



TALENT – 2nd Joint Training Event,
CERN, 19.-27. May 2014

Radiation Damage to Silicon Detectors

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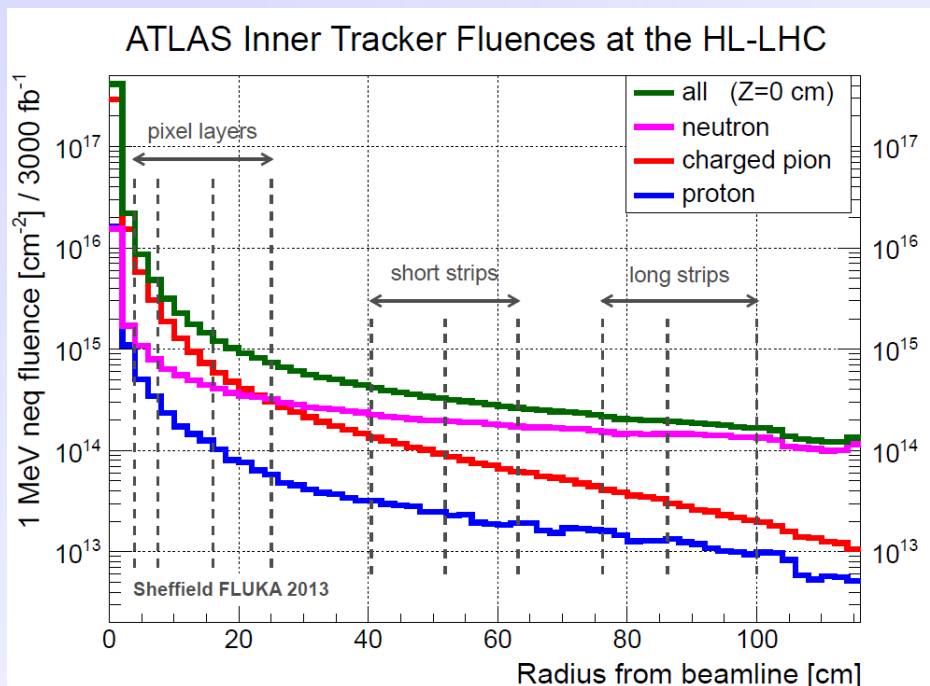
CERN - PH-DT-DD - Solid State Detector Lab - SSD

- **Motivation**
- **I. The Physics of Radiation Damage in Silicon and Silicon Detectors**
 - Microscopic damage to the crystal structure
 - The NIEL (Non Ionizing Energy Loss) concept
 - Radiation induced defects
 - Defect Characterization (Measurement techniques, Defect spectroscopy)
 - Annealing of Radiation Damage (Defect kinetics)
 - Defects: Impact on device performance (Silicon Detectors)
 - The basic radiation damage effects in silicon detectors
- **II. Development of Radiation Tolerant Silicon Detectors**
 - Radiation damage effects in segmented silicon detectors
 - Mitigation techniques and approaches
 - Material engineering
 - Device engineering
 - Charge multiplication

Motivation

... quite obvious for all people working in the ATLAS IBL project.

- **LHC upgrade (and beyond.... FCC, HE-LHC, VHE-LHC)**
 - upgrade of the LHC to the High Luminosity LHC (HL-LHC) after LS3 (2023)
 - expected integrated luminosity: 3000 fb^{-1}



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

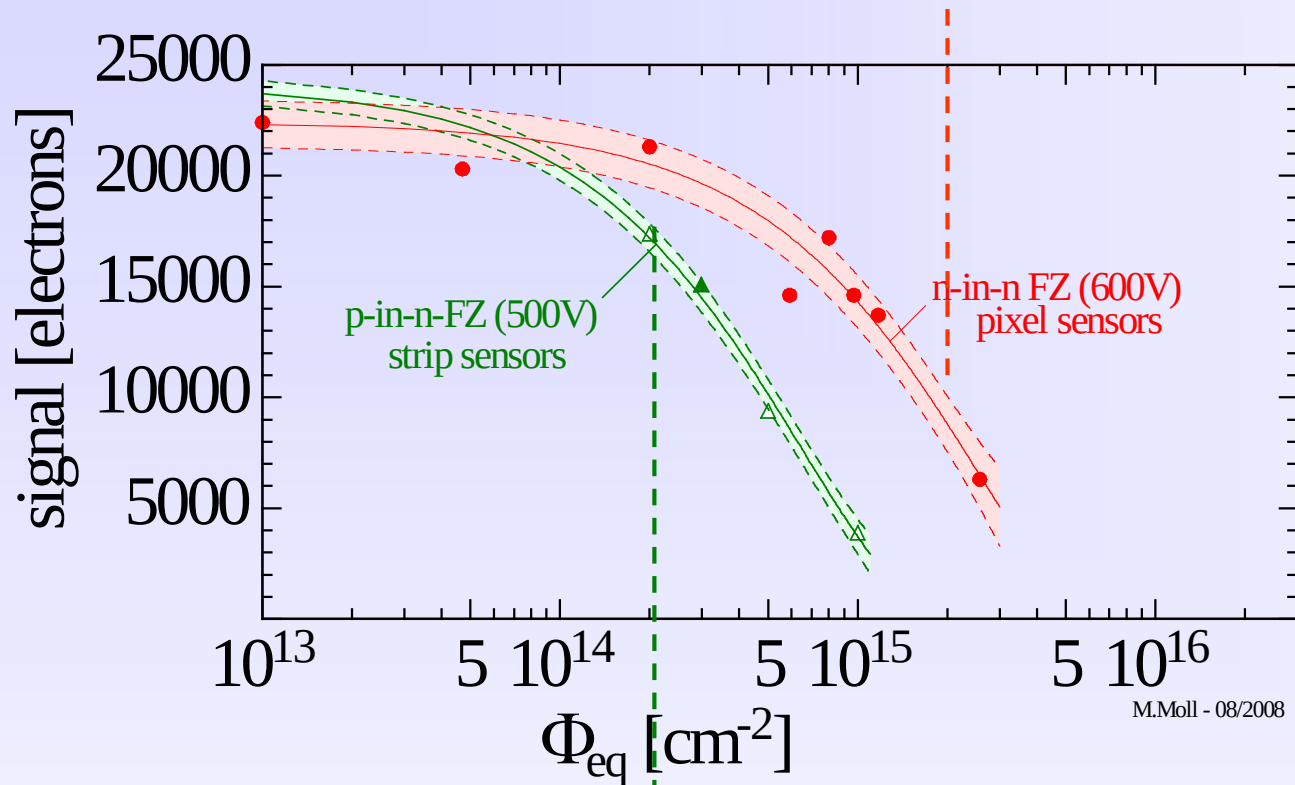
Silicon detectors will be exposed to hadron fluences equivalent to more than 10^{16} n/cm^2

→ detectors used now at LHC cannot operate after such irradiation

RD50 mission: development of silicon sensors for HL-LHC

Pixel sensors:

max. cumulated fluence for LHC



Note: Measured partly under different conditions!
Lines to guide the eye (no modeling)!

FZ Silicon Strip and Pixel Sensors

- n-in-n (FZ), 285μm, 600V, 23 GeV p
- ▲ p-in-n (FZ), 300μm, 500V, 23 GeV p
- △ p-in-n (FZ), 300μm, 500V, neutrons

References:

- [1] p/n-FZ, 300μm, (-30°C, 25ns), strip [Casse 2008]
- [2] n/n-FZ, 285μm, (-10°C, 40ns), pixel [Rohe et al. 2005]

M.Moll - 08/2008

Strip sensors:

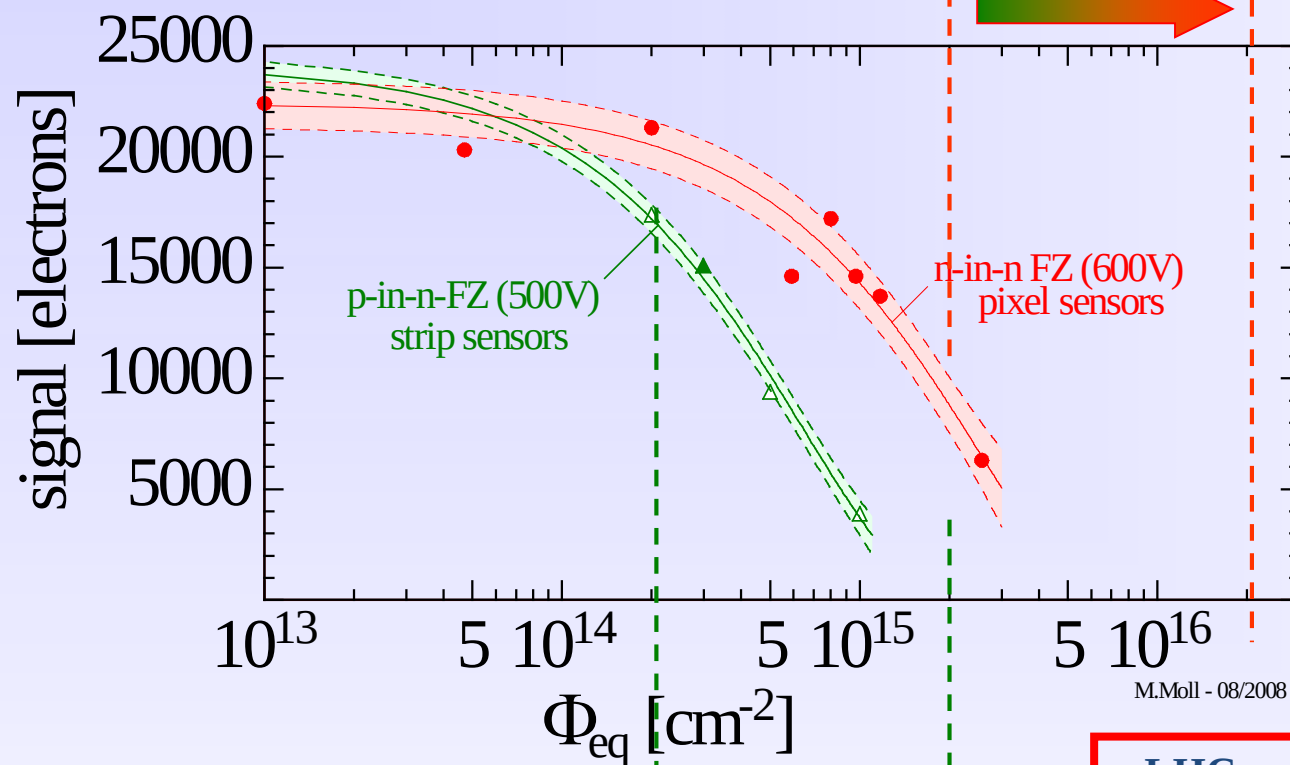
max. cumulated fluence for LHC

Situation in 2005

Pixel sensors:

max. cumulated fluence for **LHC** and **LHC upgrade**

Note: Measured partly under different conditions!
Lines to guide the eye (no modeling)!



FZ Silicon Strip and Pixel Sensors

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M.Moll - 08/2008

Strip sensors:

max. cumulated fluence for **LHC** and **LHC upgrade**

LHC upgrade needs more radiation tolerant tracking detector concepts!

*Boundary conditions & other challenges:
Granularity, Powering, Cooling, Connectivity,
Triggering, Low mass, Low cost!*

- **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)

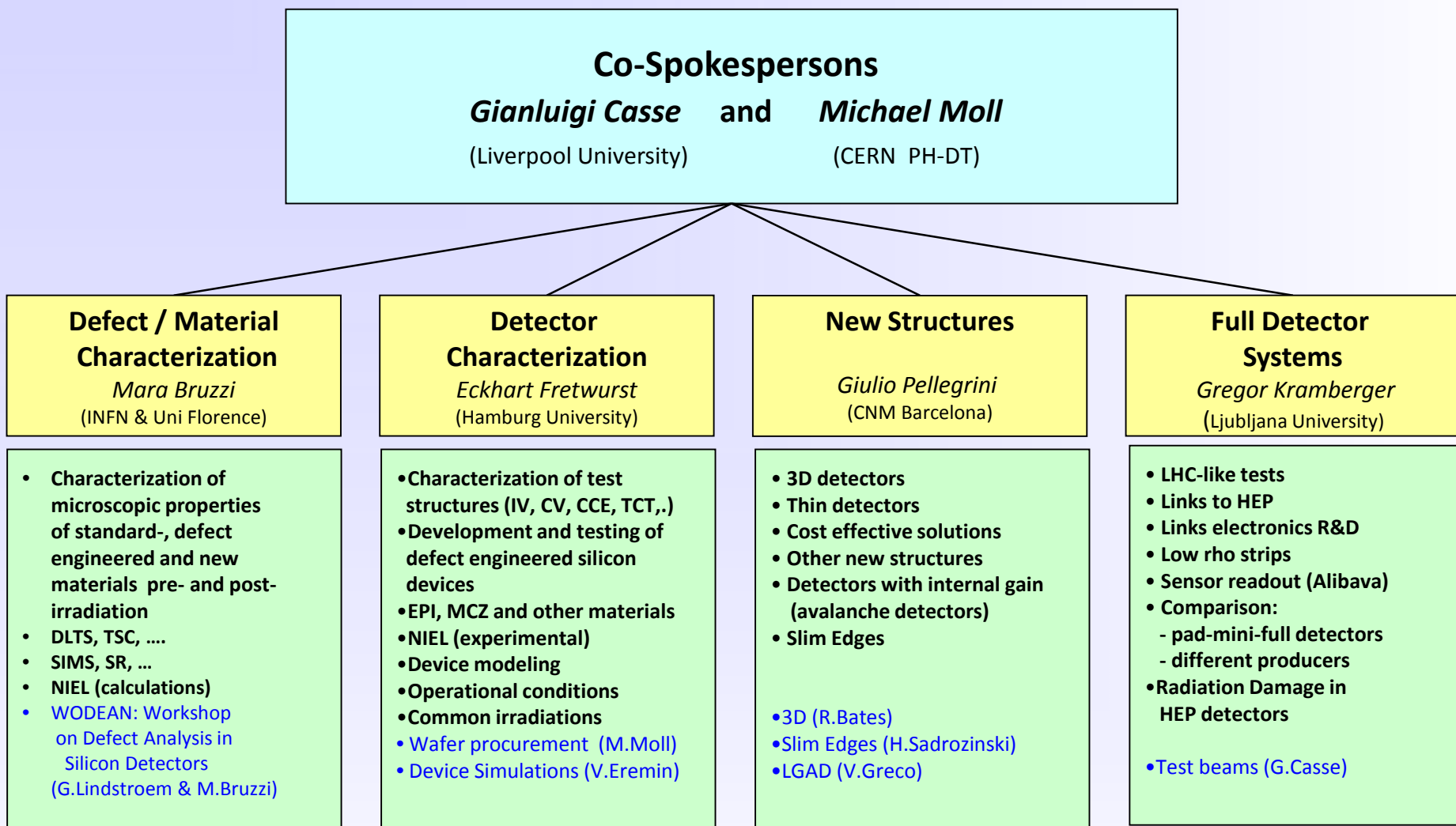
1 Middle East institute

Israel (Tel Aviv)

1 Asian institute

India (Delhi)

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



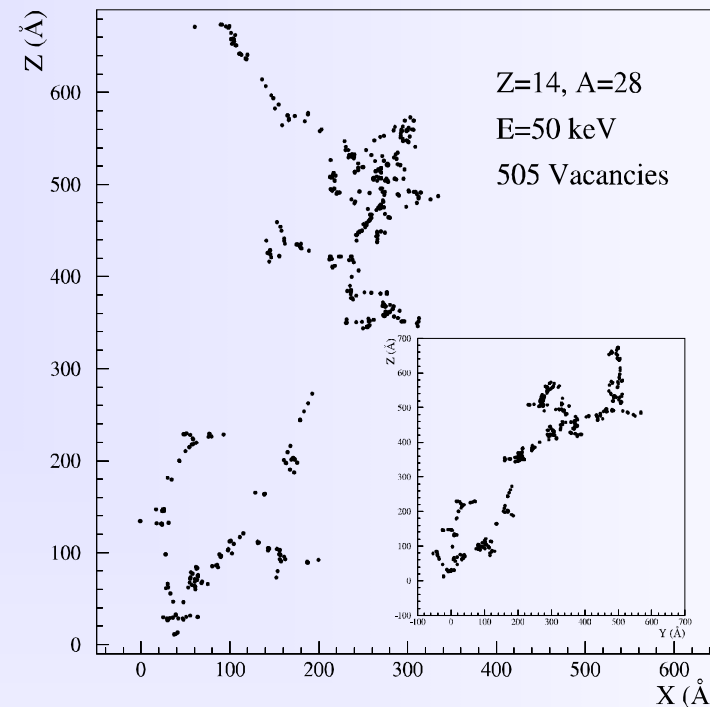
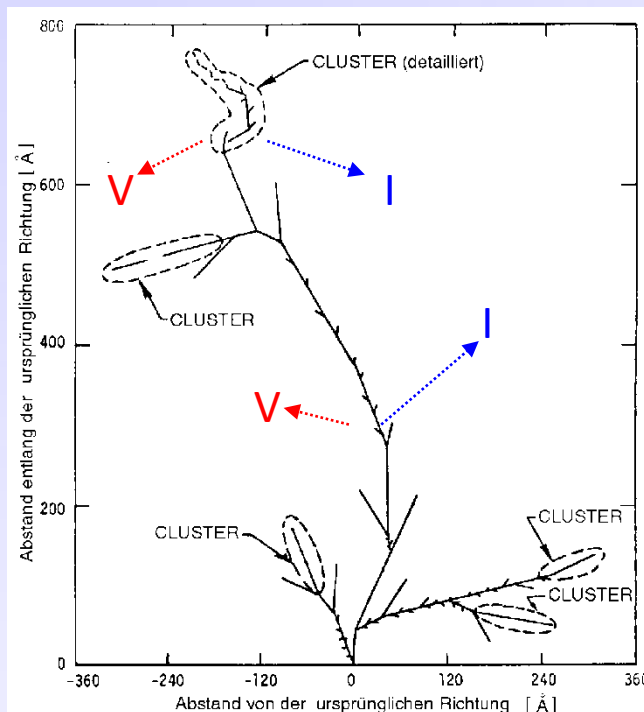
Collaboration Board Chair & Deputy: G.Kramberger (Ljubljana) & J.Vaitkus (Vilnius), Conference committee: U.Parzefall (Freiburg)
CERN contact: M.Moll (PH-DT), Secretary: V.Wedlake (PH-DT), Budget holder & GLIMOS: M.Glaser (PH-DT)

Radiation Damage – Microscopic Defects

- Spatial distribution of vacancies created by a 50 keV Si-ion in silicon.
(typical recoil energy for 1 MeV neutrons)

M.Huhtinen 2001

van Lint 1980

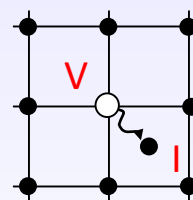


particle

Si_S

$E_K > 25 \text{ eV}$

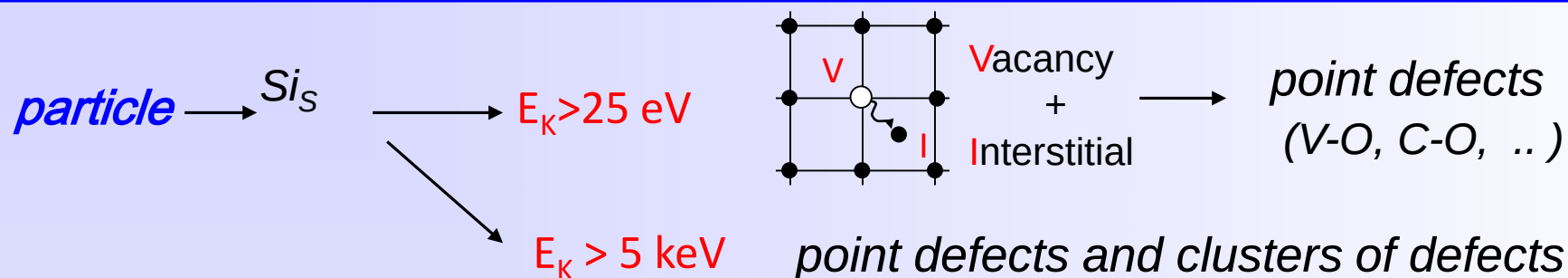
$E_K > 5 \text{ keV}$



Vacancy
+
Interstitial

*point defects
(V-O, C-O, ..)*

point defects and clusters of defects



• ^{60}Co -gammas

- Compton Electrons with max. $E_\gamma \approx 1 \text{ MeV}$ (no cluster production)

• Electrons

- $E_e > 255 \text{ keV}$ for displacement
- $E_e > 8 \text{ MeV}$ for cluster

• Neutrons (elastic scattering)

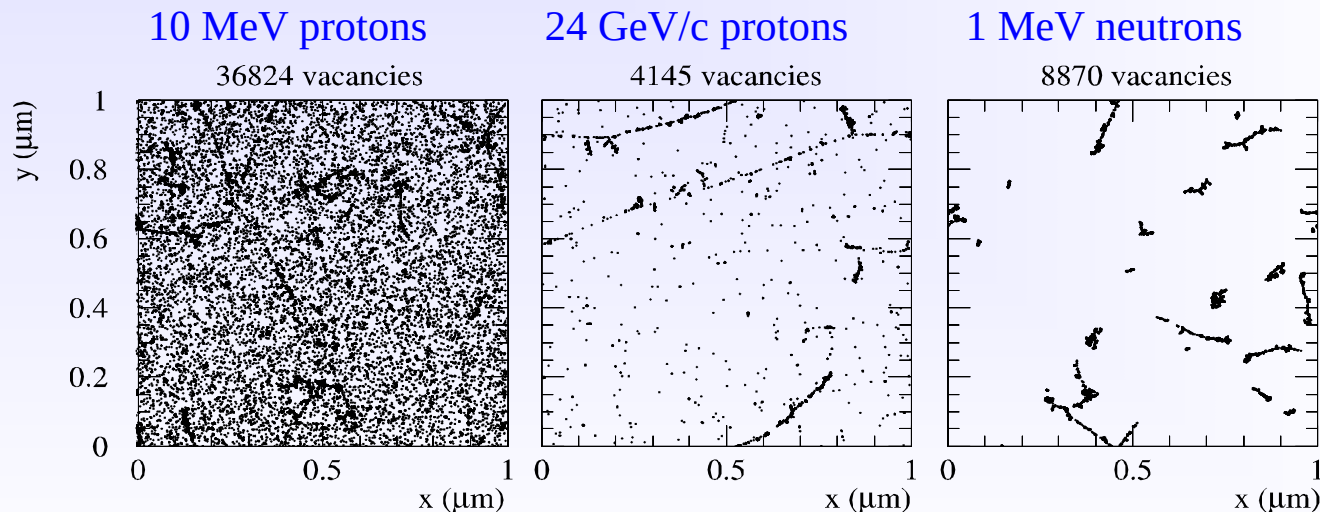
- $E_n > 185 \text{ eV}$ for displacement
- $E_n > 35 \text{ keV}$ for cluster

only point defects $\longleftrightarrow$ point defects & clusters $\longleftrightarrow$ mainly clusters

Simulation:

Initial distribution of vacancies in $(1\mu\text{m})^3$ after $10^{14} \text{ particles/cm}^2$

[Mika Huhtinen NIMA 491(2002) 194]



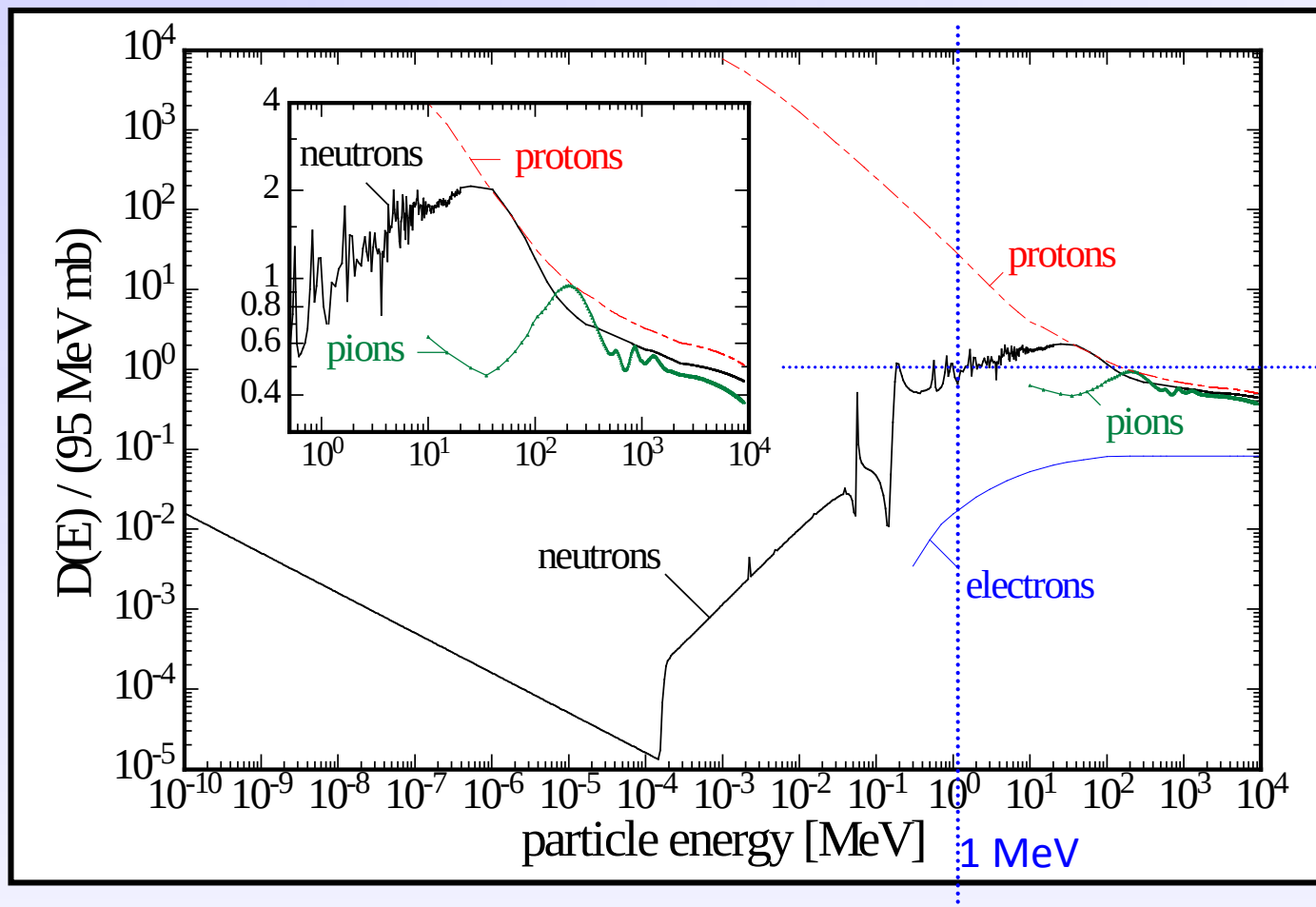
- How to normalize radiation damage arising from different particles?
 - NIEL – Non Ionizing Energy Loss scaling using hardness factor κ of a radiation field (or monoenergetic particle) with respect to 1 MeV neutrons

$$\kappa = \frac{1}{D(1\text{MeV neutrons})} \cdot \frac{\int D(E) \phi(E) dE}{\int \phi(E) dE}$$

- E energy of particle
- $D(E)$ displacement damage cross section for a certain particle at energy E
- $D(1\text{MeV neutrons}) = 95 \text{ MeV}\cdot\text{mb}$
- $\phi(E)$ energy spectrum of the radiation field

The integrals are evaluated for the interval $[E_{\text{MIN}}, E_{\text{MAX}}]$, being E_{MIN} and E_{MAX} the minimum and maximum cut-off energy values, respectively, and covering all particle types present in the radiation field

NIEL – Non Ionizing Energy Loss Displacement damage functions



**1 MeV neutron
equivalent
damage**

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

$$\kappa_p = 0.62 \text{ (24 GeV/c protons)}$$

$$\kappa_p = 1.85 \text{ (26 MeV protons)}$$

$$\kappa_\pi = 1.14 \text{ (300 MeV pions)}$$

$$\kappa_n = 0.92 \text{ (reactor neutrons
>100 keV)}$$

- Hypothesis: Damage parameters scale with the NIEL**

- Be careful, does not hold for all particles & damage parameters (see later)

Defect Characterization

Defect characterization

Aim:

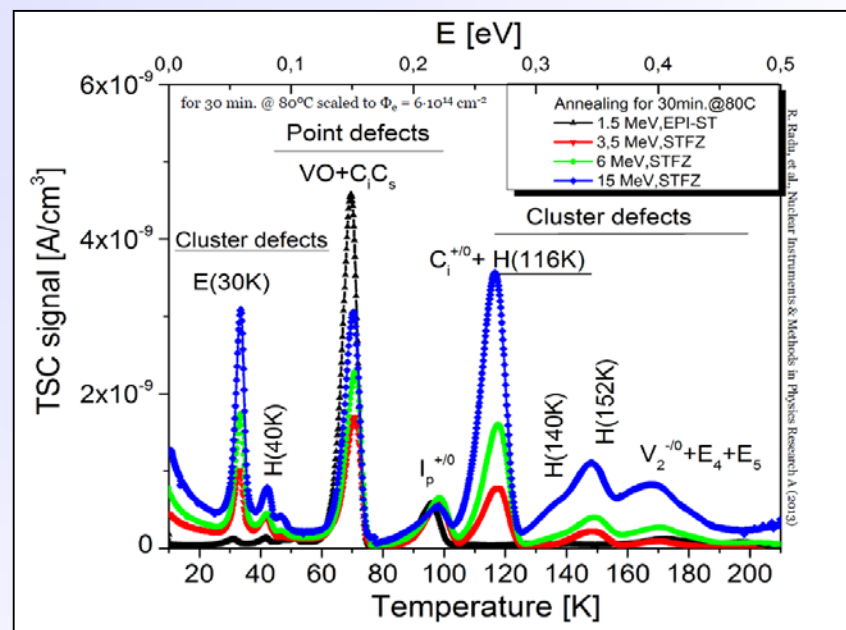
- Identify defects responsible for Trapping, Leakage Current, Change of N_{eff} , Change of E-Field
- Understand if this knowledge can be used to mitigate radiation damage (e.g. defect engineering)
- Deliver input for device simulations to predict detector performance under various conditions

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!

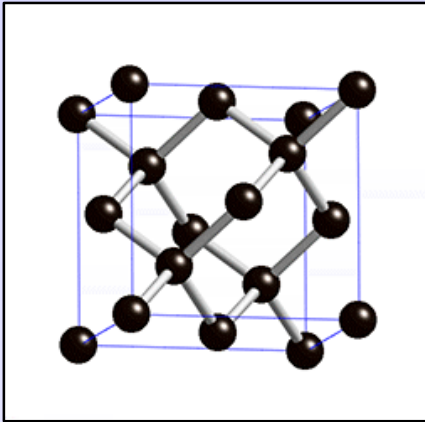


Example: TSC measurement on defects produced by electron irradiation (1.5 to 15 MeV)

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

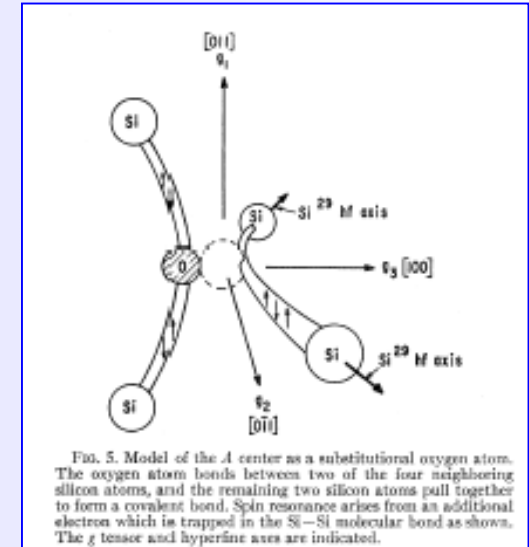
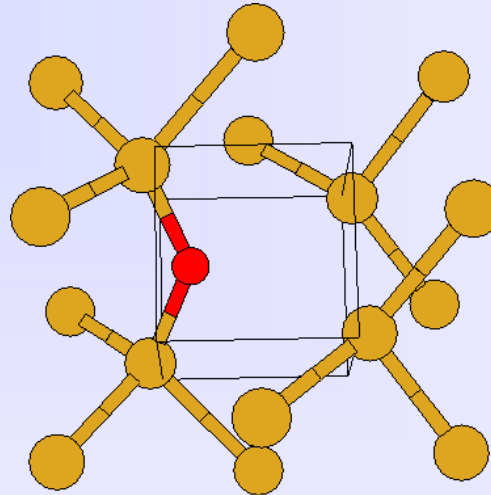
- **Diamond lattice structure**

- FCC – Face Centered Cubic lattice



- **V-O defect (A centre) - Structure**

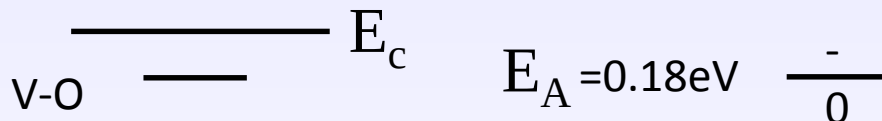
- The dominant centers for vacancy capture in high purity silicon is the isolated oxygen interstitial O_i . Trapping of the vacancy results in the V-O centre, the so called A-centre.



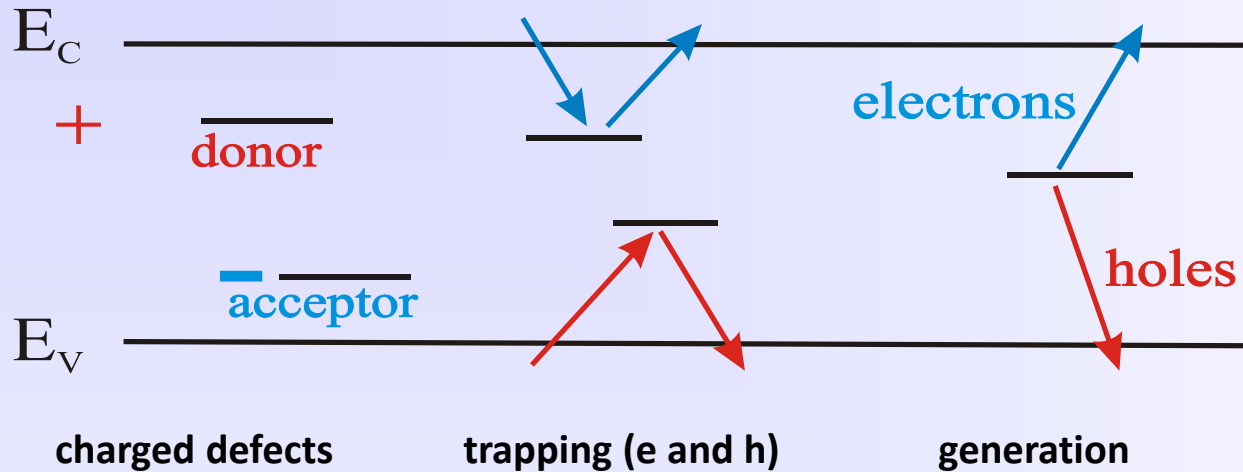
Watkins, Corbett: Phys.Rev.,121,4,
(1961),1001

- **V-O defect (A centre) - Electrical activity**

- The A centre has an acceptor level in the upper half of the band gap.



Shockley-Read-Hall statistics



Impact on detector properties can be calculated if all defect parameters are known:

$\sigma_{n,p}$: cross sections

ΔE : ionization energy

N_t : concentration

- **TSC – Thermally Stimulated Current**

- **Cooling**

- Under bias or without

- **Filling (charge injection)**

- Forward bias, zero bias or light

- **Recording**

- Measure current while ramping up the temperature

- **Peak heights or integral over peak**

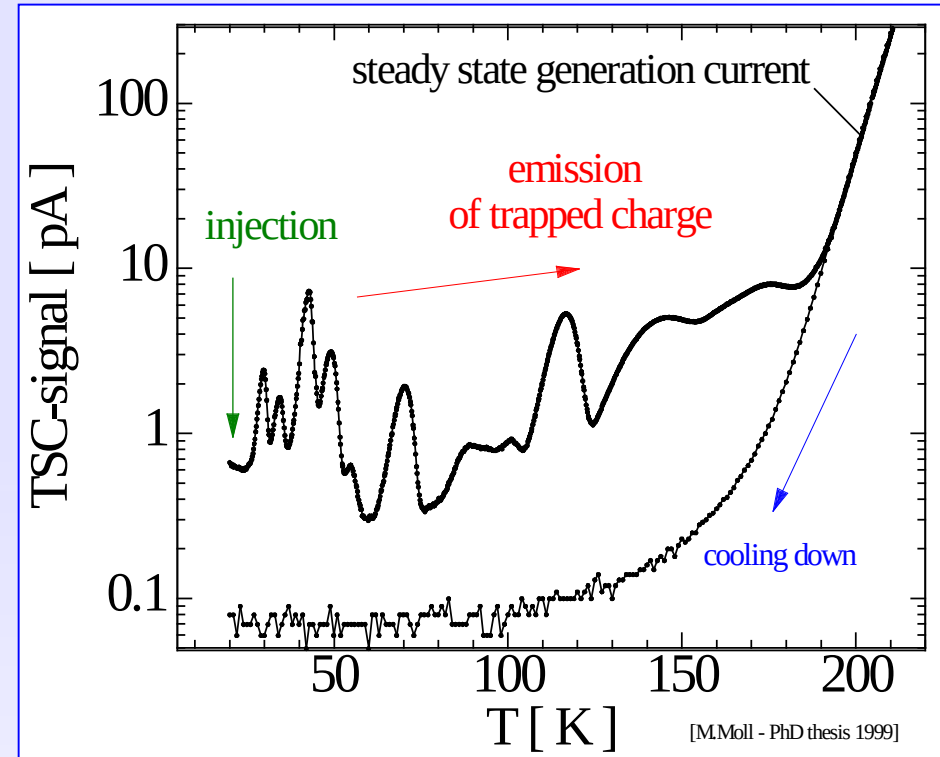
⇒ **Defect concentration**

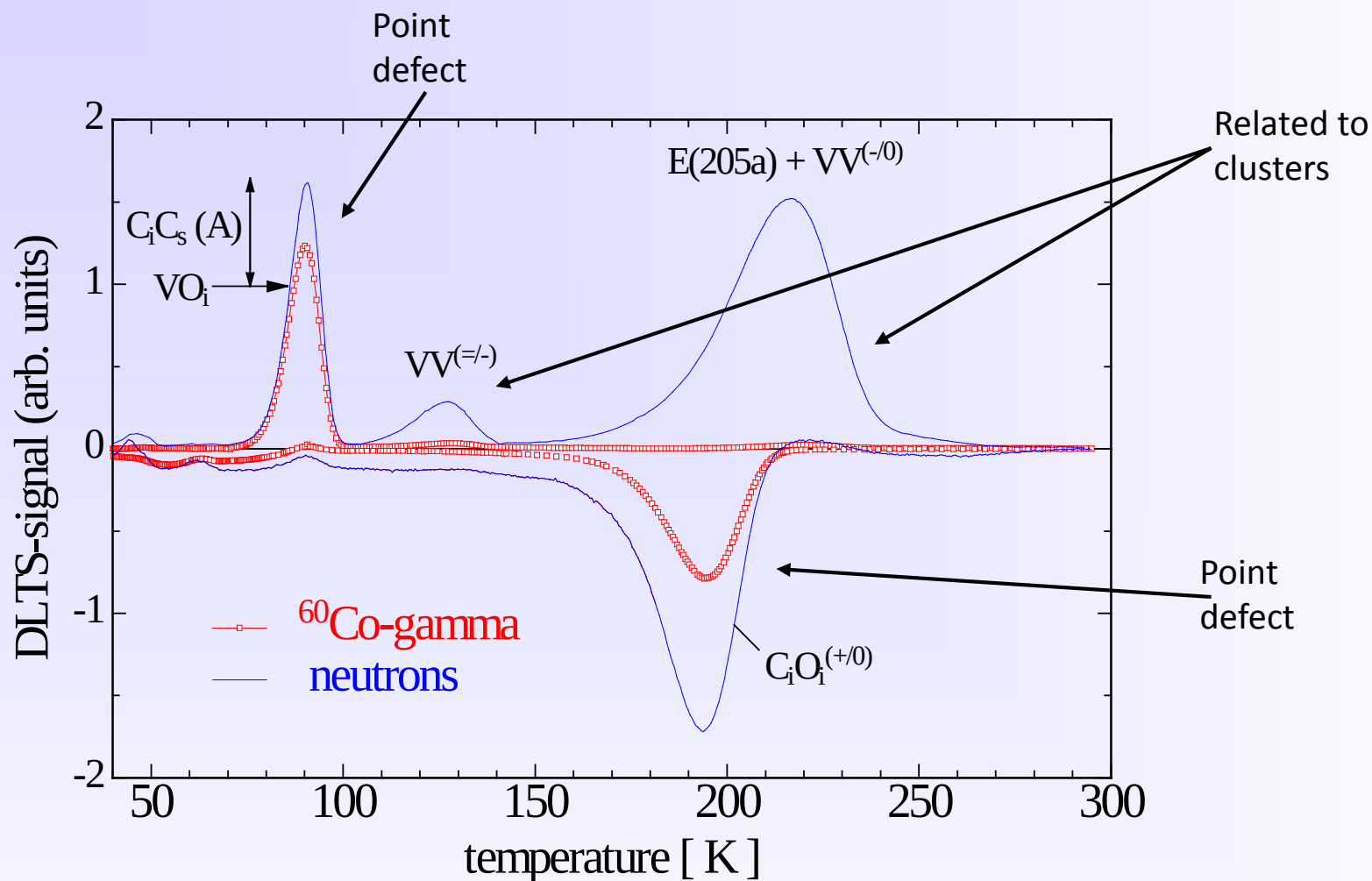
- **Peak position (Peak temperature)**

⇒ **ΔE and cross section**

(requires many measurements)

- **Current:**
$$I_{TSC}(T) = -\frac{1}{2} q \cdot A \cdot N_t \cdot W \cdot e_n(T) \exp\left(-\frac{1}{b} \int_{T_i}^T e_n(T) dT\right)$$

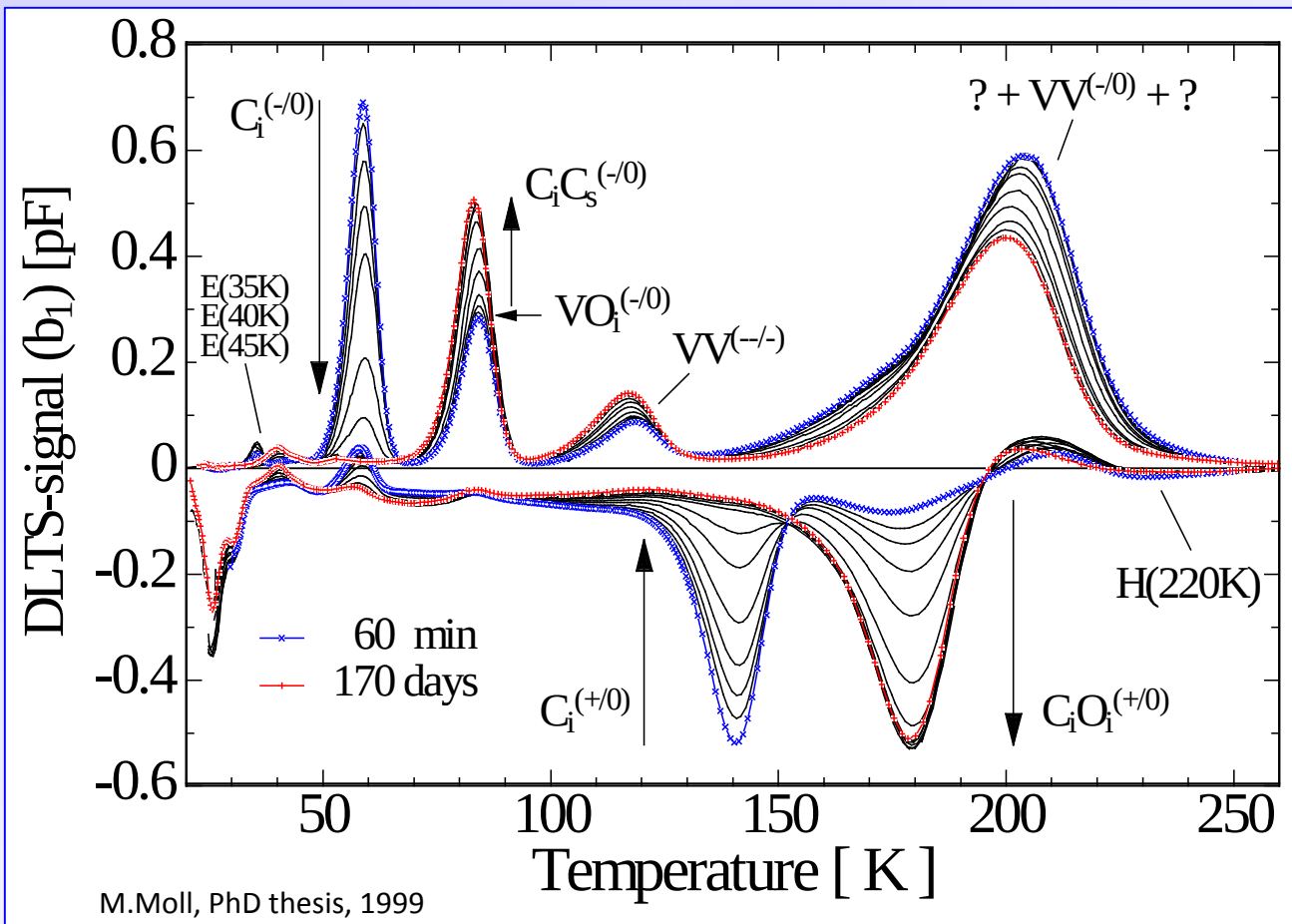




Deep Level Transient Spectroscopy

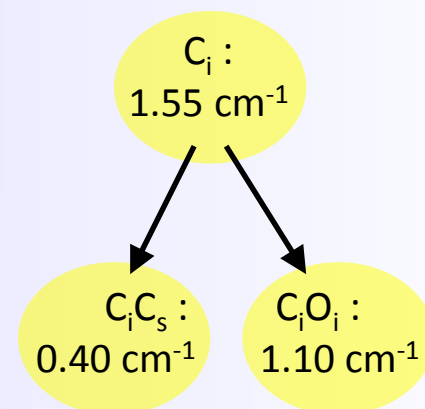
M.Moll, PhD thesis, 1999

Deep Level Transient Spectroscopy



Introduction Rates

$$N_t/\Phi_{eq}$$



example : $\Phi_{eq} = 1 \times 10^{14} \text{ cm}^{-2}$

defects $\approx 1 \times 10^{14} \text{ cm}^{-3}$

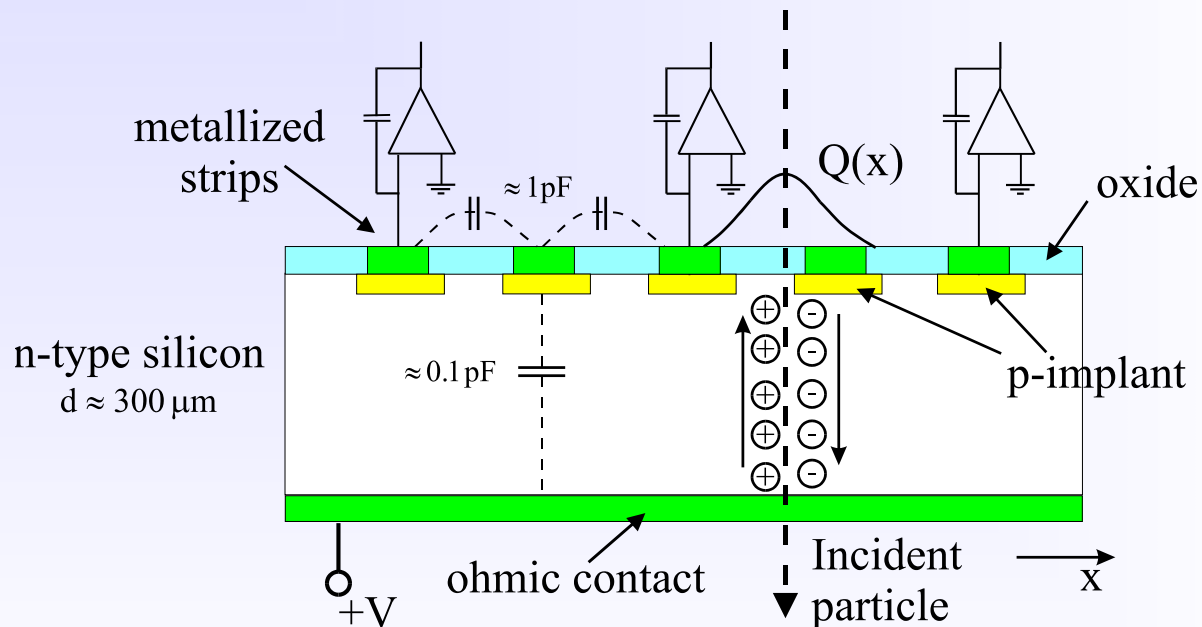
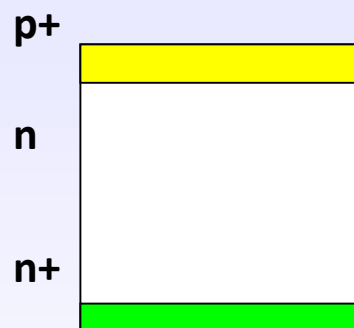
space charge $\approx 5 \times 10^{12} \text{ cm}^{-3}$

- Introduction rates of main defects $\approx 1 \text{ cm}^{-1}$
- Introduction rate of negative space charge $\approx 0.05 \text{ cm}^{-1}$

Impact of Defects on Detector Properties

Reminder: Basic structure of silicon detectors

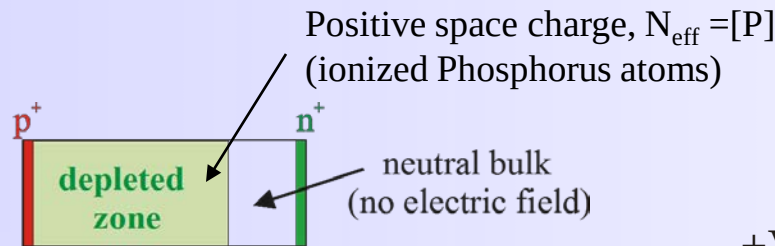
- Detectors are basically **p⁺- n diodes** made on **high resistivity silicon**
- Standard detector grade silicon:
 - Float Zone silicon (FZ)
 - n-type: 2...20 KΩcm
 - [P] = 20...2×10¹¹ cm⁻³ (very low concentration !! below 1ppba = 5×10¹³cm⁻³)
 - [O] ≈ several 10¹⁵cm⁻³
 - [C] ≈ some 10¹⁵cm⁻³, usually [C] < [O]
 - crystal orientation: <111> or <100>



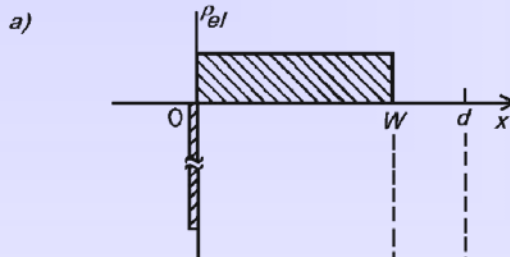
Reminder: Reverse biased abrupt p⁺-n junction

Poisson's equation

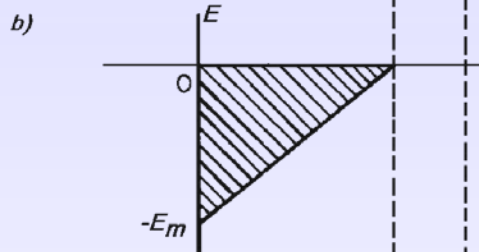
$$-\frac{d^2}{dx^2} \phi(x) = \frac{q_0}{\epsilon \epsilon_0} \cdot N_{eff}$$



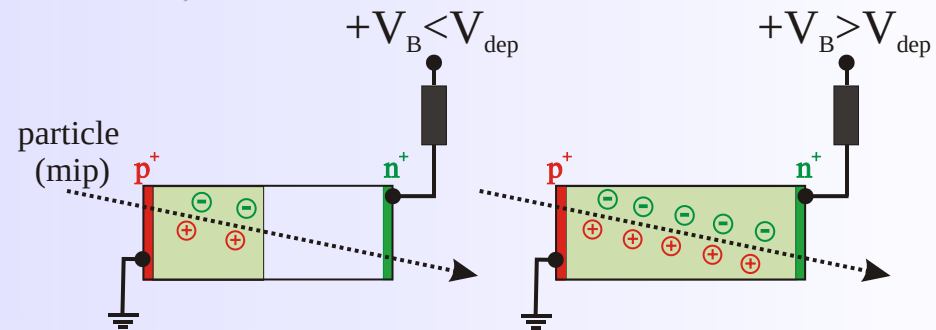
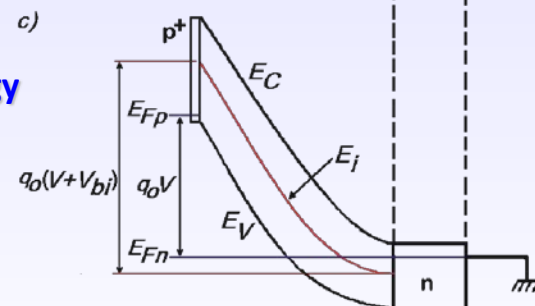
Electrical
charge density



Electrical
field strength



Electron
potential energy



Full charge collection only for $V_B > V_{dep}$!

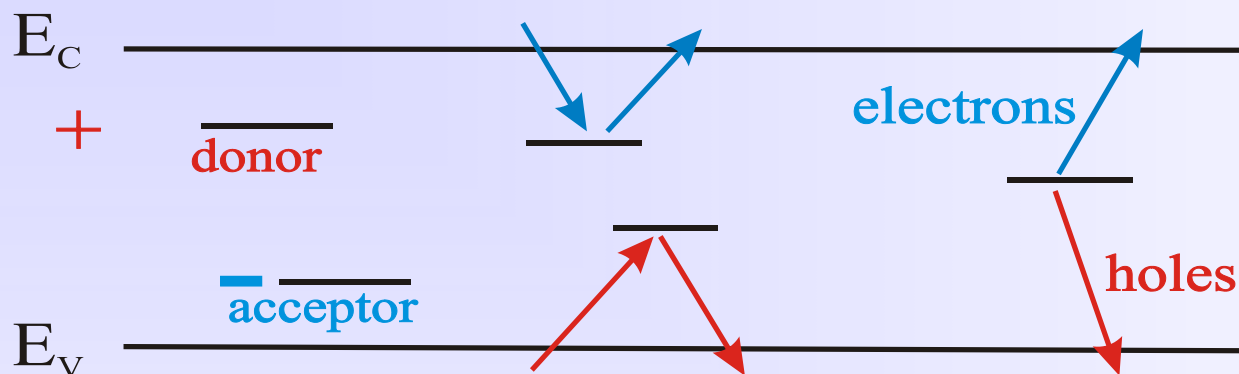
depletion voltage

$$V_{dep} = \frac{q_0}{\epsilon \epsilon_0} \cdot |N_{eff}| \cdot d^2$$

effective space charge density

Impact of Defects on Detector Properties

Shockley-Read-Hall statistics



charged defects
 $\Rightarrow N_{\text{eff}}, V_{\text{dep}}$
 e.g. donors in upper
 and acceptors in lower
 half of band gap

Trapping (e and h)
 $\Rightarrow \text{CCE}$
 shallow defects do not
 contribute at room
 temperature due to fast
 detrapping

generation
 $\Rightarrow \text{leakage current}$
 Levels close to midgap
 most effective

Impact on detector properties can be calculated if all defect parameters are known:

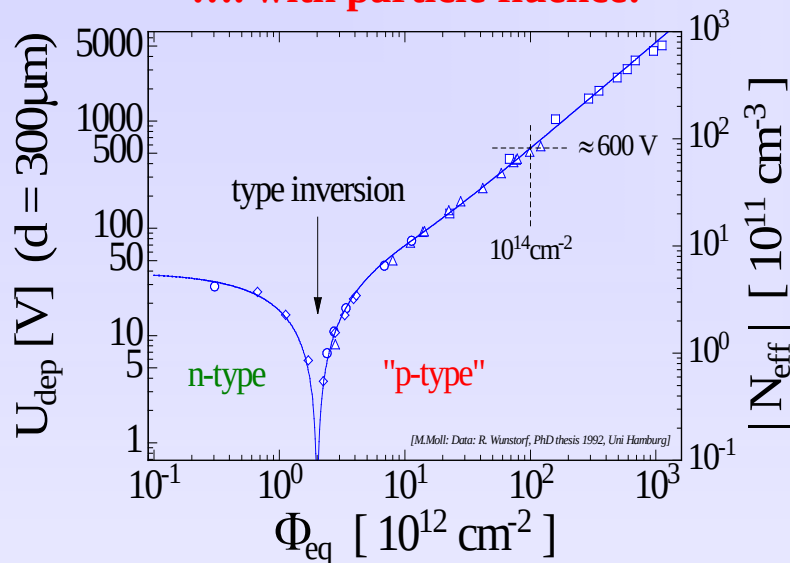
$\sigma_{n,p}$: cross sections

ΔE : ionization energy

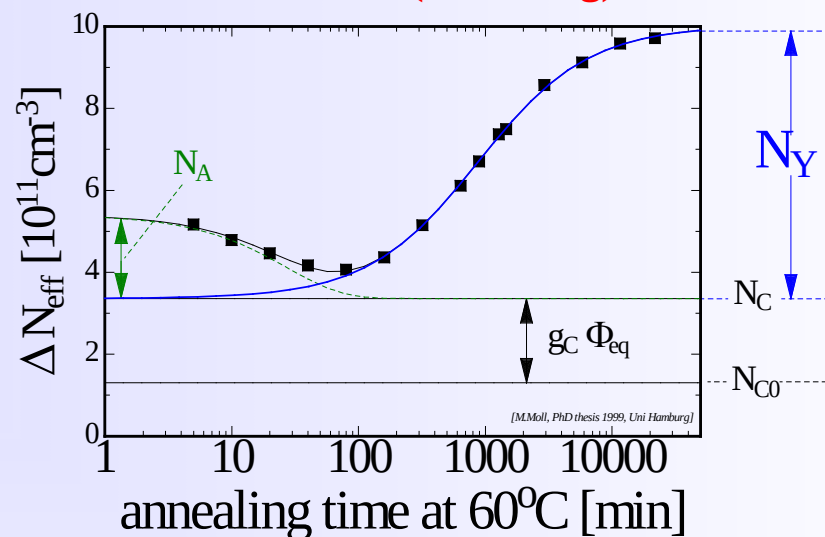
N_t : concentration

Change of Depletion Voltage V_{dep} (N_{eff})

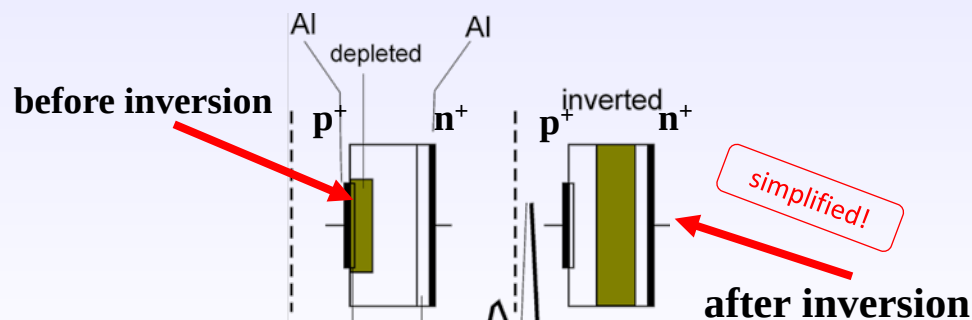
.... with particle fluence:



.... with time (annealing):



- “**Type inversion**”: N_{eff} changes from positive to negative (Space Charge Sign Inversion)

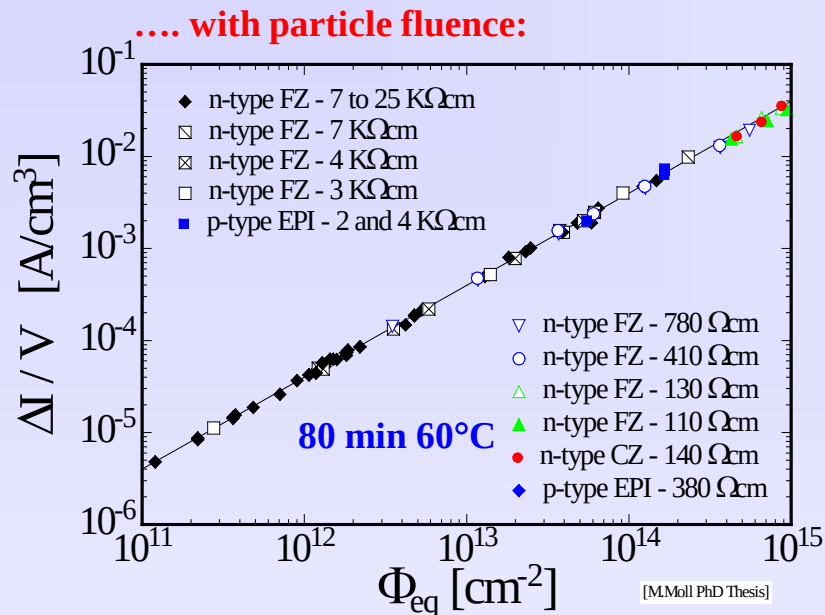


- Short term: “**Beneficial annealing**”
- Long term: “**Reverse annealing**”
- time constant depends on temperature:
 - ~ 500 years (-10°C)
 - ~ 500 days (20°C)
 - ~ 21 hours (60°C)

- Consequence: **Detectors must be cooled even when the experiment is not running!**

not for n-readout?!

Change of Leakage Current (after hadron irradiation)

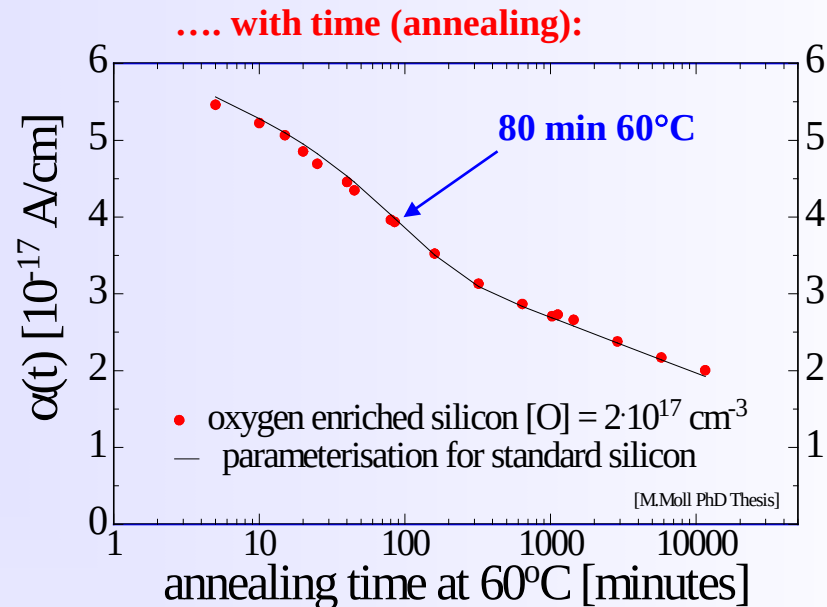


- Damage parameter α (slope in figure)

$$\alpha = \frac{\Delta I}{V \cdot \Phi_{eq}}$$

Leakage current
per unit volume
and particle fluence

- α is constant over several orders of fluence and independent of impurity concentration in Si
⇒ can be used for fluence measurement



- Leakage current decreasing in time (depending on temperature)
- Strong temperature dependence

$$I \propto \exp\left(-\frac{E_A}{2k_B T}\right) \quad E_A = 1.21 \text{ eV}$$

Consequence:

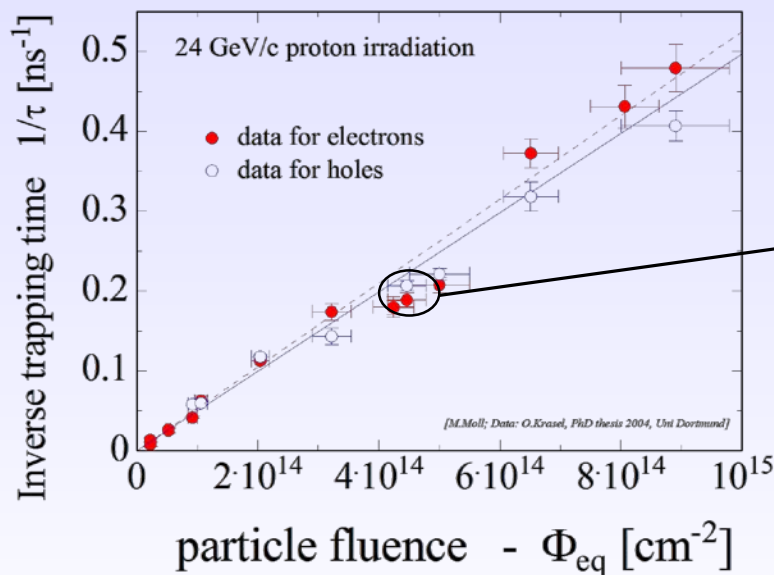
Cool detectors during operation!
Example: $I(-10^\circ\text{C}) \sim 1/16 I(20^\circ\text{C})$

■ Deterioration of Charge Collection Efficiency (CCE) by trapping

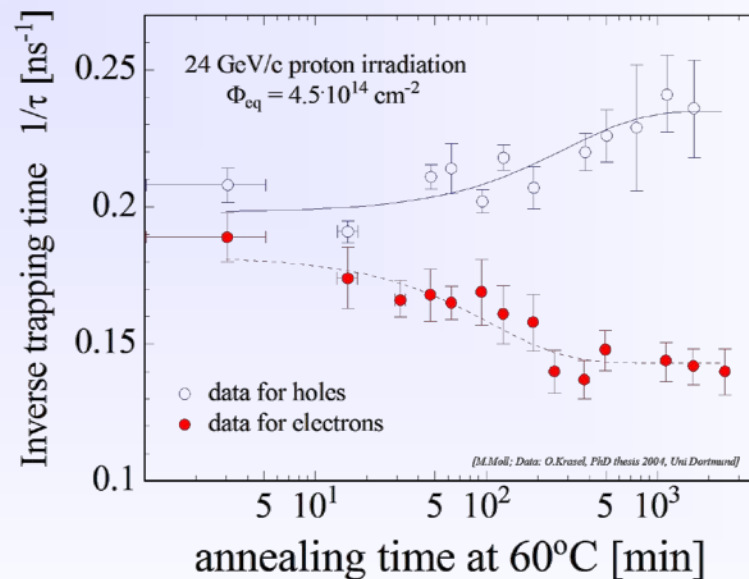
Trapping is characterized by an effective trapping time τ_{eff} for electrons and holes:

$$Q_{e,h}(t) = Q_{0e,h} \exp\left(-\frac{1}{\tau_{\text{eff } e,h}} \cdot t\right) \quad \text{where} \quad \frac{1}{\tau_{\text{eff } e,h}} \propto N_{\text{defects}}$$

Increase of inverse trapping time ($1/\tau$) with fluence



..... and change with time (annealing):



Summary: Radiation Damage in Silicon Sensors

■ Two general types of radiation damage to the detector materials:

• Bulk (Crystal) damage due to Non Ionizing Energy Loss (NIEL)

- displacement damage, built up of crystal defects –

Influenced
by impurities
in Si – Defect
Engineering
is possible!

I. Change of **effective doping concentration** (higher depletion voltage,
under- depletion)

II. Increase of **leakage current** (increase of shot noise, thermal runaway)

III. Increase of **charge carrier trapping** (loss of charge)

Same for
all tested
Silicon
materials!

• Surface damage due to Ionizing Energy Loss (IEL)

- accumulation of positive in the oxide (SiO_2) and the Si/ SiO_2 interface –
affects: interstrip capacitance (noise factor), breakdown behavior, ...

■ Impact on detector performance and Charge Collection Efficiency (depending on detector type and geometry and readout electronics!)

Signal/noise ratio is the quantity to watch

⇒ Sensors can fail from radiation damage !

Can be
optimized!

Mitigation of radiation damage

Scientific strategies:

- I. Material engineering
- II. Device engineering
- III. Change of detector operational conditions

CERN-RD39
“Cryogenic Tracking Detectors”
operation at 100-200K
to reduce charge loss

• Defect Engineering of Silicon

Deliberate incorporation of impurities or defects into the silicon bulk to improve radiation tolerance of detectors

- **Needs:** Profound understanding of radiation damage
 - microscopic defects, macroscopic parameters
 - dependence on particle type and energy
 - defect formation kinetics and annealing
- **Examples:**
 - Oxygen rich Silicon (DOFZ, Cz, MCZ, EPI)
 - Oxygen dimer & hydrogen enriched Si
 - Pre-irradiated Si
 - Influence of processing technology

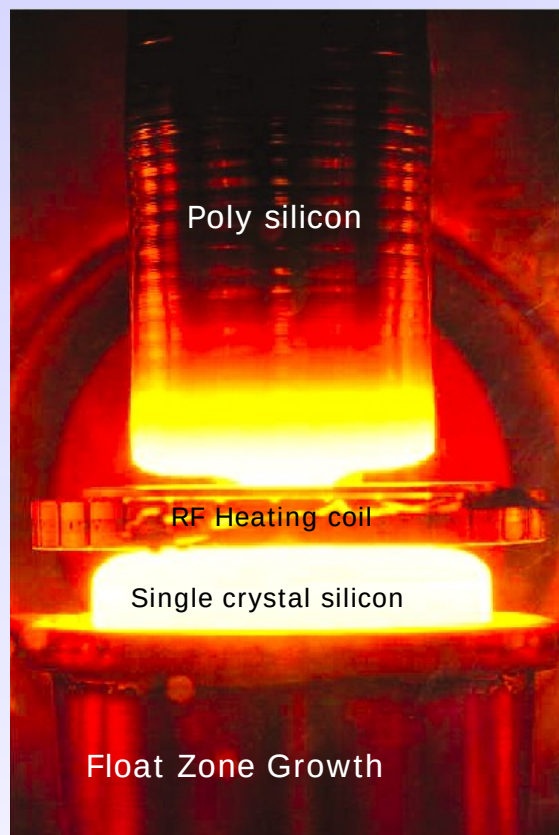
• New Materials

- Silicon Carbide (SiC), Gallium Nitride (GaN)
- **Diamond** (CERN RD42 Collaboration)
- Amorphous silicon, Gallium Arsenide

• Device Engineering (New Detector Designs)

- p-type silicon detectors (n-in-p)
- thin detectors, epitaxial detectors
- 3D detectors and Semi 3D detectors, Stripixels
- Cost effective detectors
- Monolithic devices

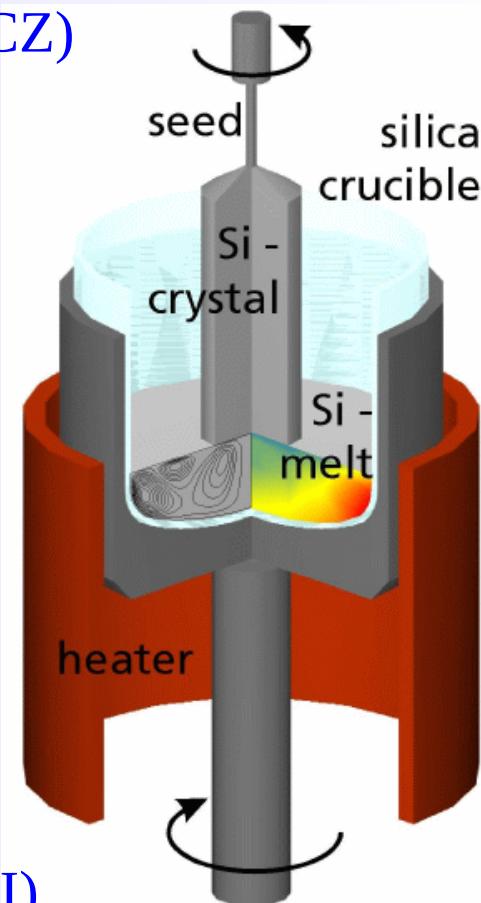
• Floating Zone Silicon (FZ)



- Basically all silicon tracking detectors made out of FZ silicon
- Some pixel sensors out of DOFZ Diffusion Oxygenated FZ silicon

• Czochralski Silicon (CZ)

- The growth method used by the IC industry.
- Difficult to produce very high resistivity



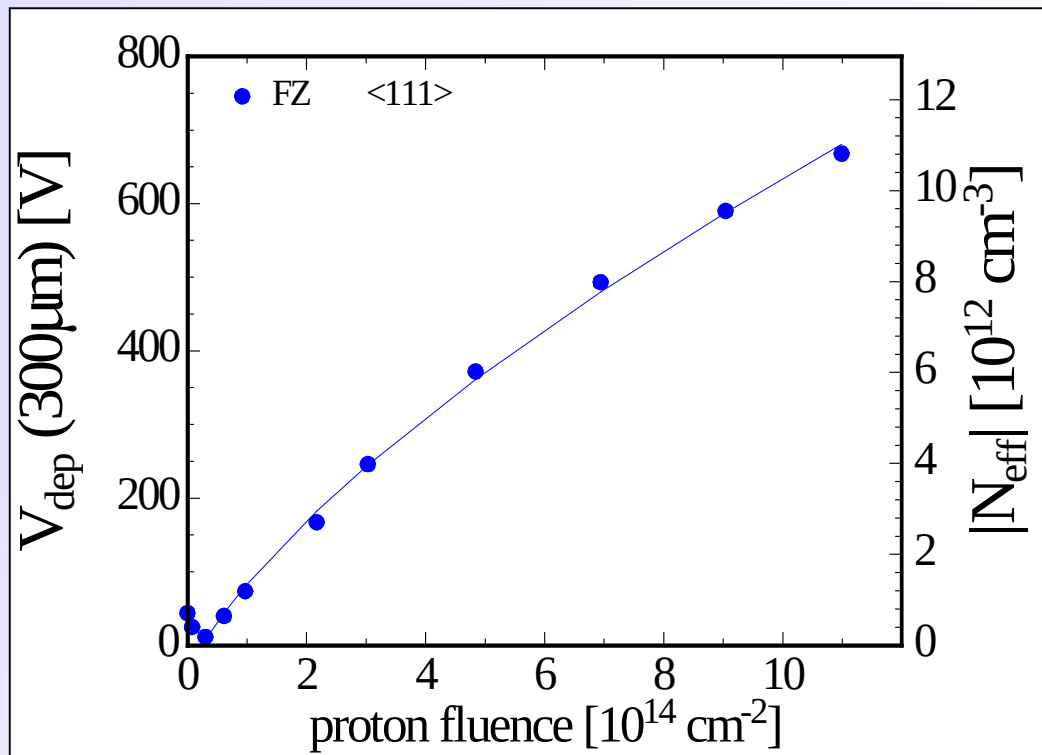
• Epitaxial Silicon (EPI)

- Chemical-Vapor Deposition (CVD) of Si
- up to 150 μm thick layers produced
- growth rate about 1 $\mu\text{m}/\text{min}$

24 GeV/c proton irradiation

• Standard FZ silicon

- type inversion at $\sim 2 \times 10^{13} \text{ p/cm}^2$
- strong N_{eff} increase at high fluence



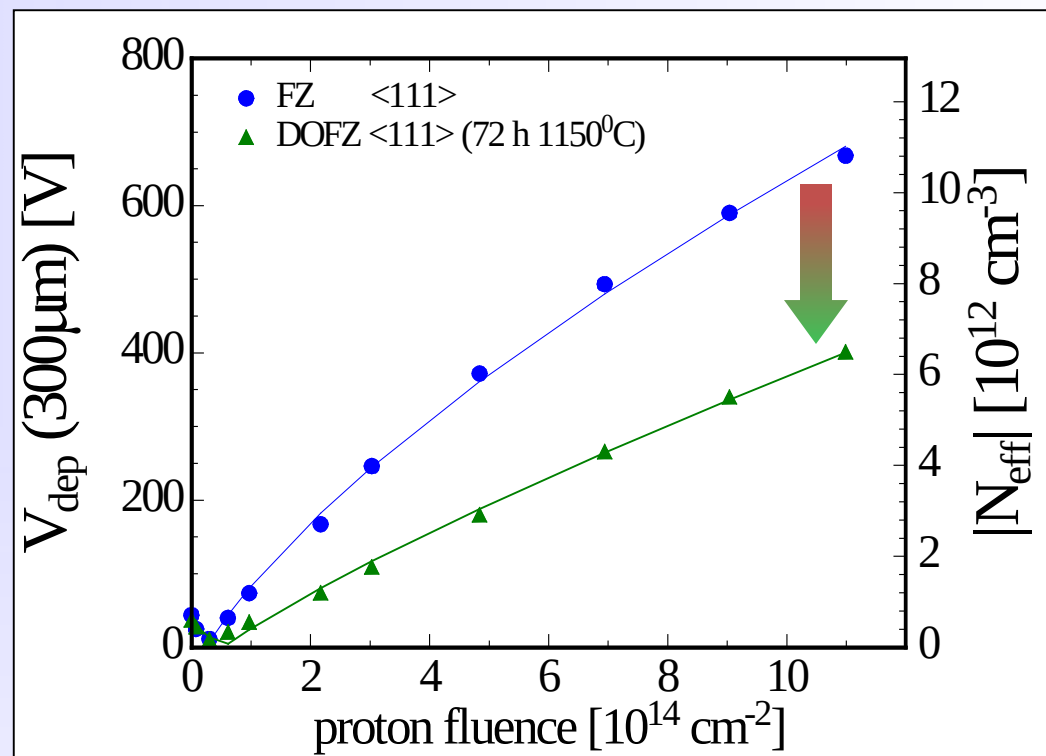
24 GeV/c proton irradiation

• Standard FZ silicon

- type inversion at $\sim 2 \times 10^{13} \text{ p/cm}^2$
- strong N_{eff} increase at high fluence

• Oxygenated FZ (DOFZ)

- type inversion at $\sim 2 \times 10^{13} \text{ p/cm}^2$
- reduced N_{eff} increase at high fluence



24 GeV/c proton irradiation

• Standard FZ silicon

- type inversion at $\sim 2 \times 10^{13}$ p/cm²
- strong N_{eff} increase at high fluence

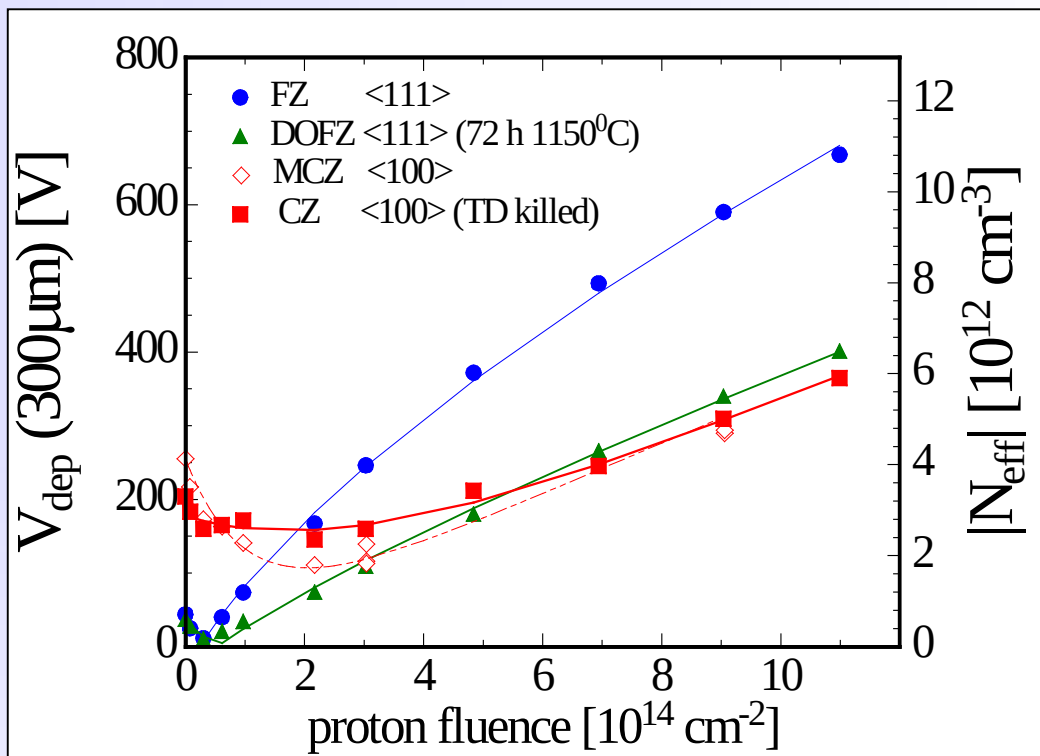
• Oxygenated FZ (DOFZ)

- type inversion at $\sim 2 \times 10^{13}$ p/cm²
- reduced N_{eff} increase at high fluence

• CZ silicon and MCZ silicon

- “no type inversion” in the overall fluence range

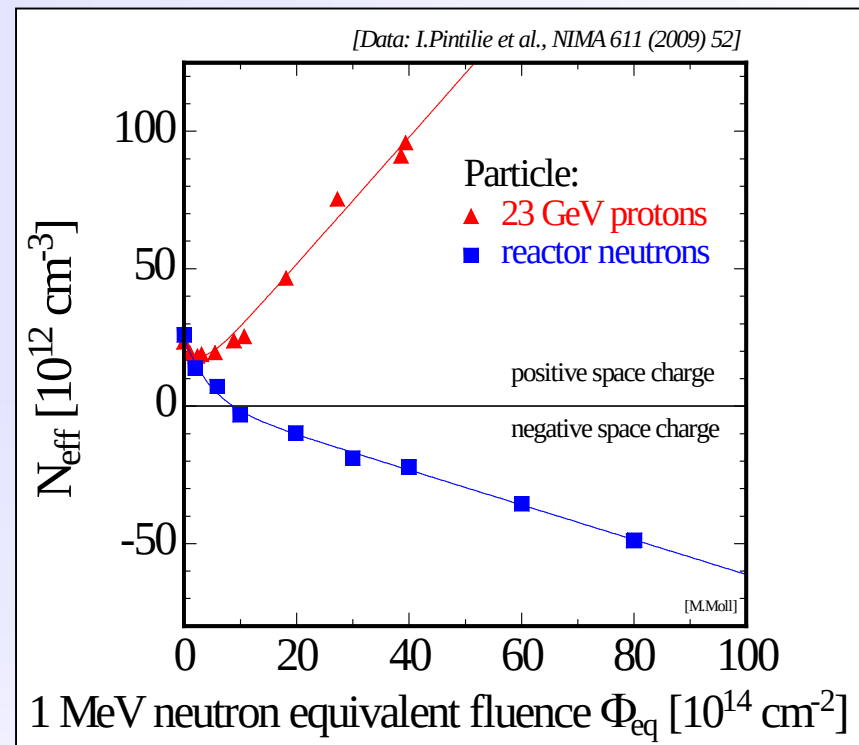
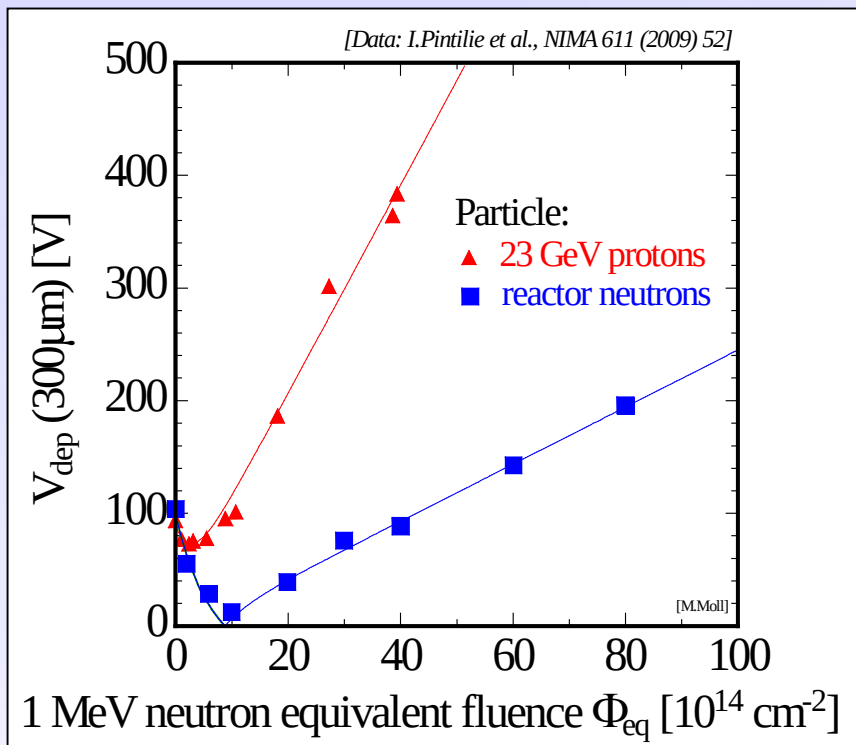
(for experts: there is no “real” type inversion, a more clear understanding of the observed effects is obtained by investigating directly the internal electric field; look for: TCT, MCZ, double junction)



• Common to all materials *(after hadron irradiation, not after γ irradiation):*

- reverse current increase
- increase of trapping (electrons and holes) within $\sim 20\%$

- **Epitaxial silicon** (*EPI-DO*, 72 μm , 170 Ωcm , diodes)
irradiated with **23 GeV protons** or **reactor neutrons**

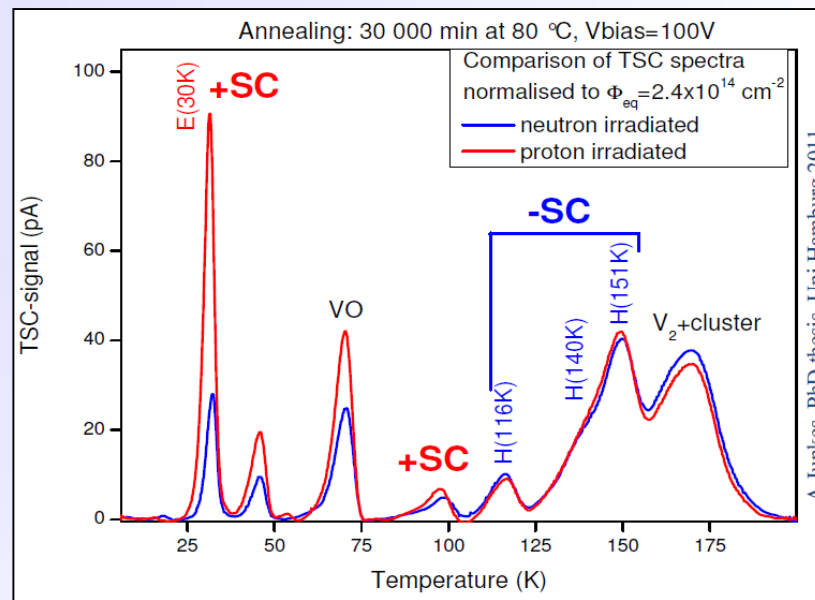
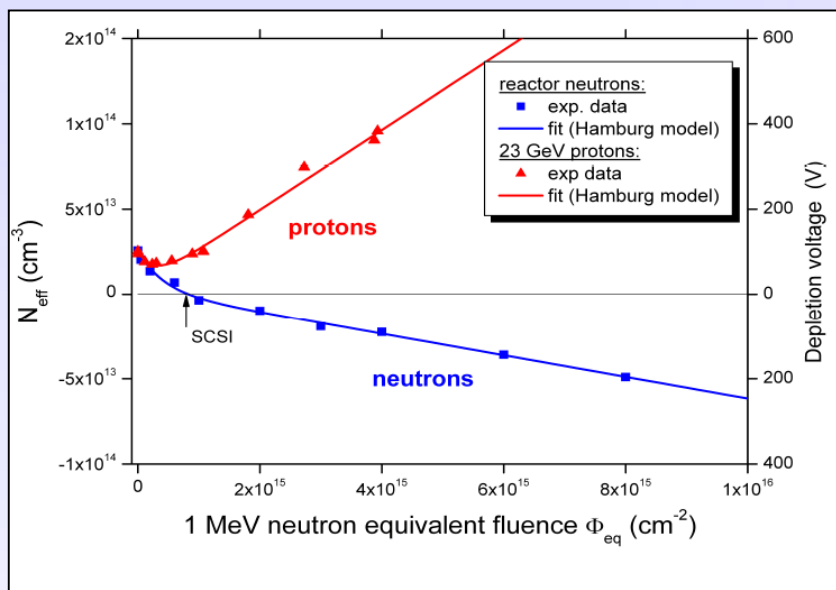


depletion voltage →

$$V_{\text{dep}} = \frac{q_0}{\epsilon \epsilon_0} \cdot |N_{\text{eff}}| \cdot d^2$$

← absolute effective
space charge density

- **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, $72\mu\text{m}$, $170\Omega\text{cm}$) irradiated with **23 GeV protons** or **reactor neutrons**



- **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)

Summary on defects with strong impact on device performance after irradiation

Some identified defects

Phosphorus: shallow dopant
(positive charge)

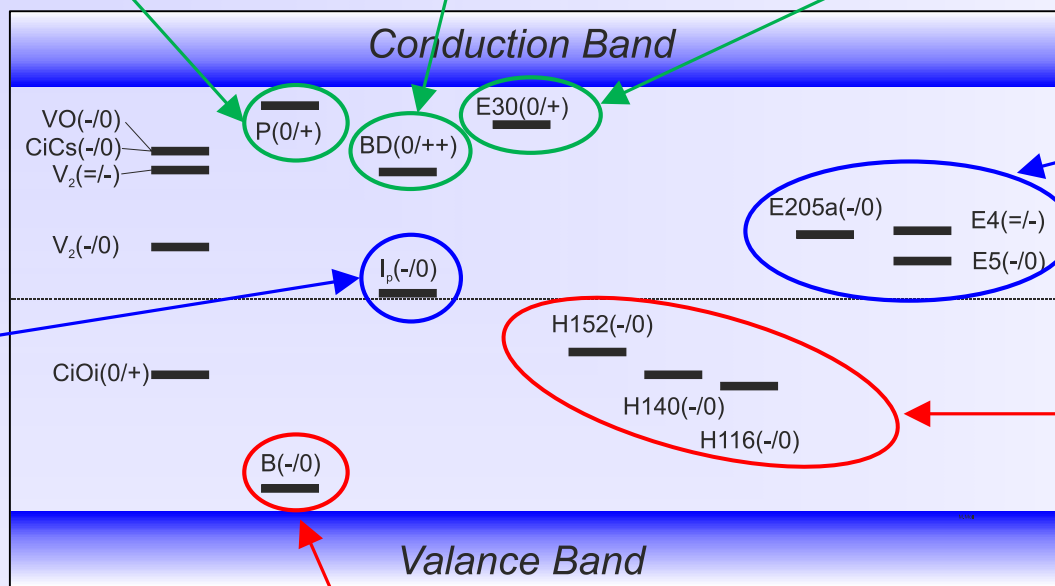
positive charge
(higher introduction after
proton than after neutron
irradiation, oxygen dependent)

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

leakage current
& neg. charge
current after γ irrad,
 V_2O (?)

Leakage
current
E4/E5: V_3 (?)

Reverse
annealing
(negative charge)



Boron: shallow dopant
(negative charge)

A table with levels and cross sections is given
in the next slide (spare slide).

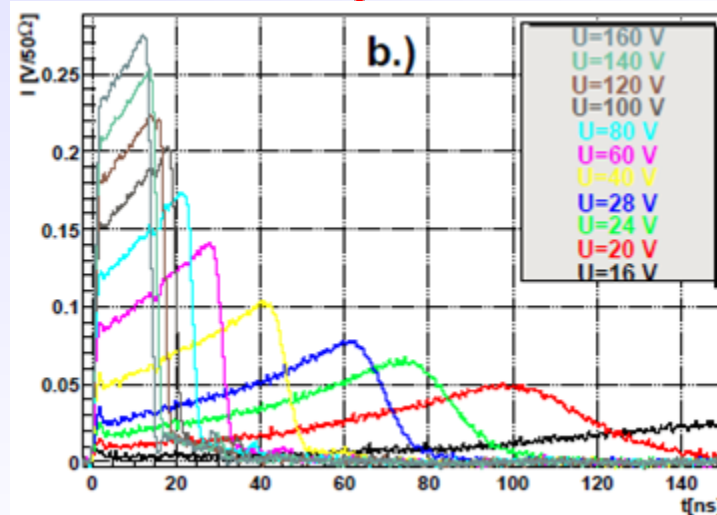
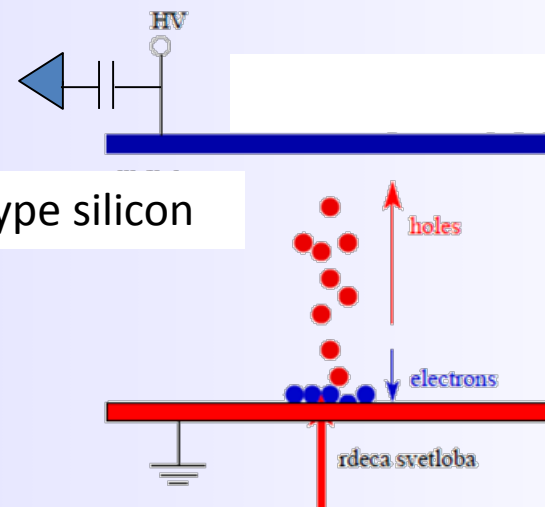
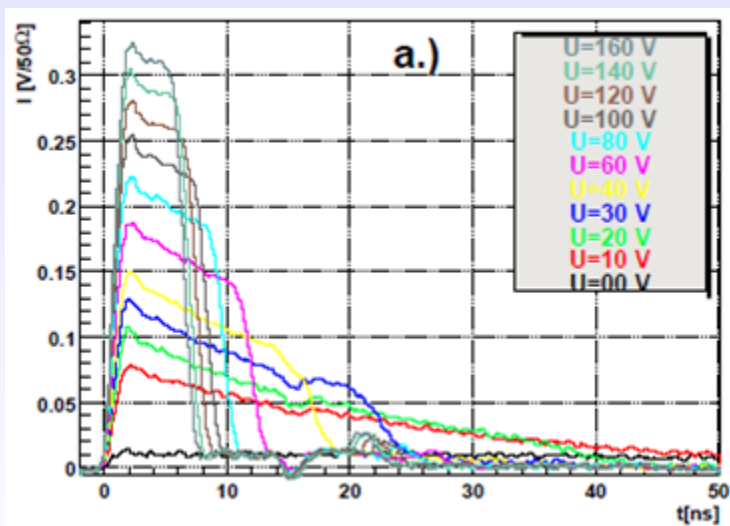
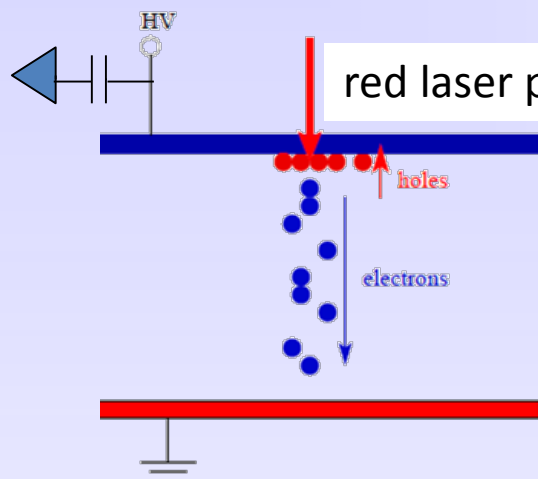
- **Trapping: Indications that E205a and H152K are important** (further work needed)
- Converging on consistent set of defects observed after p, π , n, γ and e irradiation.
- Defect introduction rates are depending on particle type and particle energy and (for some) on material!

Signal formation and electric field in radiation damaged sensors

A brief introduction

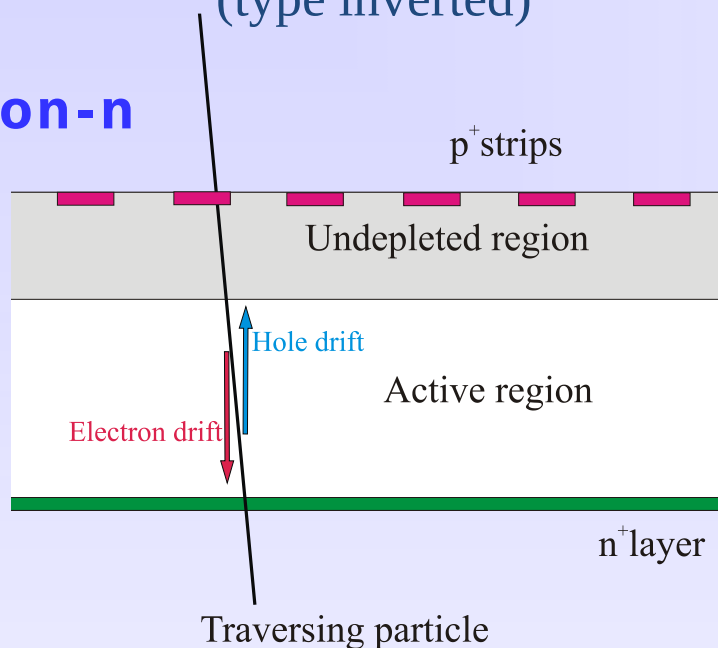
*..more details about (laser induced) field characterization
methods are given in the presentation of
Marcos Fernandez Garcia*

$$I_{e,h}(t) = e_0 \cdot N_{e,h} \cdot \exp(-t/\tau_{eff,e,h}) \cdot \frac{v_{e,h}(t)}{d} \approx \frac{e_0 \cdot N_{e,h} \cdot \mu_{e,h}}{d} \cdot \exp(-t/\tau_{eff,e,h}) \cdot E(t)$$



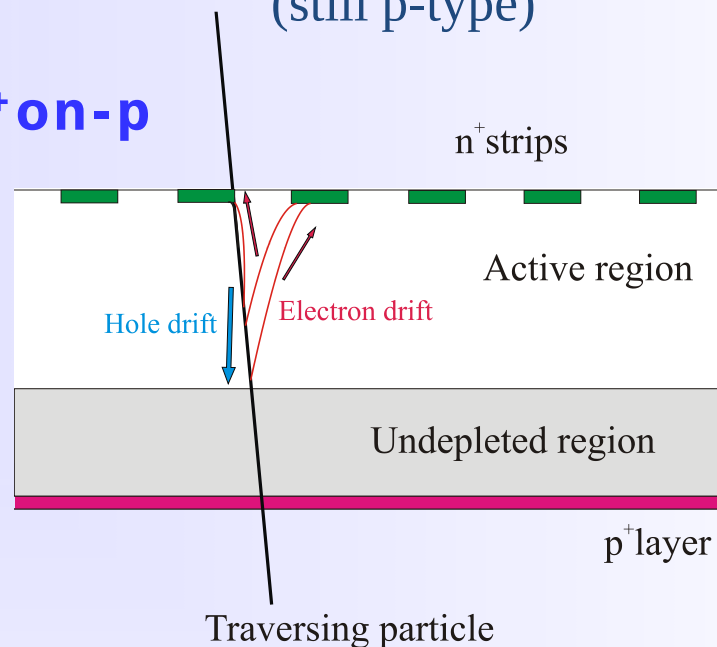
n-type silicon after high fluences:
(type inverted)

p⁺ on-n



p-type silicon after high fluences:
(still p-type)

n⁺ on-p



p-on-n silicon, under-depleted:

- Charge spread – degraded resolution
- Charge loss – reduced CCE

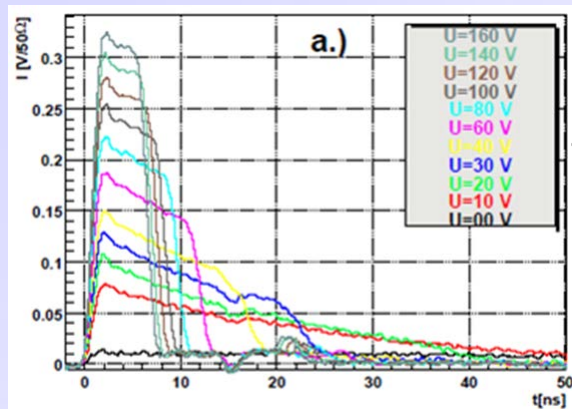
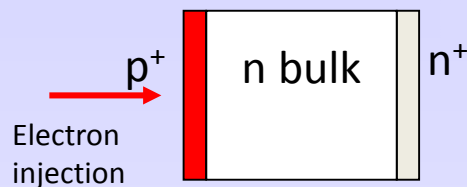
n-on-p silicon, under-depleted:

- Limited loss in CCE
- Less degradation with under-depletion
- Collect electrons (3 x faster than holes)

Comments:

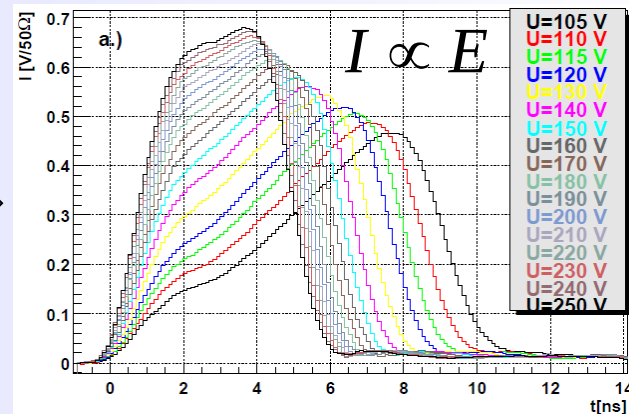
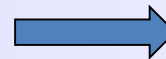
- Instead of n-on-p also n-on-n devices could be used
- **Reality is much more complex: Usually double junctions form leading to fields at front and back!**

Space Charge Sign Inversion

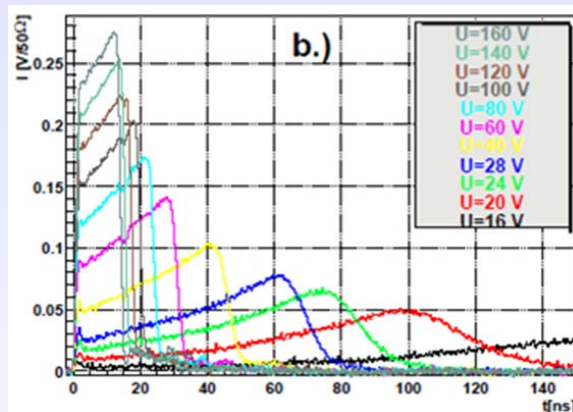


$V_{dep}=20\text{ V}$

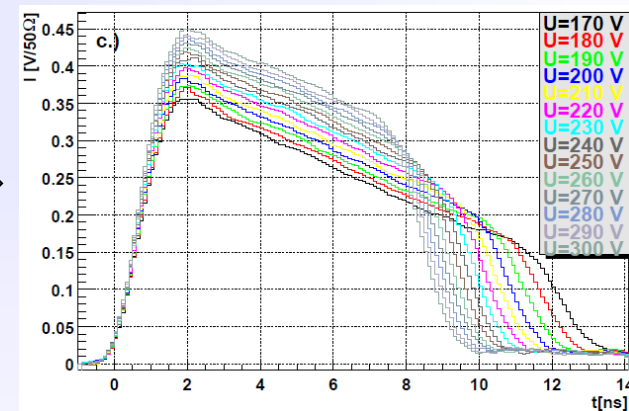
$\Phi_{eq}=5 \cdot 10^{13}\text{ cm}^{-2}$



$V_{dep}=70\text{ V}$

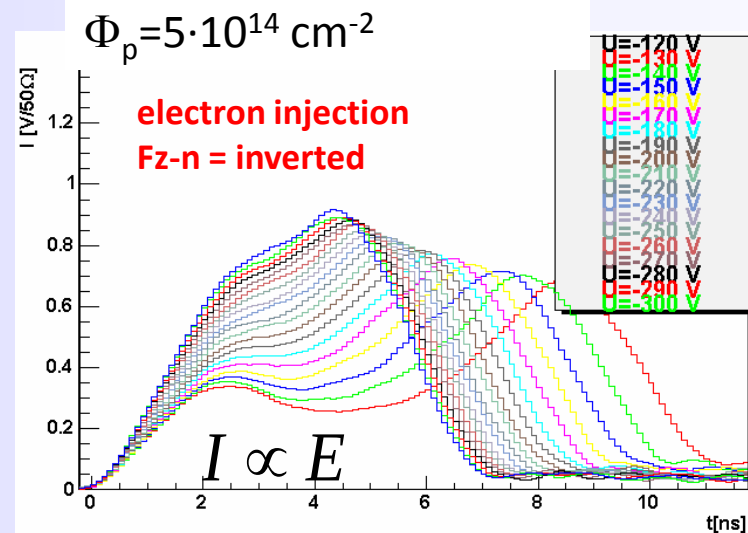
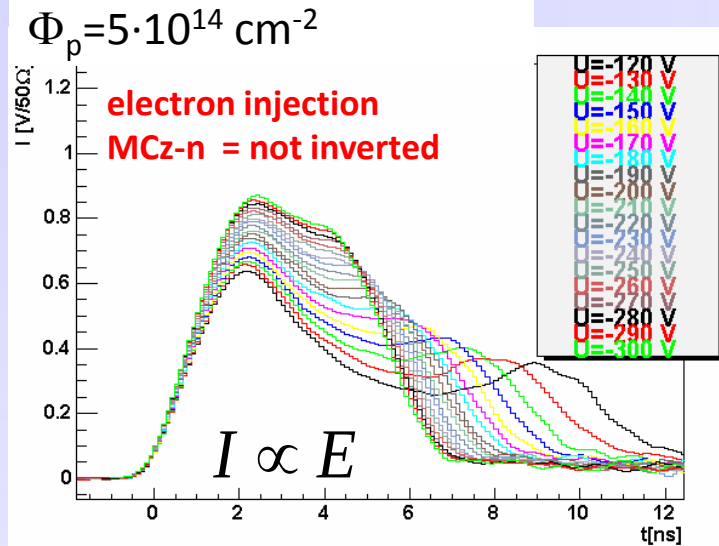


$\Phi_{eq}=5 \cdot 10^{13}\text{ cm}^{-2}$

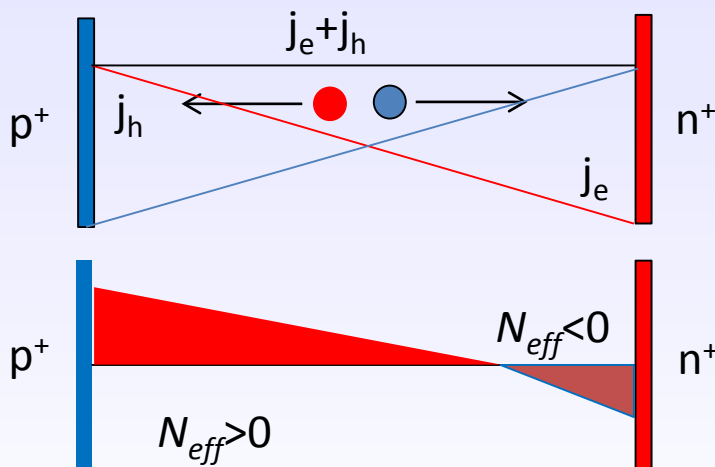


Remember – the shape of I gives you the shape of E

Double junction – polarization effects



Induced current has a non-monotonic shape – sign of different space charge

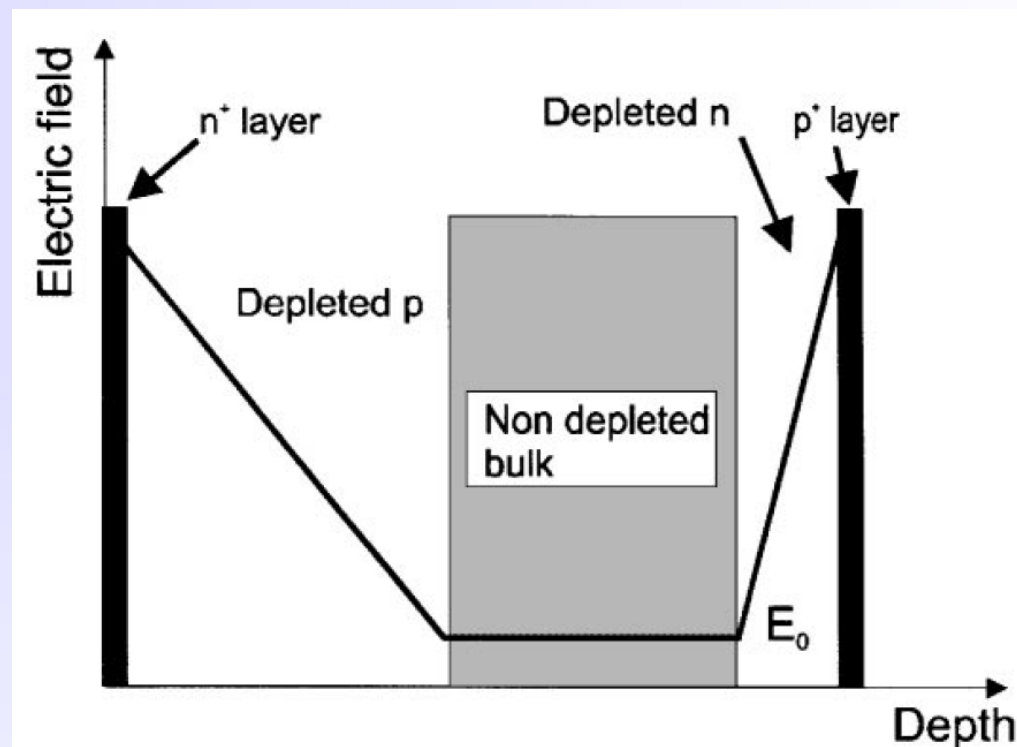
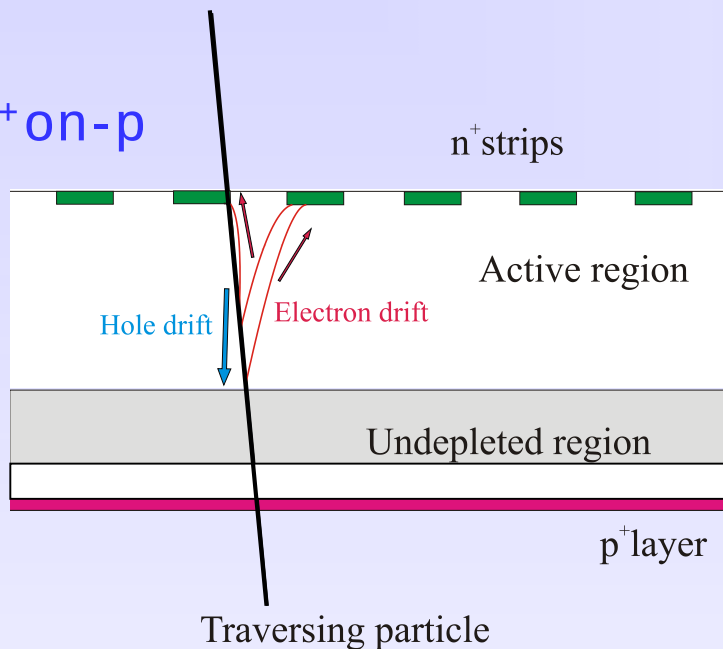


- This effect is present in all detector types
- It gets more pronounced at high fluences
- It is more pronounced for charged hadron irradiated detectors and oxygen rich material – point defects dominant?
- It gets more pronounced at low temperatures

[G.Kramberger]

p-type silicon after high fluences:
(still “p-type”)

n^+ on-p



- Dominant junction close to n^+ readout strip for FZ n-in-p
- For MCZ p-in-n even more complex fields have been reported:
 - no “type inversion”(SCSI) = dominant field remains at p implant
 - “equal double junctions” with almost symmetrical fields on both sides

Segmented sensors with readout on the n-implant (n-in-p or n-in-n)

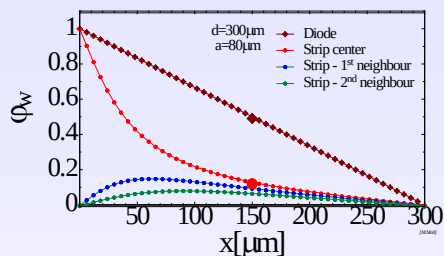
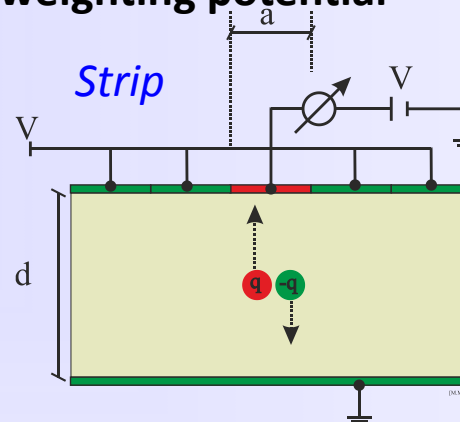
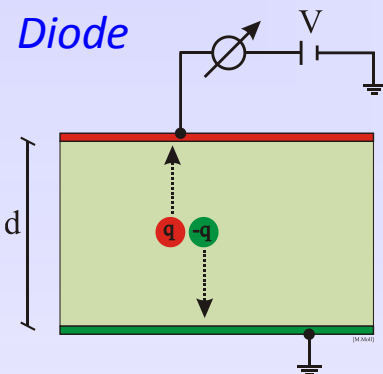
Signal induced in sensors by e-h pairs

Diode vs. Strip

- Induced charge (Ramo-Theorem)

- Total charged induced on the electrode by moving a charge can be calculated from the weighting potential

$$Q = -q \cdot (\phi_w(\vec{x}_2) - \phi_w(\vec{x}_1))$$



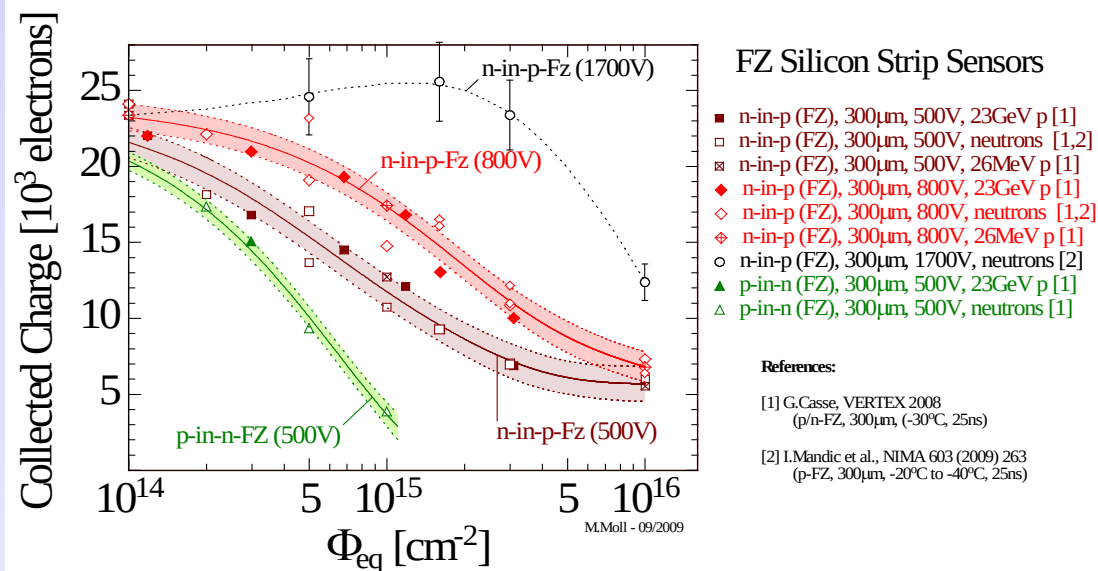
- Total collected charge in both cases 100% ($Q = q$) when charges have reached the electrodes, however

- Diode: 50% from (+q); 50% from (-q)
- Strip: 87% from (+q); 13% from (-q)

- In a p-in-n strip sensor the holes give a higher contribution to the (m.i.p.) signal than the electrons!

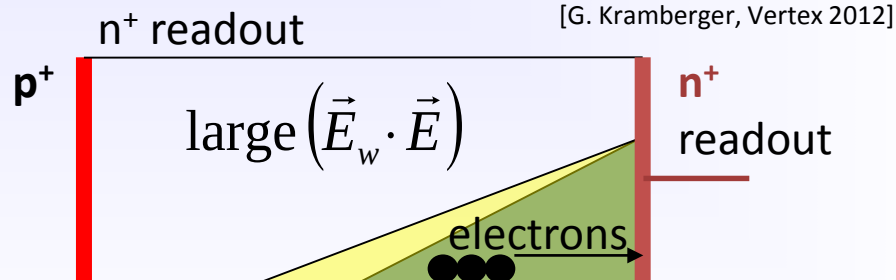
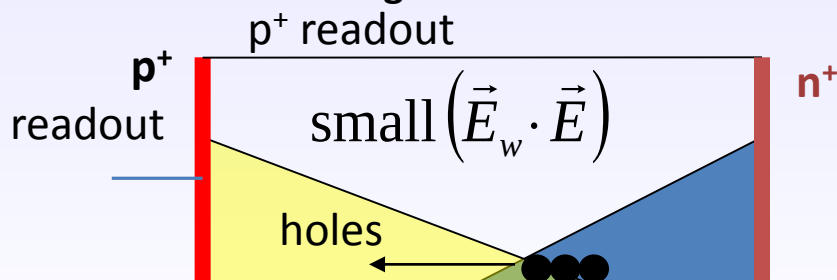
Segmented sensors: n^+ vs. p^+ readout

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



[M.Moll (RD50), "Recent advances in the development of radiation tolerant Silicon Detectors for the Super-LHC (ISBN: 978-981-4307-51-2/3), April 2010, World Scientific, pp 101-110.

- 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:**



• Planar segmented detectors n-in-p or n-in-n

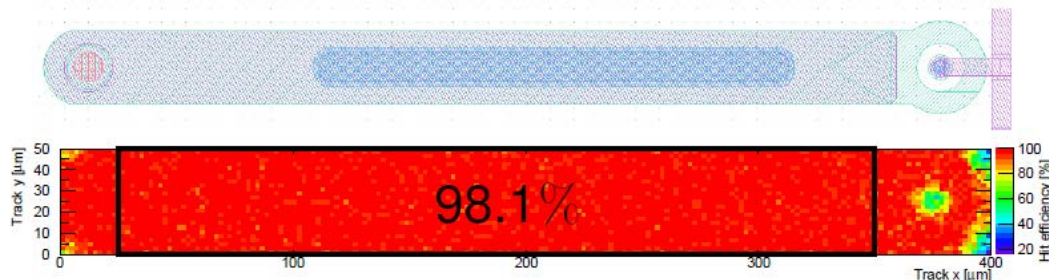
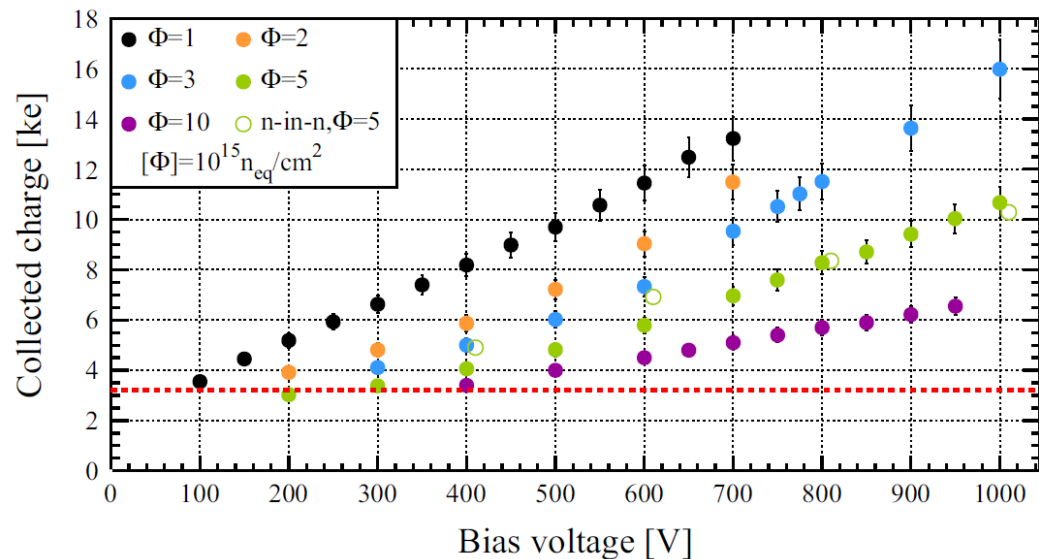
- results on highly irradiated planar segmented sensors have shown that these devices are a feasible option for the innermost layers of LHC upgrade

Example:

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

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

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



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

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

- Optimizing the sensor thickness
- Measurement of thin FZ p-type pixel sensors: 75, 100, 150 and 285 μm (MPI/CIS)

From M.Moll VERTEX 2013 proceedings

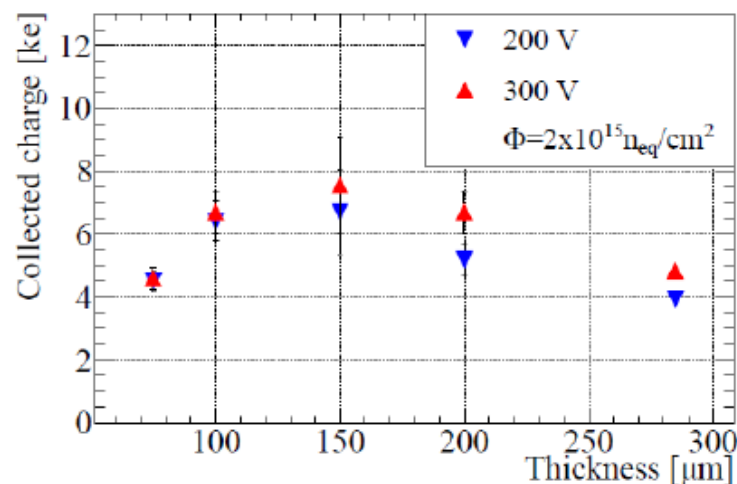
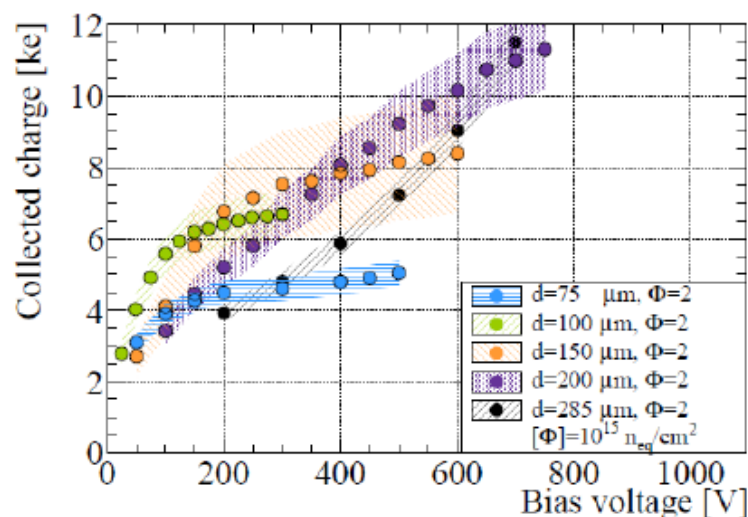
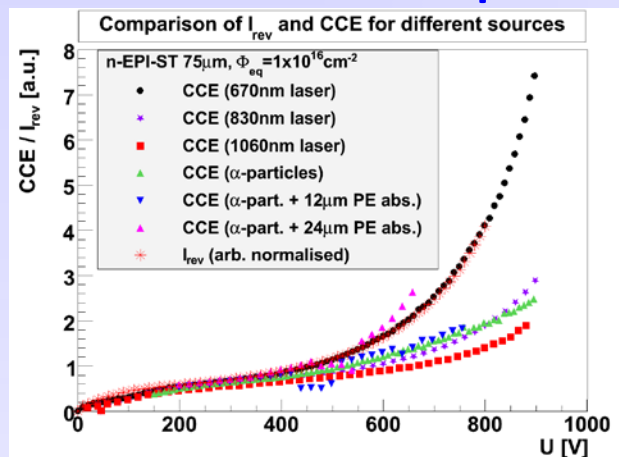


Figure 4: Comparison of collected charge as measured with a Sr^{90} source on irradiated ($\phi_{\text{eq}} = 2 \times 10^{15} \text{ n}_{\text{eq}}\text{cm}^{-2}$) p-type pixel sensors with different thickness bump-bonded to ATLAS FEI4 readout chips [23]. Left: Collected charge as function of voltage. Right: Collected charge as function of device thickness for 200V and 300V.

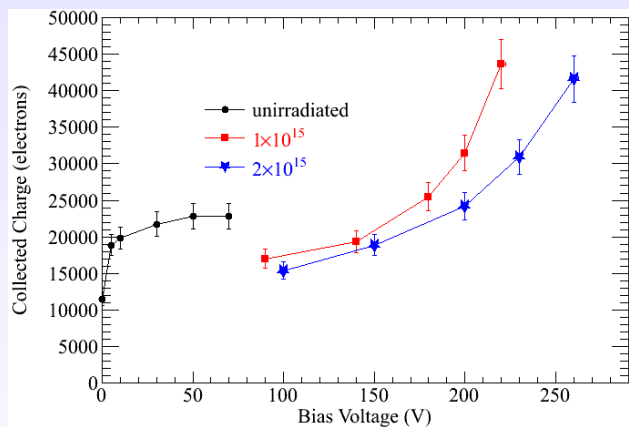
[23] S.Terzo. Irradiated n-in-p planar pixel sensors with different thicknesses and active edge designs. *23rd RD50 Workshop, November 2013.*

Charge Multiplication (Sensors with intrinsic gain)

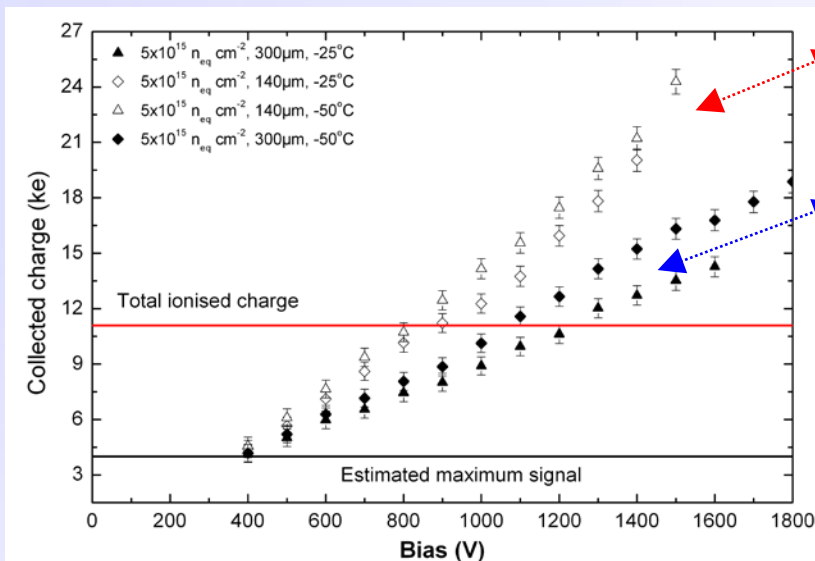
- Charge Multiplication observed and characterized after high levels of irradiation with different techniques and in several different types of devices



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



3D sensors ($\Phi_{eq} = 1-2 \times 10^{15} \text{ cm}^{-2}$)
Charge Collection (test beam)



140 μm thick device

300 μm thick device

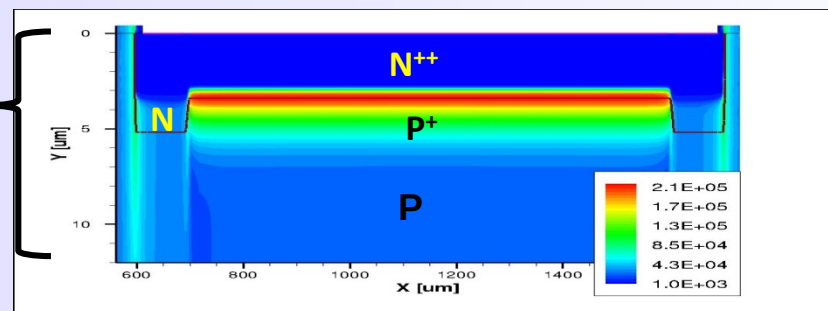
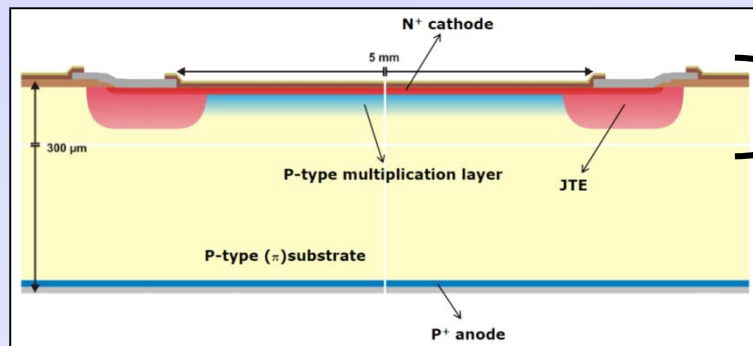
Strip sensors ($\Phi_{eq} = 5 \times 10^{15} \text{ cm}^{-2}$, 26 MeV p)
Charge Collection (Beta source, Alibava)

Questions:

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

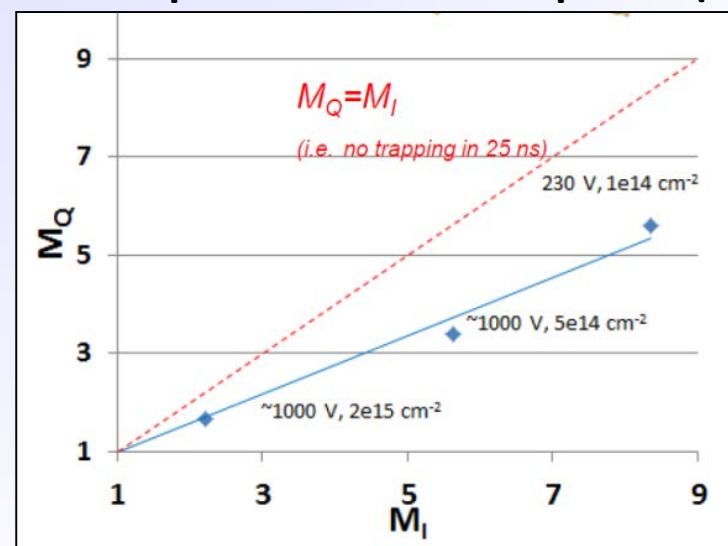
Ref: Diode: J.Lange et al, 16th RD50 Workshop, Barcelona
Strip: G. Casse et al., NIMA 624, 2010, Pages 401-404
3D: M.Koehler et al., 16th RD50 Workshop, Barcelona

- **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 (⁹⁰Sr)
- **Gain reduces with irradiation**
 - Dropping to about 1.5 after $2e15 \text{ n/cm}^2$
 - Why? Boron removal in p-type layer?
 - Current and noise scale as expected with multiplication
 - Charge (Sr-90) Multiplication versus Current Multiplication (Sr-90)
- **Further work ongoing (strip, pixel, ...)**



[G.Kramberger, RD50, June 2013]

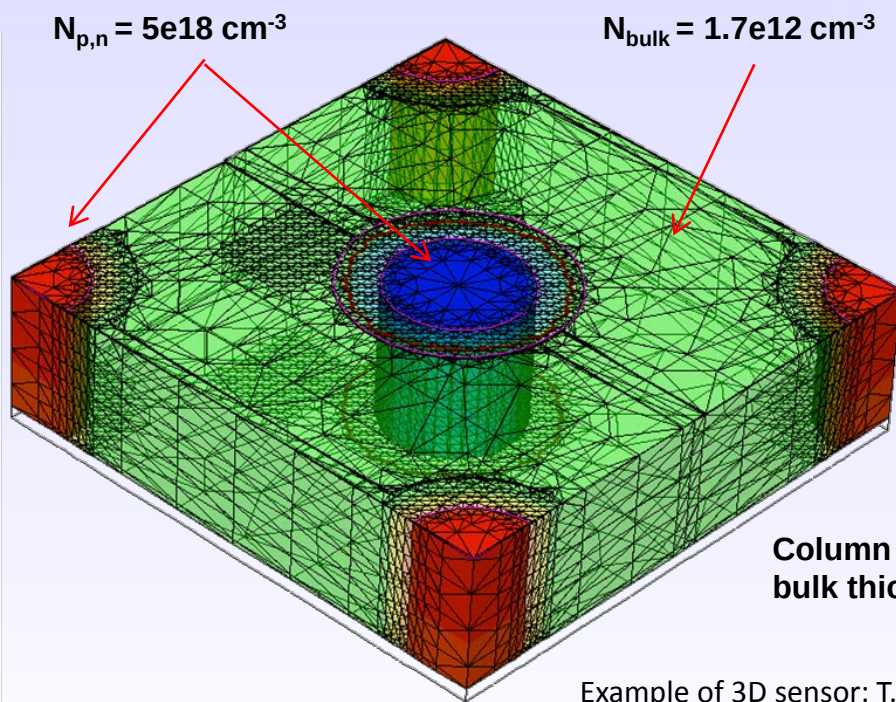
TCAD device simulations

• Why do we need TCAD simulations ?

▪ Complexity of the problem

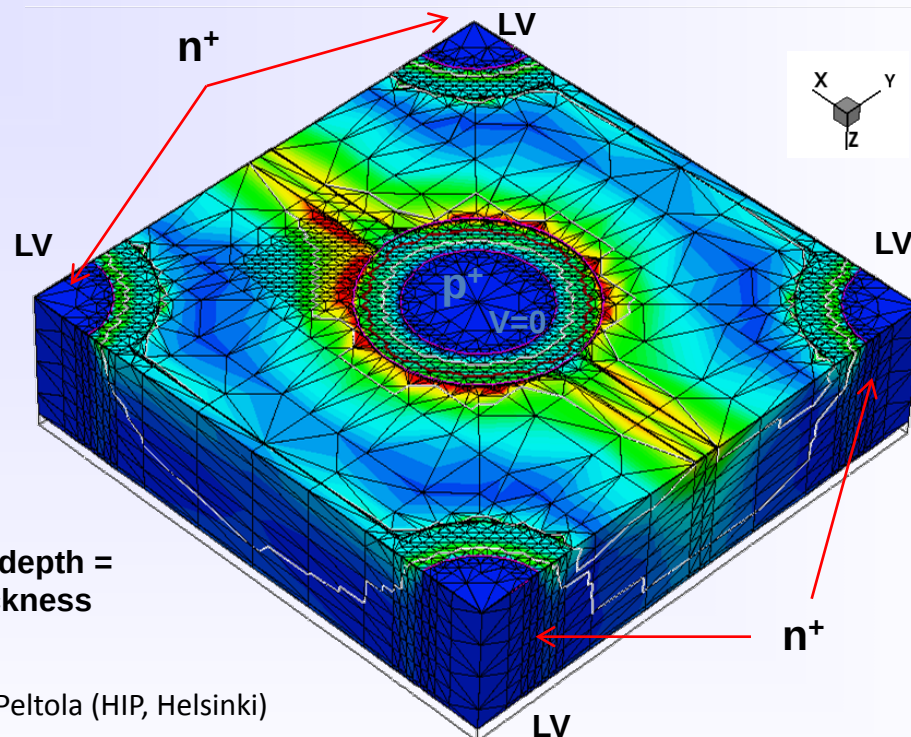
- Coupled differential equations (semiconductor equations)
- Impact of defects depending on local charge densities, field-strength, ... (“feedback loop”)
- Complex device geometry and complex signal formation in segmented devices
- *Example: 3D sensors*

Doping profiles



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

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



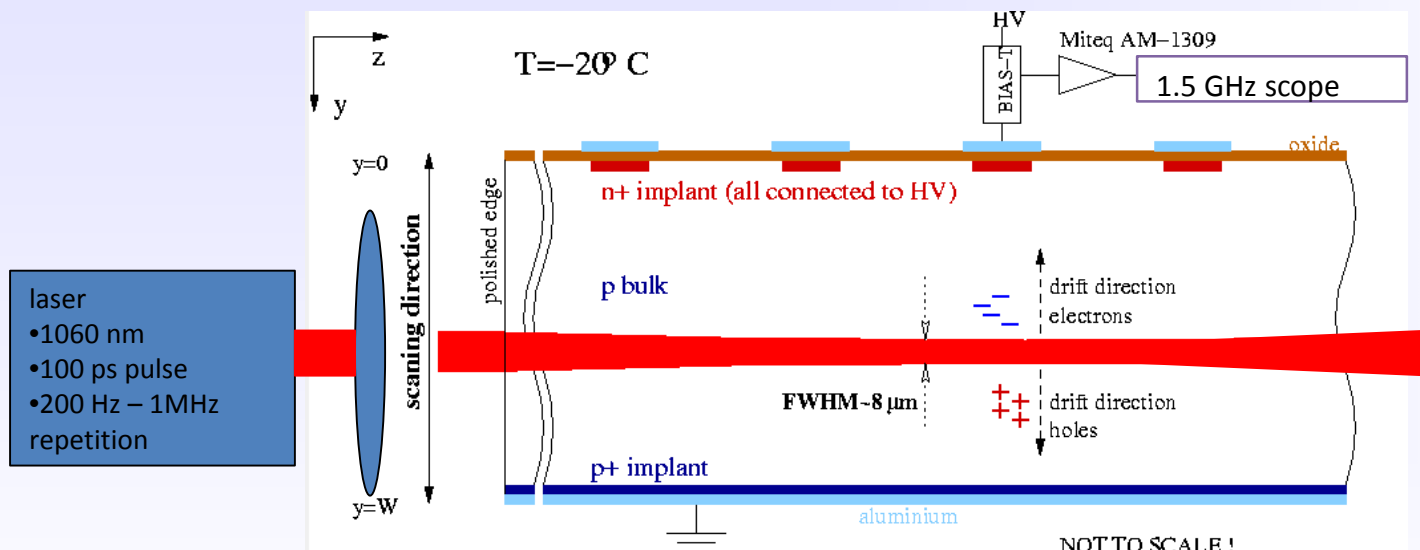
- **RD50 recommendations for silicon detectors in LHC detector upgrades**
 - **Innermost layers: fluences up to $2 \cdot 10^{16} n_{eq}/cm^2$**
 - **present results show that planar sensors are good enough**
 - readout on n-type electrode is essential!
 - n-in-p (or n-in-n becoming “n-in-p” after inversion) detectors
 - need high bias voltage , but may be less demanding with thin sensors
 - **3D detectors promising**
 - lower bias voltage, more difficult to produce but IBL clearly demonstrates feasibility
 - **Outer layers: fluences up to $10^{15} n/cm^2$**
 - **n-in-p type FZ microstrip detectors are ATLAS and CMS baseline choice:**
 - 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
- **Not covered: Monolithic Devices, Diamond....**

see following talks

- **Most references to particular works given on the slides**
- **Some additional material taken from the following presentations:**
 - *RD50 presentations: <http://www.cern.ch/rd50/>*
 - *Anthony Affolder: Presentations on the RD50 Workshop in June 2009 (ATLAS fluence levels)*
 - *Some slides taken from Gregor Kramberger (Ljubljana, Jozef Stefan Institute), various presentations*
- **Books containing chapters about radiation damage in silicon sensors**
 - *Helmuth Spieler, "Semiconductor Detector Systems", Oxford University Press 2005*
 - *Frank Hartmann, "Evolution of silicon sensor technology in particle physics", Springer 2009*
 - *L.Rossi, P.Fischer, T.Rohe, N.Wermes "Pixel Detectors", Springer, 2006*
 - *Gerhard Lutz, "Semiconductor radiation detectors", Springer 1999*
- **Research collaborations and web sites**
 - *CERN RD50 collaboration (<http://www.cern.ch/rd50>) - Radiation Tolerant Silicon Sensors*
 - *CERN RD39 collaboration – Cryogenic operation of Silicon Sensors*
 - *CERN RD42 collaboration – Diamond detectors*
 - *Inter-Experiment Working Group on Radiation Damage in Silicon Detectors (CERN)*
 - *ATLAS IBL, ATLAS and CMS upgrade groups*

Annex: Edge - TCT

- 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**



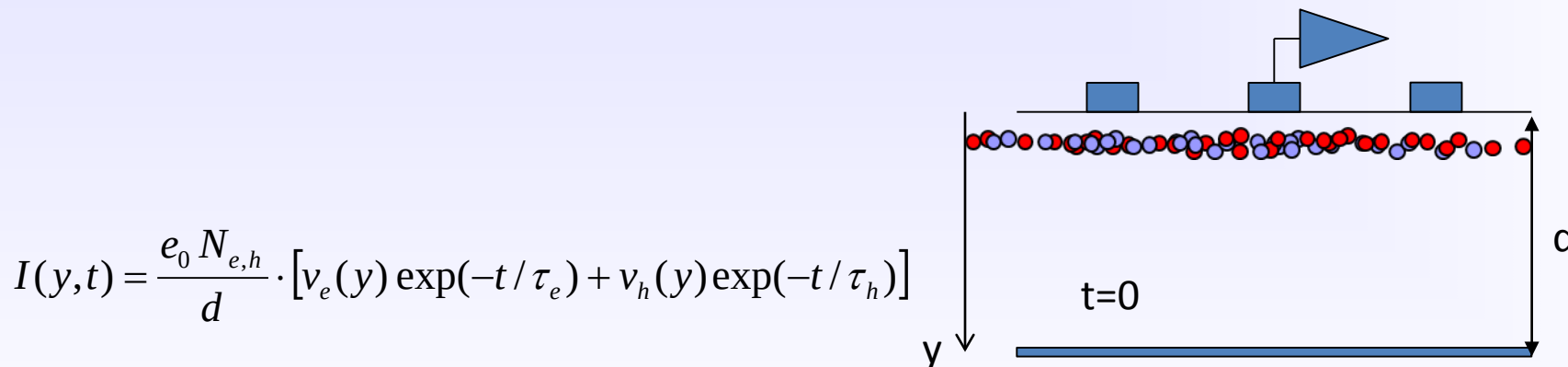
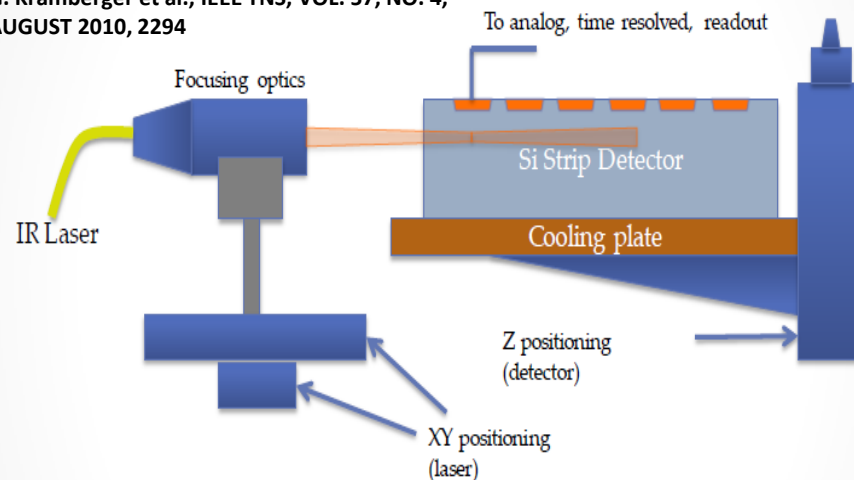
- **Classical TCT:** information of the field from $I(t)$

Edge-TCT: information of the field from $I(\text{depth})$

- A narrow 8 μm beam is used to generate e-h pairs at known depth
- Measured current is average over the width of the strip

Edge-TCT meritev

G. Kramberger et al., IEEE TNS, VOL. 57, NO. 4, AUGUST 2010, 2294



- Classical TCT: information of the field from $I(t)$

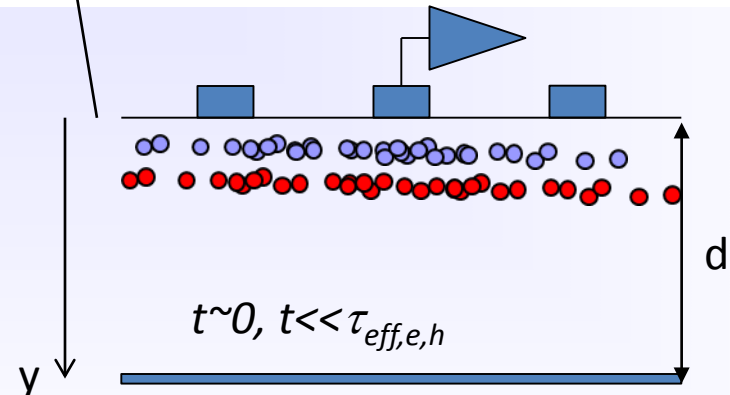
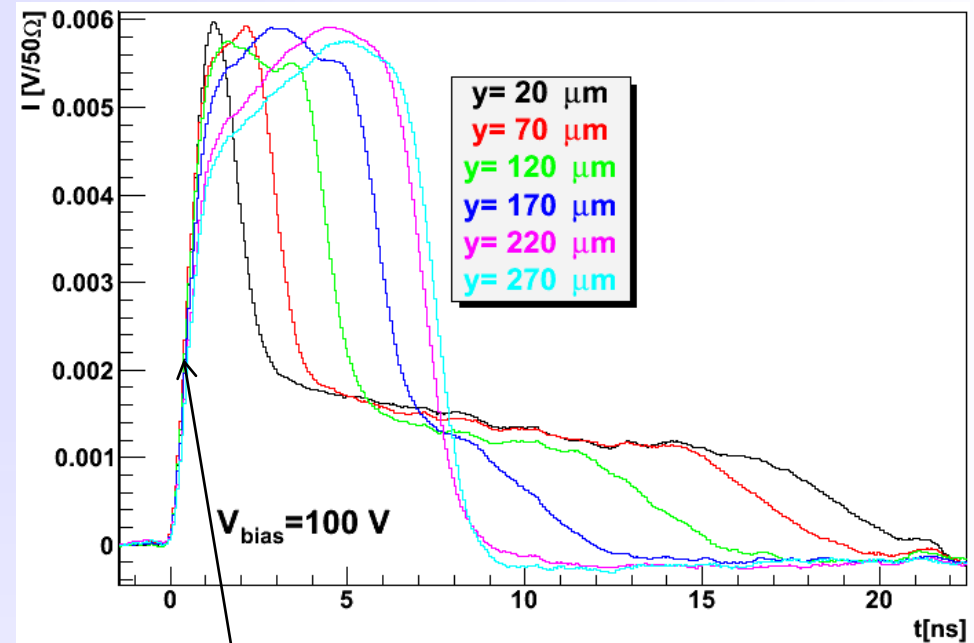
Edge-TCT: information of the field from $I(\text{depth})$

- A narrow $8\ \mu\text{m}$ beam is used to generate e-h pairs at known depth
- Measured current is average over the width of the strip

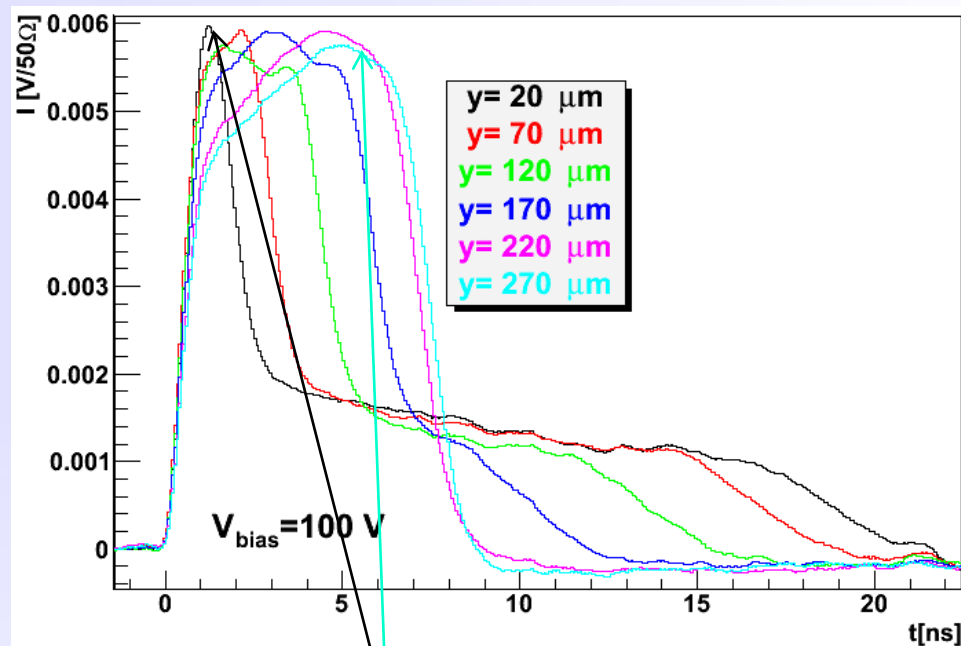
VELOCITY PROFILE:

$$I(y, t \sim 0) = e_0 N_{e,h} \cdot \frac{v_e(y) + v_h(y)}{d}$$

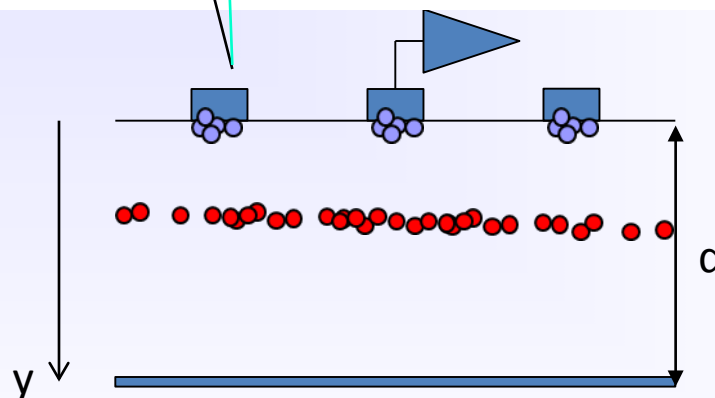
$$v_e(y) + v_h(y) \propto I(y, t \sim 0)$$



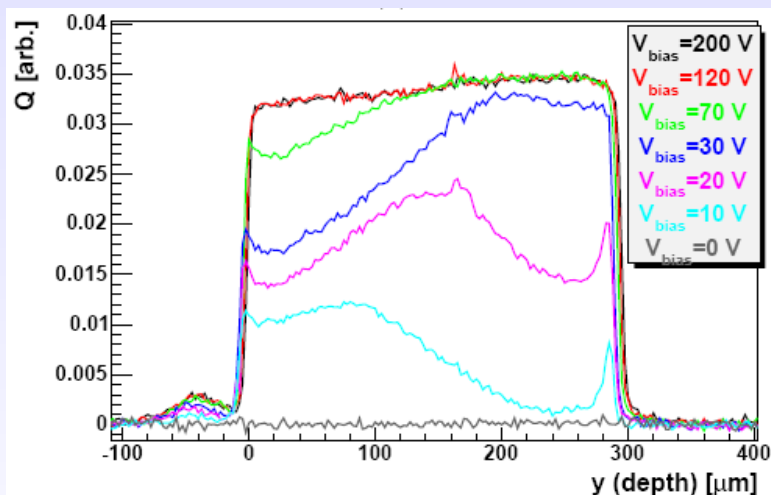
- Classical TCT: information of the field from $I(t)$
- Edge-TCT: information of the field from $I(\text{depth})$
- A narrow $8\ \mu\text{m}$ beam is used to generate e-h pairs at known depth
- Measured current is average over the width of the strip



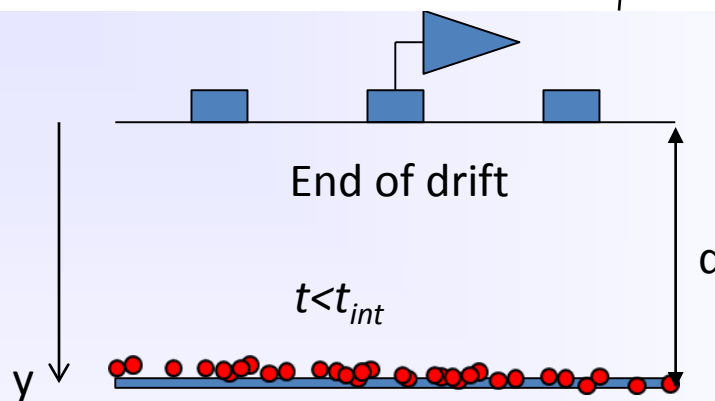
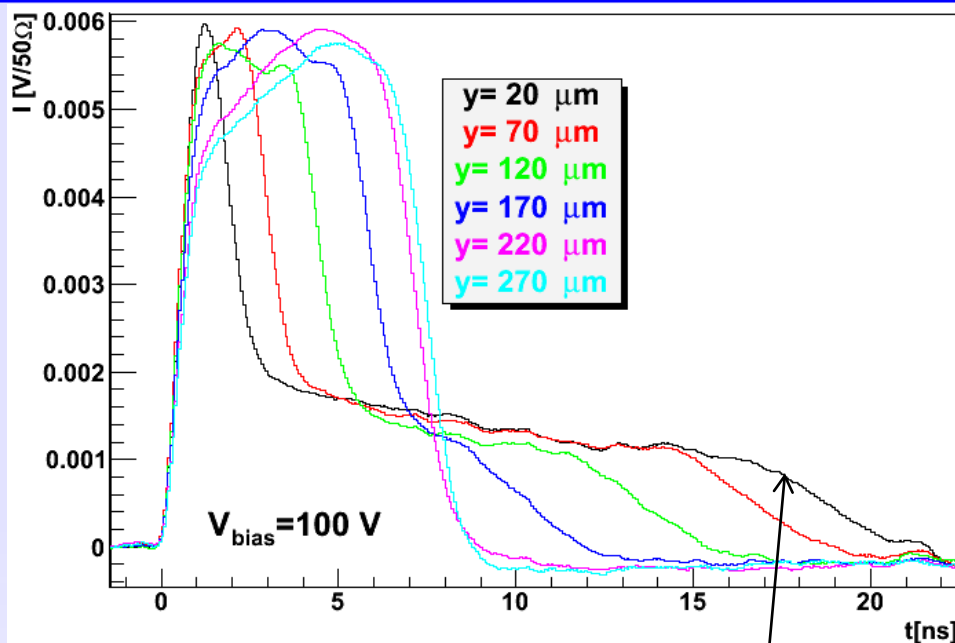
Electrons finish their drift.



- Classical TCT: information of the field from $I(t)$
- Edge-TCT: information of the field from $I(\text{depth})$
- A narrow $8\ \mu\text{m}$ beam is used to generate e-h pairs at known depth
- Measured current is average over the width of the strip

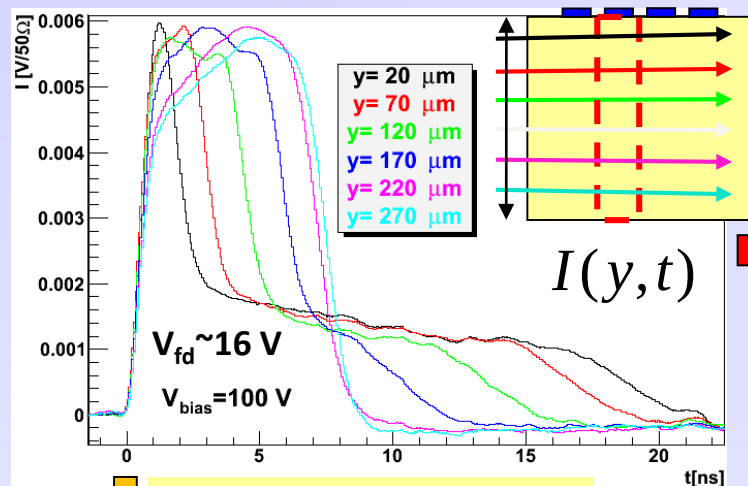


$$Q(y) = \int_{t=0}^{t_{\text{int}}} I(y, t) dt$$



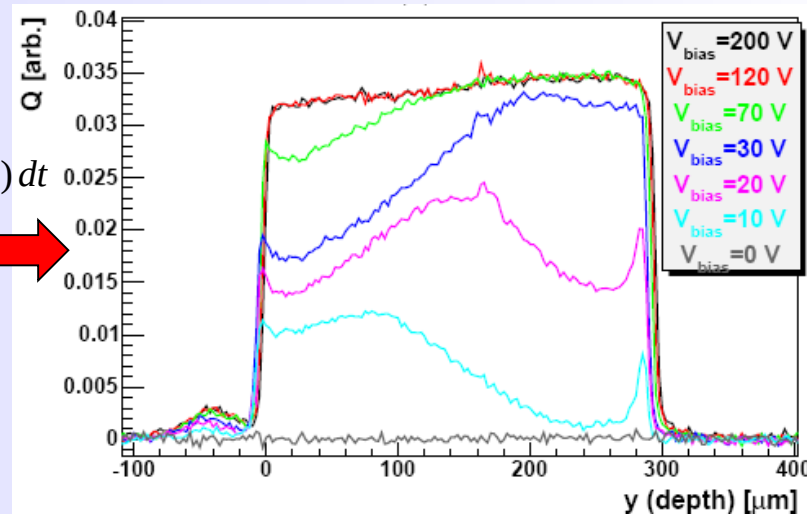
Charge collection and velocity profiles

RD50 Micron p-type sensor



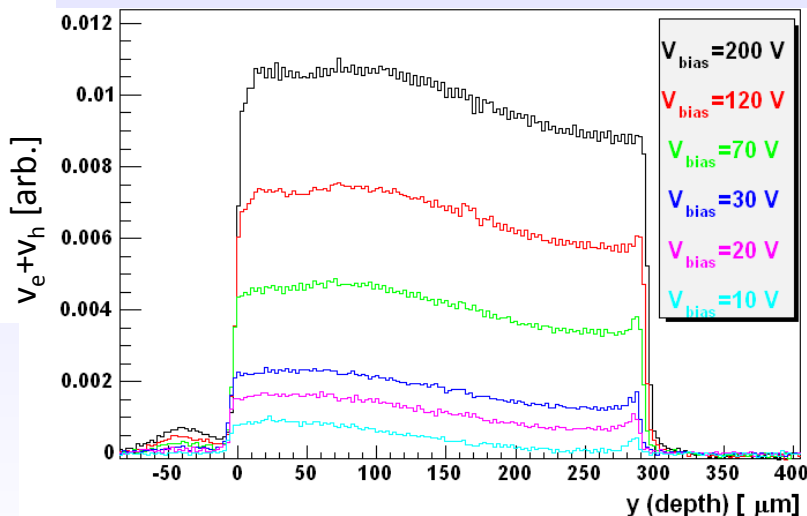
$$Q(y) = \int_0^{25\text{ns}} I(y, t) dt$$

CHARGE COLLECTION PROFILE

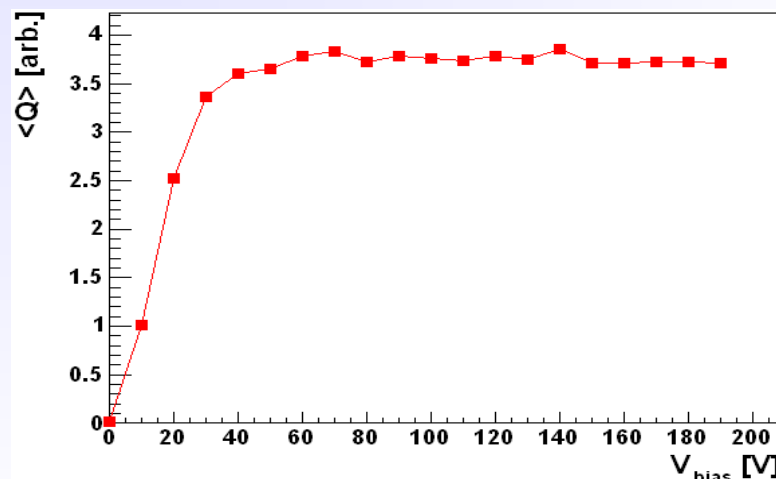


$$I(y, t \sim 0) \propto v_e + v_h$$

VELOCITY PROFILE

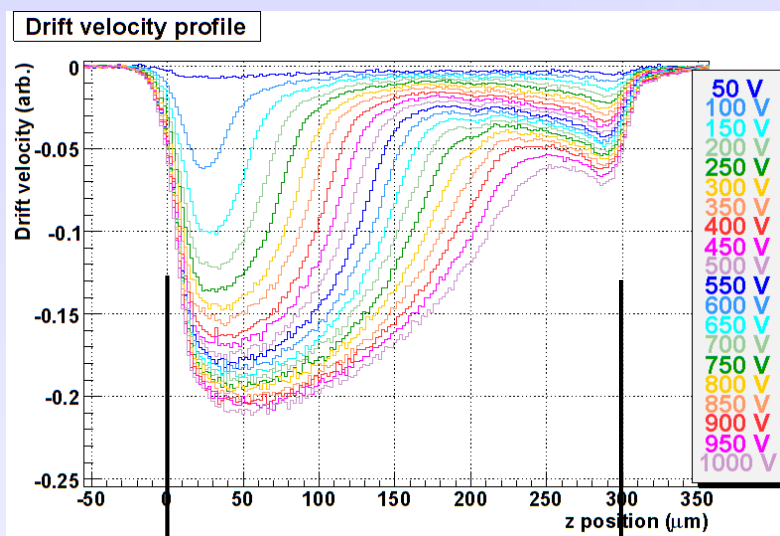


$$Q_{mip} \propto \langle Q \rangle = \int_0^{25\text{ns}} I(y, t) dt$$



- **Sensors:** MCZ and FZ p-type ministrip sensors (pitch: 80 μm , width 20 μm)
- **Irradiation:** 10¹⁶ p/cm² with 24 GeV/c protons (6.1×10^{15} $n_{\text{eq}}/\text{cm}^2$)
- **Annealing:** Isothermal at 60°C (results after 560 min shown below)

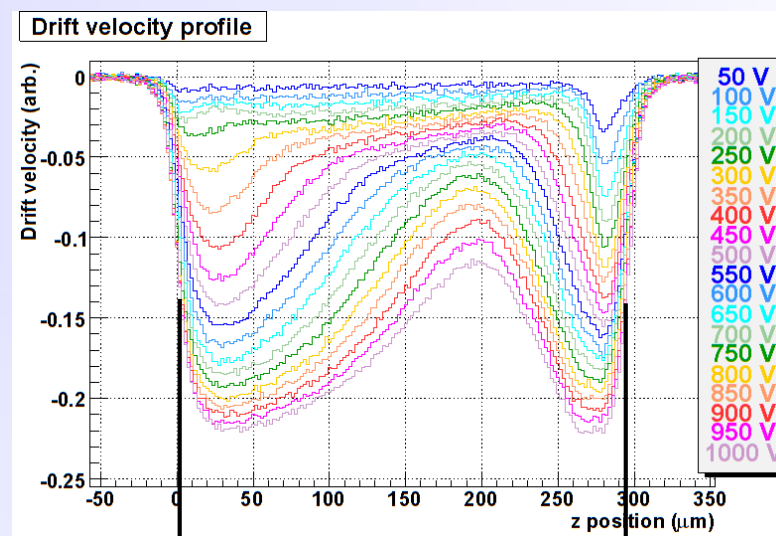
FZ



Front electrode
(n-p junction)

Back electrode
(p⁺ contact)

MCZ



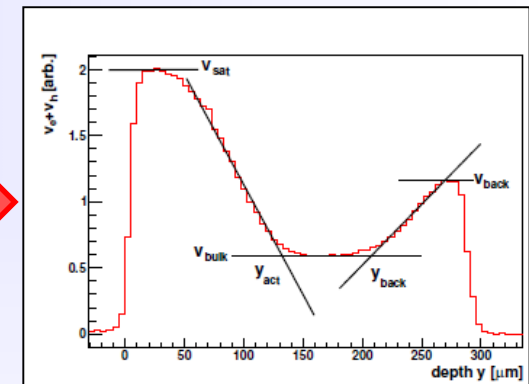
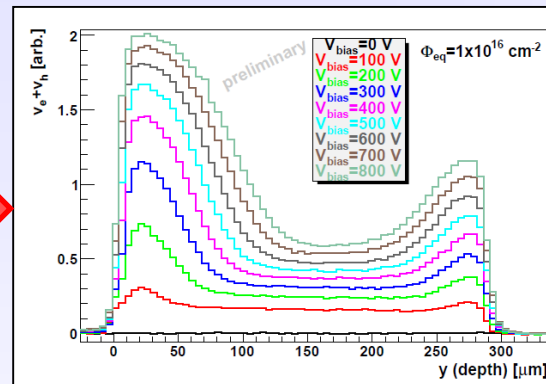
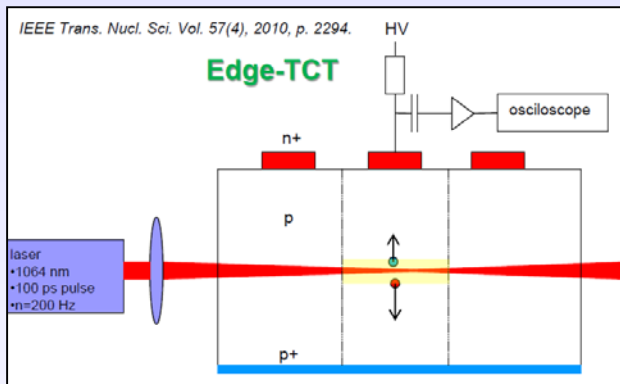
Front electrode
(n-p junction)

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

- **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 ($v_e + v_h$)

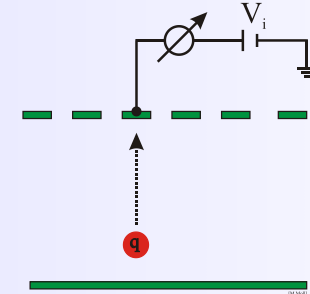


fit to extract parameters

Annex: n-readout devices

Improved charge collection and annealing behaviour

- **Task:** Calculate the current (signal) induced in an electrode by a moving point charge



- **Shockley-Ramo Theorem:**

- The charge Q and current i on an electrode induced by a moving point charge q are given by:

$$Q = -q \cdot \phi_w(\vec{x})$$

$$i = q \cdot \vec{v} \cdot \vec{E}_w(\vec{x})$$

- v is the instantaneous velocity of the charge q
- ϕ_w and E_w are the **weighting potential** and **weighting Field**

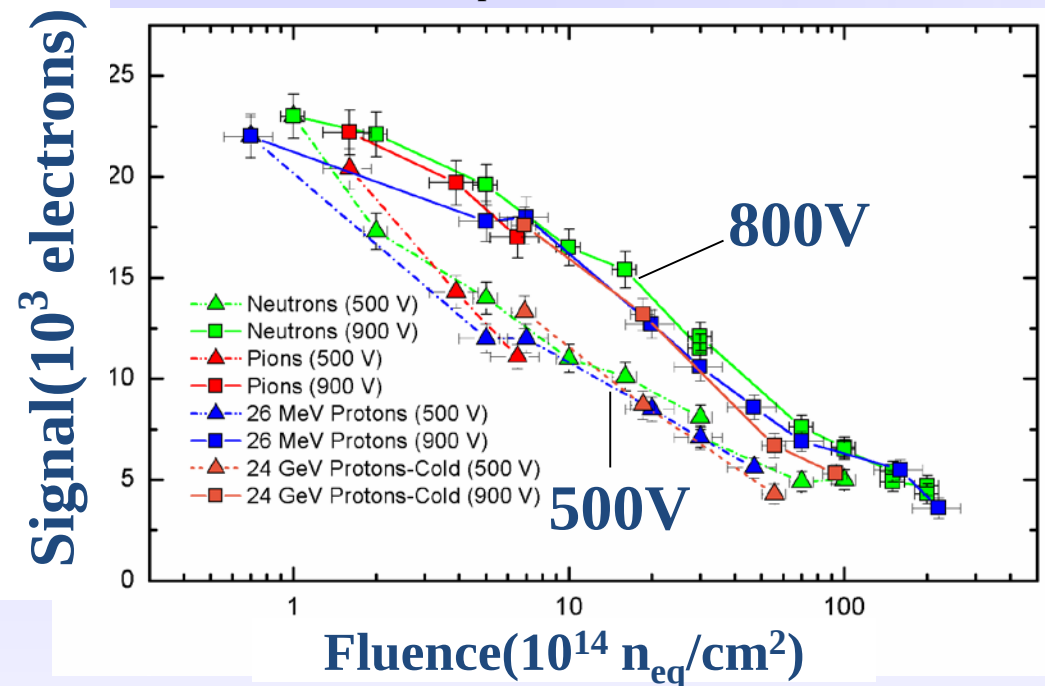
E_w and ϕ_w represent the electric field and potential that would exist when the selected electrode is set to unit potential while all other electrodes are set to ground

- **Note:**

- The electric field determines the charge trajectory (not the weighting field)!
- The weighting field depends only on geometry and determines how moving charges couple to a specific electrode.
- Signal induced on the electrode by moving a charge from x_1 to x_2 only depends on the weighting potentials at x_1 and x_2 , not on the trajectory and not on the electric field.

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

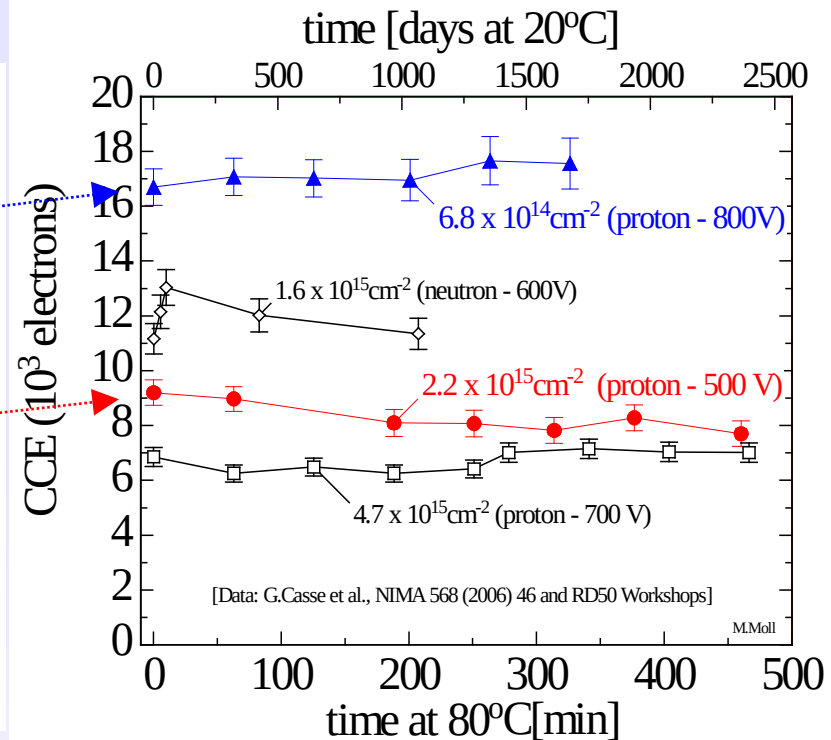
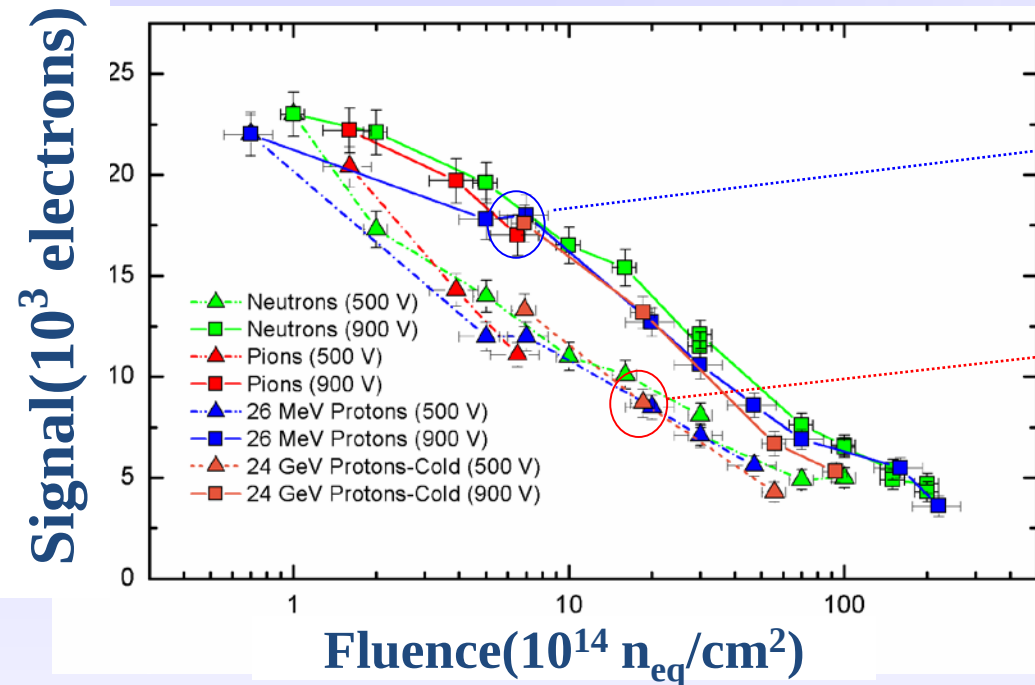
[A.Affolder, Liverpool, NIMA 623, 2010, 177–179]



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

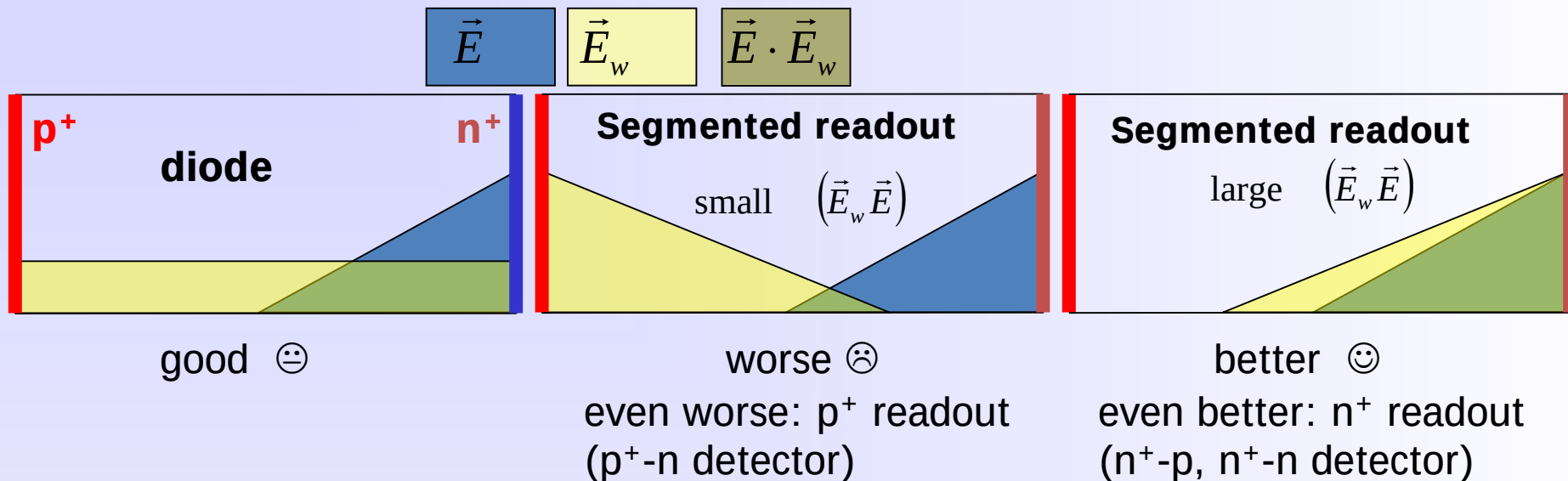
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[A.Affolder, Liverpool, NIMA 623, 2010, 177–179]



- **CCE: $\sim 7300e$ ($\sim 30\%$)**
after $\sim 1 \times 10^{16} cm^2$ 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**

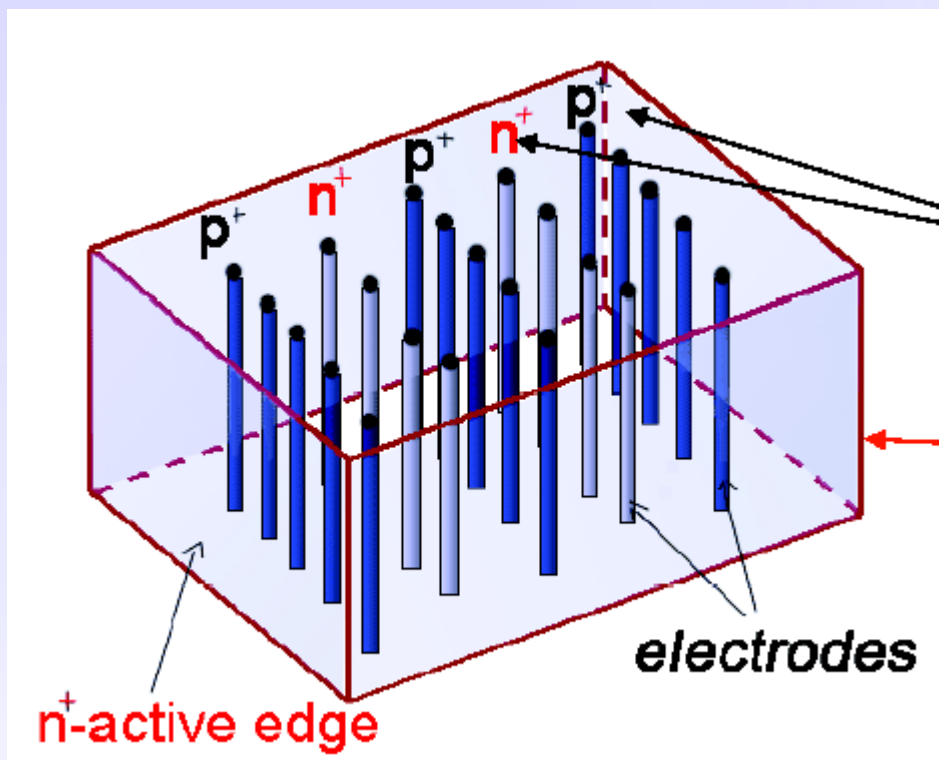


How to get maximum signal?

- use of n⁺-n or n⁺-p device (electron collection) with $\text{pitch} \ll \text{thickness}$
- implant width close to pitch (depends on FE elec. – inter-electrode capacitance)
- for a given cell size of a pixel detector

$$\frac{\text{pitch}_x}{\text{pitch}_y} \rightarrow 0, \infty$$

Annex: 3D sensors

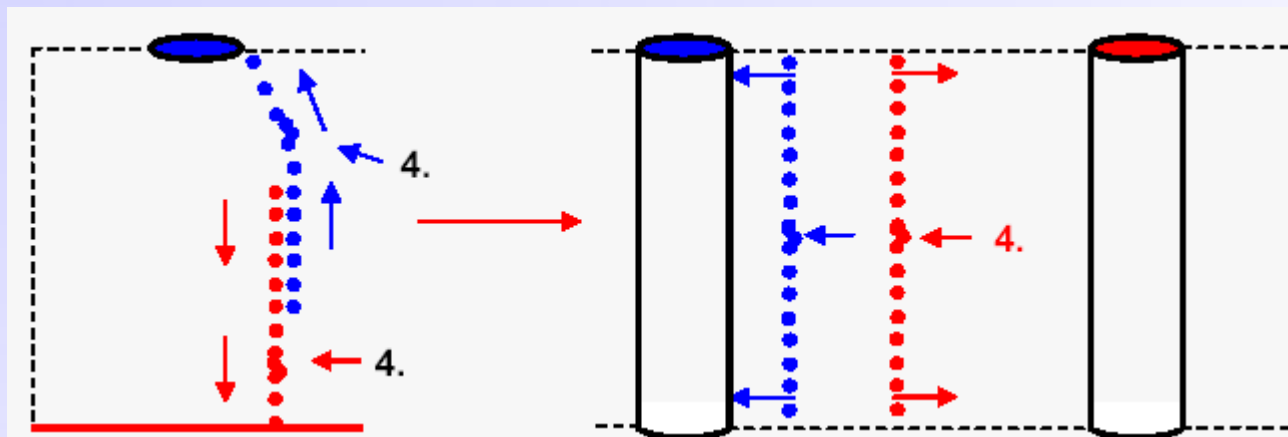


Combine traditional VLSI processing and MEMS (Micro Electro Mechanical Systems) technology.

Both electrode types are processed inside the detector bulk instead of being implanted on the wafer's surface.

The edge is an electrode. Dead volume at the Edge < 5 microns! Essential for forward physics experiments and material budget

S.I. Parker, C.J. Kenny, J. Segal, Nucl. Instr. and Meth. A395 (1997) 328.



Pros.

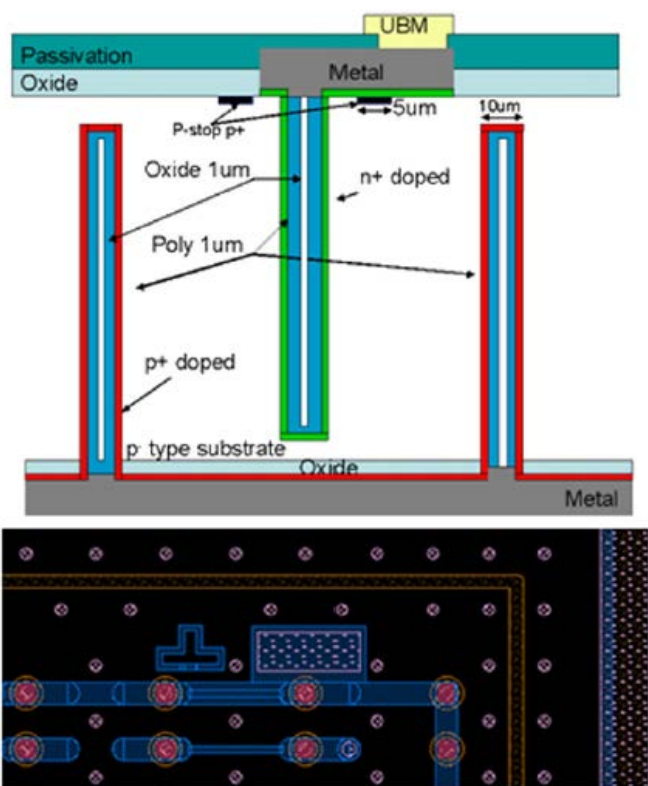
- Better charge collection efficiency
- Faster charge collection (depends on inter-column spacing)
- Reduced full depletion voltage and by that the power
- Larger freedom for choosing electrode configuration

Cons.

- Columns are dead area (aspect ratio ~30:1)
- Spatially non-homogenous CCE (efficiency=function of position)
- Much higher electrode capacitance (hence noise), particularly if small spacing is desired – small drift length
- Availability on large scale
- Time-scale and cost

3D sensors:

- used in IBL, excellent up to $\Phi_{eq} = 5 \cdot 10^{15} \text{ n/cm}^2$, promising results also for HL-LHC,
- operation at lower voltage in innermost HL-LHC tracking layer(s)



CNM 3D sensor

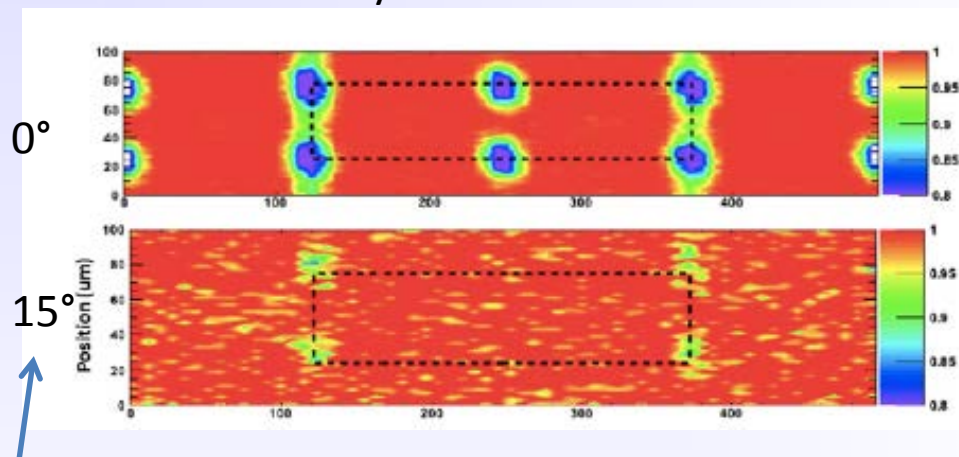
[G. Pellegrini, et al., NIMA 592 (2008) 38].

Work of ATLAS 3D Sensor R&D Collaboration:

Test beam, CNM, sensors,

$\Phi_{eq} = 5 \cdot 10^{15} \text{ n/cm}^2$, Bias voltage = 160 V

Track efficiency > 98%



Track incidence angle

[S. Grinstein, NIMA 699 (2013) 61–66]
[S. Tsiskaradze, 19th RD50 workshop]

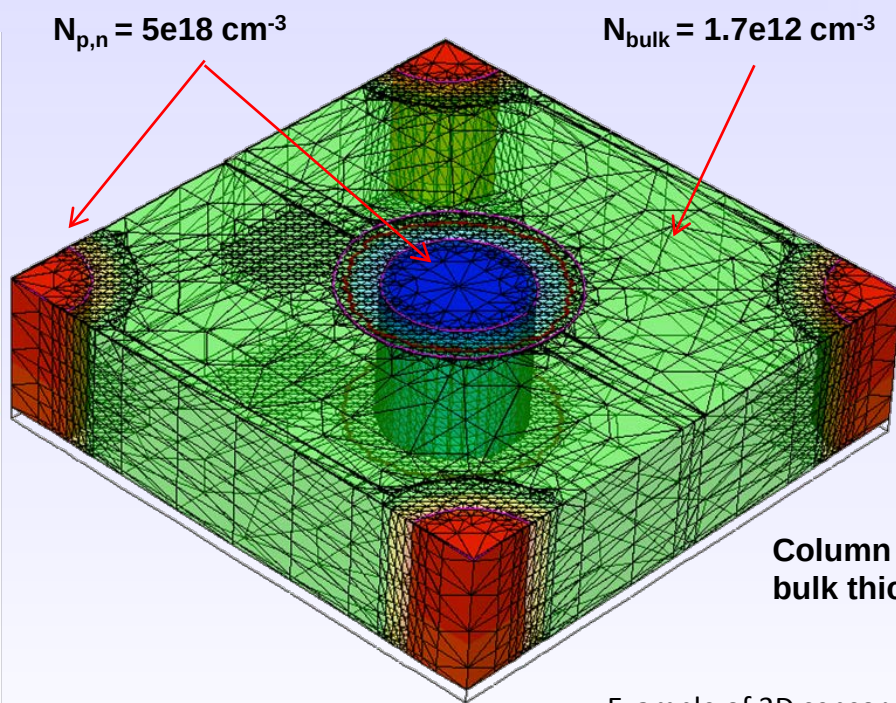
Annex: TCAD device simulations

• Why do we need TCAD simulations ?

▪ Complexity of the problem

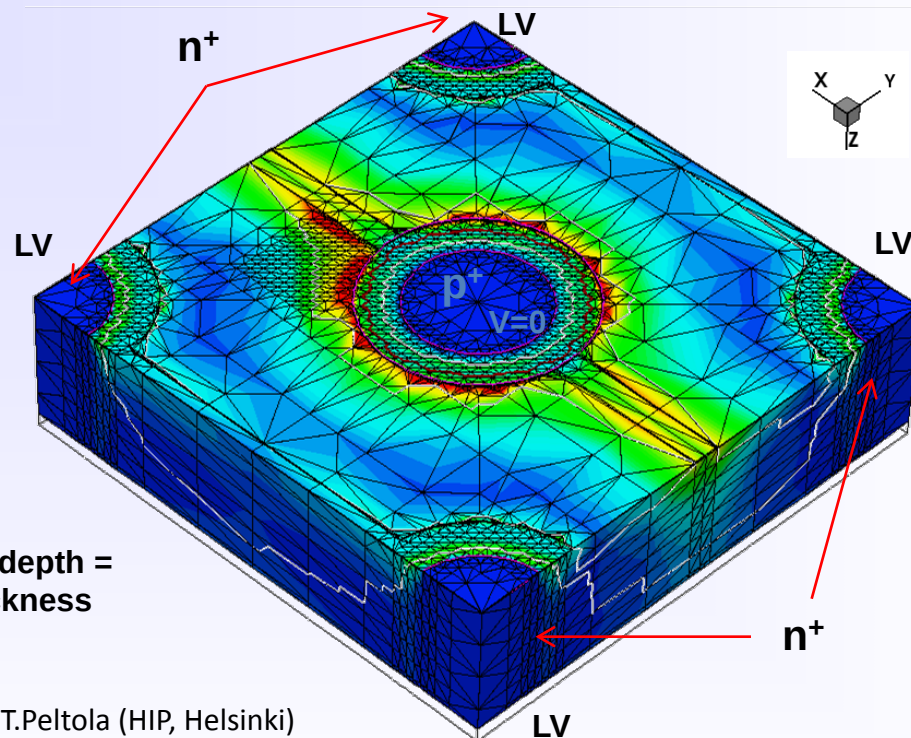
- Coupled differential equations (semiconductor equations)
- Impact of defects depending on local charge densities, field-strength, ... (“feedback loop”)
- Complex device geometry and complex signal formation in segmented devices

Doping profiles



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

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



- **Device simulation of irradiated sensors**

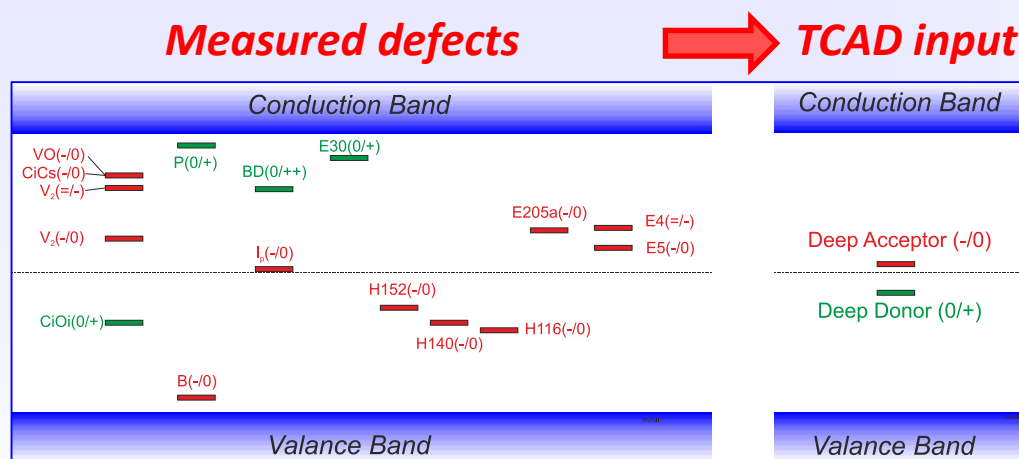
- Using: Custom made simulation software and Silvaco & Synopsis TCAD tools

- 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

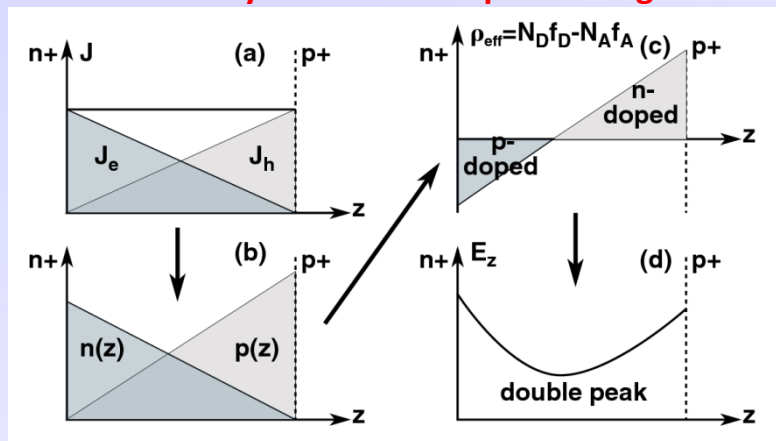


- Why do we need TCAD simulations? → Complexity of the problem!

- Example: The double junction effect after high levels of irradiation

Current density

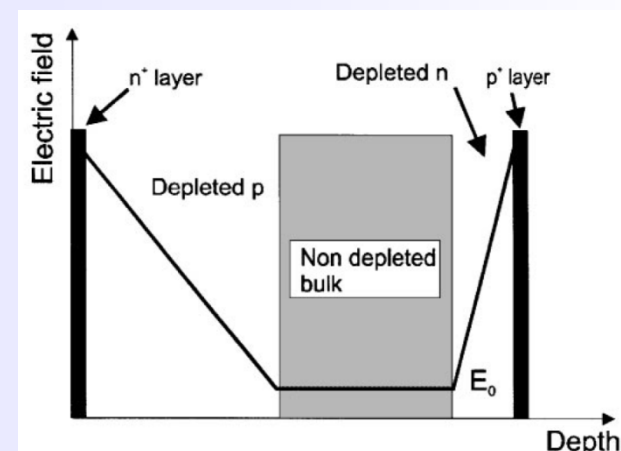
Space Charge



Free carrier density

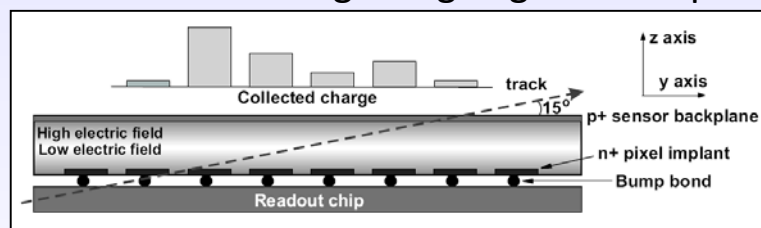
E-Field

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

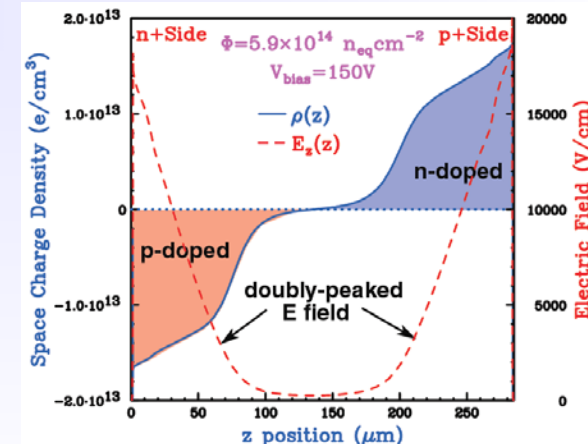
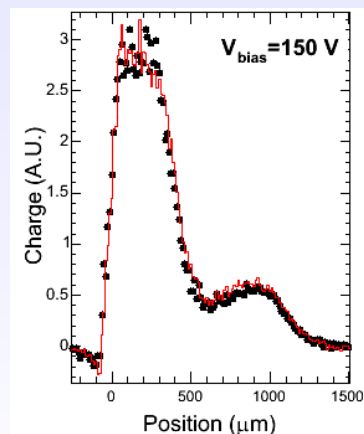


- Example: Measurement & TCAD simulation of the double junction

CMS test beam – grazing angle technique



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



- TCAD 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

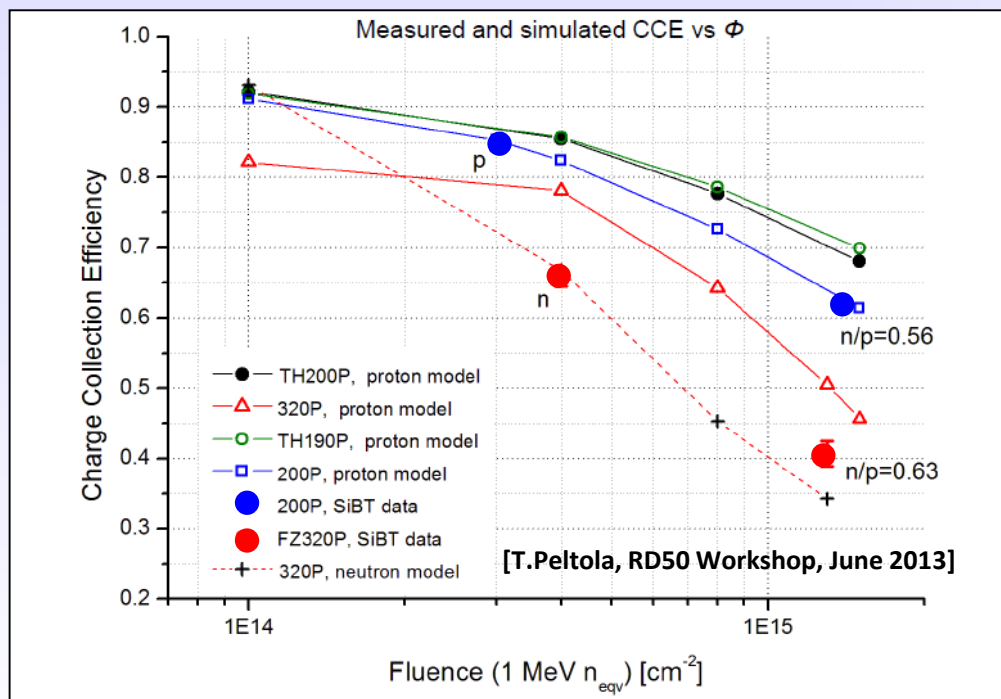
[R.Eber, RD50 Workshop, June 2013]

Neutron model

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

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	$1.55 \cdot F$
Deep donor	$E_V + 0.48$	1.2e-14	1.2e-14	$1.395 \cdot F$

- Same set of data used to simulate CCE measurements taken in a CMS test beam



- 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.

Annex: Charge Multiplication

Charge multiplication

