Development of Silicon Detectors for Tracking and Timing within the RD50 Collaboration

Matteo Centis Vignali[1], CERN EP-DT Fellow
on behalf of the RD50 collaboration[2]

12.04.2018
FCC week, Amsterdam

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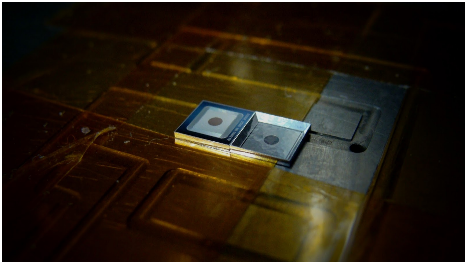
[2] http://rd50.web.cern.ch/rd50/

Outline

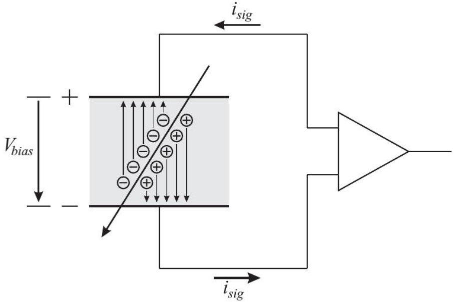
Overview of the collaboration activities with emphasis on selected topics



[30^{th} RD50 workshop, Krakow]

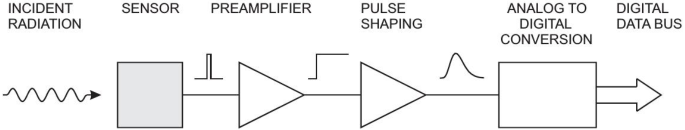
Silicon Detectors

Solid state ionization detector



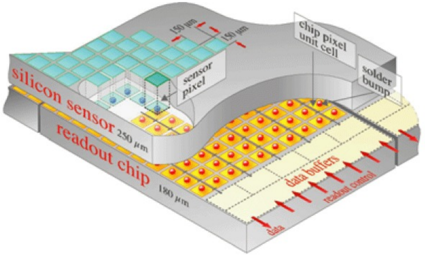
- Mono-crystalline Si
- Rectifying junction in reverse bias
- Mean ionization energy: 3.6 eV/eh
- 300 μm typical thickness
- Signal $\approx$ 24000 e^- in 300 μm
- Fast signals, O(10 ns)

Readout electronics



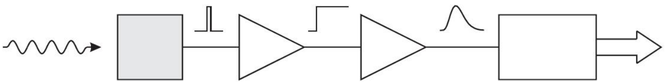
Silicon Detectors

Hybrid pixel detectors



- Mono-crystalline Si
- Rectifying junction in reverse bias
- Mean ionization energy: 3.6 eV/eh
- 300 μm typical thickness
- Signal $\approx$ 24000 e^- in 300 μm
- Fast signals, O(10 ns)
- Patterning electrodes $\rightarrow$ position sensitivity

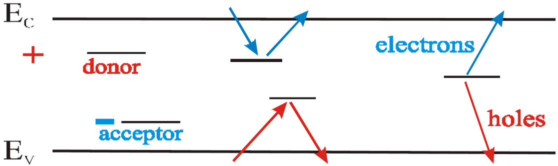
Readout electronics



Radiation Damage in Silicon Detectors

Bulk damage

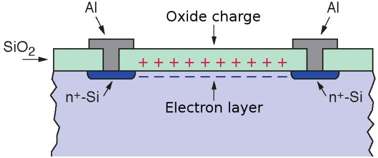
- Non ionizing energy loss (NIEL)
- Defect generation in the lattice
- Change of V_{dep}
- Increase in leakage current
  $\rightarrow$ noise
- Decrease in signal



Damage expressed as
equivalent fluence of 1 MeV neutrons Φ_{eq} [cm^{-2}]

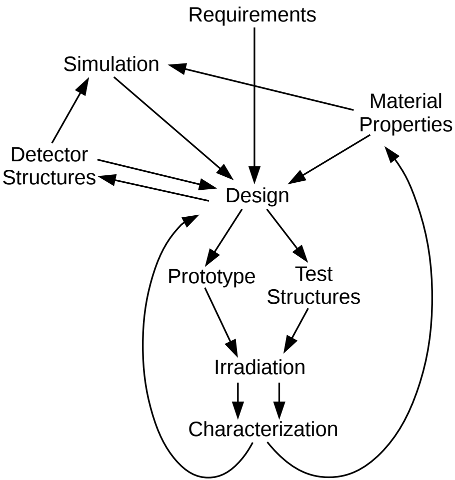
Surface damage

- Ionizing energy loss in SiO_2
- Traps at the Si-SiO_2 interface
- Build up of positive charge
- Modification of electric field
  $\rightarrow$ charge losses
  $\rightarrow$ noise
  $\rightarrow$ breakdown
- Conductive layers
- Affects sensors and electronics



Relevant quantity: dose in SiO_2

Development of Radiation-hard Silicon Detectors (A simplified recipe)



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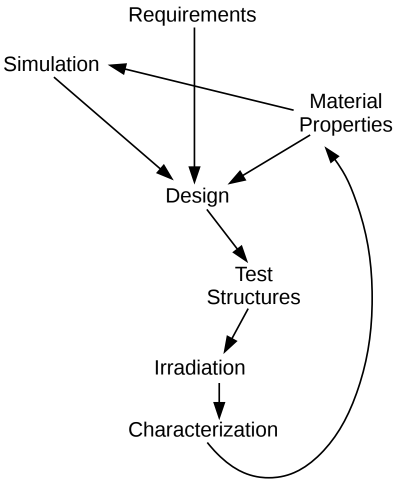

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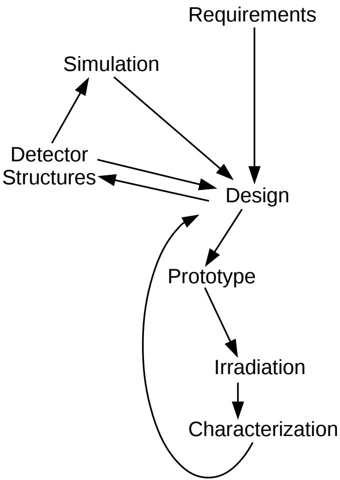
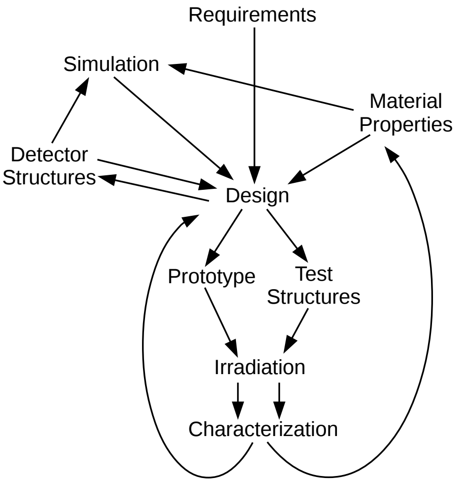


Development of Radiation-hard Silicon Detectors (A simplified recipe)



This was needed by the LHC and HL-LHC experiments

⇒ **form a collaboration**

The RD50 Collaboration

Radiation hard semiconductor devices for very high luminosity colliders

- **RD50: *60 institutes and 345 members***

47 European institutes

Austria (Vienna), Belarus (Minsk), Belgium (Louvain), Czech Republic (Prague (3x)), Finland (Helsinki, Lappeenranta), France (Paris, Orsay), Germany (Dortmund, Erfurt, Freiburg, Hamburg (2x), Karlsruhe, Munich(2x)), Italy (Bari, Perugia, Pisa, Trento, Torino), Kroatia (Zagreb) Lithuania (Vilnius), Netherlands (NIKHEF), Poland (Krakow, Warsaw(2x)), Romania (Bucharest (2x)), Russia (Moscow, St.Petersburg), Slovenia (Ljubljana), Spain (Barcelona(3x), Santander, Seville(2x), Valencia), Switzerland (CERN, PSI, Zurich), United Kingdom (Birmingham, Glasgow, Lancaster, Liverpool, Oxford, RAL)

8 North-American institutes

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

1 Middle East institute

Israel (Tel Aviv)

1 Asian institute

India (Delhi)

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

RD50 Structure

Co-Spokespersons

Gianluigi Casse and *Michael Moll*

(Liverpool University, UK & FBK-CMM, Trento, Italy) (CERN EP-DT)

Defect / Material Characterization
Ioana Pintilie
(NIMP Bucharest)

- Characterization of microscopic properties of standard-, defect engineered and new materials pre- and post-irradiation
- DLTS, TSC, ...
- SIMS, SR, ...
- NIEL (calculations)
- Cluster and Point defects
- Boron related defects

Detector Characterization
Eckhart Fretwurst
(Hamburg University)

- Characterization of test structures (IV, CV, CCE, TCT,.)
- Development and testing of defect engineered devices
- EPI, MCZ and other materials
- NIEL (experimental)
- Device modeling
- Operational conditions
- Common irradiations

- Wafer procurement (M.Moll)
- Acceptor removal (Kramberger)
- TCAD simulations

New Structures
Giulio Pellegrini
(CNM Barcelona)

- 3D detectors
- Thin detectors
- Cost effective solutions
- Other new structures
- Detectors with internal gain
- LGAD: Low Gain Avalanche Det.
- Deep depleted Avalanche Det.
- Slim Edges
- HVCMOS

- LGAD (S.Hidalgo)
- HVCMOS (E. Vilella)
- Slim Edges (V.Fadeyev)

Full Detector Systems
Gregor Kramberger
(Ljubljana University)

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

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

FCC is the next Project on the Horizon

[M. Fernandez Garcia, VERTEX 2017]

Summary

Activity in RD50 organized around several workgroups including, defect studies, new sensor technologies, TCAD and fast simulators, new characterization techniques,...

Close link to R&D foundries (CNM-IMB Barcelona, FBK- Trento) **and commercial** companies (CIS, Micron,...) allow for fast and efficient development of new sensor concepts.

RD50 keeps **close links to the LHC experiments**. Most of groups in RD50 are part of ATLAS, CMS or LHCb.

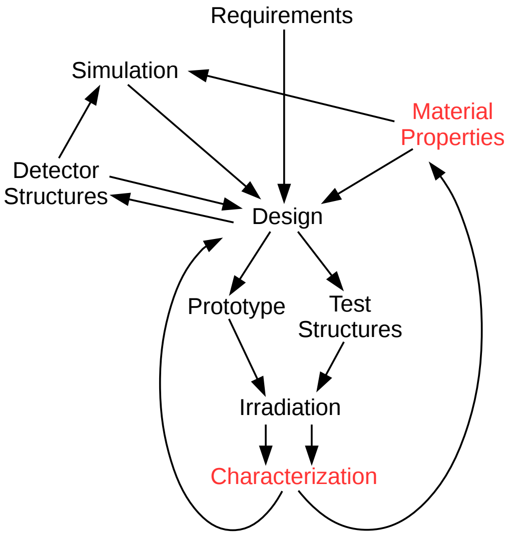
Some **hot**-topics are actively studied in RD50: **acceptor removal**, detectors with **gain**, **timing** in Silicon, to mention some.

RD50 co-funds “common projects” involving several RD50 institutes targeting a specific R&D question (thin LGADs, 3D for HL-LHC, Ga doping of LGAD, TPA-TCT, RD50 common Test Beam, RD50 CMOS submission).

Some of the **most important** contributions **triggered by RD50** collaboration towards the upgrade of LHC: *p-type silicon, double column 3D detectors, radiation damage models for TCAD simulations, radiation damage models for experiments operation, fast timing in Si, new characterization techniques...*

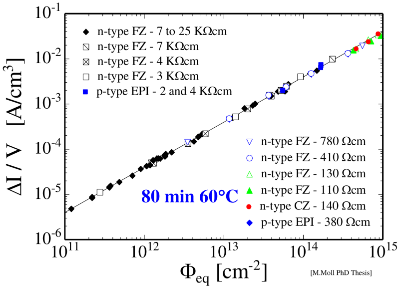
NEXT CHALLENGE: The **FCC**

Material Characterization

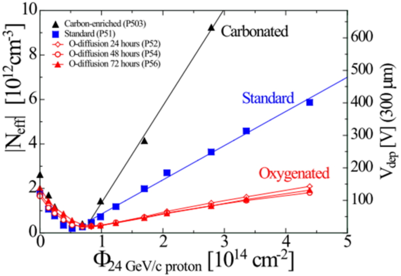


Current- and Capacitance-Voltage Characteristics

[M. Moll, PhD thesis]



[G. Lindström, NIM A466 (2001) 33]

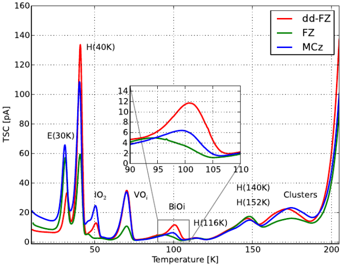


Change in macroscopic properties

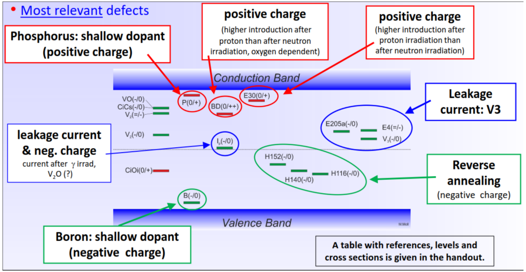
- Current
- Power consumption
- Noise
- Effective doping concentration
- Operational voltage

Defect Spectroscopy

[E. Donegani, RADECS 2016]



[M. Moll, Future Silicon Detector R&D 2018]



Measurement techniques usually employ temperature scans to characterize defects

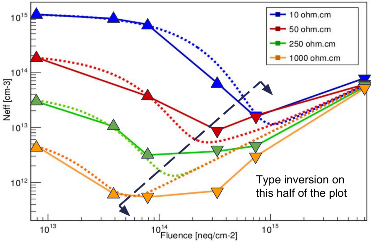
Microscopic explanation of macroscopic properties

- Defects properties
- Defects concentration
- Introduction rate
- Defects identification

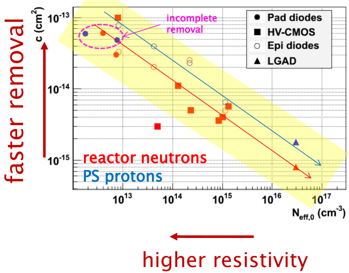
Acceptor Removal

Change in doping in boron-doped p-type silicon

[P. de Almeida, “Trento” workshop 2018]



[G. Kramberger, “Hiroshima” symposium 2017]



Affects:

- p-type silicon sensors
- LGADs $\rightarrow$ gain reduction
- CMOS sensors $\rightarrow$ change in depletion region

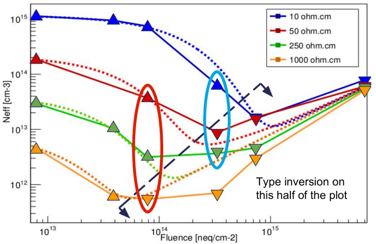
$$N_{eff}(\Phi) = N_{eff}(0) - N_c(1 - e^{-c\phi}) + g_c\Phi$$

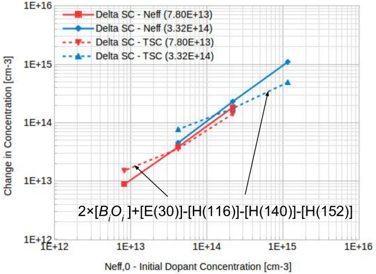
$N_{eff} \rightarrow$ effective doping concentration
$N_c \rightarrow$ “removable” dopants
$c \rightarrow$ acceptor removal constant
$\Phi \rightarrow$ fluence
$g_c \rightarrow$ introduction rate

Acceptor Removal

Change in doping in boron-doped p-type silicon

[P. de Almeida, "Trento" workshop 2018]



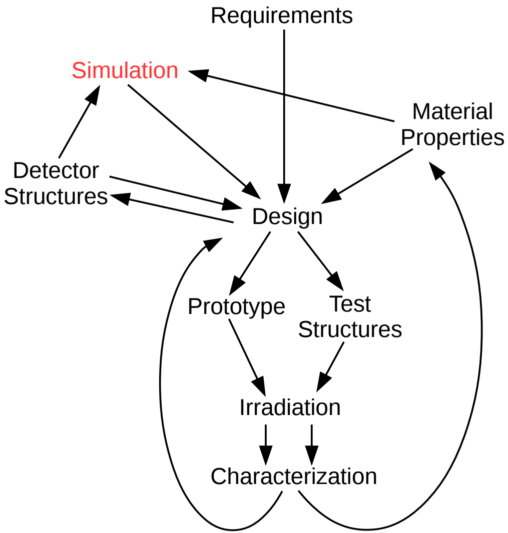


Defect spectroscopy
⇒ microscopic interpretation of change in space charge
Understanding of damage mechanism
⇒ material engineering

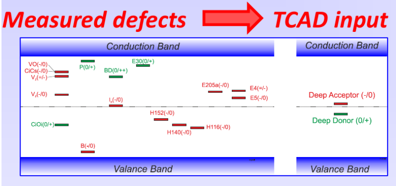
Assumptions:

- E(30) contributes positive space charge
- H(116)-H(140)-H(152) contribute negative space charge
- B_iO_i contributes twice its concentration

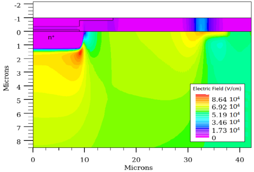
Simulation


Requirements
Simulation
Material Properties
Detector Structures
Design
Prototype
Test Structures
Irradiation
Characterization

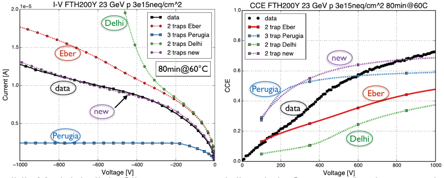
TCAD Simulations



[R. Dalal, VERTEX 2014]



[J. Schwandt, 27th RD50 workshop]



Delhi's Model, built in Silvaco, was used directly in Synopsys for these results.

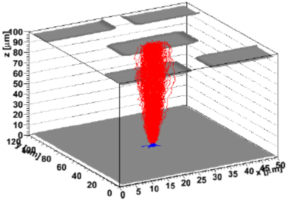
- Excellent tools for sensor and process design and simulation
- "Effective" radiation damage models
  $\rightarrow$ a few defects (2-3) to parametrize all effects
  (E field, generation, trapping....)
- Many models available
- Within their fluence validity:
  Predictive power after irradiation
- Computing intensive
- Validation of models with dedicated test structures is fundamental
- Models up to $\Phi_{eq} \approx 10^{16}\,\text{cm}^{-2}$

Fast Simulators

Reduce the amount of resources needed wrt TCAD tools

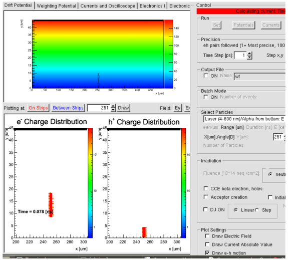
KDetSim
IJS Ljubljana

- ROOT shared library
- Scripted
- 3D simulation
- Arbitrary sensor geometry



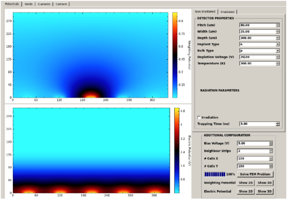
WeightField2
INFN Torino

- GUI based
- Built on ROOT
- Diodes and strips
- Accurate description of LGADs

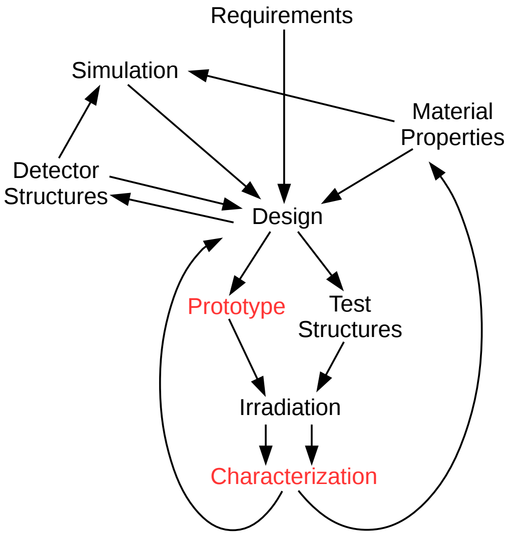


TRACS
IFCA-Santander & CERN

- GUI and CLI available
- Fit of TCT data
- Diodes and strips
- Parallel computing



Sensor Characterization

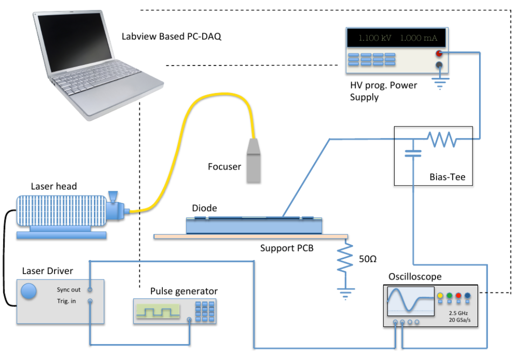


Transient Current Technique

Resolve in time the current pulse of the sensor to map the electric field

$$I = Nq_e \vec{v}_{drift} \cdot \vec{E}_w$$

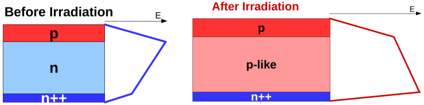
[N. Pacifico, PhD thesis]



$I \rightarrow$ current
$N \rightarrow$ number of charge carriers
$q_e \rightarrow$ electron charge
$\vec{v}_{drift} \rightarrow$ drift velocity
$\vec{v}_{drift} = \mu \vec{E}$ at low enough fields
$\vec{E}_w \rightarrow$ weighting field
$E_w = 1/d$ for a pad diode

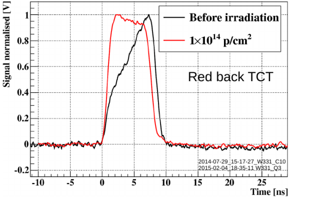
- Movement of charge induces signal
- Weighting field links the charge movement to the induced signal
- Charge carriers created using a ps pulsed laser
- High bandwidth current amplifiers and oscilloscopes used for readout

Transient Current Technique

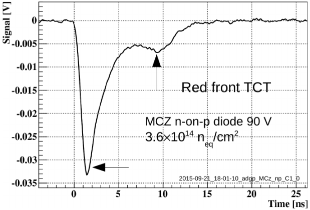


[S. Otero Ugobono, DT training seminar, 2017]

Space Charge Sign Inversion (SCSI)



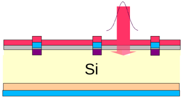
Double Junction effect



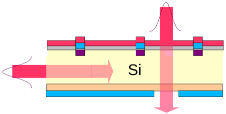
Pad diode at low enough field:

$$I = Nq_e \mu E / d$$

Current proportional to E



- Red light:
  $\rightarrow$ absorption length O(μm)
  $\rightarrow$ one kind of charge carrier drifting
- Infrared light:
  $\rightarrow$ absorption length O(mm)
  $\rightarrow$ mimic particle signal
  $\rightarrow$ edge illumination:
  probe bulk more directly



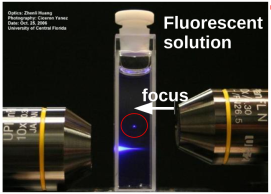
Two Photon Absorption TCT

[M. Fernandez Garcia, DT training seminar, 2017]

SPA

Single
Photon
Absorption

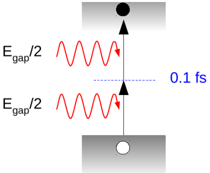
Continuous energy deposition

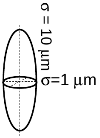


TPA

Two
Photon
Absorption

Energy confinement

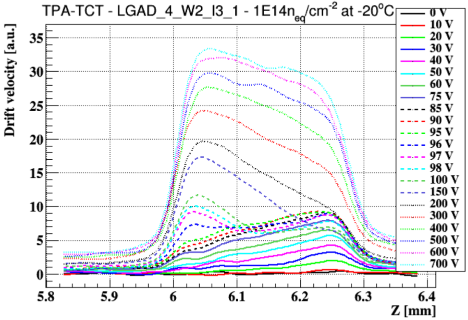




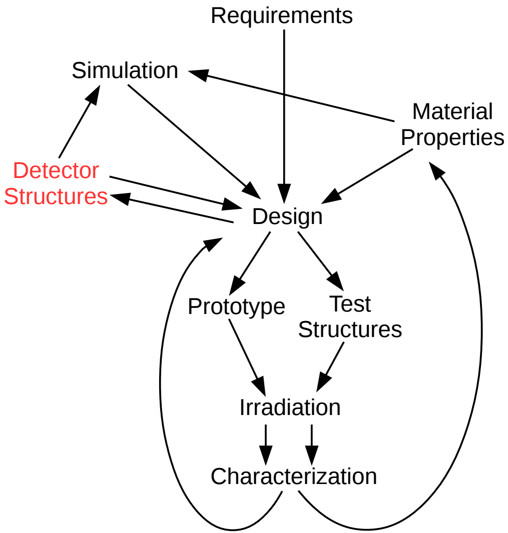
- Absorption through virtual state
- Femtosecond laser
- Point-like generation of charge carriers
- Move point through the sensor

- Study of the electric field of an irradiated LGAD
- The field grows from the back side till V $\approx$ 95 V
- Afterwards, the field increases from the front side

[M. Fernandez Garcia, 31st RD50 workshop]

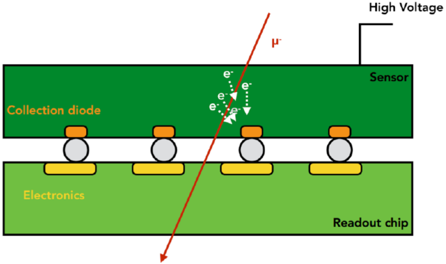


Detector Structures



Hybrid Planar Pixel Detectors

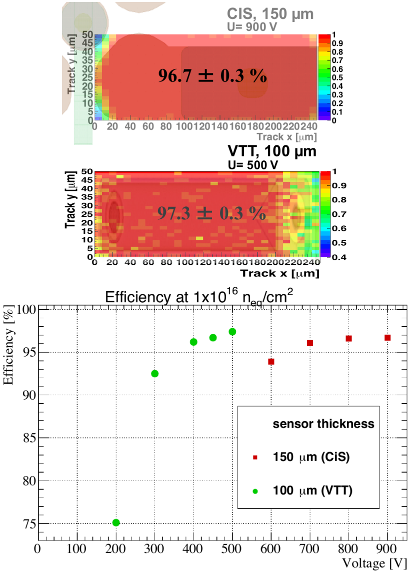
[D. Hynds, CLIC workshop 2017]



- Separate optimization of sensor and electronics
- Interconnection technology can be expensive
- Currently used in ATLAS and CMS

Thin Planar Sensors

[N. Savić, 29^{th} RD50 workshop]



$\approx 300\ \mu$m $\rightarrow \approx 100\ \mu$m

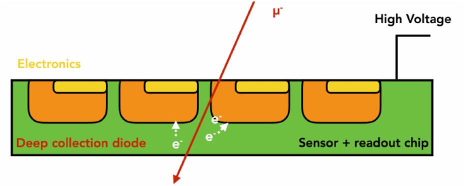
Advantages of thin sensors:

- Higher field for same bias voltage
- Smaller drift distances
- Reduced trapping

- 97% detection efficiency after $\Phi_{eq} = 10^{16}\,\text{cm}^{-2}$
- Both sensor and readout electronics were irradiated
- Biasing structures can play an important role in the efficiency after irradiation (true for all thicknesses)

CMOS Sensors

[D. Hynds, CLIC workshop 2017]



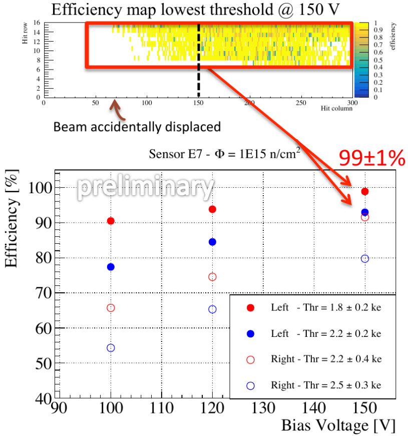
- Sensor and electronics on same silicon die
- Reduced material budget wrt hybrid
- Many different flavors
- Many foundries available from electronics industry
- Availability of manufacturers
  $+$ elimination of interconnections
  $\Rightarrow$ Reduced cost wrt hybrid
- Foreseen in ALICE upgrade $O(10\,m^2)$
- Option for outermost ATLAS pixel layer at HL-LHC

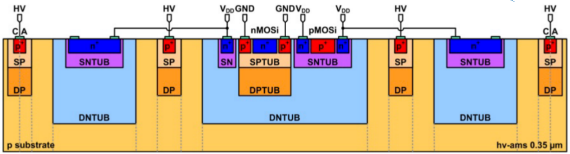
HV-CMOS

[S. Terzo, “Trento” workshop 2018]

1e15 $n_{eq}cm^{-2}$

Depleted region of ≈60-70 μm at 120-150 V (from E-TCTs)

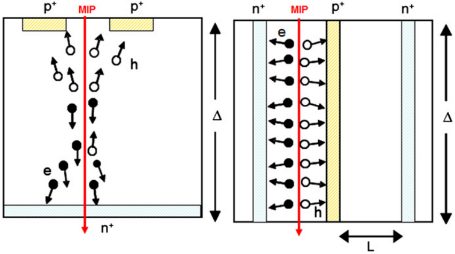




- HV-CMOS is an industry standard process that allows to apply high voltages to the substrate
- Improved depleted region, charge collection, and radiation tolerance wrt standard CMOS
- 99 ± 1% detection efficiency after $\Phi_{eq} = 10^{15}\,\mathrm{cm}^{-2}$
- Readout performed using the electronics on the die (No readout ASIC needed)

Hybrid 3D Pixel Detectors

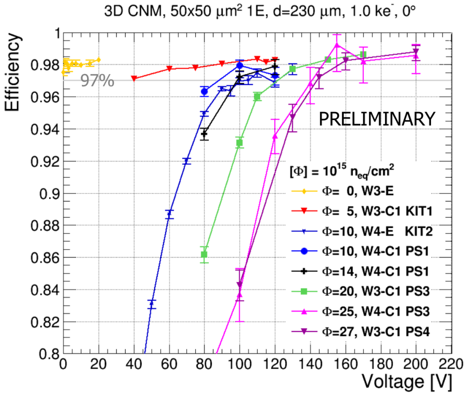
[C. Da Via, NIM A694 (2012) 321]



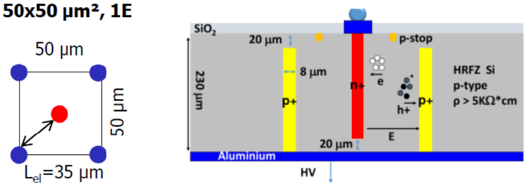
- "Bore" electrodes in the sensor thickness
- Decouple signal generation path from drift distance
- Closely spaced electrodes
- Operation at lower bias wrt planar sensors after irradiation
- Reduced trapping
- Used in part of ATLAS IBL
- Baseline for innermost ATLAS pixel layer at HL-LHC

Beam Test Results after $\Phi_{eq} = 2.7 \cdot 10^{16}\,\mathrm{cm}^{-2}$

[J. Lange, “Trento” workshop 2018]



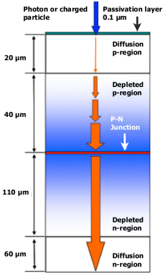
[J. Lange, “Trento” workshop 2018]



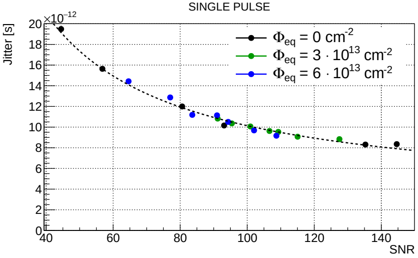
- 98% detection efficiency before irradiation (normal incidence, particles through columns)
- Both sensor and readout electronics were irradiated
- 98% detection efficiency after $\Phi_{eq} = 2.7 \cdot 10^{16}\,\mathrm{cm}^{-2}$

Deep Diffused APDs for Timing

[M. Centis Vignali, “Trento” workshop 2018]



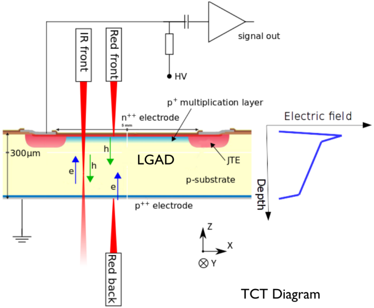
Laser setup measurement

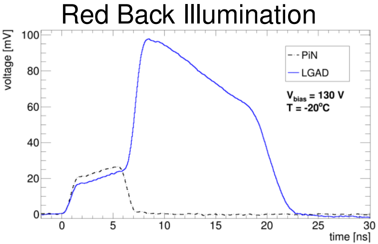


- Diffusion process to create some 10s of μm deep in the sensor
- Charge multiplication
- Bias $\approx$ 1800 V
- Gain $\approx$ 500
- Active area $2 \times 2\,\text{mm}^2$
- Jitter = 9 ps after $\Phi_{eq} = 6 \cdot 10^{13}\,\text{cm}^{-2}$ @ 1 MIP laser intensity
- A lower resolution is expected for charged particles

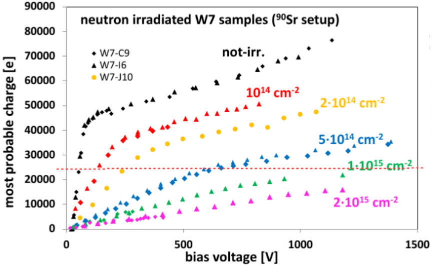
Low Gain Avalanche Detectors

[S. Otero Ugobono, VERTEX 2017]





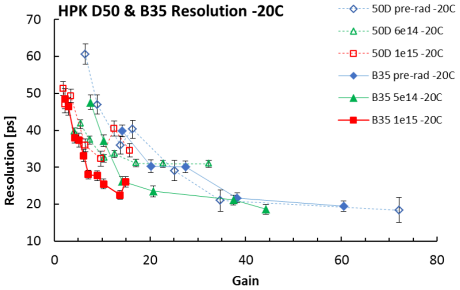
[G. Kramberger JINST 10 P07006]

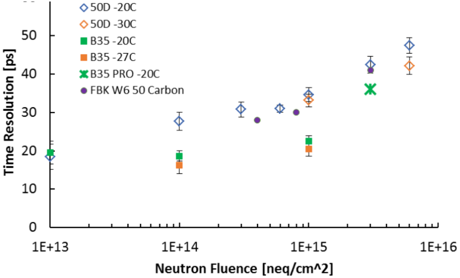


- Charge multiplication
- Multiplication layer to create high field region
- Gain: 10-50
- Increase signal
- Steep rising edge for timing
- Foreseen in ATLAS and CMS timing layers for HL-LHC

LGADs for Timing

[H. Sadrozinski, "Trento" workshop 2018]



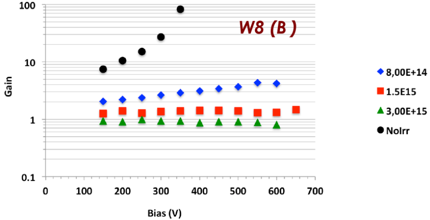


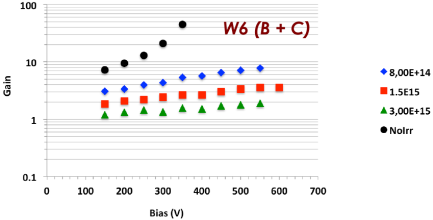
- Thickness of 50 or 35 μm
- Typical channel dimension $\approx 1\,\text{mm}^2$
- Readout electronics plays a major role in timing applications
- Measurements using charged particles
- 35 μm devices:
  $\sigma_t = 27\,\text{ps}$ up to $\Phi_{eq} = 10^{15}\,\text{cm}^{-2}$
  $\sigma_t = 36\,\text{ps}$ at $\Phi_{eq} = 3 \cdot 10^{15}\,\text{cm}^{-2}$

Radiation Hardening of LGADs

[R. Arcidiacono, “Trento” Workshop 2018]

Gain = Q(LGAD) / Q(PiN)

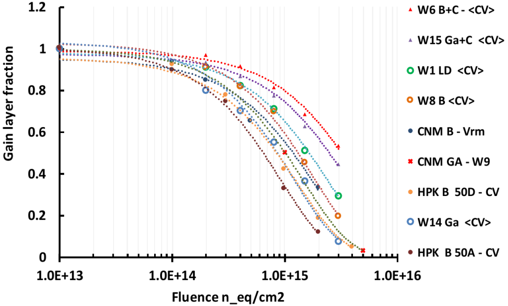




Carbon co-implantation makes the gain layer more radiation hard

- Multiplication layer affected by acceptor removal
- Go thinner (previous slide)
- Modify the mult. layer doping profile
- Use of different dopants to reduce the effect (Ga, C co-implantation)

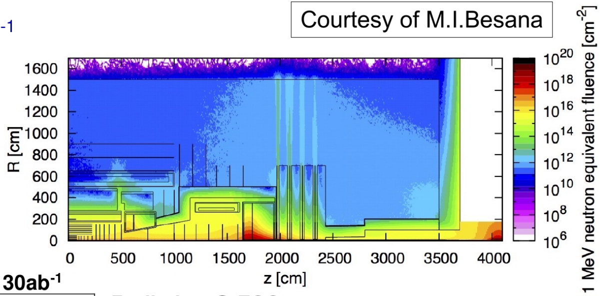
[R. Arcidiacono, “Trento” Workshop 2018]



FCC-hh Requirements

[Z. Drásal, 30^{th} RD50 meeting]

- 1 MeV neq fluence after $30ab^{-1}$



Long-term damage for Tracker after $30ab^{-1}$

R [mm]	z[m]	Dose [MGy]	1 MeV equivalent Fluence [cm^{-2}]
25	0	320	$5.5\ 10^{17}$
60	0	88	$1.25\ 10^{17}$
100	0	40	$6\ 10^{16}$
150	0	23	$3.3\ 10^{16}$
270	0	8.8	$1.51\ 10^{16}$
900	0	0.65	$3.2\ 10^{15}$
25	5	410	$3.7\ 10^{17}$
50	16	250	$2\ 10^{17}$

Radiation @ FCC:

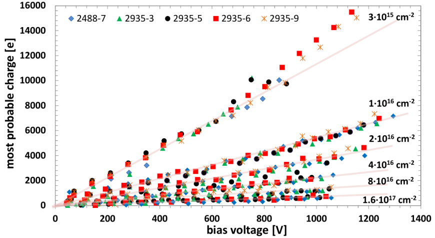
→ @R=25mm: **~$6x10^{17}$ neq cm^{-2} ,TID~0.4GGy**

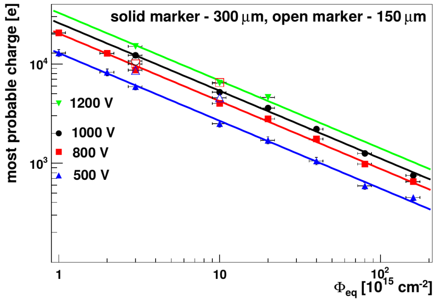
- **LHC** = 1
- **HL-LHC** → **20x LHC**
- **FCC** → **600x LHC**

FCC-hh tracker ⇒ 30 × HL-LHC Track $\sigma_t \approx 5$ ps FCC-hh calorimeters: $\Phi_{eq} \approx 5 \cdot 10^{18}\,cm^{-2}$

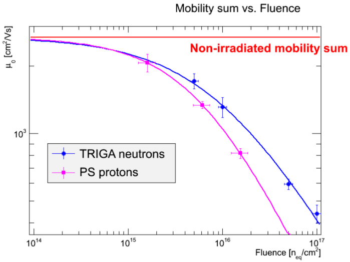
Results at $\Phi_{eq} = 10^{17}\,\mathrm{cm}^{-2}$

[G. Kramberger, JINST 8 P08004]

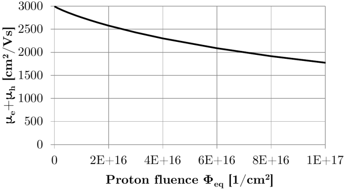




[M. Mikuž, VERTEX 2017]

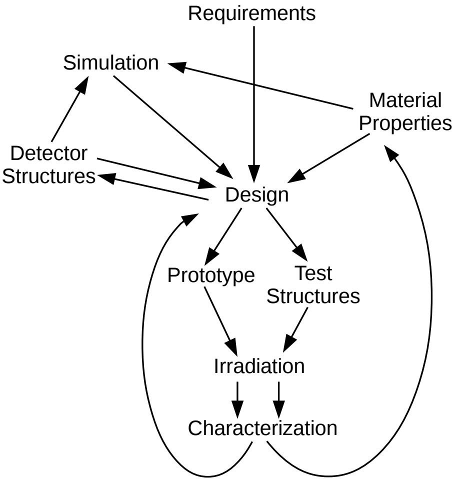


[C. Scharf, PhD thesis]



- Fluence beyond HL-LHC
- 1 ke collected charge after $\Phi_{eq} = 1.6 \cdot 10^{17}\,\mathrm{cm}^{-2}$ (study done using spaghetti diodes)
- Silicon sensors are still working
- Started study of fundamental properties

Developments for FCC



- The FCC-hh requirements are being defined
- Tracker: 30× radiation hardness for HL-LHC
- Track $\sigma_t \approx 5\,\text{ps}$
- First results in material characterization
- Fundamental properties of Si to be understood at these fluences
- New characterization techniques needed
- New dosimetry techniques needed (See talk of G. Gorine)
- Similar time scale and rad. hard. improvement as for LHC, HL-LHC: now is time to start

Silicon is a good candidate for tracking and timing at FCC-hh

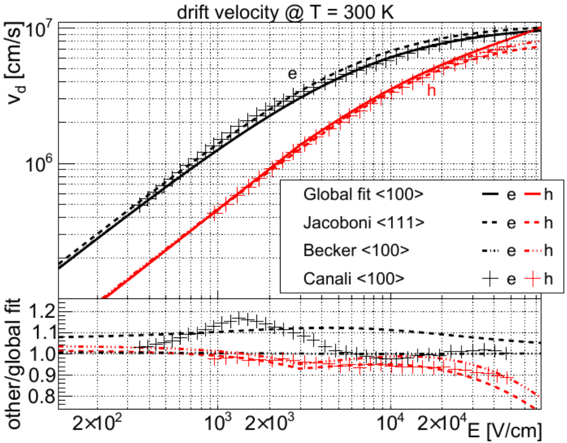
Conclusions

- RD50 groups experts in radiation hard silicon sensors from different experiments
- Both fundamental research and project-driven developments carried out within the collaboration
- Characterization techniques and new sensor structures are developed within the collaboration and together with foundries
- This talk left out many interesting topics: see RD50 website
- FCC-hh tracker requirements: $\Phi_{eq} \approx 6 \cdot 10^{17}\,\text{cm}^{-2}$, track $\sigma_t \approx 5\,\text{ps}$
  $\Rightarrow$ a leap in technology is needed
- The increase in radiation hardness needed for FCC-hh and the time scale are similar to the ones of LHC, HL-LHC
  $\Rightarrow$ now is time to start
- Silicon is a good candidate for tracking and timing at FCC-hh

Backup Material

Drift Velocities in Silicon

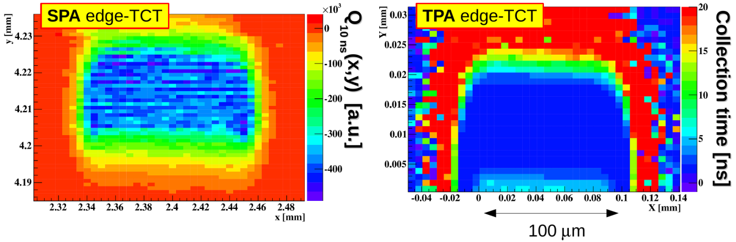
[C. Scharf, JINST 10 C11008]

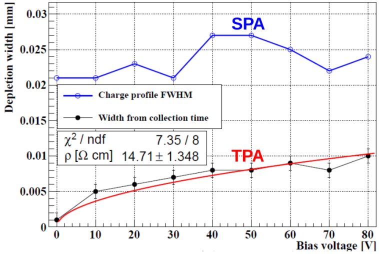


SPA TCT vs TPA TCT

[M. Fernandez Garcia, DT training seminar, 2017]

Single vs Two Photon-TCT





Comparison of SPA and TPA-TCT for an HVCMOS detector

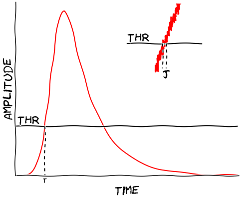
TPA-TCT is a 2016-KT funded project

SPA: 2D spatial resolution
TPA: 3D spatial resolution,
factor 10 improvement in 2D resolution

Time Resolution

$$\sigma_t^2 = \sigma_{\text{jitter}}^2 + \sigma_{\text{time walk}}^2 + \sigma_{\text{Landau noise}}^2 + \sigma_{\text{distortion}}^2 + \sigma_{\text{TDC}}^2$$

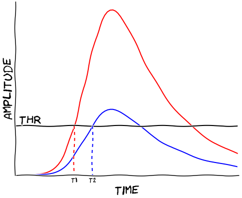
Jitter



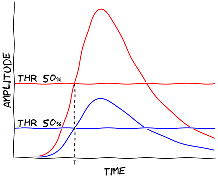
$$\sigma_{\text{jitter}} = \sigma_n / \frac{dV}{dt}$$

Increase $\frac{dV}{dt}$, SNR

Time walk



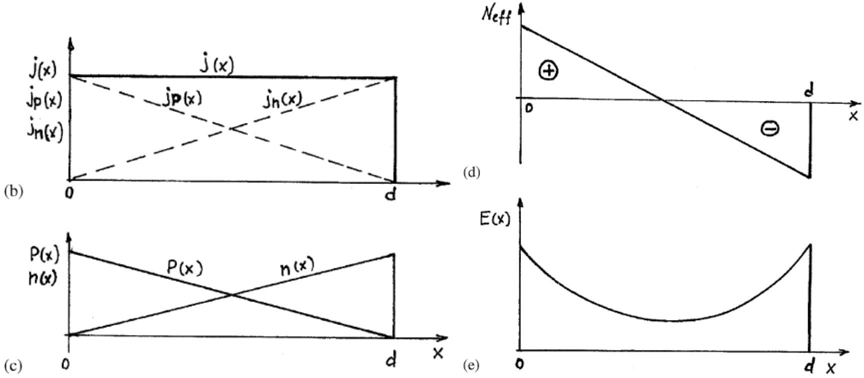
Correct for it, e.g. CFD



- Landau noise: non-uniformity in the energy deposited per unit length
- Distortion: change in signal shape due to detector non-uniformities
- TDC: resolution of the TDC, if no other effects: $\text{bin}/\sqrt{12}$

Double Junction Effect

[V. Eremin, NIM A476 (2002) 556]

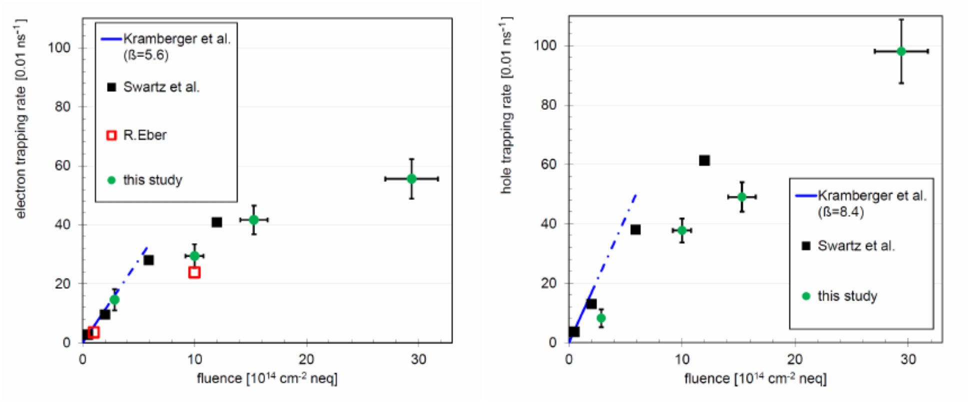


- Trapping of thermally generated carriers
- Modification of space charge
- Double junction

Charge Trapping

$$Q_{e,h}(t) = Q_{e,h}(0)\exp\left(-\frac{t}{\tau_{eff\ e,h}}\right)$$

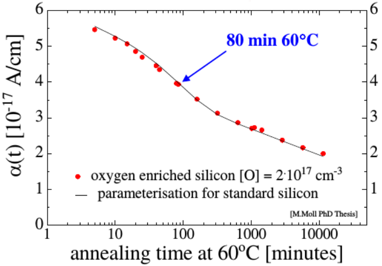
[W. Adam, JINST 11 P04023]



Annealing

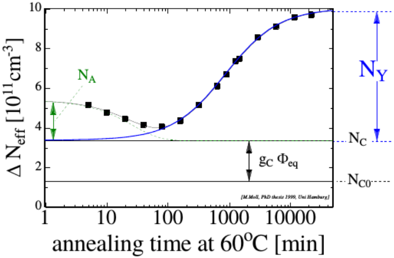
Current generation

[M. Moll, PhD thesis]



Doping concentration

[M. Moll, PhD thesis]



Trapping time

[O. Krasel, PhD thesis]