2012 Nuclear Science Symposium, Medical Imaging Conference
& Workshop on Room-Temperature Semiconductor X-Ray and Gamma-Ray Detectors
October 29 - November 3, 2012, Disneyland Hotel, Anaheim, California

UNI FREIBURG

Silicon Sensors for HL-LHC Tracking Detectors

N25: Radiation Damage Effects
31. October 2012

Susanne Kuehn
University of Freiburg, Germany
On behalf of the RD50 Collaboration

RD50 - Radiation hard semiconductor devices for very high luminosity colliders

Outline

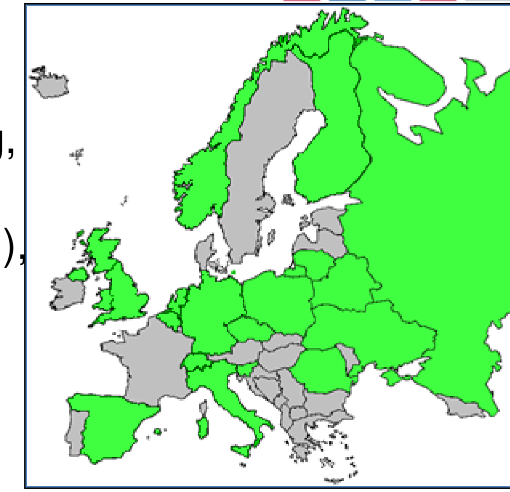
- Introduction
- Research Fields of RD50
  - Material and Defect Characterization
  - Detector Characterization and Simulation
  - Full Detector Systems
  - New Structures
- Achievements and Findings for LHC Experiments

Only a selection on interesting topics, the full variety of RD50 can be found on:
http://rd50.web.cern.ch/rd50/

The RD 50 Collaboration

38 European and Asian institutes

Belarus (Minsk), Belgium (Louvain), Czech Republic (Prague (3x)), Finland (Helsinki, Lappeenranta), Germany (Dortmund, Erfurt, Freiburg, Hamburg, Karlsruhe, Munich), Italy (Bari, Florence, Padova, Perugia, Pisa, Trento), Lithuania (Vilnius), Netherlands (NIKHEF), Norway (Oslo)), 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)



8 North-American institutes

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

1 Middle East institute Israel (Tel Aviv)

1 Asian institute India (Delhi) since 2011/12

M.Moll 06/2012

→ 48 institutes and 261 members

14th Workshop
in Freiburg, 2009

10th Anniversary

First workshop and
approval of collaboration in 2002

More details on: http://rd50.web.cern.ch/rd50/

Structure and Research Fields of RD 50

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**

- 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**
- **Device modeling**
- **Operational conditions**
- **Common irradiations**
- New Materials (E.Verbitskaya)
- Wafer procurement (M.Moll)
- **Simulations** (V.Eremin)

New Structures

Richard Bates (Glasgow Uni)
Giulio Pellegrini (CNM Barcelona)

- **3D detectors**
- **Thin detectors**
- **Cost effective solutions**
- **Other new structures**

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

Full Detector Systems

Gregor Kramberger
(Ljubljana University)

- **LHC-like tests**
- **Test beams**
- **Links to HEP**
- **Links electronics R&D**
- **Comparison:**
  - **pad-mini-full detectors**
  - **different producers**

- Pixel Europe (T.Rohe)
- Pixel US (D.Bortoletto)
- Test beams (G.Casse)

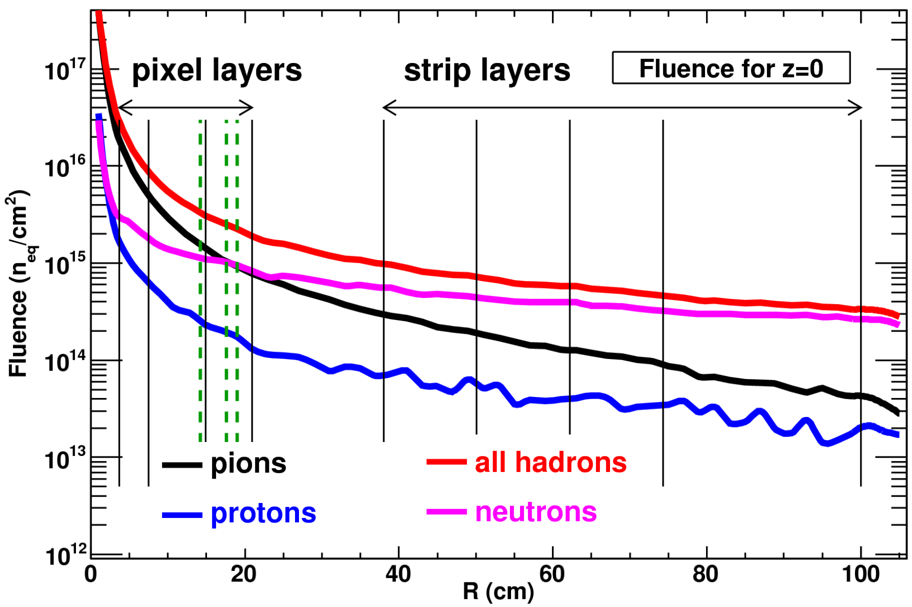
Collaboration Board Chair & Deputy: E.Fretwurst (Hamburg) & J.Vaitkus (Vilnius), Conference committee: U.Parzefall (Freiburg)
CERN contact: M.Moll (PH-DT), Secretary: V.Wedlake (PH-DT), Budget holder & GLIMOS: M.Glaser (PH-DT)

M.Moll 06/2012

Challenge: Radiation Damage at the LHC

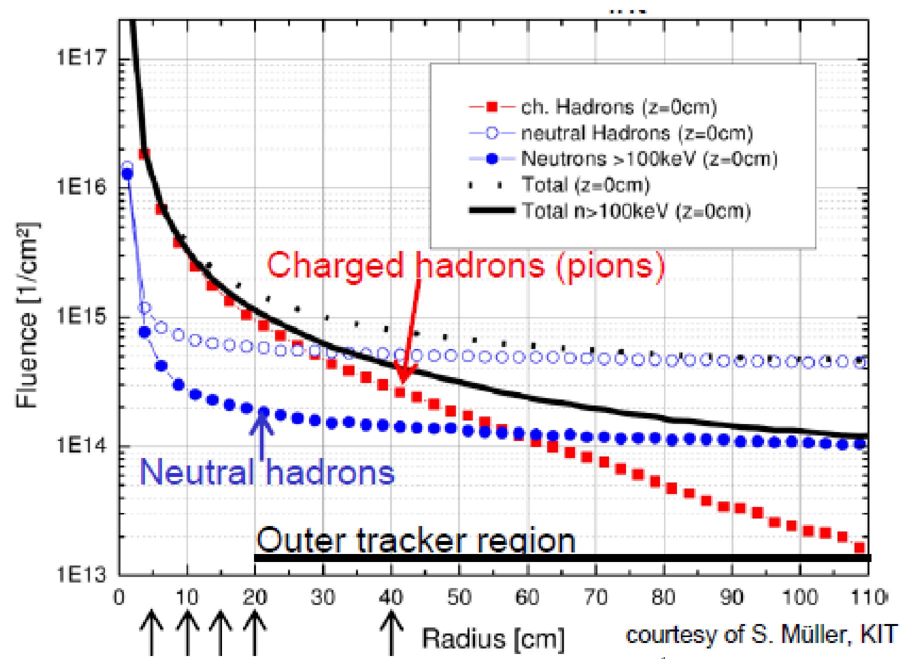
Planned upgrade of the LHC in ~2022: 3000 fb^{-1} expected integrated luminosity
Expected particle fluences for

the ATLAS Inner tracker:



ATLAS Radiation Taskforce
http://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/RADIATION/RadiationTF_document.html

the CMS tracker:



J. Erfle, 20th RD50 Workshop, 2012

→ Pixel damage due to neutrons and pions, strips mainly due to neutrons

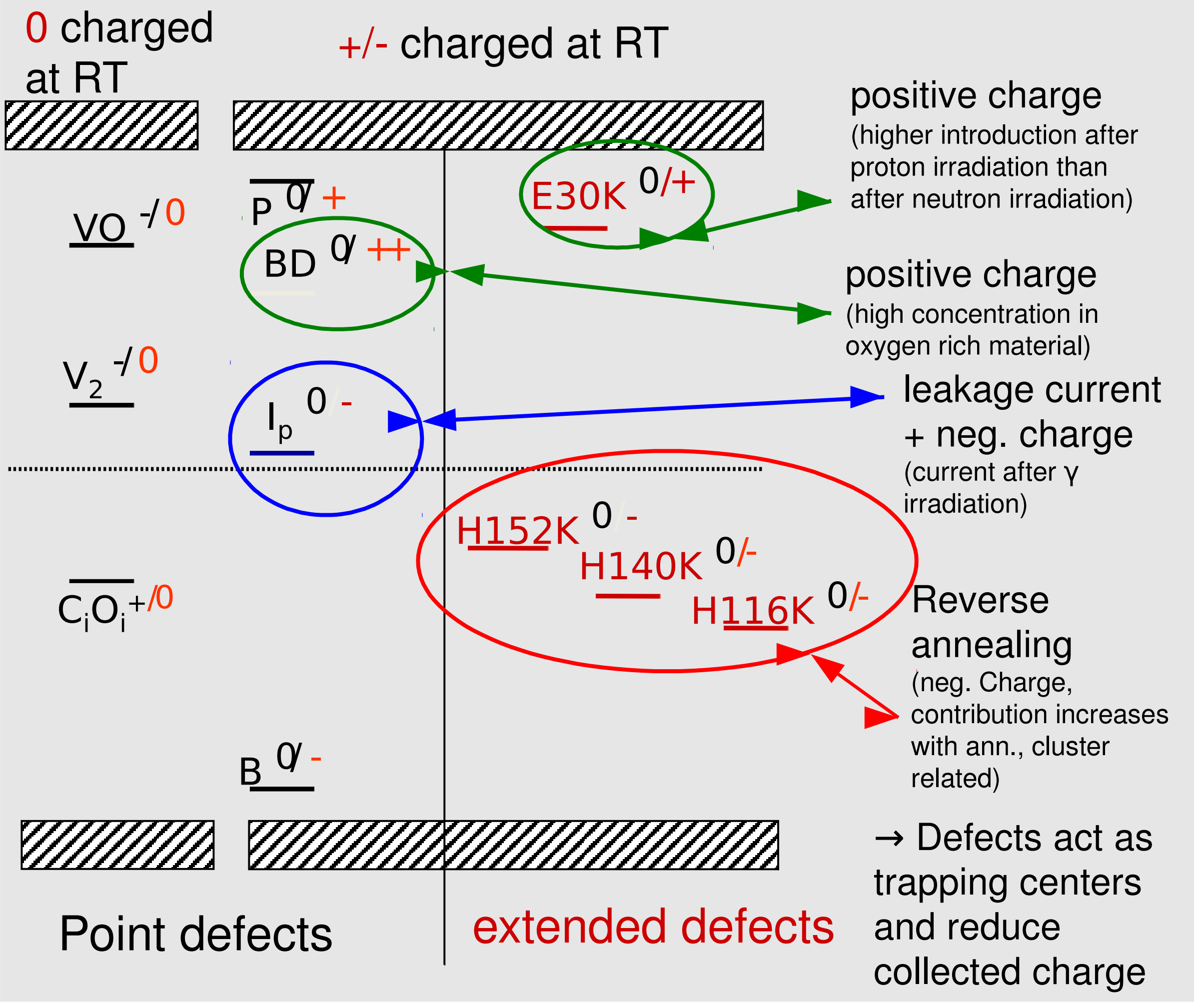
→ Investigation and understanding of radiation damage of sensors needed

Defect and Material Characterization

• WODEAN (Workshop on Defect Analysis in Silicon Detectors) since 2005 including 10 RD 50 institutes and lead by G. Lindstroem and M. Bruzzi

• Goal: Identify defects causing change of detector properties, namely trapping, leakage current and N_{eff} (V_{dep})

• Work: Defect Analysis on identical samples performed with the various tools available in the RD 50 Collaboration:
e.g. C-DLTS (Capacitance Deep Level Transient Spectroscopy), I-DLTS (Current Deep Level Transient Spectroscopy), TCT (Transient Charge Technique) or CV/IV, etc. ....



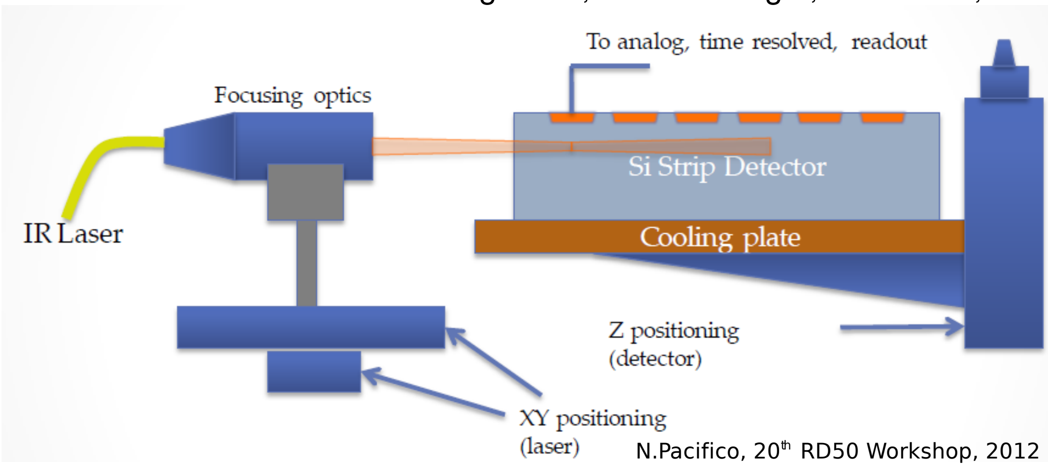
G. Casse, M.Moll, LHCC report 2012

I.Pintilie et al., Appl. Phys. Lett.92 024101,2008

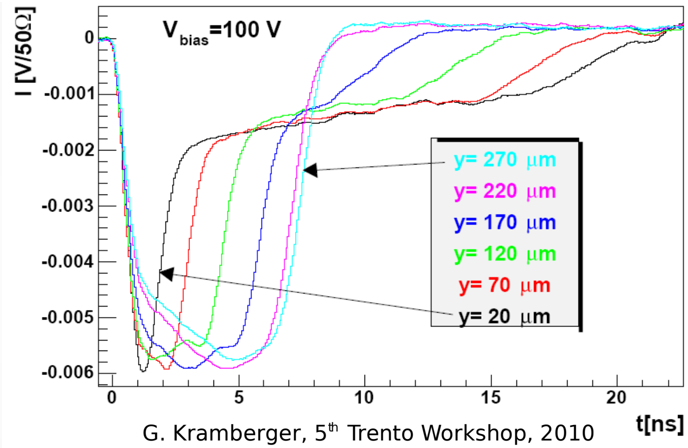
Detector Characterization: Investigation of Electric Fields with Edge-TCT

• Goal: Measurement of electric field in unirradiated and irradiated devices, usual TCT (Transient Charge Technique) not working due to trapping after irradiation

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



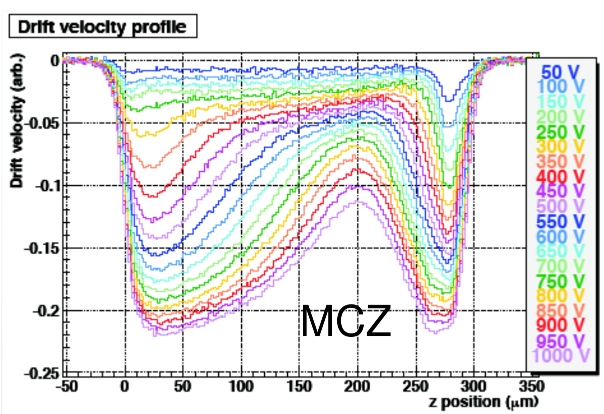
N.Pacifico, 20th RD50 Workshop, 2012

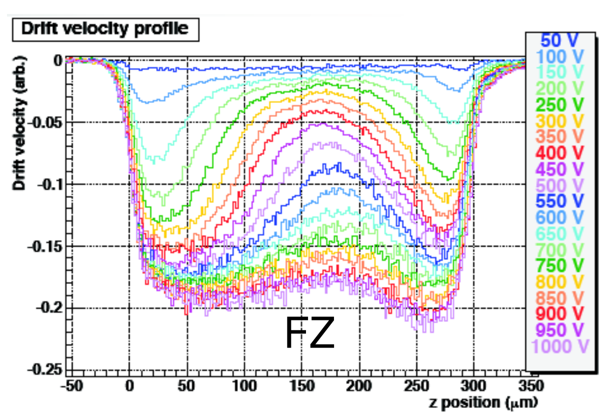


G. Kramberger, 5th Trento Workshop, 2010

• Example: n-on-p strip detector (pitch 80 μm), irradiated to $1*10^{16}$ neq/cm^2, with protons, no annealing

N.Pacifico, 20th RD50 Workshop, 2012





I(y,t~0) proport. v_e+v_h

Different drift velocity in FZ and MCZ silicon

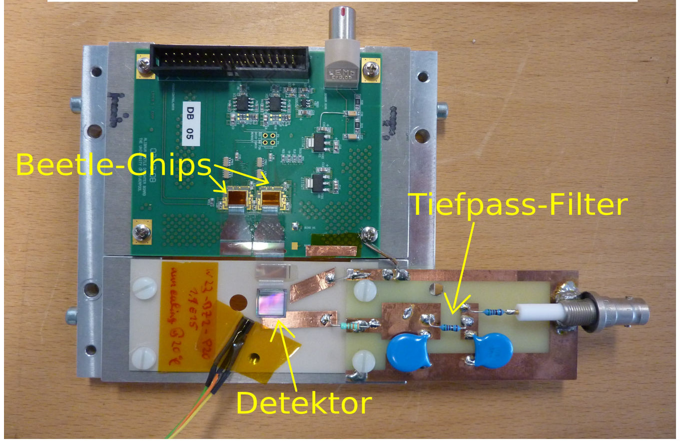
See also next talk N25-2

Full detector systems: Goals and Tools

Systematic evaluation of strip and pixel sensors before and after irradiation with protons, neutrons, pions

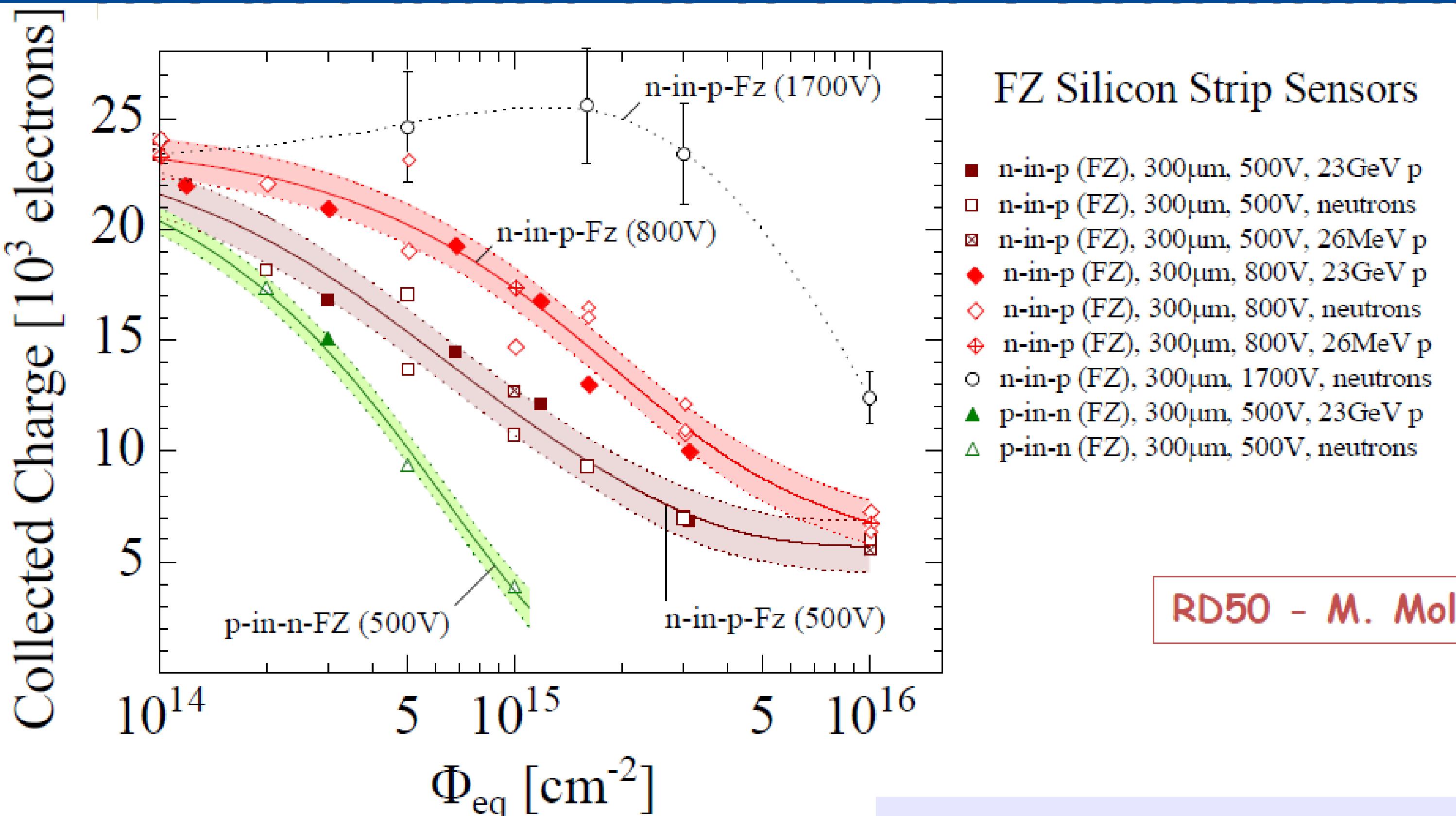
- Use fast (40 MHz) analogue or binary readout electronics
- Determine parameters like collected charge, noise, signal-to-noise by using beta source set-ups, laser set-ups and testbeams
- Design and realization of pixel/strip detectors in contact with manufacturers
  (CiS, CNM, HIP, HPK, Micron, Sintef)

ALIBAVA daughter board with detector



- RD50 test beam setup (additional to other setups in the Collaboration (EUDET, CMS))
  - Based on ALIBAVA system with analogue fast readout
  - Device under test and sensors for track reconstruction run with same readout
  - Allows easy handling and high resolution measurements

Full detector systems: Planar Detectors FZ

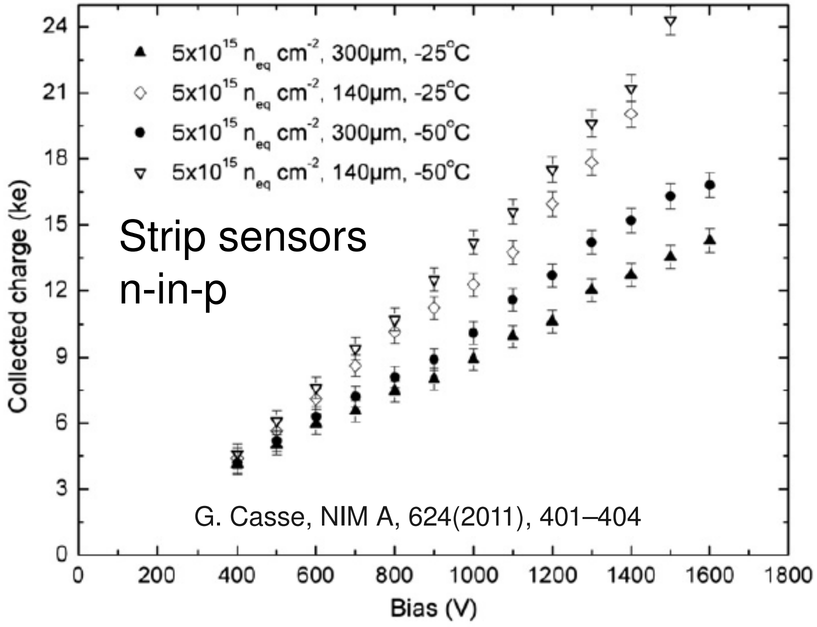


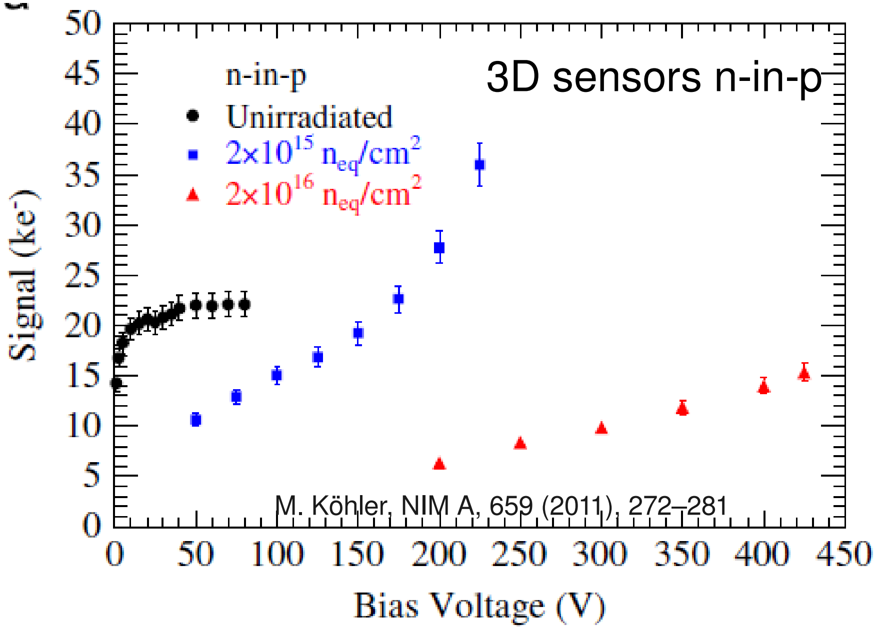
→ n-in-p performs best:
- No space charge inversion
- Collection of electrons (fast), shorter trapping times
- Charge multiplication at high bias voltages

Annealing:
More investigations ongoing, aim for
→ proper description of scaling
→ recommendations for HEP community regarding temperature sensitive operation

Full detector systems: Charge Multiplication

More than 100% collected charge seen after irradiation to 2-5*10^{15} neq/cm^2: charge multiplication observed in pad, strip and 3D detectors





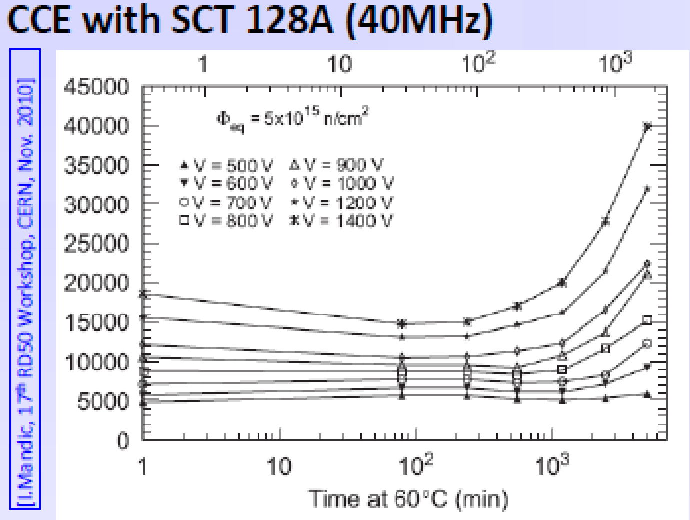
Charge Collection (Beta source, Alibava readout)

Goals: Understanding and Simulating charge multiplication

→ **Simulation Group** formed, lead by V. Eremin (Ioffe):
- Start from common parametrization
- Understand trapping, charge multiplication and avalanche effects
- Estimate electric fields and currents

Full detector systems: Charge Multiplication

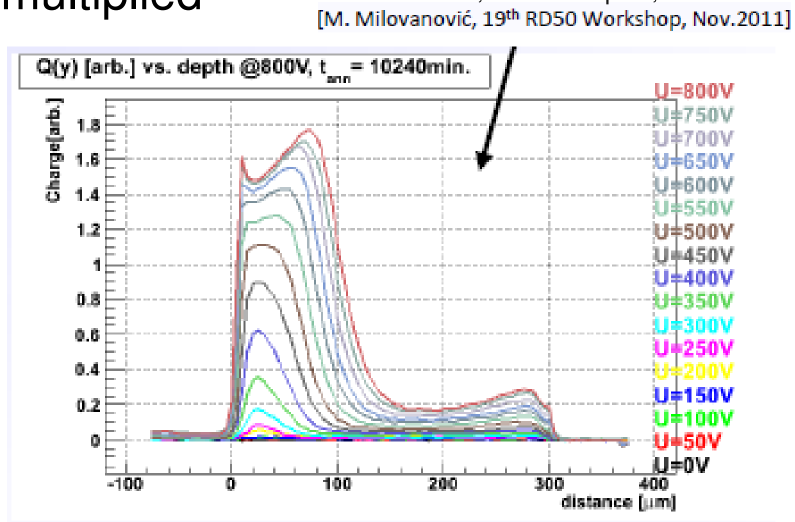
CM observed after long annealing times



HPK FZ n-in-p strip sensors, thickness 320 µm

Edge-TCT measurements indicate where charge is generated and multiplied

G. Casse M. Moll, LHCC Report, 2012



• Increase of the electric field close to the strips causing impact ionization/carrier injection when high concentrations of effective acceptors are introduced at very high fluences.

• **Open questions:** long-term stability, operation at high voltages, behaviour of signal-to-noise ratio

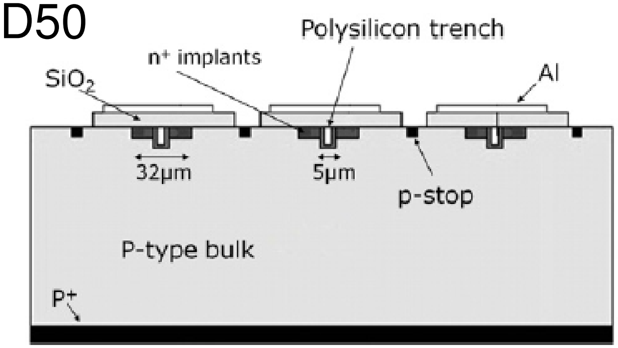
• **Problems:** high leakage currents, noise multiplication

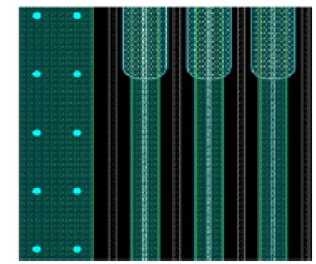
Full detector systems: Enhancing Charge Multiplication

Production of sensors with trenches within RD50

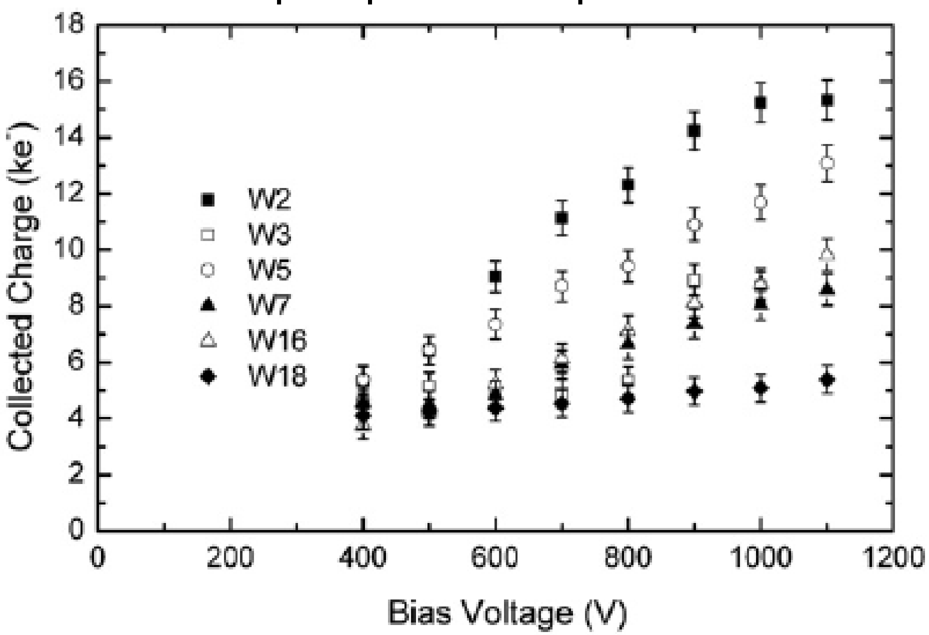
Geometry variations:

- Deeper junctions
- Altered doping gradient
- Ratio of strip implant and pitch

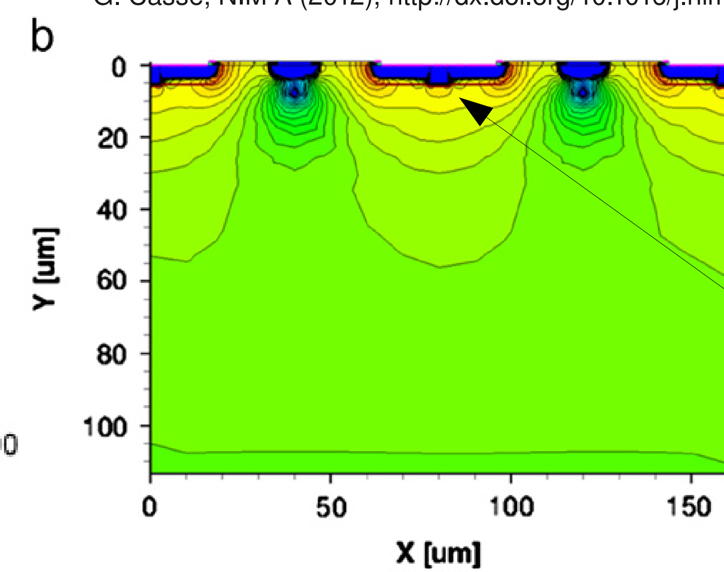




G. Casse, NIM A (2012), http://dx.doi.org/10.1016/j.nima.2012.04.033



Standard n-in-p sensor 300 μm thick, Trenches with 5 (W2), 10 (W7 std), 50 (W5) μm width, Deep diffusion 5 μm (W16), as implant (W18) after $5*10^{15}$ neq/cm^2



High electric field (reduced trapping)

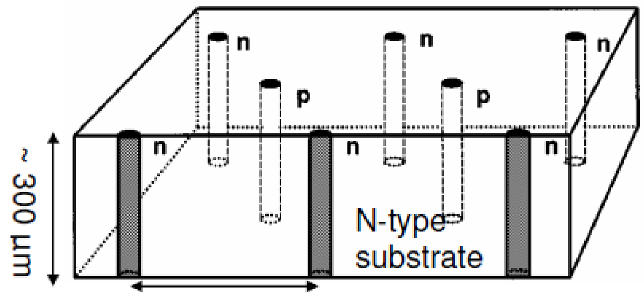
P. Fernández-Martínez, NIM A 658 (2011) 98-102

More in talk N25-3

→ Higher collected charge for 5 and 50 μm trenches but higher noise to be avoided

New Structures: 3D sensors

First proposed in 1997 by Parker et al.
- Decoupling of depletion voltage and detector thickness (collected charge)

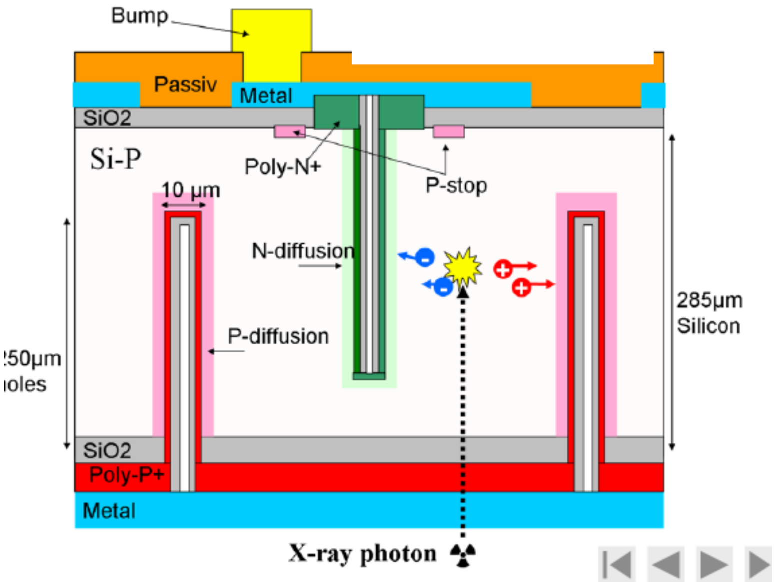


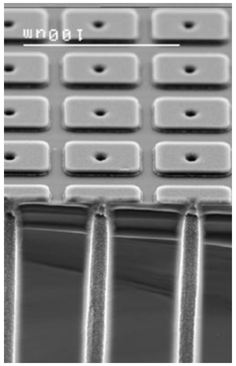
Parker et al. NIM A 395 (1997) 328

Today available in double-sided technology from different suppliers (CNM, FBK, Sintef)

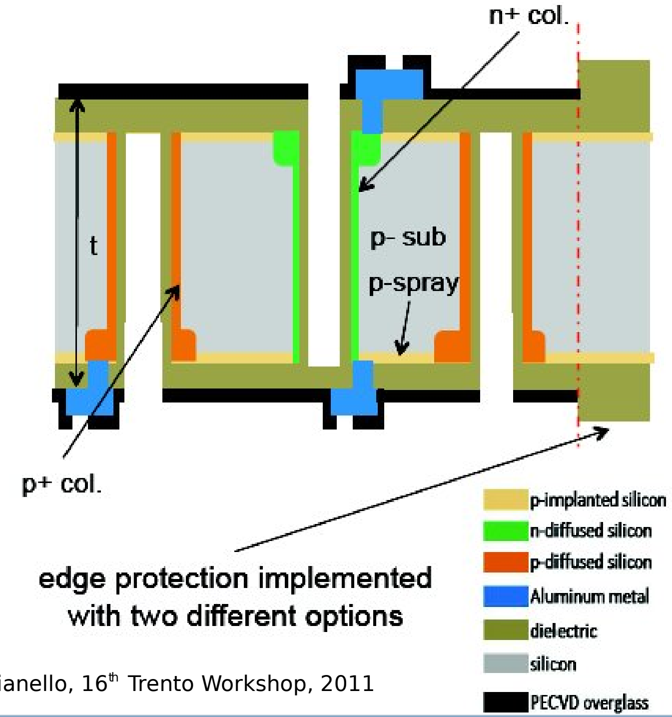
- CNM: columns part. filled

- FBK 3D double side double type sensor: columns through wafer, empty





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



E. Vianello, 16th Trento Workshop, 2011

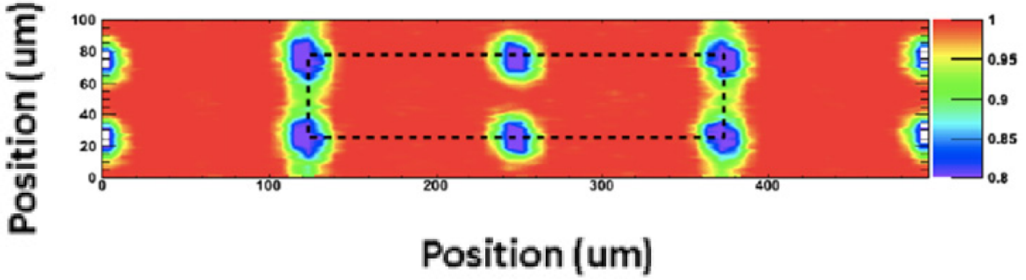
New Structures: 3D sensors

Albert-Ludwigs-Universität Freiburg

3D sensors of CNM and FBK show good performance before and after irradiation in charge collection measurements with beta sources and position resolved efficiency measurements with laser set-ups

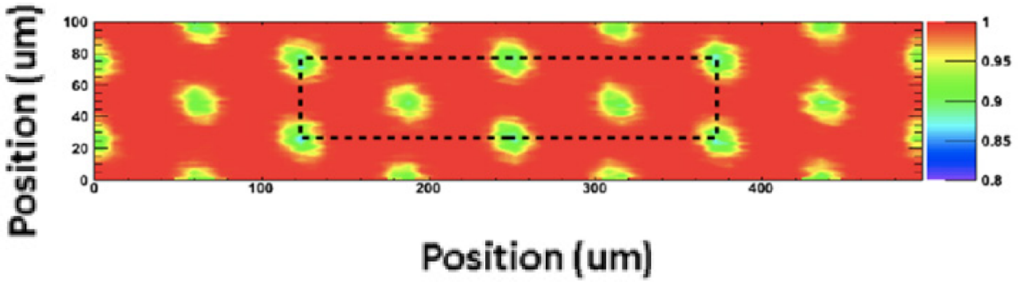
Ex: Testbeam results of 3D pixel devices

S. Grinstein et al. NIM A (2012), http://dx.doi.org/10.1016/j.nima.2012.03.043



Efficiency map for neutron irrad. $5*10^{15}$ neq/cm^2 CNM detector, particles perpendicular, V_{bias} = 160 V

→ Overall eff. 97.5 %



Efficiency map for unirrad, FBK detector, particles perpendicular, V_{bias} = 20 V

→ Overall eff. 98.8 %

→ ~ 20 % of sensors for ATLAS IBL will be 3D sensors

Summary: Achievements of RD 50 in light of LHC experiments

- Observed radiation damage in LHC experiments agrees with predictions developed by RD 50
  - Leakage current increase in ATLAS, depletion voltage evolution in LHCb

- P-type silicon shows radiation hardness and good performance for fluences of about $1*10^{16}$ neq/cm^2
  → candidate material for upgrade of LHC strip tracking detectors
  → scaling of annealing to be investigated further

- New structures like 3D devices show good performance after irradiation and application in LHC experiments foreseen

- Charge multiplication investigation started systematically to allow its exploitation
  → long-term stability to be tested

→ Radiation Damage Inter-Experiment Working Group
  - Common detector productions, test beams
  - “LHC-wide” exchange of knowledge

Further Contributions related to RD 50

- RD 50 collaboration works on radiation hard semiconductor devices for LHC experiments and tested plenty of different devices (material, geometry, engineering)

- Several posters on topics of RD 50 collaboration:
  N1-179, N1-181, N1-182
  N14-57, N14-58, N14-198, N14-204, N14-206, N14-208, N14-215

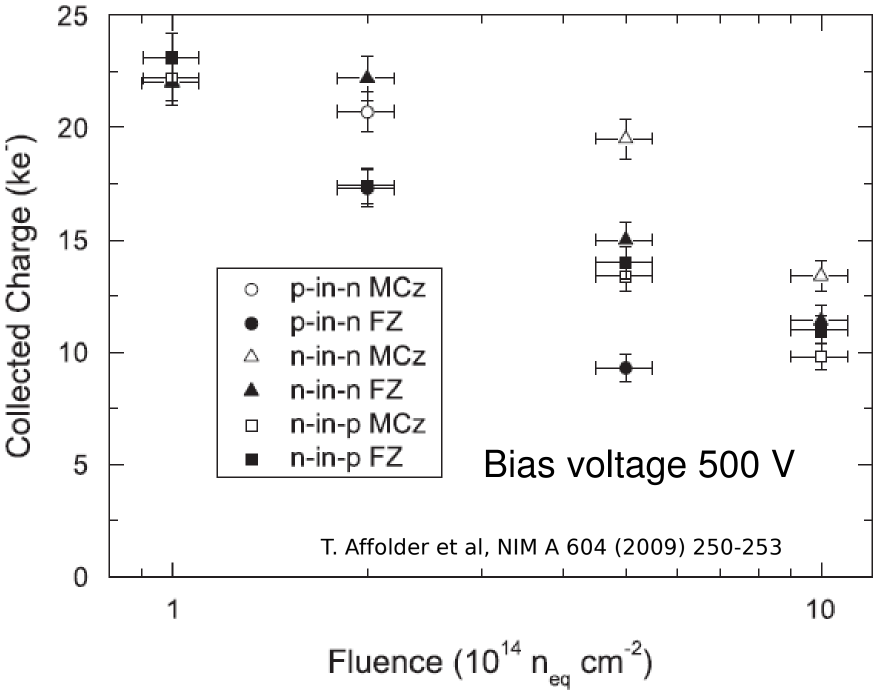
- And many talks:
  N18-7, N25-2, N25-3, N25-4
  N33-1, N33-3, N33-5, NR01-2

Very active community and many projects ongoing!

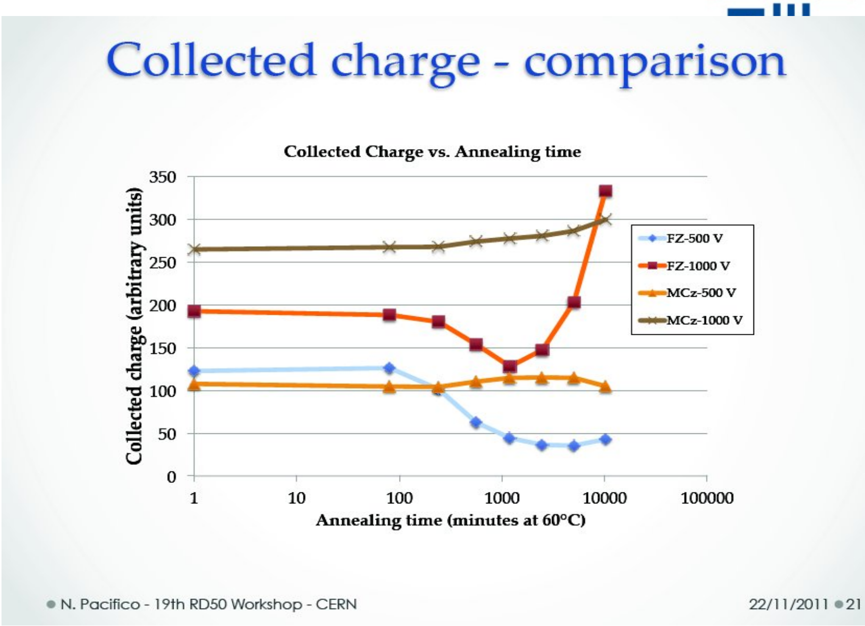
Thank you to all colleagues for the material!

Backup

Full detector systems: FZ vs. MCZ



Sensors 300 µm thick and neutron irradiated



N.Pacifico, 19th RD50 Workshop, 2011

- MCZ performs better than FZ
- MCZ less affected by annealing

  In oxygen rich MCZ, damage compensated

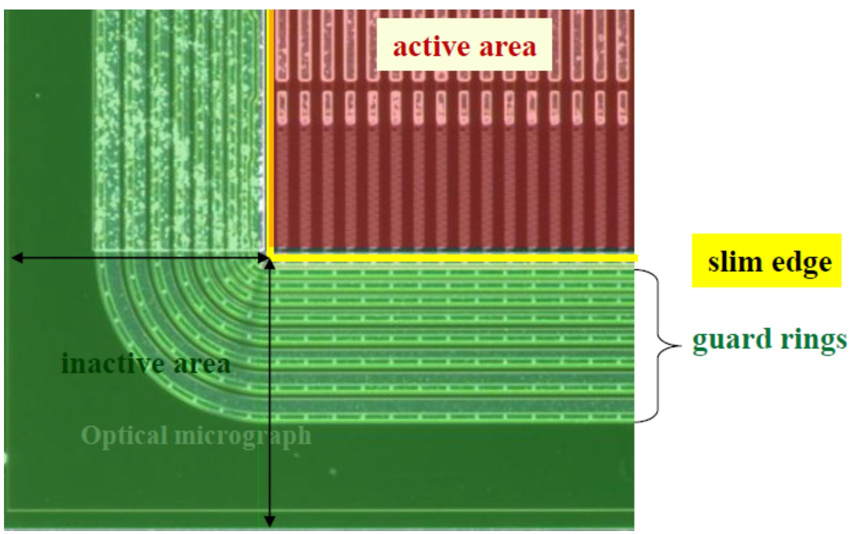
Annealing:
More investigations ongoing, aim for
→ proper description of scaling
→ recommendations for HEP community regarding temperature sensitive operation

Further projects in RD 50

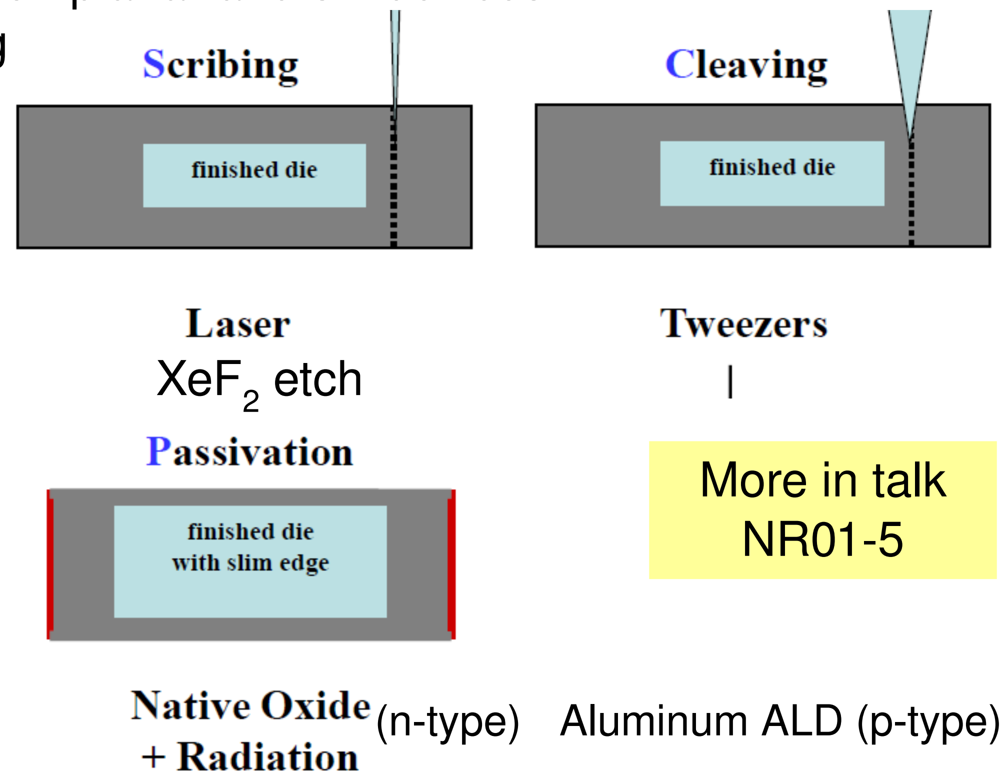
- Investigation of thin sensors
  - 140 µm strip and 75 µm and 150 µm pixel devices tested, allow lower bias voltages
  - With charge multiplication thin sensors give large signals after high fluences

More in talk N25-4

- RD 50 slim edge project to reduce dead space of inactive volume
  - Exploits scribe and cleave technique on planar and 3D devices
  - Performance after irradiation ongoing



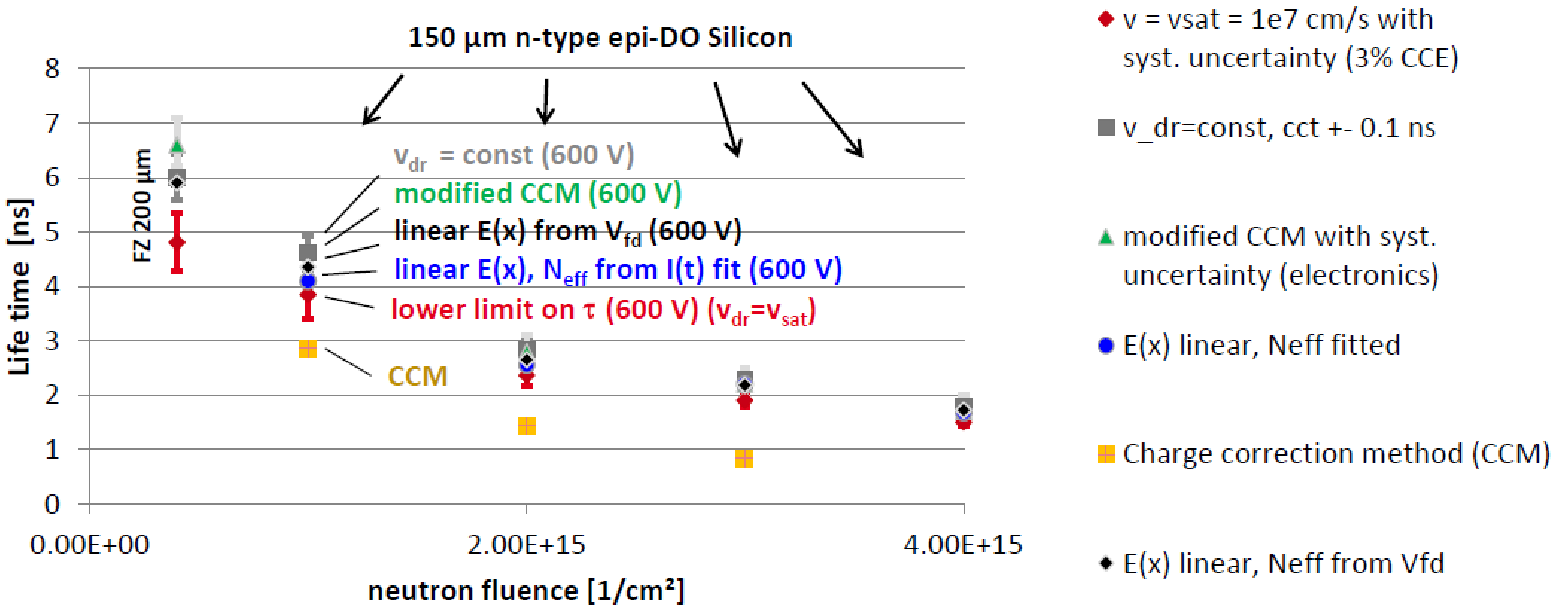
V. Fadeyev, 20th RD50 Workshop, 2012



More in talk NR01-5

TCT: Lifetime of charges

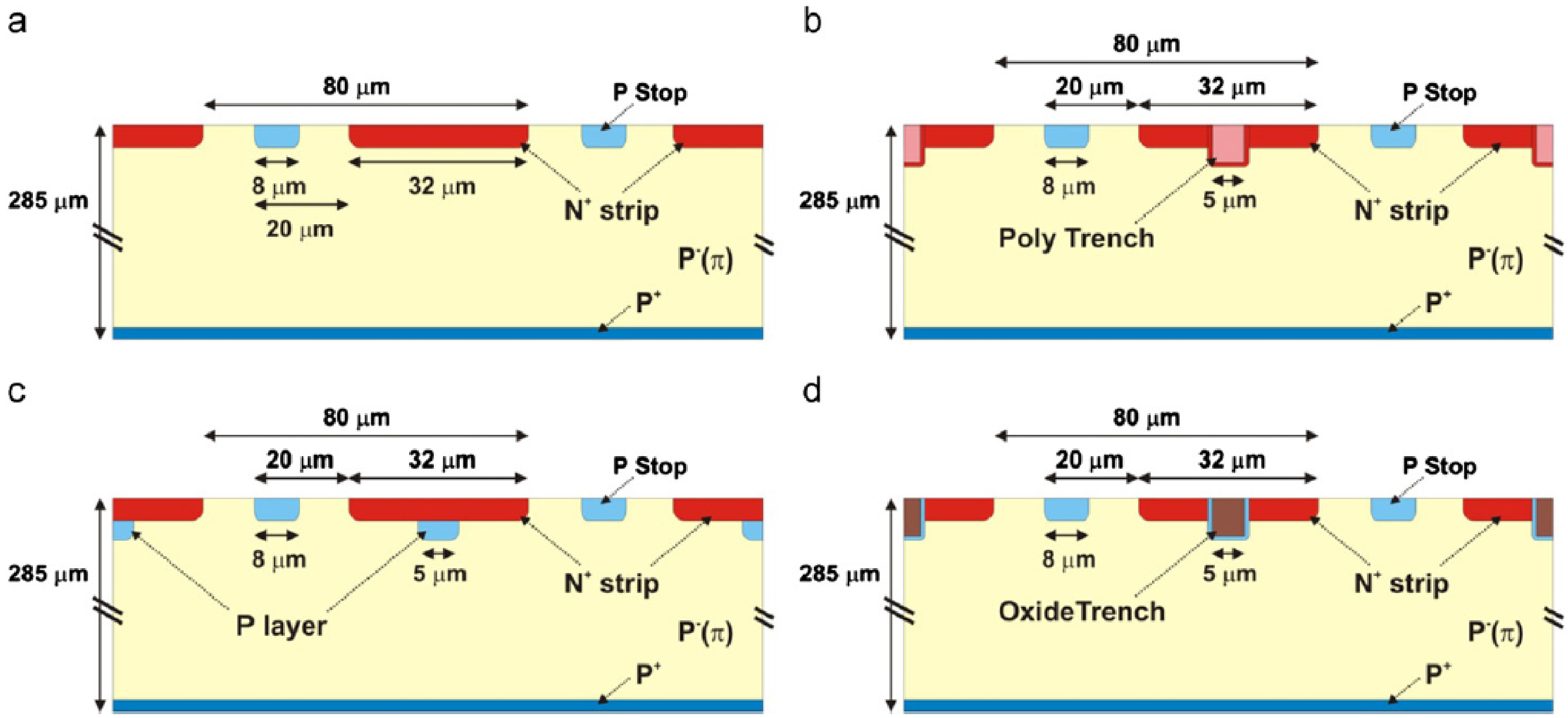
Estimate and Understand with TCT measurements the charge life time



T. Pöhlsen, 20th RD50 Workshop, 2012

Trenches

a standard, b poly trench including poly silicon doped with phosphorus, c p-layer with p-type diffusion, d oxide trench



P. Fernández-Martínez, NIM A 658 (2011) 98-102