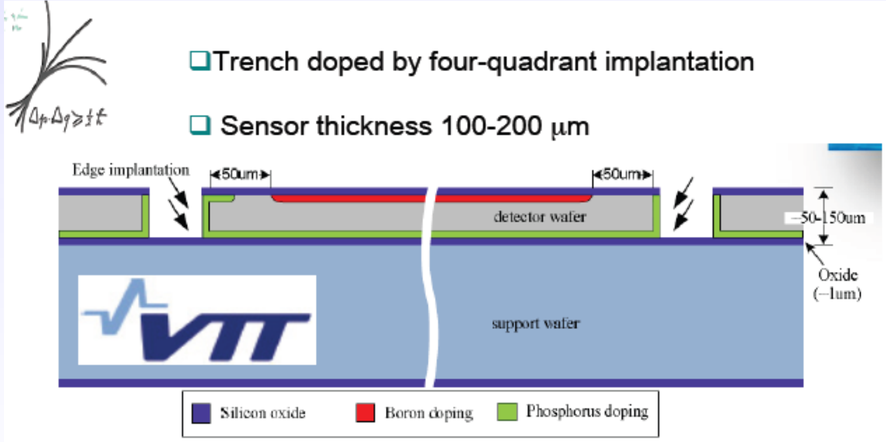
- **Scribe** XeF$_2$ etch, diamond scribe, DRIE
- **Cleave** automated, manual
- **Passivate** nitride, oxide (n-type)
  alumina ALD (p-type)

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

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

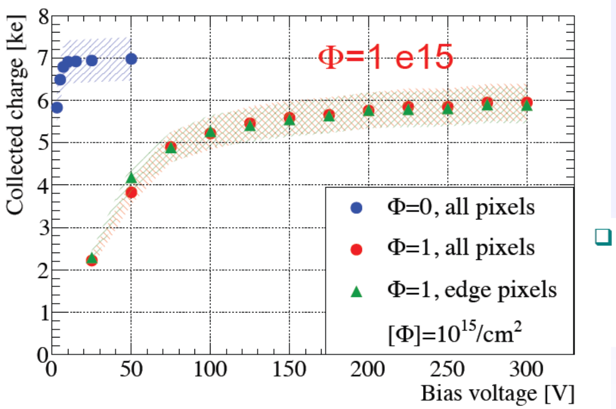
• Active edges (VTT & MPI Munich)

- **Thin wafers with active edges produced at VTT** [A.Macchiolo, 22nd RD50, Albuquerque, June 2013]



❑ Trench doped by four-quadrant implantation

❑ Sensor thickness 100-200 μm



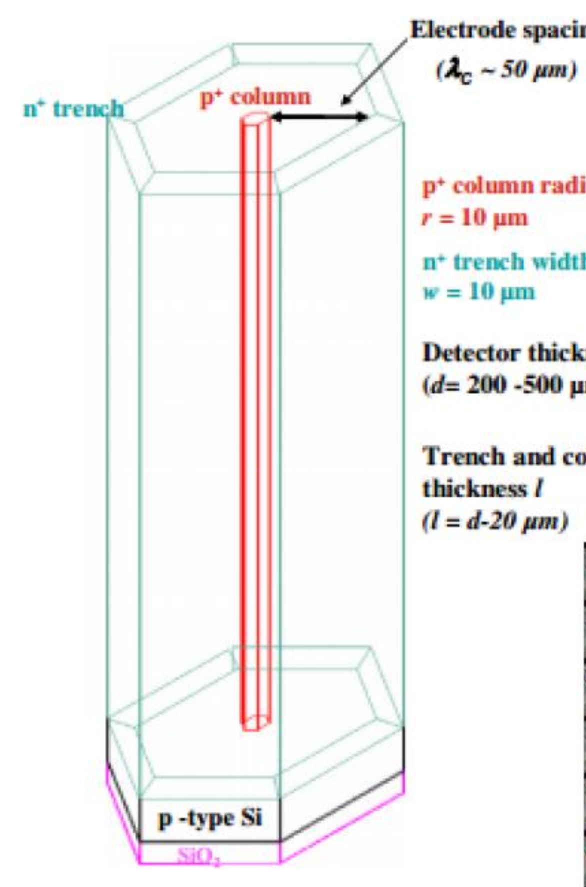
10^{15} p/cm^2

Testbeam:
no difference between
edge and other pixel!

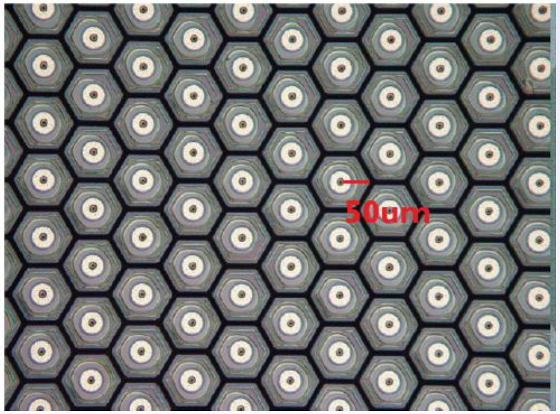
❑ FE-I3 100 μm thick sensor with 125 μm slim edge, threshold 1500 e- → 87% CCE at 300 V for both all and edge pixels after irradiation at KIT

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

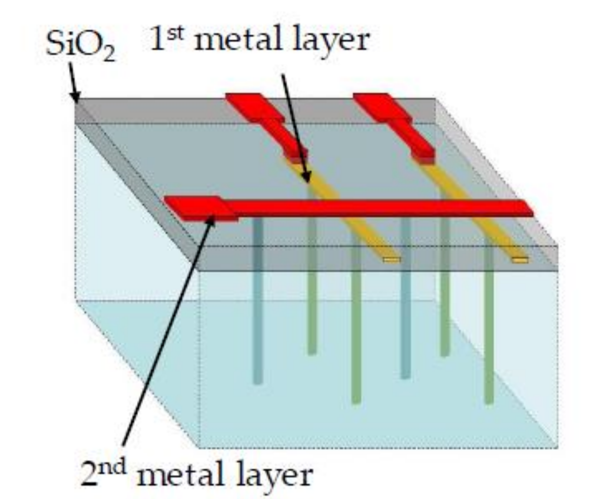
- **Exploring the possibilities of DRIE etching (BNL & CNM)**
  - **3D sensors (well known, installed in ATLAS IBL)**
  - **3D Trench Electrode Detectors**

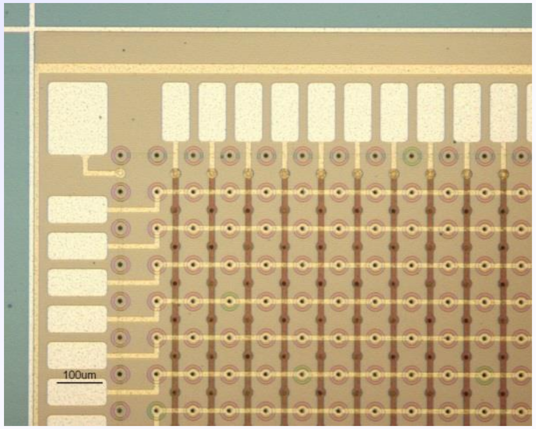


- **Aim**: Function as 3D but with a more homogeneous field (no saddle point)
- First prototypes produced
- CV/IV measured up to 100V
- Next: CCE measurements



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





Conclusions

- **RD50 recommendations for silicon detectors in LHC detector upgrades**
  - **Innermost layers: fluences up to $2 \cdot 10^{16}$ n_{eq} /cm^2**
    - **present results show that planar sensors are good enough**
      - readout on n-type electrode is essential!
      - n-in-p (or n-in-n becoming "n-in-p" after inversion) detectors
      - need high bias voltage , but may be less demanding with thin sensors
    - **3D detectors promising**
      - lower bias voltage
      - may be more difficult to produce but IBL results are encouraging
  - **Outer layers: fluences up to 10^{15} n/cm^{-2}**
    - **n-in-p type FZ microstrip detectors are ATLAS and CMS baseline:**
      - Collected charge over 10^4 electrons at 500 V (over $1.5 \cdot 10^4$ el. at 900 V)
    - **p-in-n MCz detectors possible option**
      - exploit damage compensation in mixed radiation field
      - lower cost , but need some more evaluation
- **On-going research on sensors exposed to high radiation fields:**
  - Material studies ongoing (p,n, MCZ, FZ, EPI, sensor thickness, …)
  - Characterization of defects & extraction of reliable TCAD modeling input parameters
  - E-Field characterization and comprehensive parameterization of sensor performance
  - Exploitation of avalanche effects for radiation hardness and speed

RD50 Status Report: 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

Spare Slides

- Some spare slides

- More details on [**http://www.cern.ch/rd50/**](http://www.cern.ch/rd50/)

  - **Take a look at the most recent RD50 Workshops**

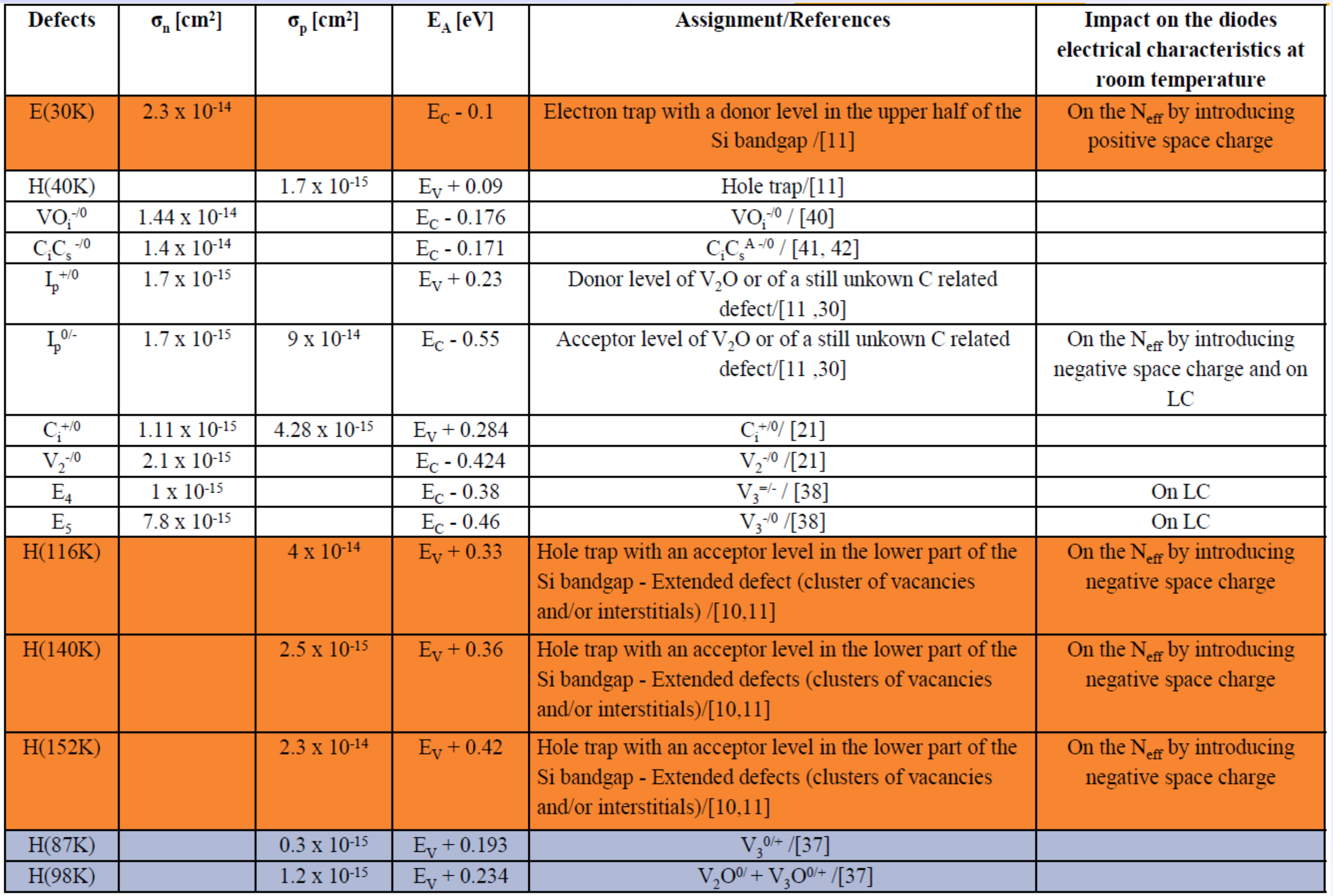
RD50 main achievements & links to LHC Experiments

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 and CMS 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.**

RD50 Microscopic Defects – Levels and Cross sections

- **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)	2.3×10^{-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)		1.7×10^{-15}	E_V + 0.09	Hole trap/[11]	
$VO_i^{-/0}$	1.44×10^{-14}		E_C - 0.176	$VO_i^{-/0}$ / [40]	
$C_iC_s^{-/0}$	1.4×10^{-14}		E_C - 0.171	$C_iC_s^{A\,-/0}$ / [41, 42]	
$I_p^{+/0}$	1.7×10^{-15}		E_V + 0.23	Donor level of V_2O or of a still unkown C related defect/[11 ,30]	
$I_p^{0/-}$	1.7×10^{-15}	9×10^{-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
$C_i^{+/0}$	1.11×10^{-15}	4.28×10^{-15}	E_V + 0.284	$C_i^{+/0}$/ [21]	
$V_2^{-/0}$	2.1×10^{-15}		E_C - 0.424	$V_2^{-/0}$ /[21]	
E_4	1×10^{-15}		E_C - 0.38	$V_3^{=/-}$ / [38]	On LC
E_5	7.8×10^{-15}		E_C - 0.46	$V_3^{-/0}$ /[38]	On LC
H(116K)		4×10^{-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)		2.5×10^{-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)		2.3×10^{-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)		0.3×10^{-15}	E_V + 0.193	$V_3^{0/+}$ /[37]	
H(98K)		1.2×10^{-15}	E_V + 0.234	$V_2O^{0/} + V_3O^{0/+}$ /[37]	

Results consistent with previous RD50 works on hadron damage

- **BD defect:**
  - $E_i^{BD} = E_c - 0.225$ eV
  - $\sigma_n^{BD} = 2.3 \cdot 10^{-14}$ cm²

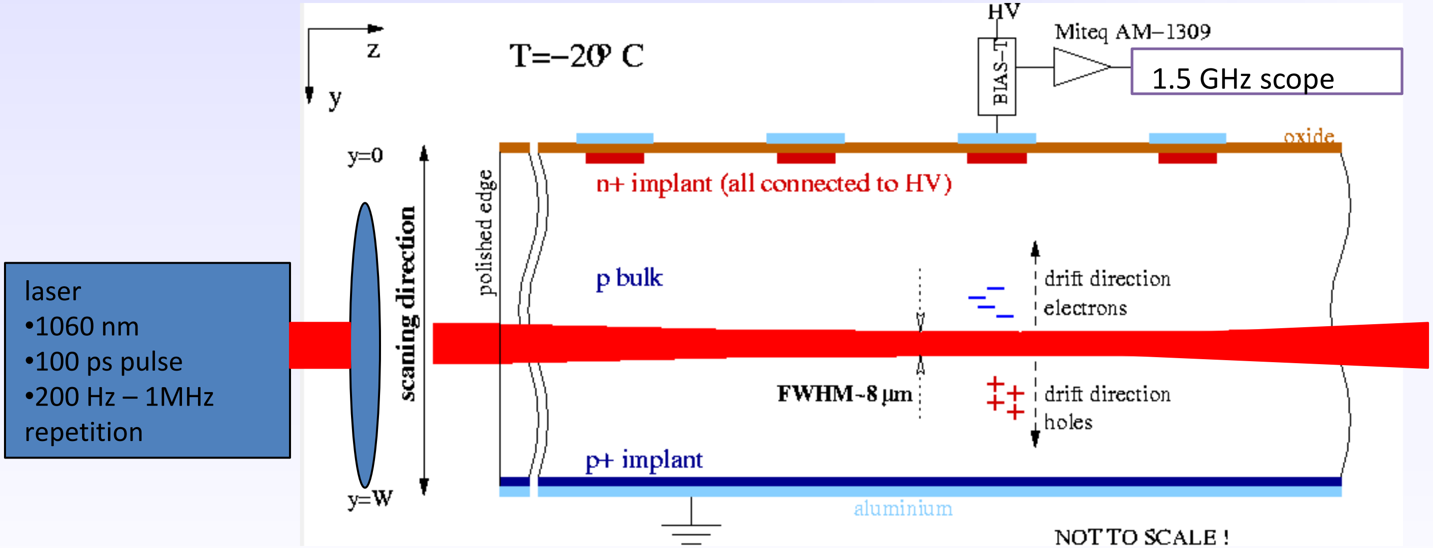
- **Converging on consistent set of defects observed after proton, pion, neutron, gamma and electron irradiations by various techniques** (Introduction rates depend of course strongly on the type of irradiation and for some of the defects on the material.)

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

Edge-TCT to Study Fields

- Edge-TCT: Illuminate sensor from the side
- Scan across detector thickness
- Measure charge and induced current as function of depth
- Reconstruct electric field

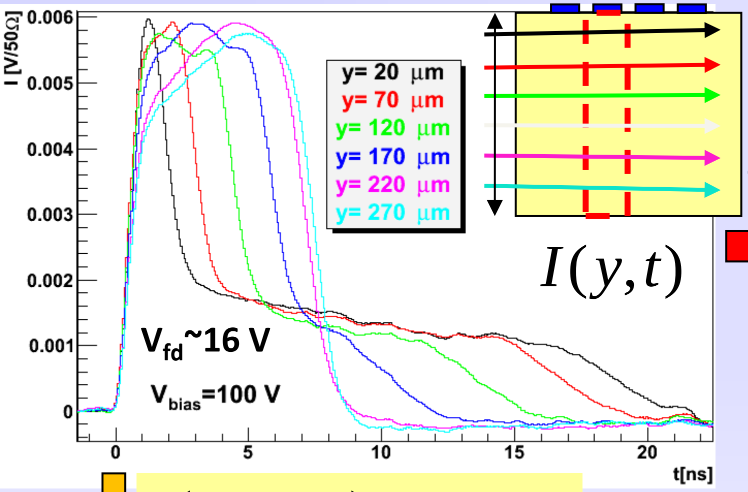
- **Expectation**
  - **Significant electric field only in depleted silicon**
  - **Charge generated in undepleted part of detector is lost**
- **Field not easy to probe but recently became accessible using Edge-TCT**


laser
•1060 nm
•100 ps pulse
•200 Hz – 1MHz repetition

[G. Kramberger, 17th RD50 Workshop, Nov. 2010]

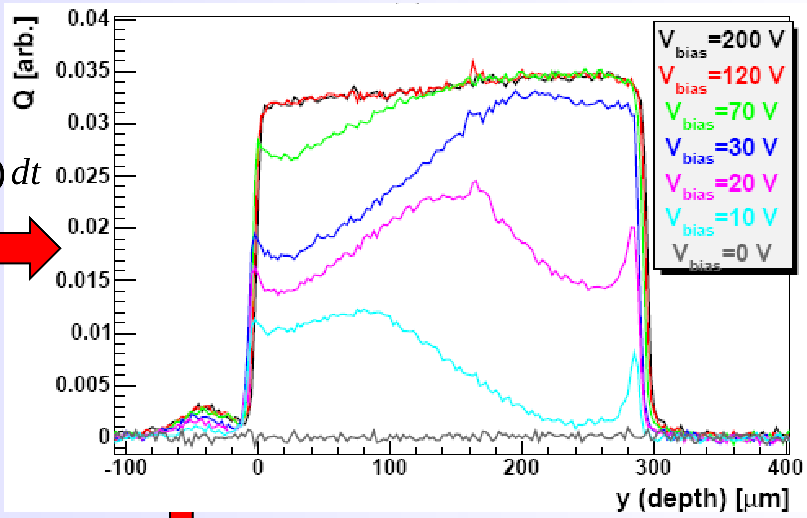
Charge collection and velocity profiles

RD50 Micron p-type sensor



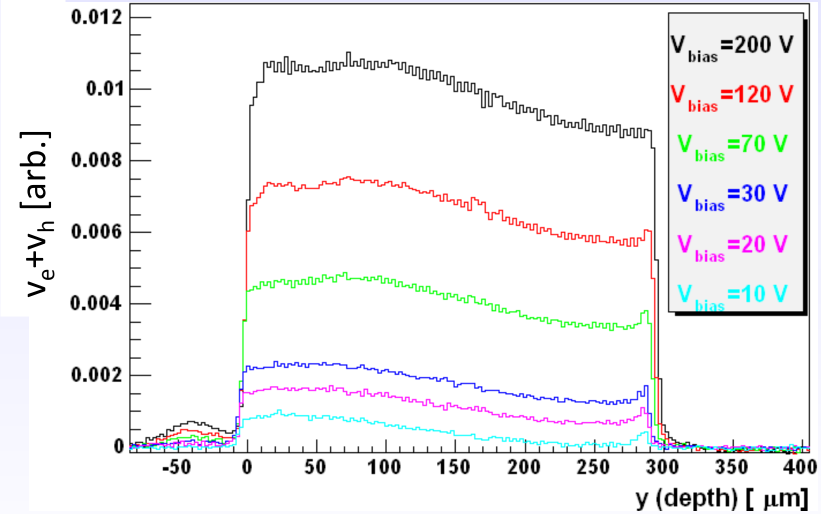
$$Q(y)=\int_0^{25ns} I(y,t)\,dt$$

CHARGE COLLECTION PROFILE

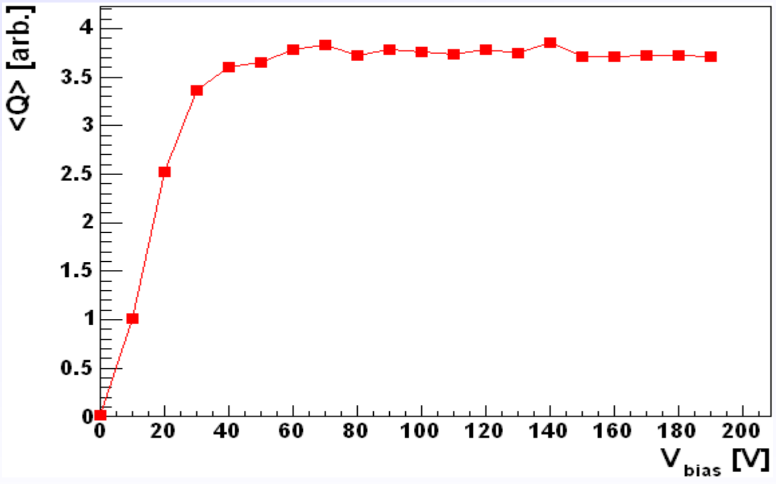


$$I(y,t\sim 0)\propto v_e+v_h$$

VELOCITY PROFILE



$$Q_{mip}\propto\langle Q\rangle=\int_0^{25ns} I(y,t)\,dt$$

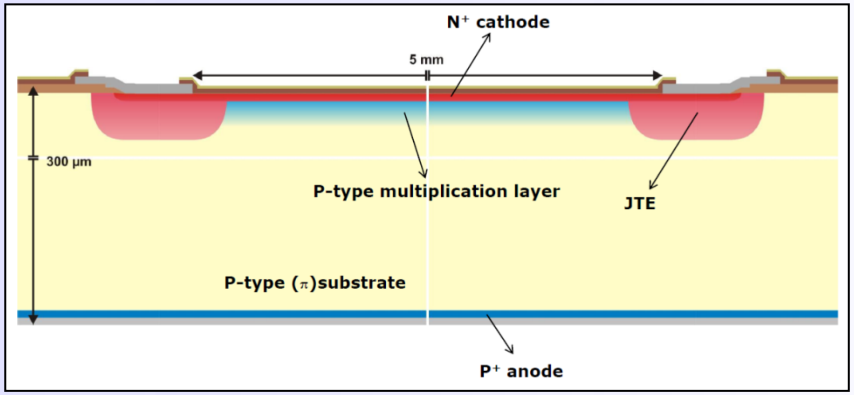


[G. Kramberger, 17th RD50 Workshop, Nov. 2010]

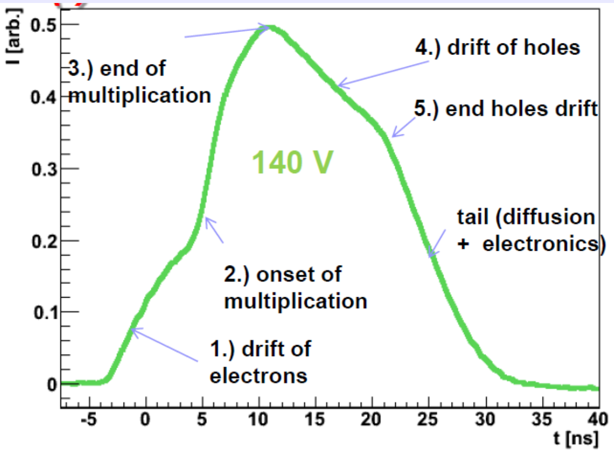
First production of low gain diodes

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

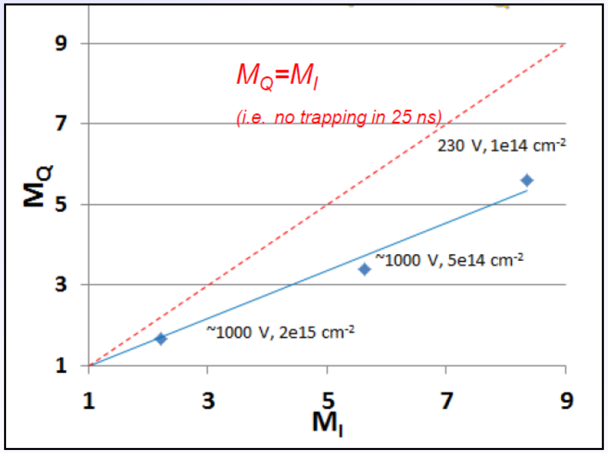
n^{++} - p^{+} - p – p^{+} stucture



- **Gain of ~10 before irradiation**
  - **Spectra are Landau spectra (^{90}Sr)**
- **Gain reduces with irradiation**
  - **Dropping to about 1.5 after 2e15 n/cm^2. 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)



[G.Kramberger, 22nd RD50 Workshop, Albuquerque, June 2013]

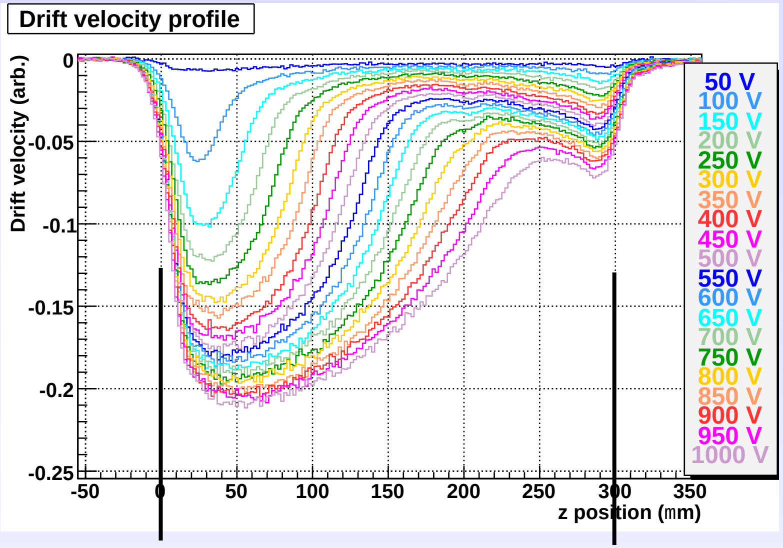
RD50

Edge-TCT – Example – Drift velocity

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

- **Sensors: MCZ and FZ p-type ministrip sensors** (pitch: 80μm, width 20μm)
- **Irradiation: 10^{16} p/cm^2 with 24 GeV/c protons** (6.1×10^{15} n$_{eq}$/cm^2)
- **Annealing: Isothermal at 60°C** (results after 560 min shown below)

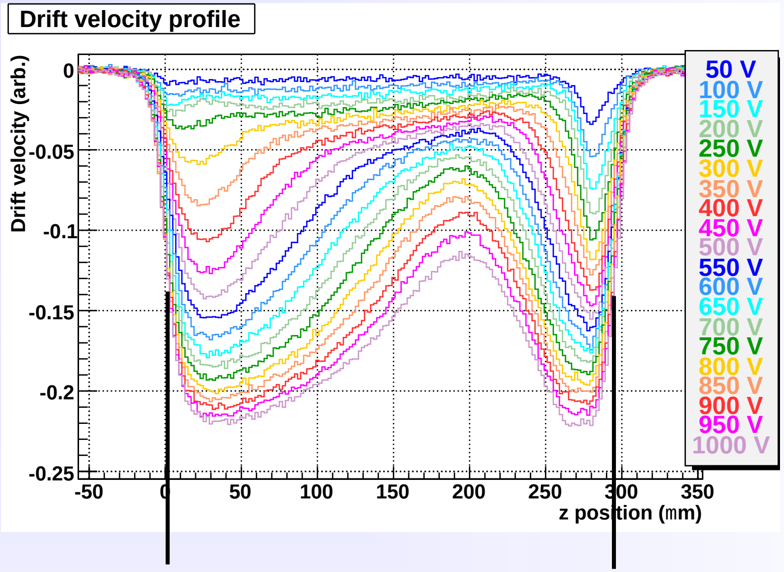
FZ



Front electrode
(n-p junction)

Back electrode
(p$^+$ contact)

MCZ



Front electrode
(n-p junction)

Back electrode
(p$^+$ contact)

- **Presence of electric field throughout sensor** (although depletion voltage expected to be > 6000 V)
- **MCZ: High electric field at back electrode** (but not ‘useful’ for this p-type sensor)
  - At this annealing stage both sensors give the same signal (as measured with beta particles on Alibava CCE system)
  - ~7400 electrons (most probable) at 1000 V