Summer students workshop – August 2018
CERN SSD – Solid State Detectors (EP-DT-DD)

EP-DT
Detector Technologies

Characterization of irradiated silicon sensors & Effects of Radiation on Solid State Particle Detector Performance

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OUTLINE:

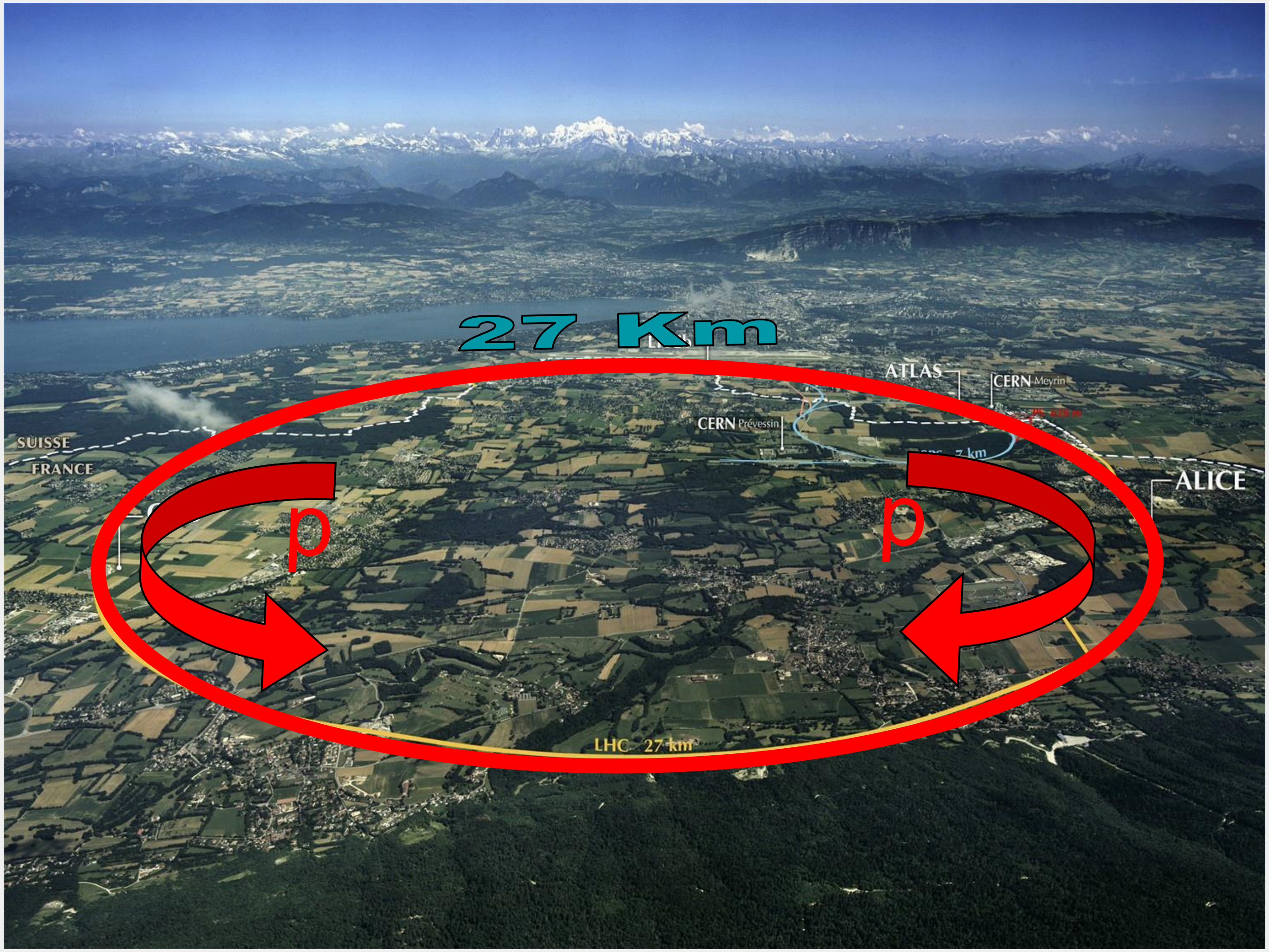
- **Particle Detectors: LHC and LHC Detectors**
- **Semiconductors: p-n junction**
- **Characterization techniques of silicon sensors**
- **Radiation damage and radiation tolerant silicon detectors**
- **Conclusions and Outlook**

Slides are available here https://indico.cern.ch/event/750363/

How does an LHC detector look like?

detector look like?

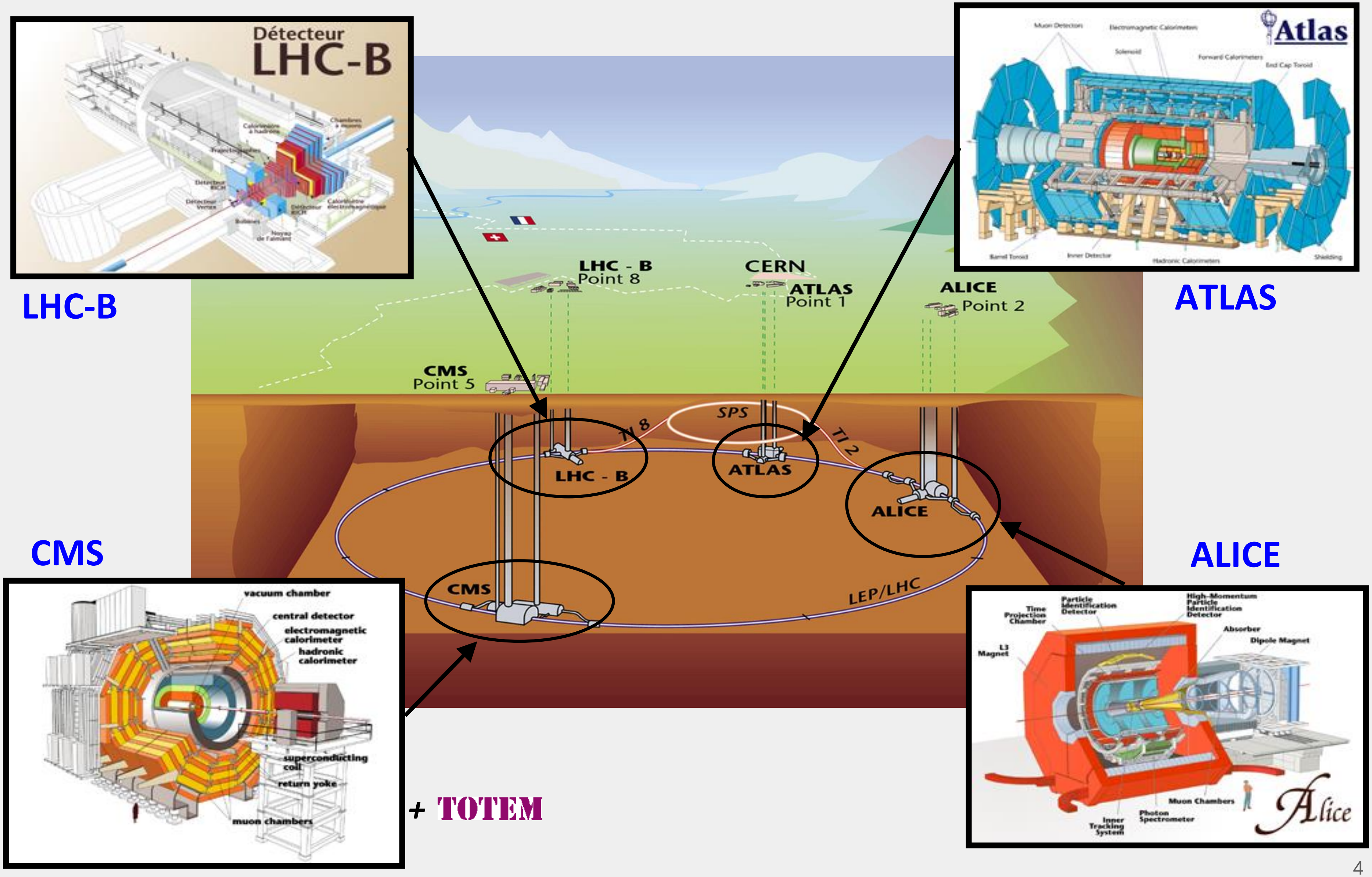
CERN & LHC - Large Hadron Collider



- **LHC experiments located at 4 interaction points**

- **CERN:**
  - 21 member states
  - ~12300 scientists (Users)
  - 3700 staff or paid personnel
  - Budget(2016) ~1000MCHF
- **LHC**: Installation in existing LEP tunnel (27 Km)
  - ≈ 4000 MCHF (machine+experiments)
  - 1232 dipoles B=8.3T
  - pp $\sqrt{s}$ = 14 TeV
    $L_{design} = 10^{34}$ cm^{-2} s^{-1}
  - Heavy ions
    (e.g. Pb-Pb at $\sqrt{s}$ ~ 1000 TeV)
- **Circulating beams: 10.9.2008**
- **Incident: 18.9.2008**
- **Beams back: 19.11.2009**
- **2012: reaching 2 x 4 TeV**
- **2015: Run 2 at 2 x 6.5 TeV**
- **2016: Reaching 10^{34} cm^{-2} s^{-1}**
  …excellent performance!
- **2019-2020: LS2; 2021: Run 3**
- **2023: LS3 …2026: HL-LHC**

LHC Experiments



LHC-B

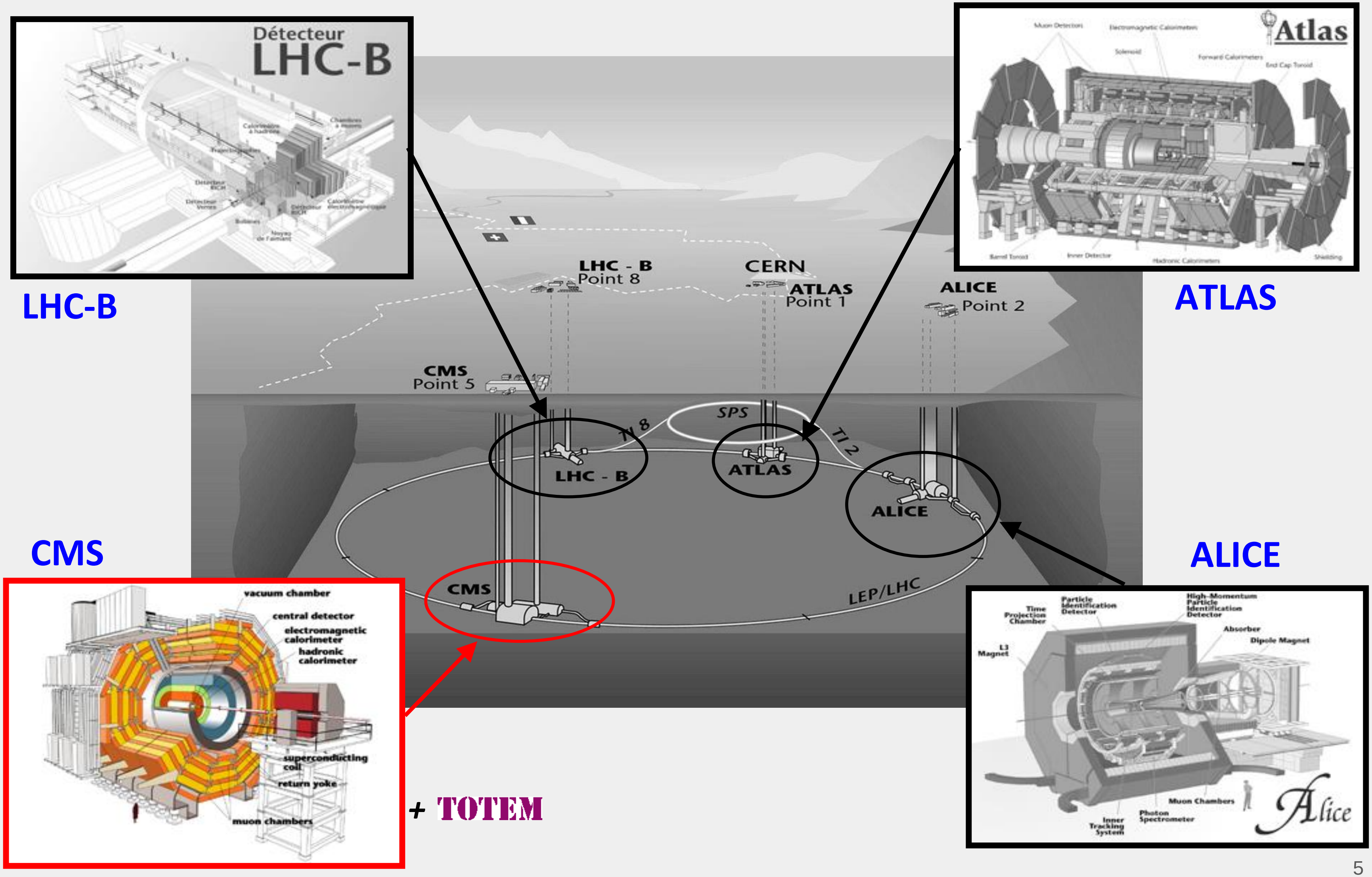
ATLAS

CMS

ALICE

+ **TOTEM**

LHC Experiments



LHC-B

ATLAS

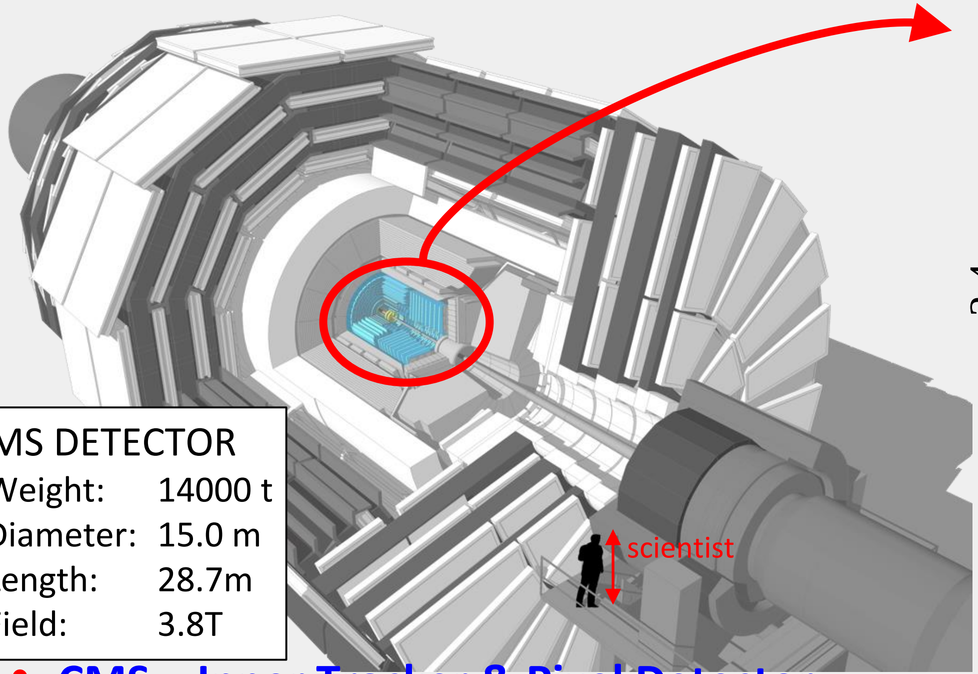
CMS

ALICE

+ **TOTEM**

Silicon Detectors in HEP

- **LHC example: The CMS DETECTOR**

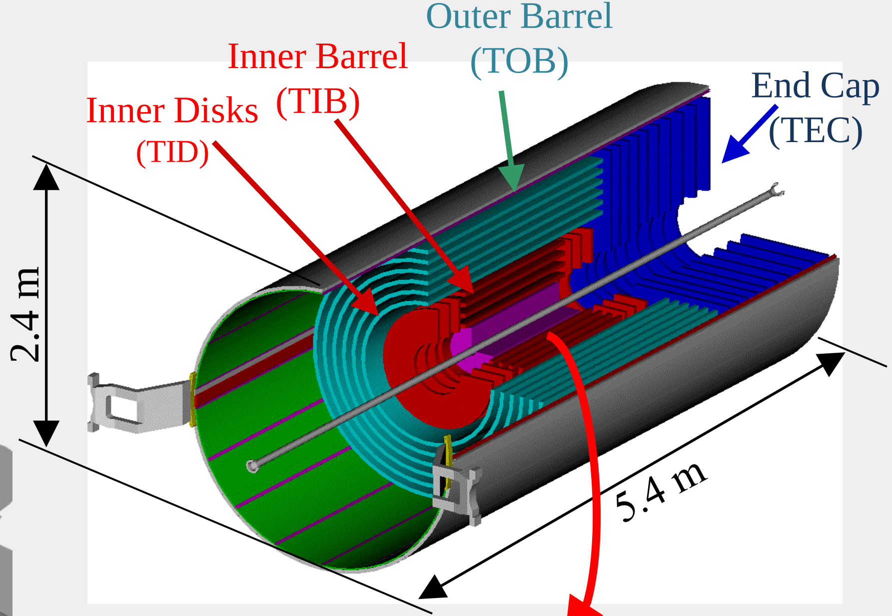


CMS DETECTOR

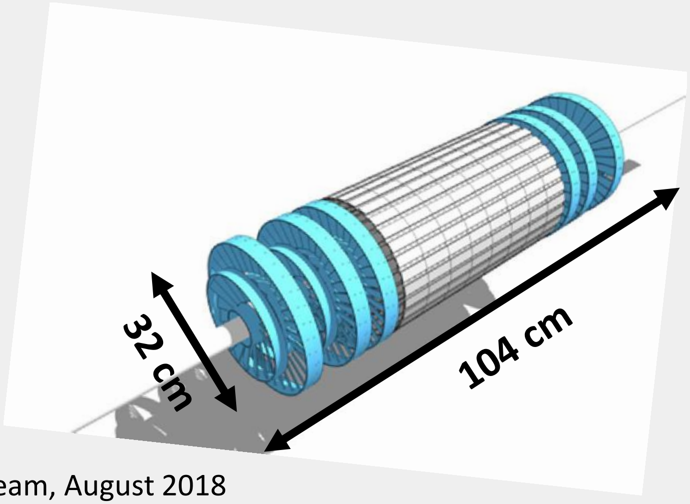
Weight:	14000 t
Diameter:	15.0 m
Length:	28.7m
Field:	3.8T

- **CMS – Inner Tracker & Pixel Detector**
  - **Micro Strip:**
  - **~ 214 m^2 of silicon strip sensors, 11.4 million strips**
  - **Pixel:**
  - **4 layers & 2 x 3 disks: silicon pixels (~ 1m^2)**
  - **124 million pixels (100x150µm^2)**
  - **Resolution: σ(rϕ) ~ 10 µm, σ(z) ~ 25µm**

- **Inner Tracker**



- **Pixel Detector** (upgraded in 2017)

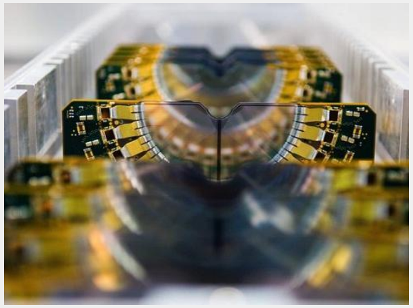


LHC Silicon Tracking Detectors

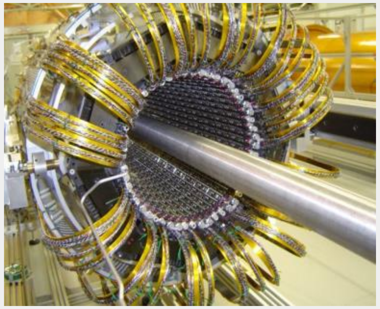
Silicon tracking detectors are used in all LHC experiments:

Different sensor technologies, designs, operating conditions,….

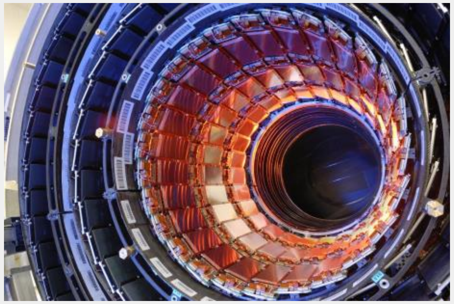
ALICE Pixel Detector



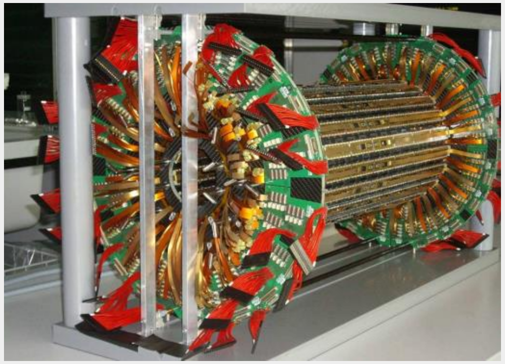
LHCb VELO



ATLAS Pixel Detector



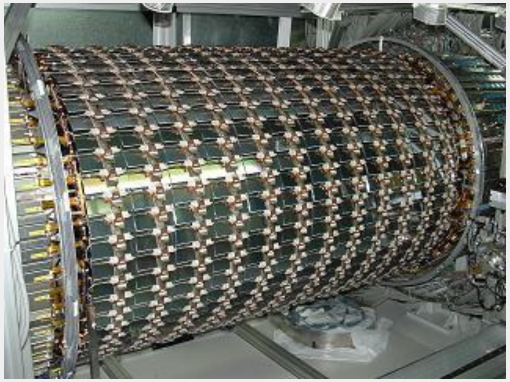
CMS Strip Tracker IB



CMS Pixel Detector

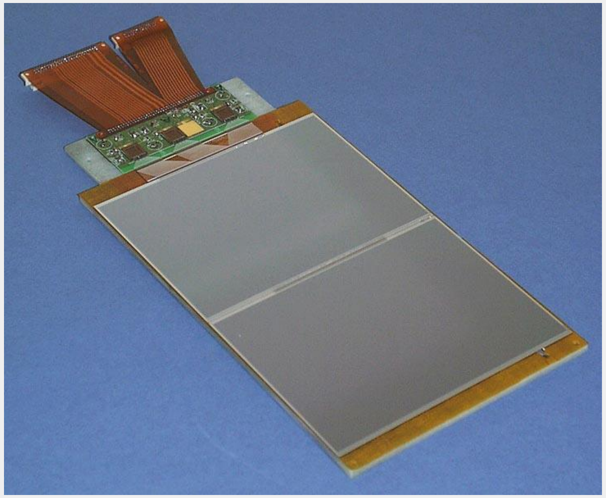
ALICE Drift Detector

ALICE Strip Detector



ATLAS SCT Barrel

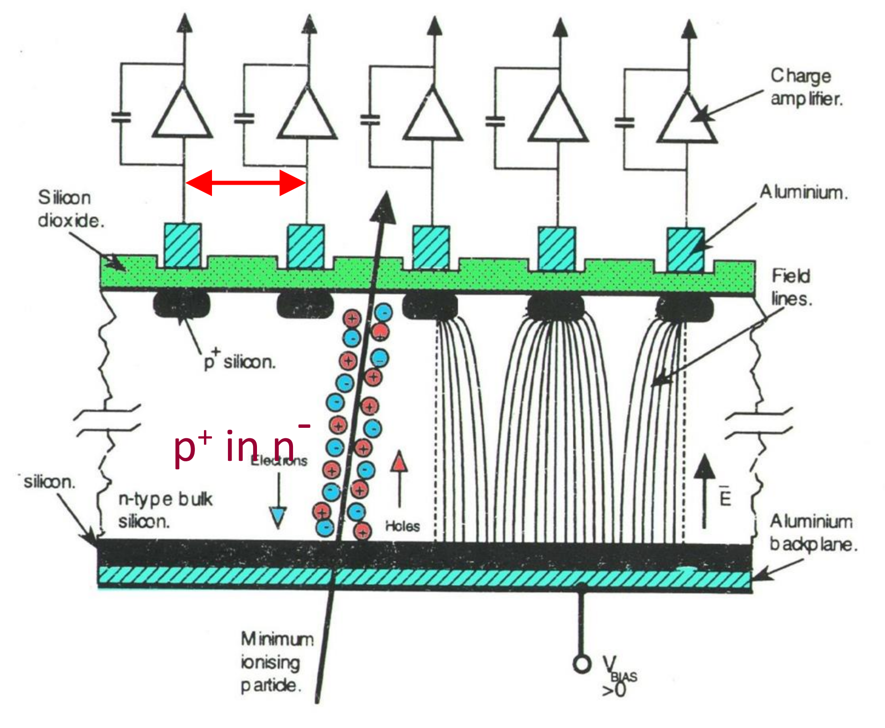
Micro-strip Silicon Detectors



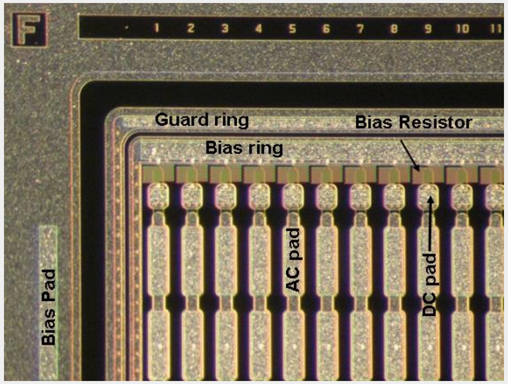
Highly segmented silicon detectors have been used in Particle Physics experiments for nearly 30 years. They are favourite choice for Tracker and Vertex detectors

(high resolution, speed, low mass, relatively low cost)

Pitch ~ 50μm



Resolution ~ 5μm



Main application: detect the passage of ionizing radiation with high <u>spatial</u> resolution and good efficiency.

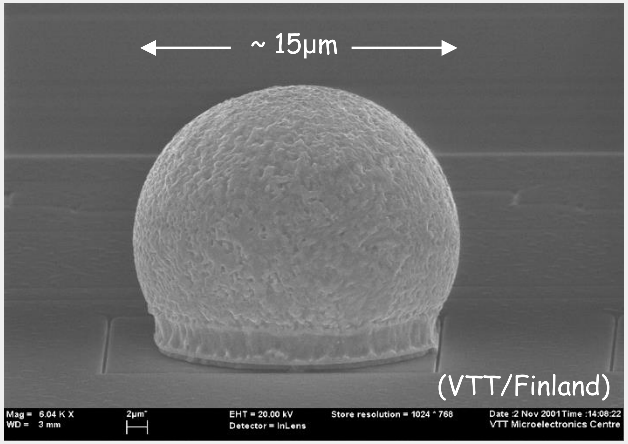
Segmentation → position

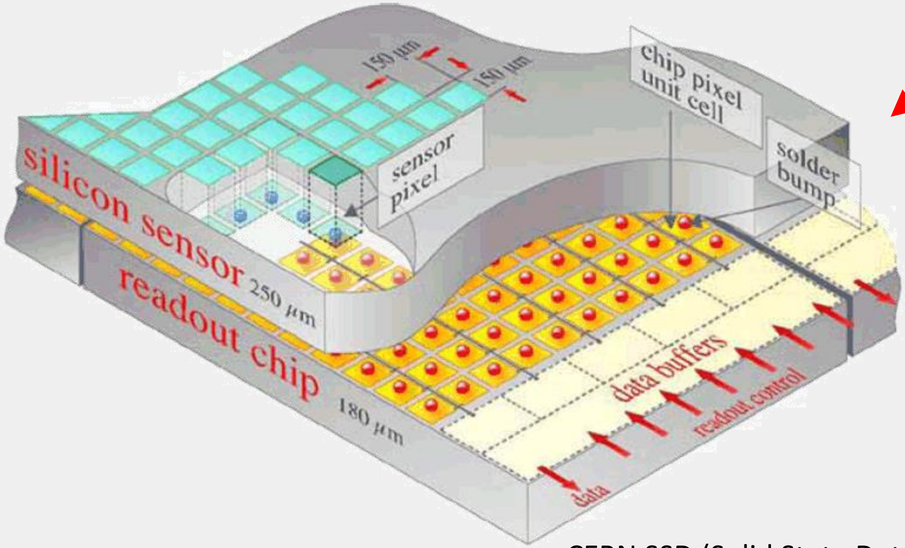
Reference: P.Allport, Sept.2010

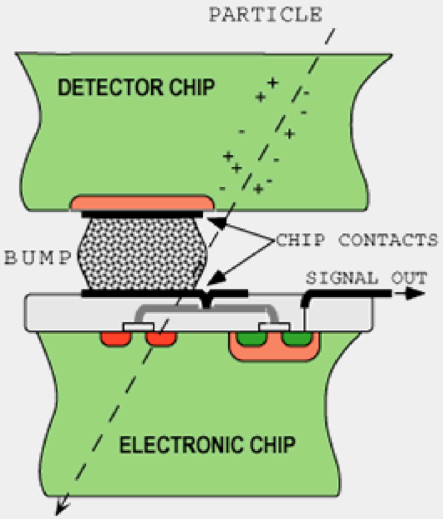
Hybrid Pixel Detectors

- **Hybrid Active Pixel Sensors**
  - **segment silicon to diode matrix with high granularity**
    (⇒ true 2D, no reconstruction ambiguity)
  - **readout electronic with same geometry**
    (every cell connected to its own processing electronics)
  - **connection by “bump bonding”**
  - **requires sophisticated readout architecture**
  - **Hybrid pixel detectors will be used in LHC experiments:**
    ATLAS, ALICE, CMS and LHCb

Solder Bump: Pb-Sn







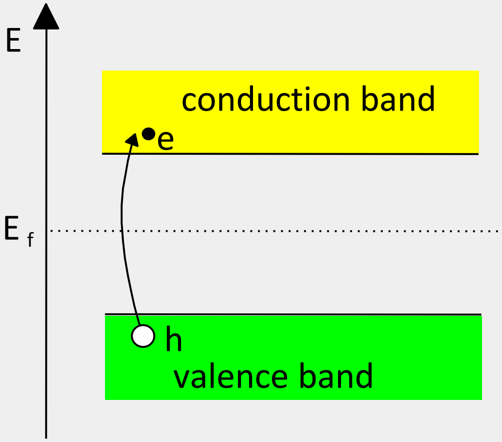
Flip-chip technique

Silicon Detectors

How does a silicon detector work?

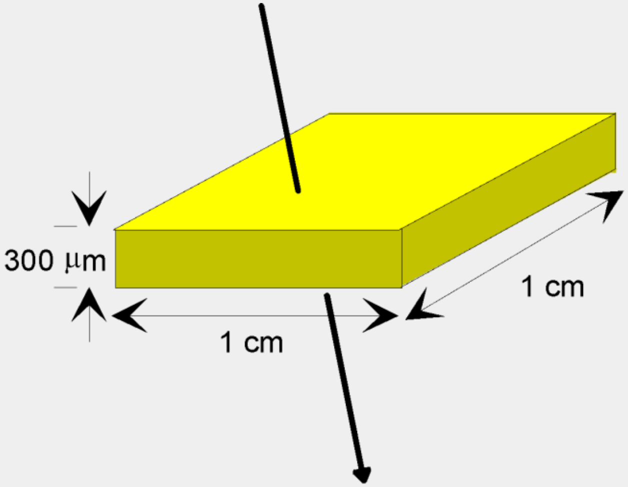
work?

How to obtain the signal?



In a pure intrinsic (undoped) semiconductor the electron density *n* and hole density *p* are equal.

$n = p = n_i$ For Silicon: $n_i \approx 1.45 \cdot 10^{10}$ cm^{-3}

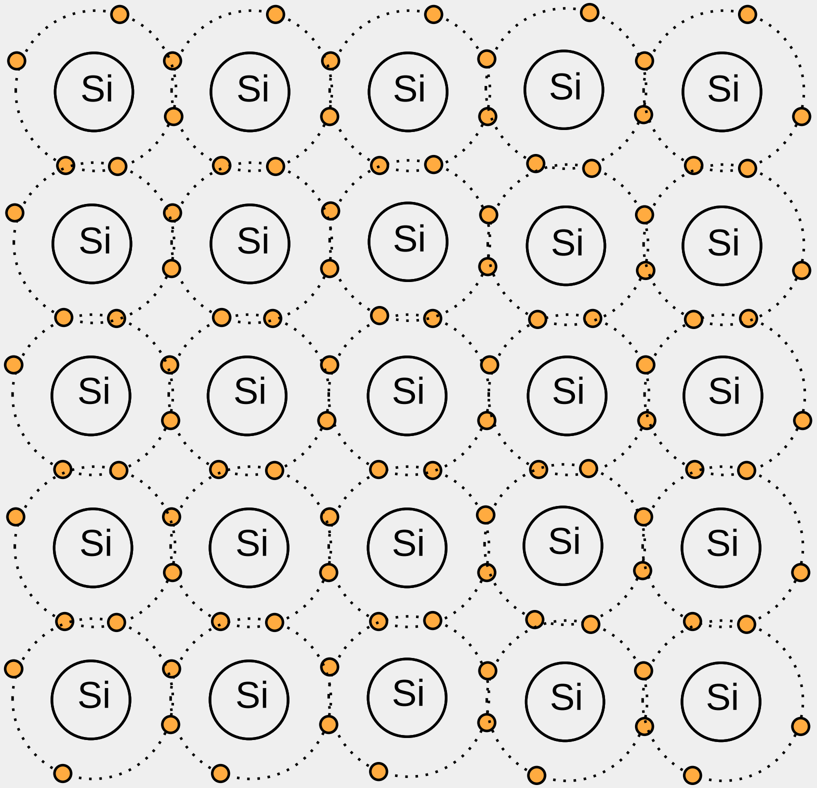


$4.5 \cdot 10^8$ free charge carriers in this volume,
but only $3.2 \cdot 10^4$ e-h pairs produced by a M.I.P.

⇒ Reduce number of free charge carriers, i.e. deplete the detector

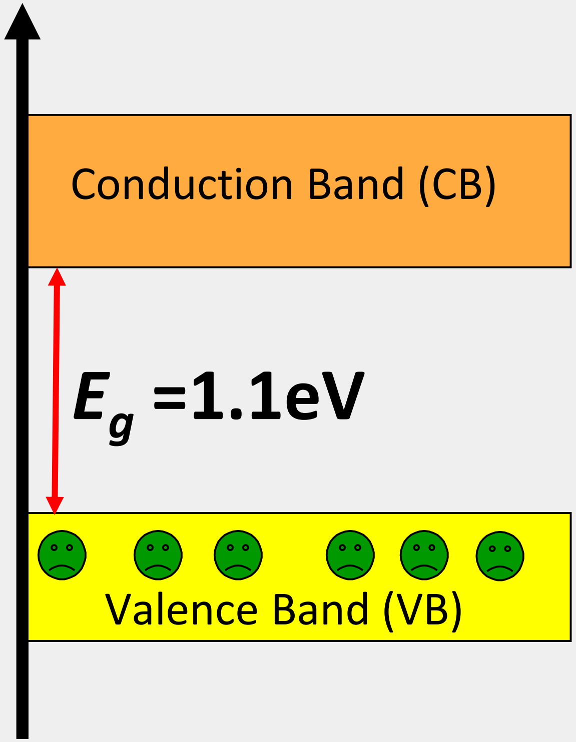
⇒ **Most detectors make use of reverse biased p-n junctions**

Covalent Bonding of Pure Silicon



Silicon atoms share valence electrons to form insulator-like bonds

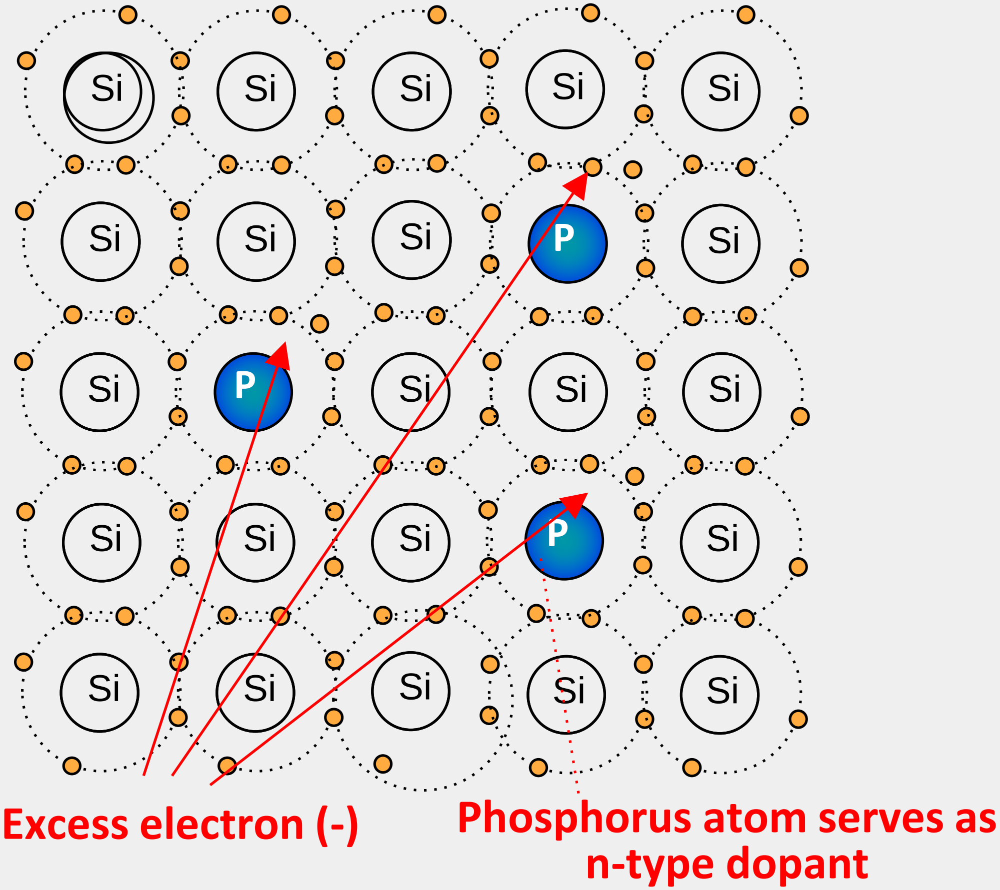
Energy

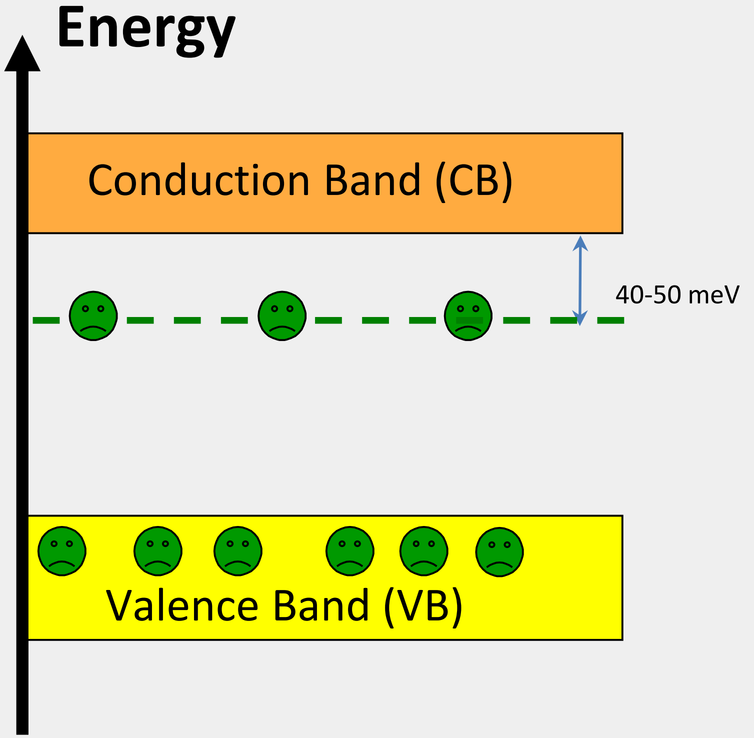


Thermal energy at RT: $3/2\ k_B T \sim 40$meV

Electrons in n-type silicon with P dopant

Donor atoms provide excess electrons to form n-type silicon



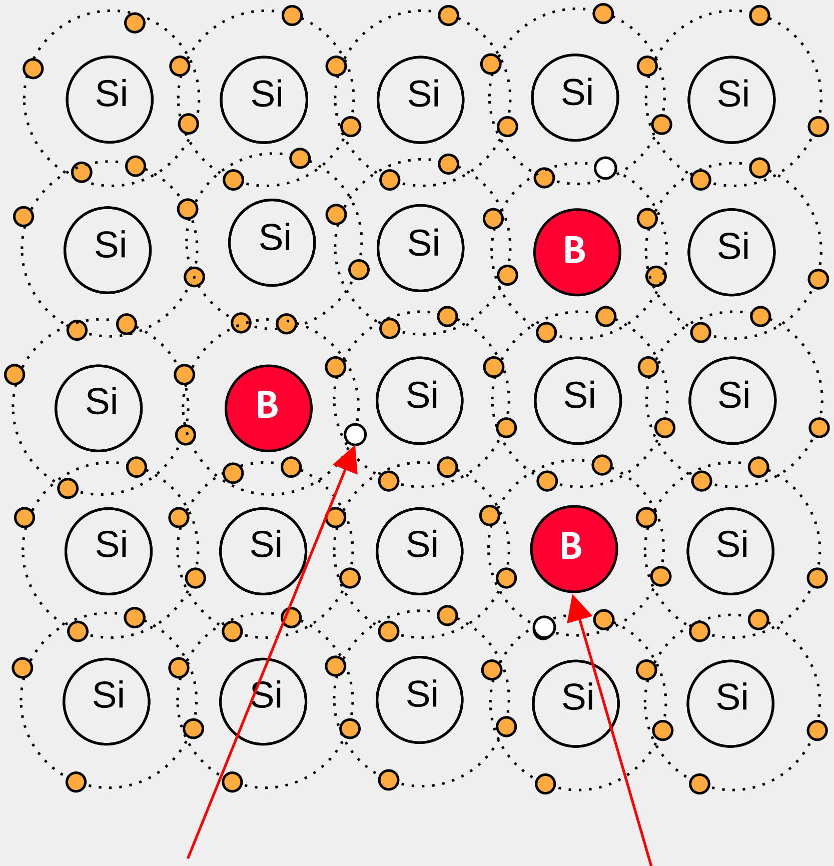


In n-type Si electrons are the majority charge carriers. They surpass the number of holes by orders of magnitude (n_i~10^{10} cm^{-3}, N_d=10^{12}-10^{18} cm^{-3}):

$$p_n = \frac{{n_i}^2}{N_d}$$

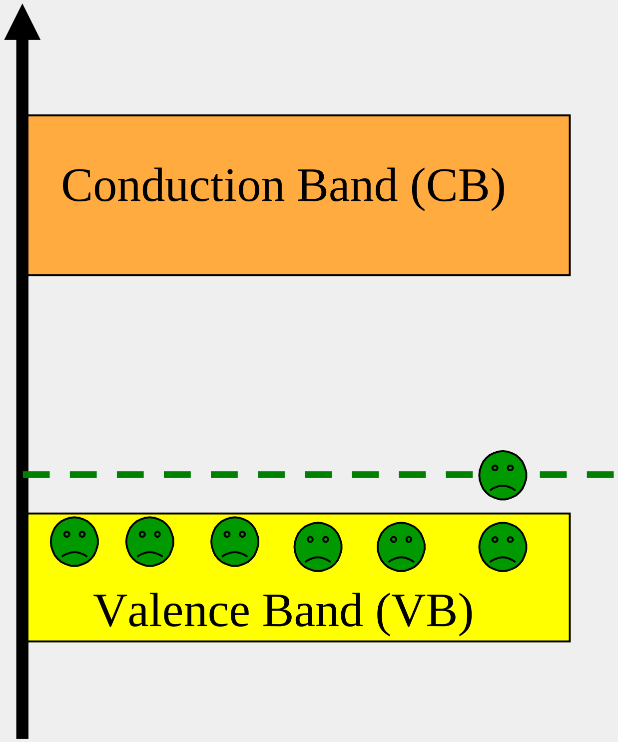
Holes in p-Type Silicon with B Dopant

Acceptor atoms provide a deficiency of electrons to form p-type silicon



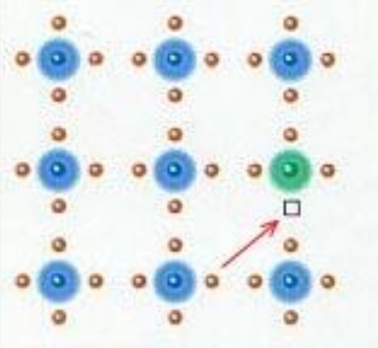
+ Hole

Boron atom serves as p-type dopant

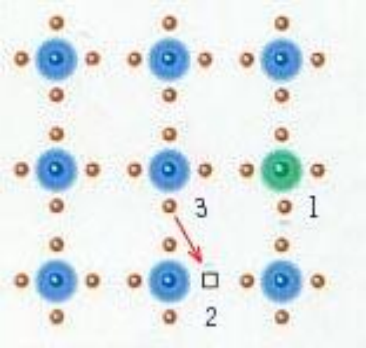


In p-type Si holes are the majority charge carriers. They surpass the number of electrons by orders of magnitude.

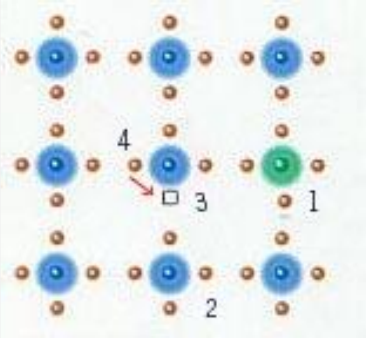
“Hole Movement in Silicon”



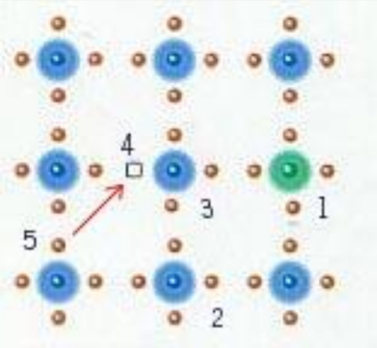
Boron is neutral, but nearby electron may jump to fill bond site



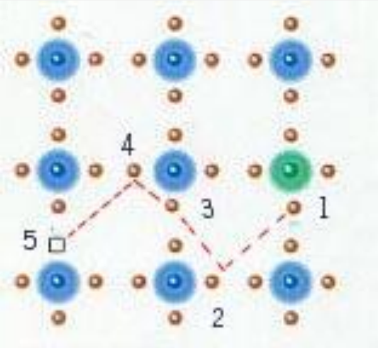
Boron is now a negative ion



Only thermal energy to kick electrons from atom to atom

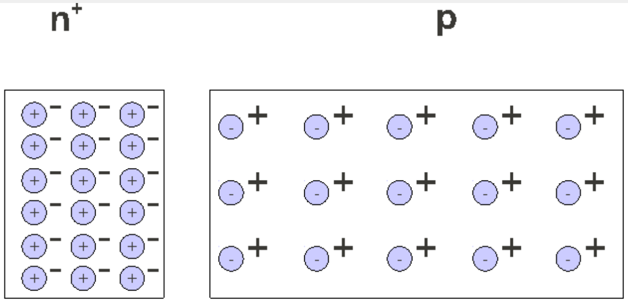


Hole moved from 2 to 3 to 4, and will move to 5

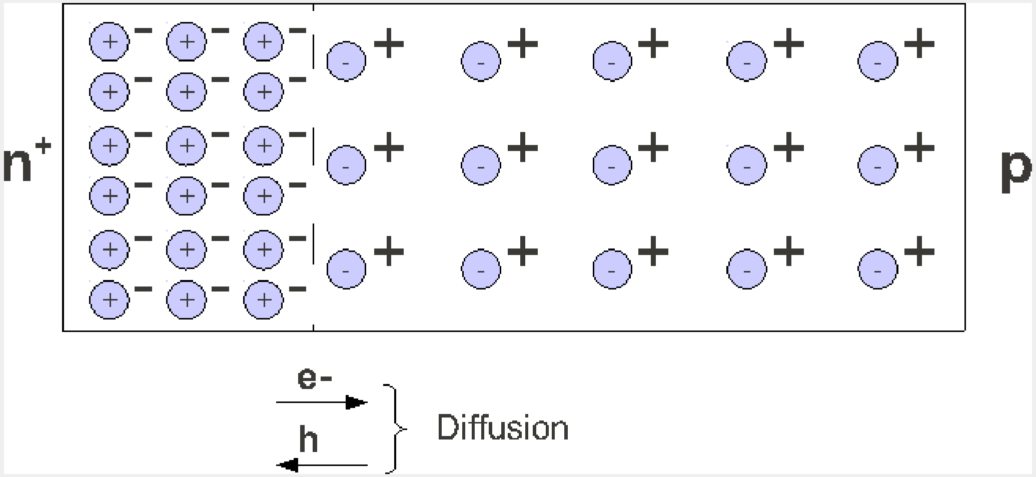


The empty silicon bond sites (holes) are thought of as being *positive*, since their presence makes that region positive.

Sketchy view of a pn-junction (I)

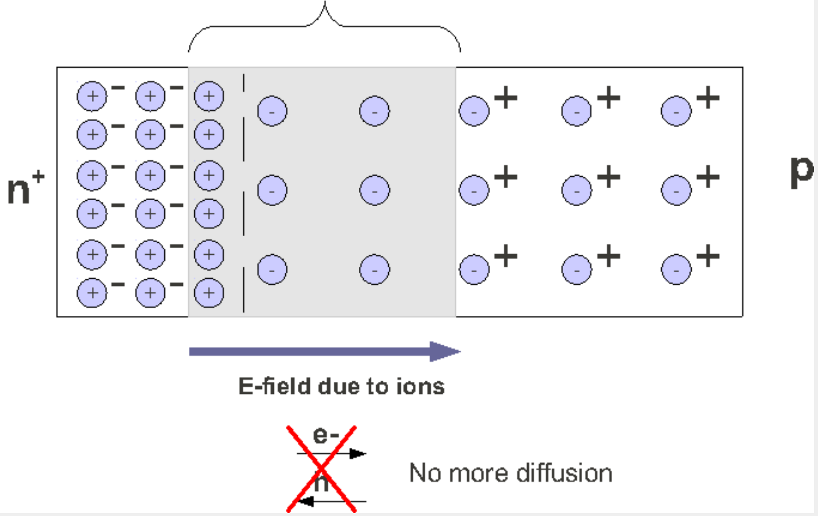


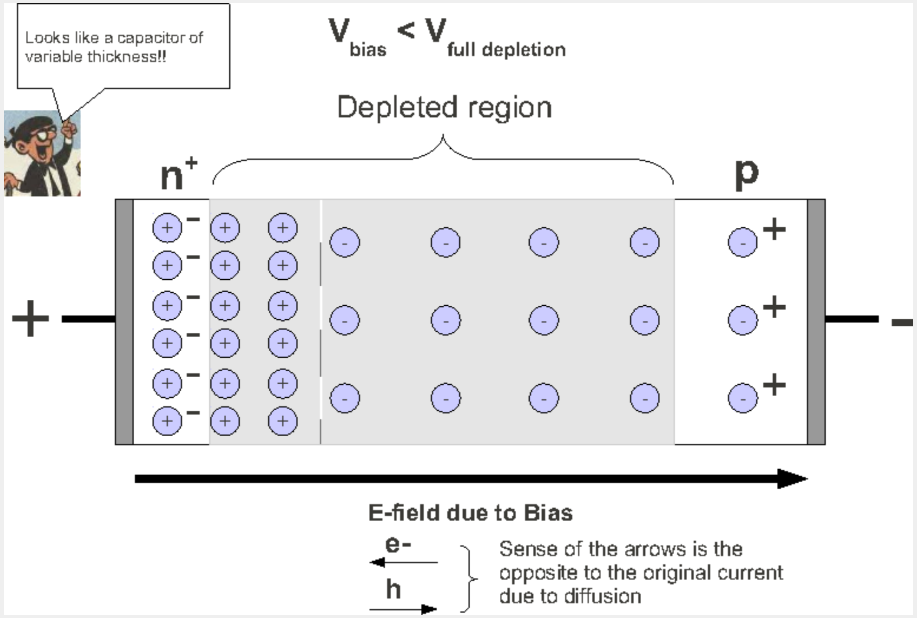
- Sketchy, not to scale
- In detectors, one element of the junction more doped than the other (here, n>>p)
- N-type detector: electrons are majority ([n]=Nd), holes are minority charge carriers ($[p]=n_i^2/N_d$).



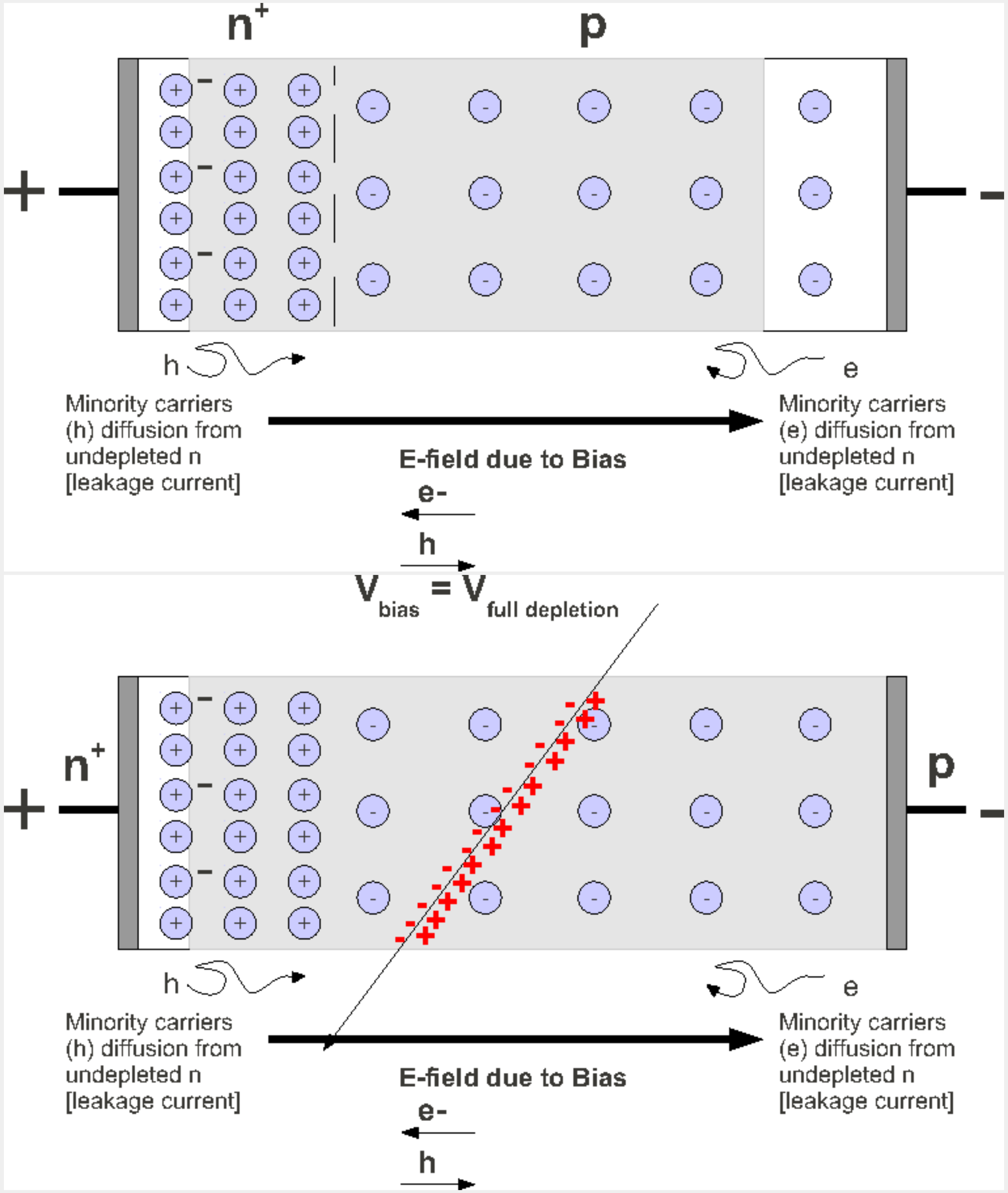
Depleted region: only fixed charges (=*space charge*), loosely bound charge carriers are depleted.

Recombination of e and h leads to deeper depletion in the less doped p side.





Sketchy view of a pn-junction (II)



Majority charge carriers in N-type and P-type have **disappeared→ no current from majority charge carriers**.

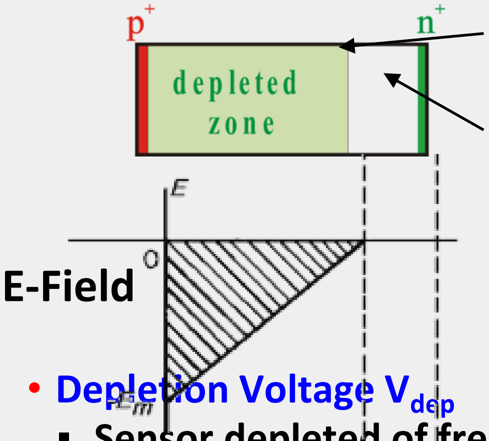
There is a **small reverse current** (leakage) coming from carriers injected by diffusion from the undepleted regions/surface (no E-field inside the undepleted bulk). Diffusion electrons (holes) enter from undepleted P (N) into depleted P SCR (N SCR). **Leakage current due to minority carriers.**

Leakage current increases with T, thickness and irradiation. It constitutes the “background noise” to the measurement.

<u>**In this workshop**</u>, we will measure the leakage current and capacitance characteristics of irradiated detectors

Depletion Voltage

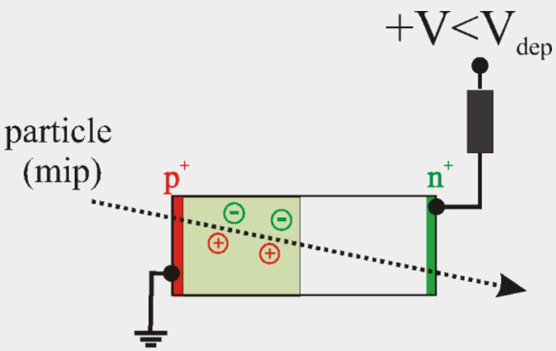
- **Below depletion ($V<V_{dep}$)**



Positive **space charge**, N_{eff} =[P] (ionized Phosphorus atoms)

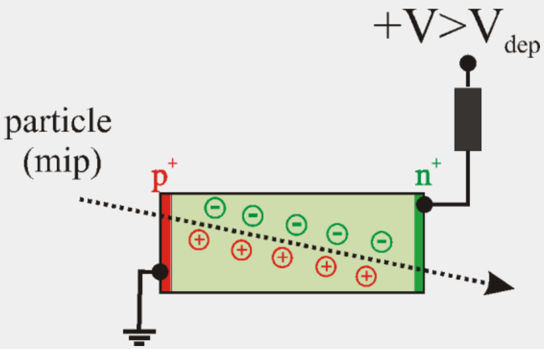
neutral bulk (no electric field)

  - **Charge generated inside depleted zone will be detected**
  - **Charge generated in 'neutral bulk' will recombine**



- **Depletion Voltage V_{dep}**
  - **Sensor depleted of free charge carriers**
  - **Electric field throughout complete device**
  - **Complete sensor volume sensitive (active)**

  - **Example:**
    - d = 300 μm
    - N_{eff} = [P] =1.5×10^{12} cm^{-3} (ρ ≈ 3kΩcm)
    - V_{dep} ≈ 100V



- **Full charge collection only for ($V>V_{dep}$)**

depletion voltage V_{dep}

detector thickness d

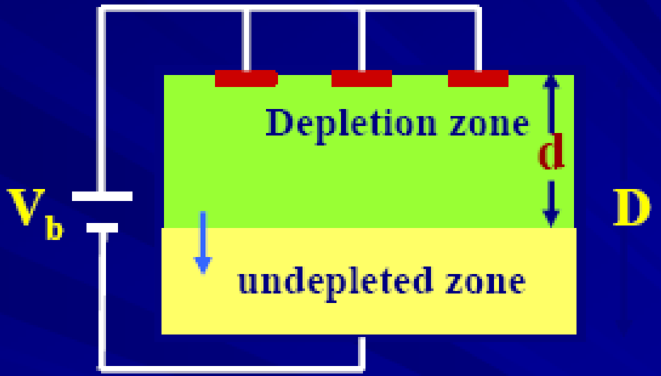
$$\boxed{V_{dep}=\frac{e}{2\cdot\varepsilon}\cdot\left|N_{eff}\right|\cdot d^{2}}$$

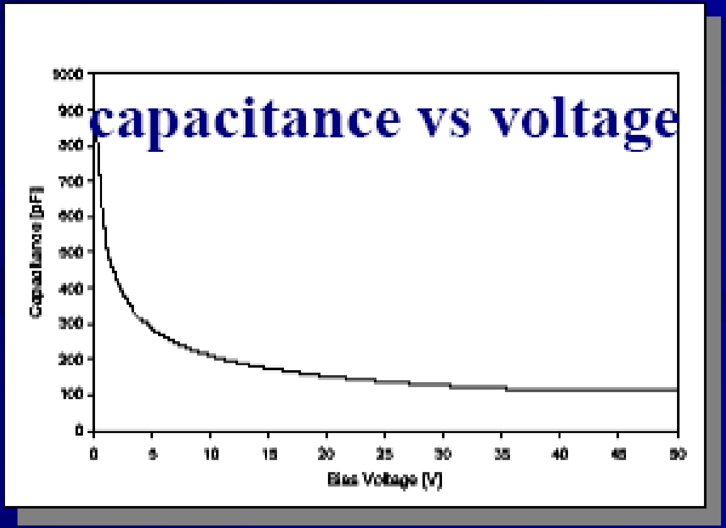
effective space charge density N_{eff}

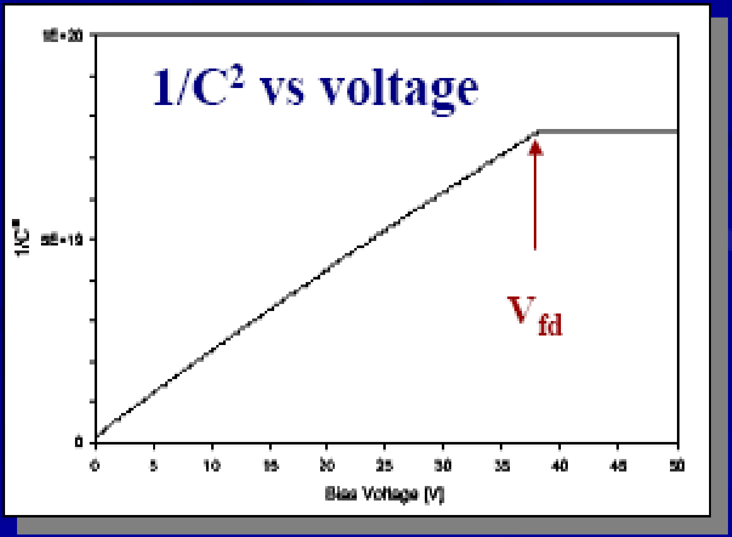
Depletion Zone: Properties

- The depletion voltage can be determined by measuring the capacitance versus reverse bias voltage. The capacitance is simply the parallel plate capacity of the depletion zone.

$$C = A\sqrt{\frac{\varepsilon}{2\rho\mu V_b}}$$



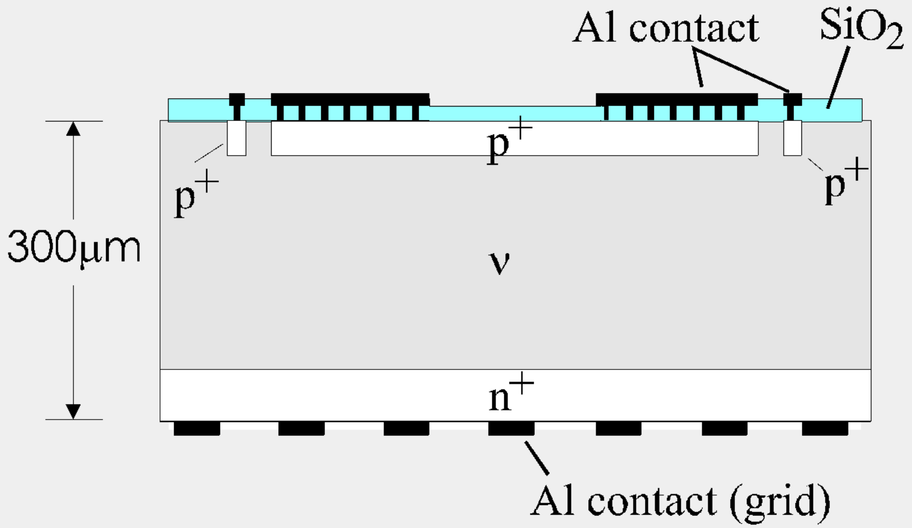


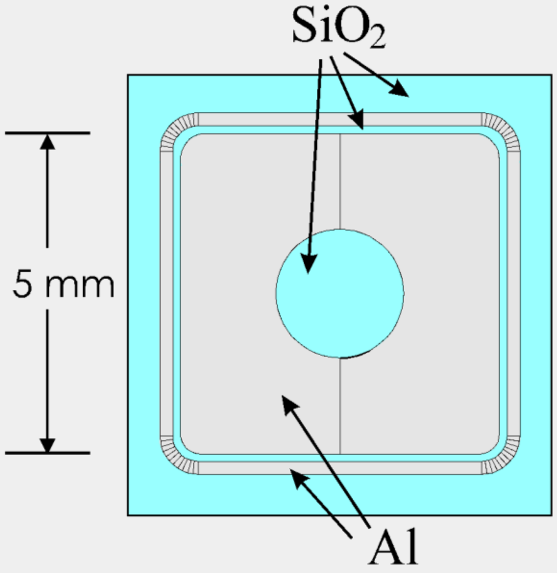


Characterization techniques

Testing Structures - Simple Diodes

Example: Test structure from ITE





- **Very simple structures in order to concentrate on the bulk features**
  - **Typical thickness: 300µm**
  - **Typical active area: 0.5 × 0.5 cm^2**
- **Openings in front and back contact**
  - **optical experiments with lasers or LED**

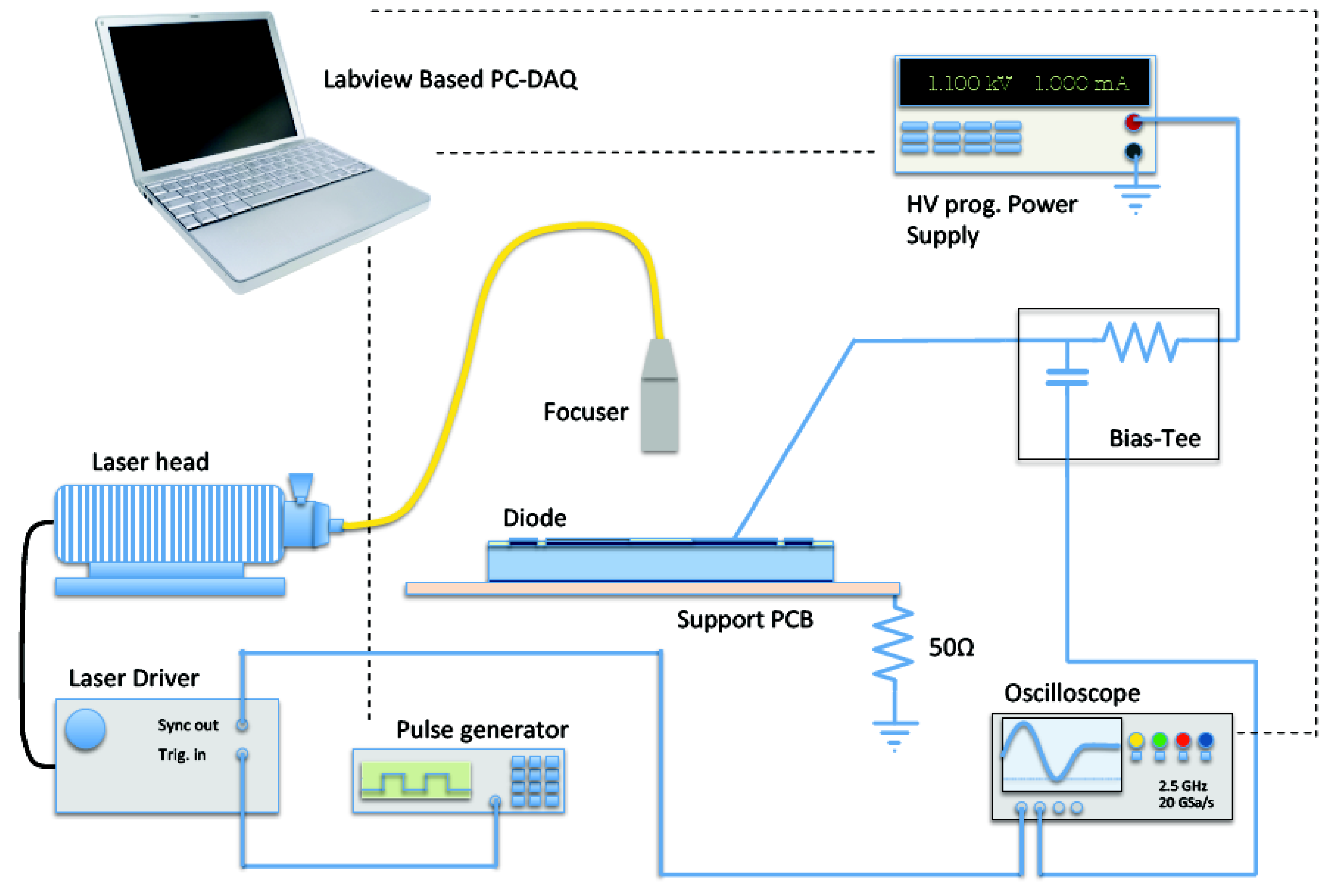
Characterization techniques for detectors

- **Detectors need to be optimized for Minimum Ionizing Particles (MIPs) detection. Study charge collection efficiency with radioactive sources (Sr90, for instance) and finally test beams (bunched beams, real scale system test).**

- **Time resolved induced currents provide information on drift velocity, electric field configuration, trapping times.**
  - Best measurement conditions can be achieved with lasers:
    - ***Reproducibility****: no fluctuations in deposited energy → averaging possible -> S/N improvement.*
    - ***Selectable absorption length****: by varying laser wavelength. Contribution from only one type of carriers (red laser, top or bottom injection) or both types (IR laser).*
    - *Easy* ***triggering***

- **TCT (Transient Current Techniques) use laser pulses to induce charge carriers in the detector. Time resolved induced currents are recorded and analysed.**

TCT setup



Nicola Pacifico, PhD thesis, Bari University, 2012

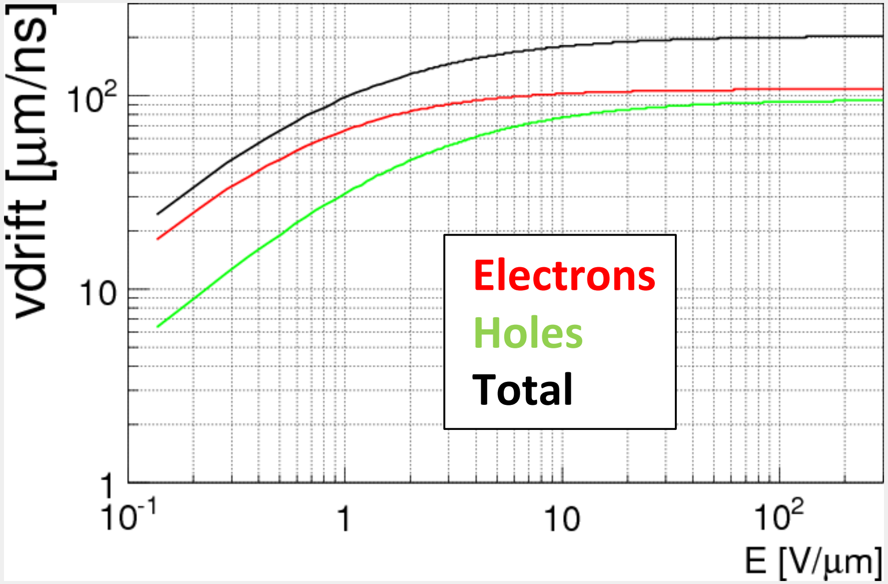
Fig. 4.7: Schematic view of a TCT setup

Transient Current Technique

- **Time resolved induced current can be calculated using Ramo theorem**

$$I(t) = -q\vec{v}\overrightarrow{E_W}$$

where $\vec{v} = \vec{v}(E)$ is the drift velocity, E is the electric field and $\overrightarrow{E_W}$ the so-called weighting field



- **Electric field** determines the charge trajectory and the velocity of the particle. It changes:
  - With bias voltage
  - Strip geometry
  - Irradiation of the detector

Electric field for typical detectors:

- Pad diode: linear electric field (~capacitor)
- Strip detector: peaked near the electrodes, linear in the center

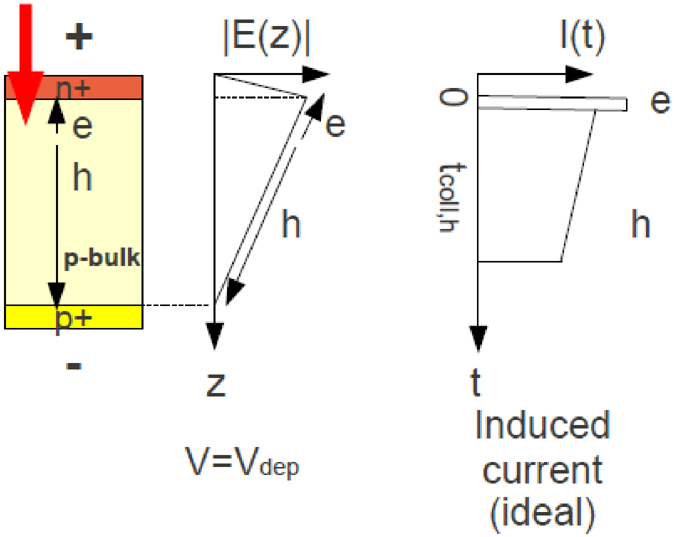
Weighting field is the derivative of the weighting potential U_W. This potential determines how charge couples to an electrode: $Q = q(U_w(2) - U_w(1))$ (induced charge by a carrier moving from position 1 to 2)

Weighting field for typical detectors:

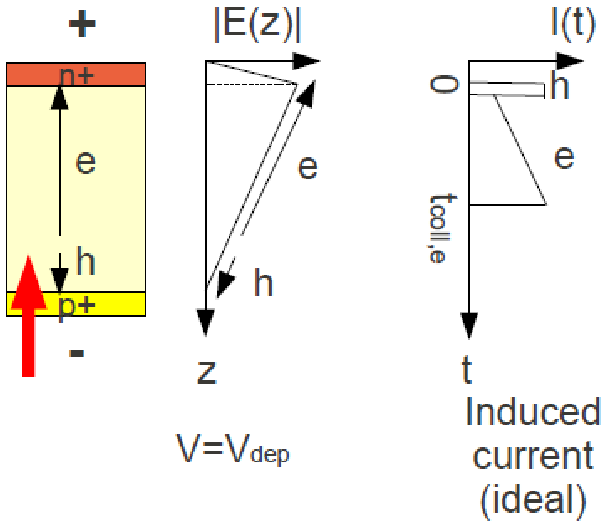
Pad diode: constant
Strip detector: very asymmetric. Peaked near the collection electrode

TCT explained: diode

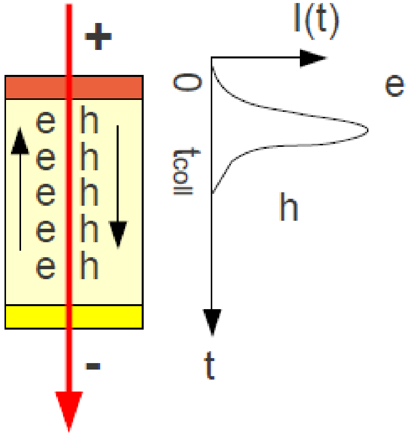
Top Red TCT (h injection)



Bottom Red TCT (e injection)

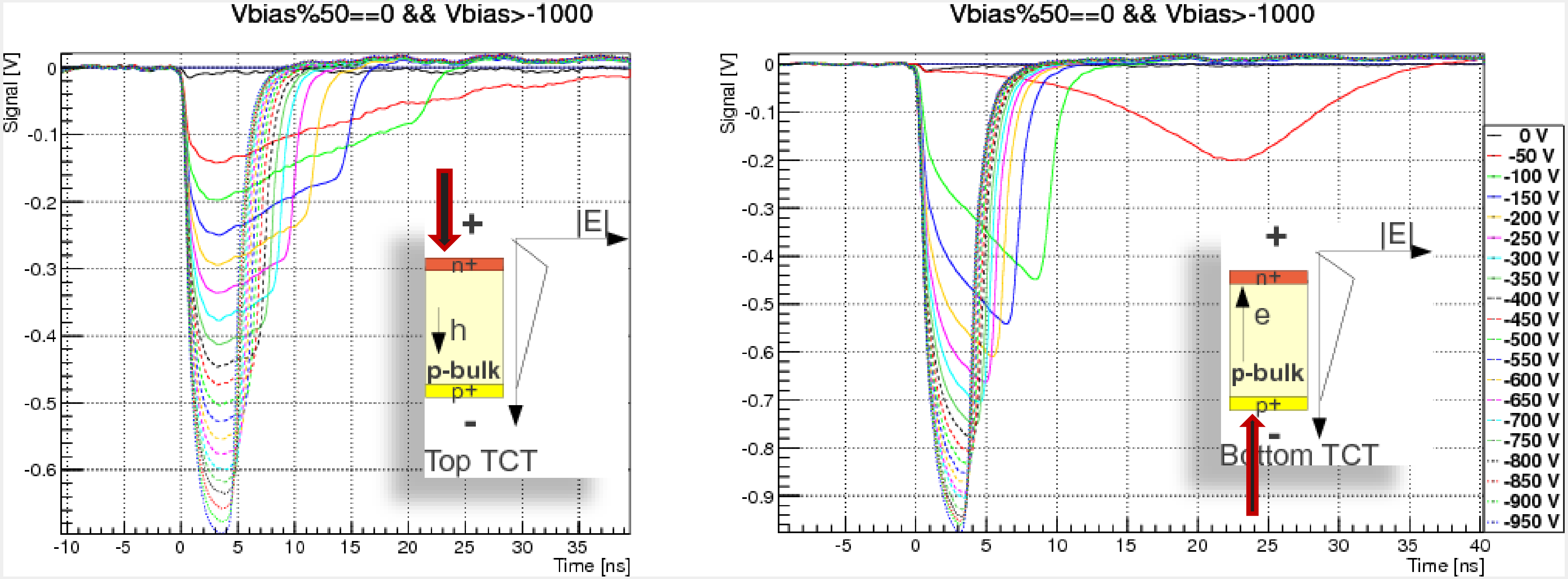


IR TCT



- Red laser penetration depth~10 μm (1 mm for IR)
- Depletion voltage V$_{dep}$ can be calculated from Q=Q(V) plots. Either IR or red back illumination is needed. Due to the low absorption depth in red, all the charge in front illumination is collected before the detector is fully depleted.

TCT example: diode



Top TCT, h-injection (p-bulk):

- Induced current maximum at front junction
- Longer **collection time** due to smaller drift velocity

Bottom TCT, e injection:

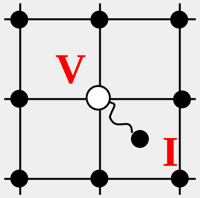
- Drift velocity increase towards the front side
- Shorter collection time, and higher amplitude of pulses, both due to higher drift velocity

Radiation Damage

What is radiation damage?

Radiation Damage – Microscopic Effects

particle → *Si_S* → E_K>25 eV



Vacancy + Interstitial → *point defects (V-O, C-O, ..)*

Si_S → E_K > 5 keV *point defects and clusters of defects*

- **^{60}Co-gammas**
  - Compton Electrons with max. $E_\gamma \approx 1$ MeV (<u>no cluster production</u>)
- **Electrons**
  - E_e > 255 keV for displacement
  - E_e > 8 MeV for cluster
- **Neutrons (elastic scattering)**
  - E_n > 185 eV for displacement
  - E_n > 35 keV for cluster

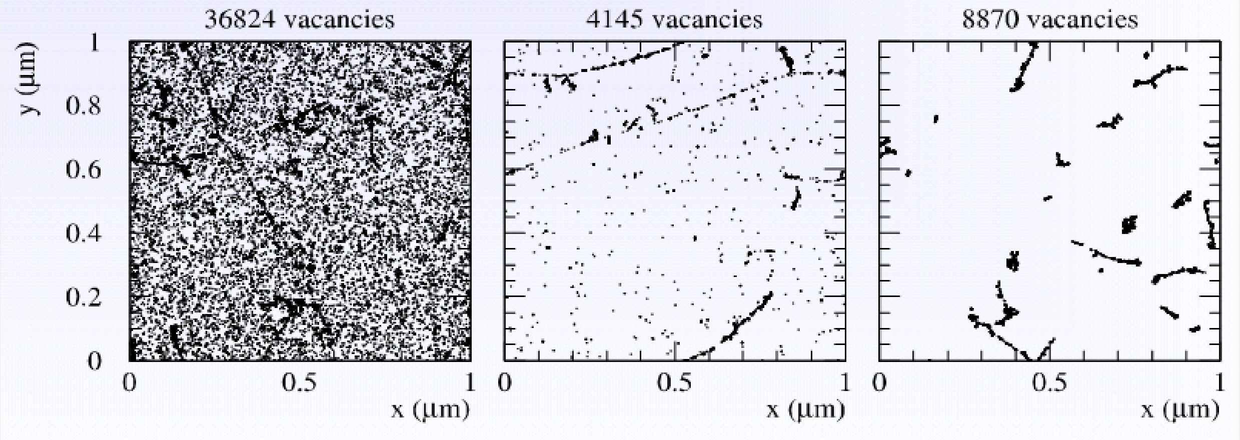
Only point defects ⟷ point defects & clusters ⟷ Mainly clusters

---

Simulation:

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

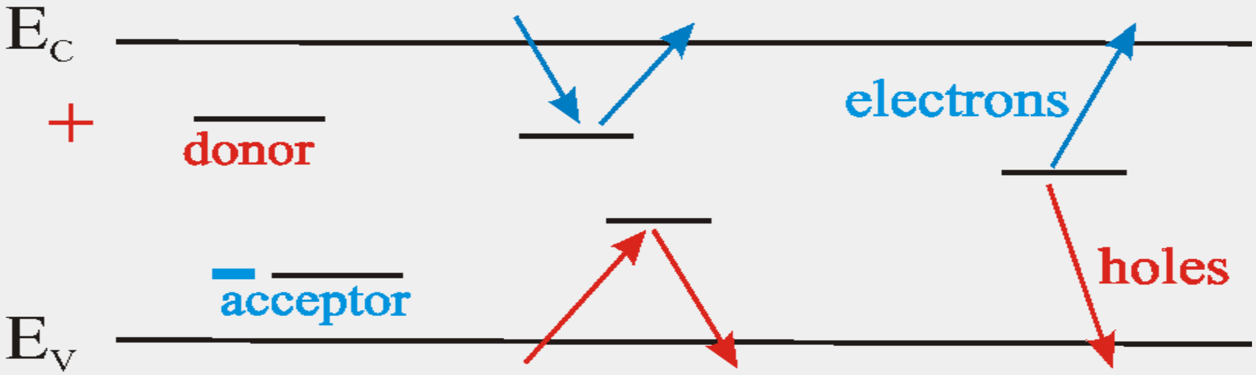
[Mika Huhtinen NIMA 491(2002) 194]



10 MeV protons **24 GeV/c protons** **1 MeV neutrons**

Impact of Defects on Detector properties

Shockley-Read-Hall statistics
(standard theory)



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

Trapping (e and h)
⇒ CCE
shallow defects do not contribute at room temperature due to fast detrapping

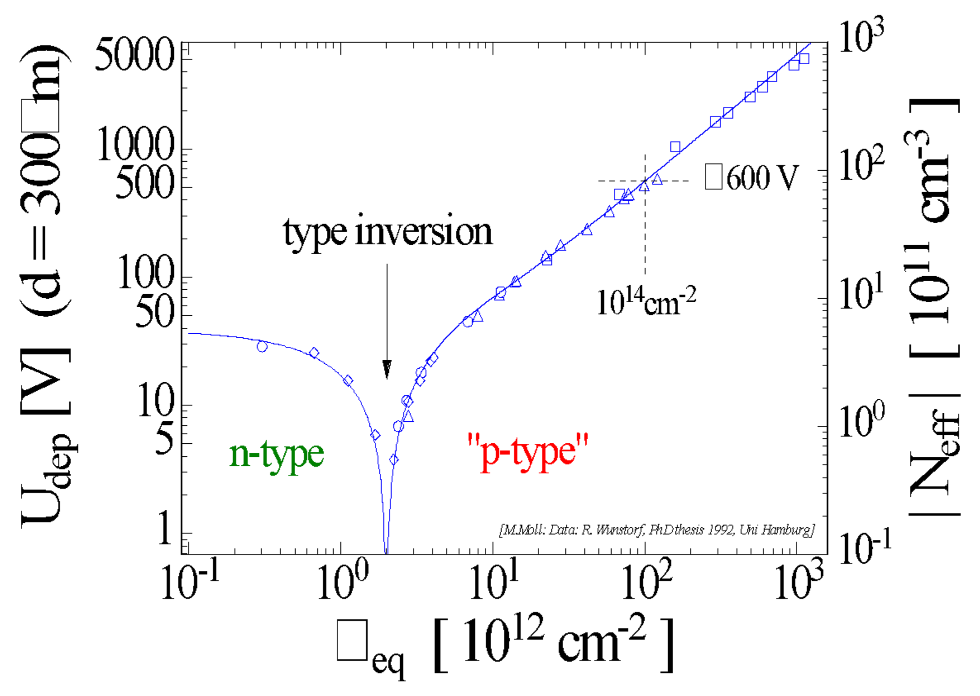
generation
⇒ leakage current
Levels close to midgap most effective

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

$\sigma_{n,p}$: cross sections **ΔE : ionization energy** **N_t : concentration**

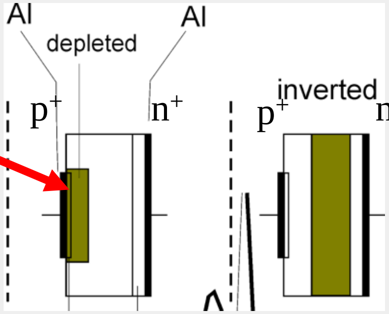
Macroscopic Effects – I. Depletion Voltage

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



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

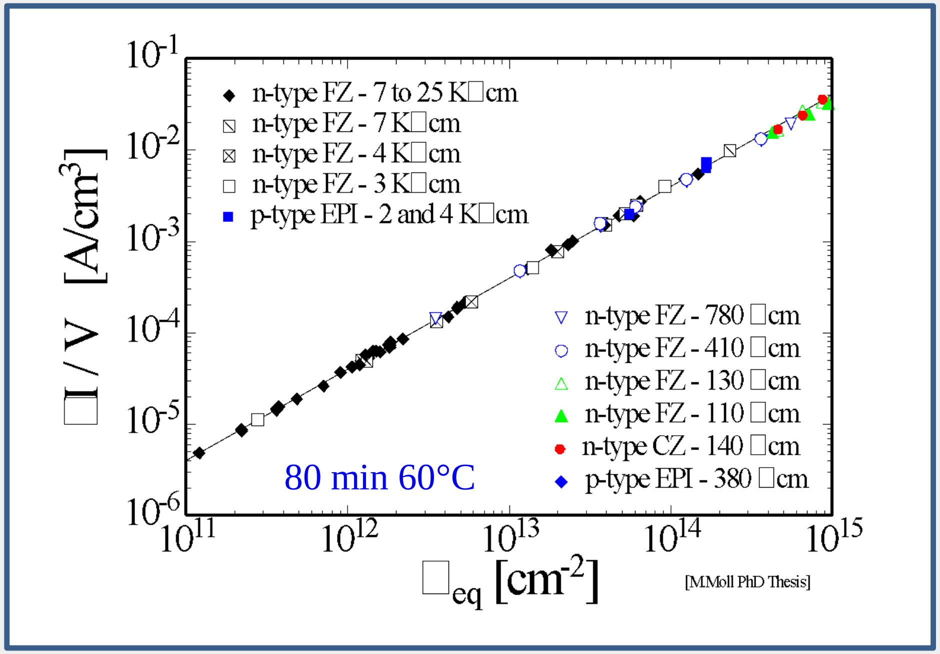
before inversion



after inversion

Radiation Damage – II. Leakage Current

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

- Strong temperature dependence

$$I \propto \exp\left(- E_{g,eff} \big/ 2k_B T \right)$$

Consequence:

Cool detectors during operation!

Example: *I*(-10°C) ~1/16 *I*(20°C)

Radiation Hard Silicon Detectors

How to make silicon detectors radiation harder?

The RD50 Collaboration

- **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

Approaches to develop radiation harder solid state tracking detectors

Scientific strategies:

1. **Material engineering**
2. **Device engineering**
3. **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

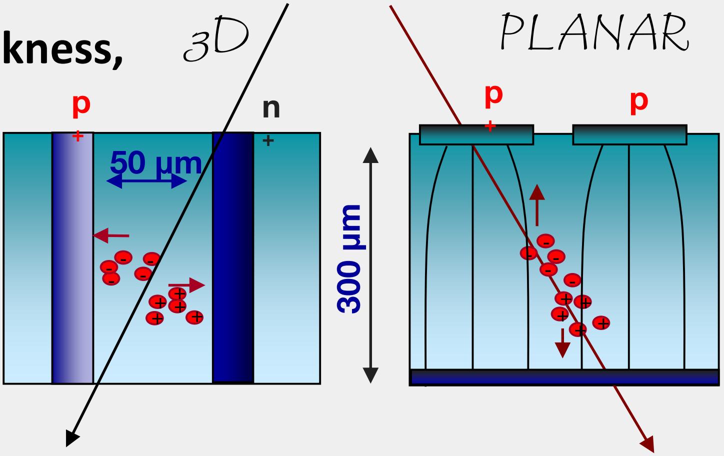
- **Needs: Profound understanding of radiation damage**
  - microscopic defects, macroscopic parameters
  - dependence on particle type and energy
  - defect formation kinetics and annealing
- **Examples:**
  - **Oxygen rich Silicon (DOFZ, Cz, MCZ, EPI)**
  - Oxygen dimer & hydrogen enriched Si
  - Pre-irradiated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

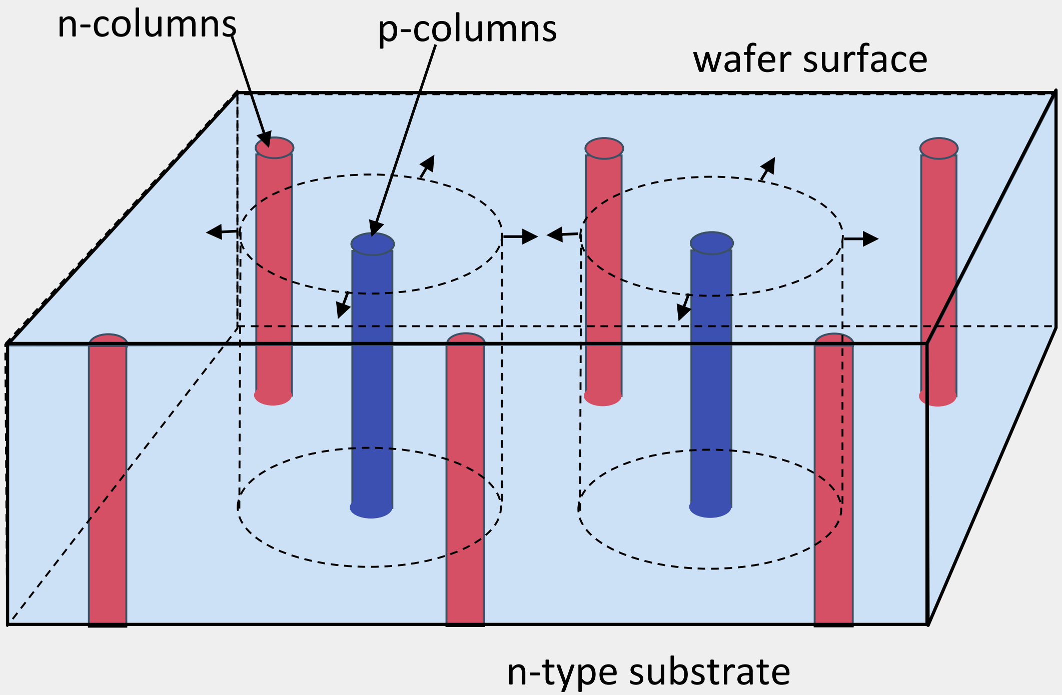
- **New Materials**
  - Silicon Carbide (SiC), Gallium Nitride (GaN)
  - **Diamond** (CERN RD42 Collaboration)
  - Amorphous silicon, Gallium Arsenide

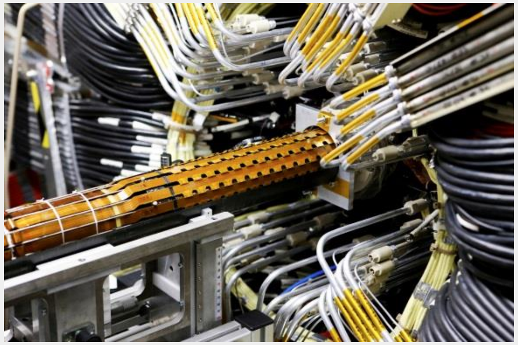
- **Device Engineering (New Detector Designs)**
  - **p-type silicon detectors (n-in-p)**
  - thin detectors, epitaxial detectors
  - **3D detectors** and Semi 3D detectors, Stripixels
  - Cost effective detectors
  - Monolithic devices

Device Engineering: 3D detector concept

- **“3D” electrodes:** - narrow columns along detector thickness,
  - diameter: 10µm, distance: 50 - 100µm
- **Lateral depletion:** - lower depletion voltage needed
  - thicker detectors possible
  - fast signal
  - radiation hard







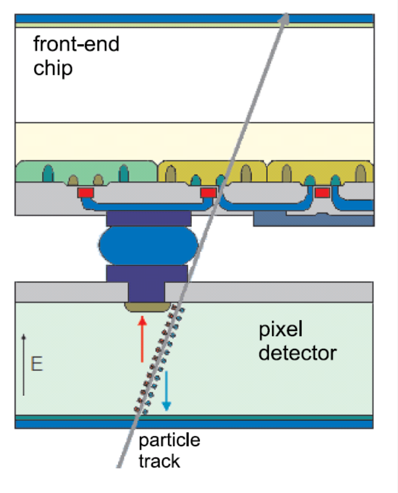
Installed in ATLAS IBL
(Inner b-layer)
& ongoing developments
for LHC phase II (2024)

CERN SSD (Solid State Detectors) team, August 2018

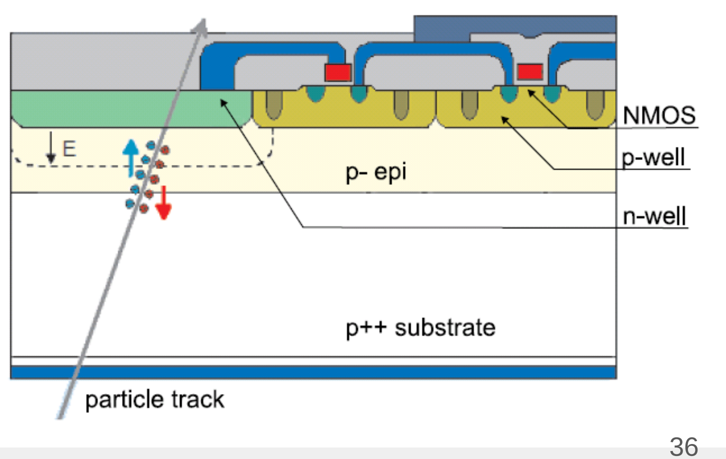
Monolithic Pixel Detectors

- Combine sensors and all or part of the readout electronics in one chip
  - No interconnection between sensor and chip needed
- Many different variations with different levels of integration of sensor and readout part
- Use of “standard” CMOS processing:
  - Wafer diameter (8”)
  - Many foundries available, lower cost per area (mass production)
  - thin detectors possible (O(50 µm Si))
  - Small cell size – high granularity, reach O(20 µm x 20 µm)
  - Possibility of stitching (combining reticles to larger areas)
- Very low material budget
- CMOS sensors installed in STAR, BELLE2 experiments
- ALICE ITS upgrade based on MAPS sensors

Hybrid Pixel Detector



CMOS (Pixel) Detector



Summary – Radiation Damage

- **Radiation Damage in Silicon Detectors**
  - Change of **Depletion Voltage** (internal electric field modifications, “type inversion”,
    reverse annealing, loss of active volume, …)
    (can be influenced by defect engineering!)
  - Increase of **Leakage Current**
  - Increase of **Charge Trapping**

Signal to Noise ratio is quantity to watch (material + geometry + electronics)

- **Microscopic defects**
  - Microscopic crystal defects are the origin to detector degradation.
- **Approaches to obtain radiation tolerant devices:**
  - **Material Engineering:** - explore and develop new silicon materials (oxygenated Si)
    - use of other semiconductors (Diamond)
  - **Device Engineering:** - look for other sensor geometries
    - 3D, thin sensors, n-in-p, n-in-n, …
    - CMOS sensors, …

Acknowledgements & References

- **Most references to particular works given on the slides**

- **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 2017***
  - ***L.Rossi, P.Fischer, T.Rohe, N.Wermes "Pixel Detectors", Springer, 2006***
  - ***Gerhard Lutz, "Semiconductor radiation detectors", Springer 1999***

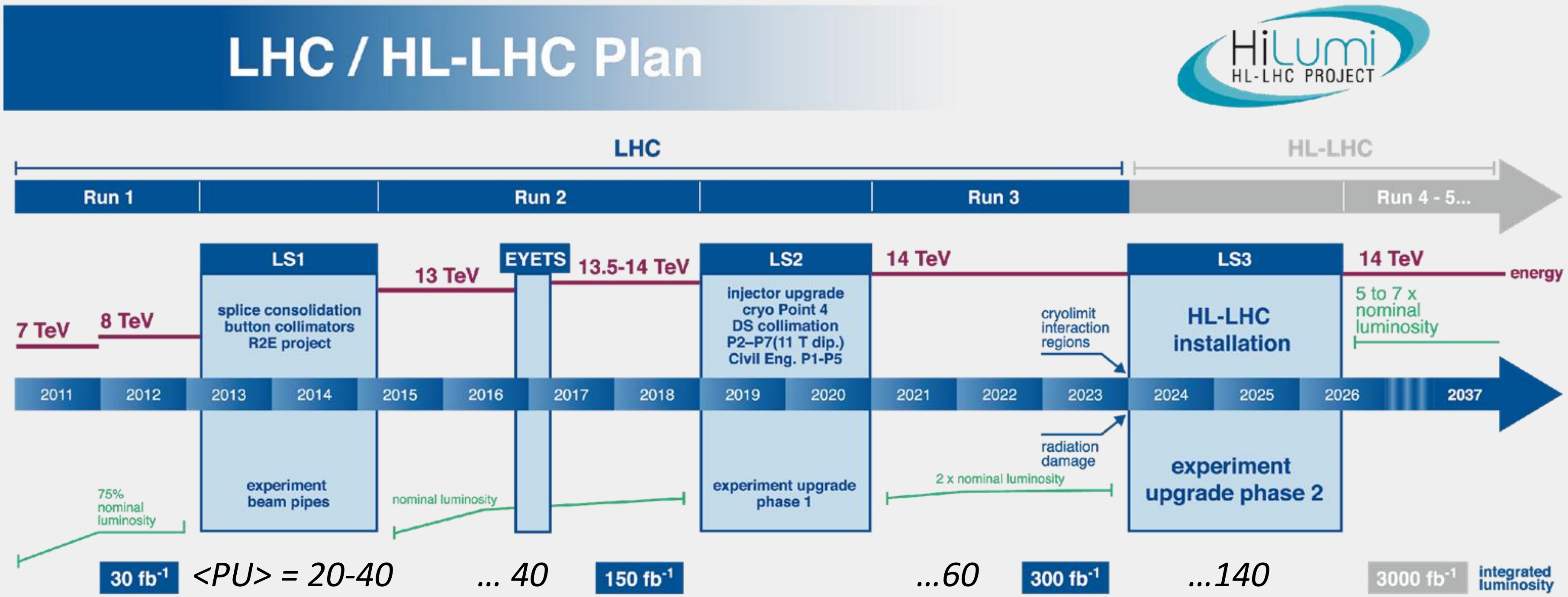
- **Research collaborations and web sites**
  - ***CERN RD50 collaboration (http://www.cern.ch/rd50) - Radiation Tolerant Silicon Sensors***
  - ***CERN RD42 collaboration – Diamond detectors***
  - ***Inter-Experiment Working Group on Radiation Damage in Silicon Detectors (CERN)***
  - ***ATLAS IBL, ATLAS and CMS upgrade groups***

…

Spare Slides

The LHC Upgrade Program

- HL-LHC luminosity upgrade (Phase II) (L = 5-7 x10^{34} $cm^{-2}s^{-1}$) in ~2026



- LS2: AlICE, LHCb major upgrades; ATLAS and CMS minor upgrades [Phase I]
- LS3: ATLAS and CMS: Major upgrades [Phase II]

<u>Challenges</u>: Build detectors that operate after 3000 fb^{-1}; Pile up, Radiation, Rates

[http://hilumilhc.web.cern.ch/ , September 2016]

The Charge signal

- **Collected Charge for a Minimum Ionizing Particle (MIP)**

- Mean energy loss
  dE/dx (Si) = 3.88 MeV/cm
  ⇒ 116 keV for 300µm thickness

- Most probable energy loss
  ≈ 0.7 ×mean
  ⇒ 81 keV

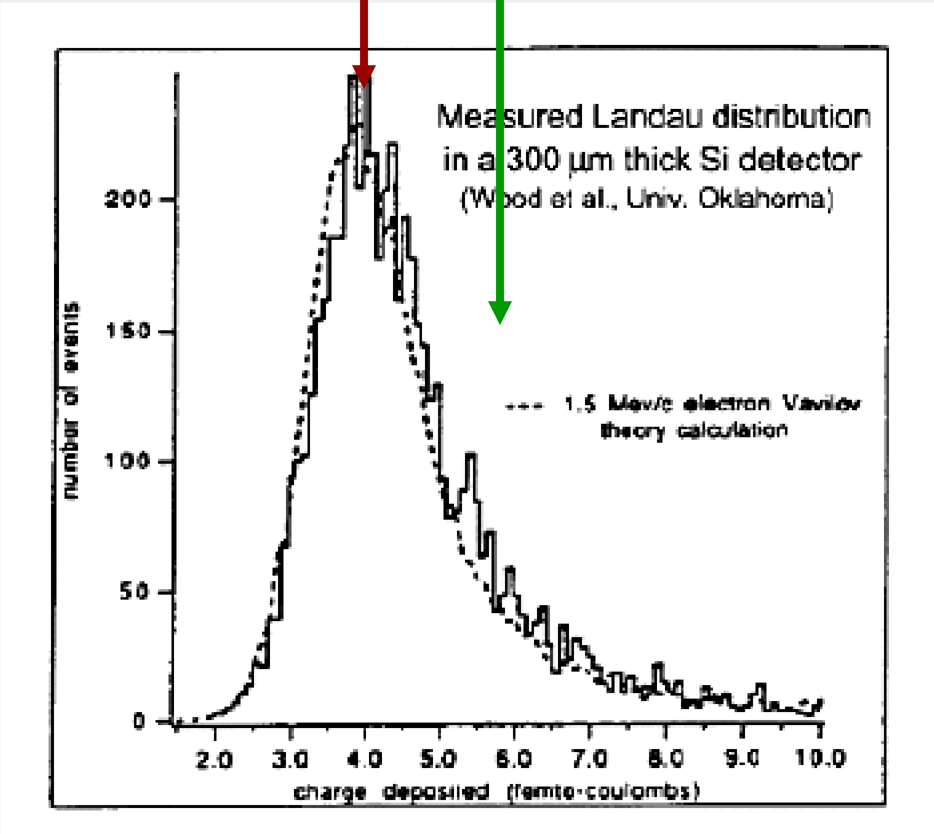
- 3.6 eV to create an e-h pair
  ⇒ 72 e-h / µm (mean)
  ⇒ 108 e-h / µm (most probable)

- Most probable charge **(300 µm)**

  ≈ 22500 e ≈ 3.6 fC

Most probable charge ≈ 0.7× mean

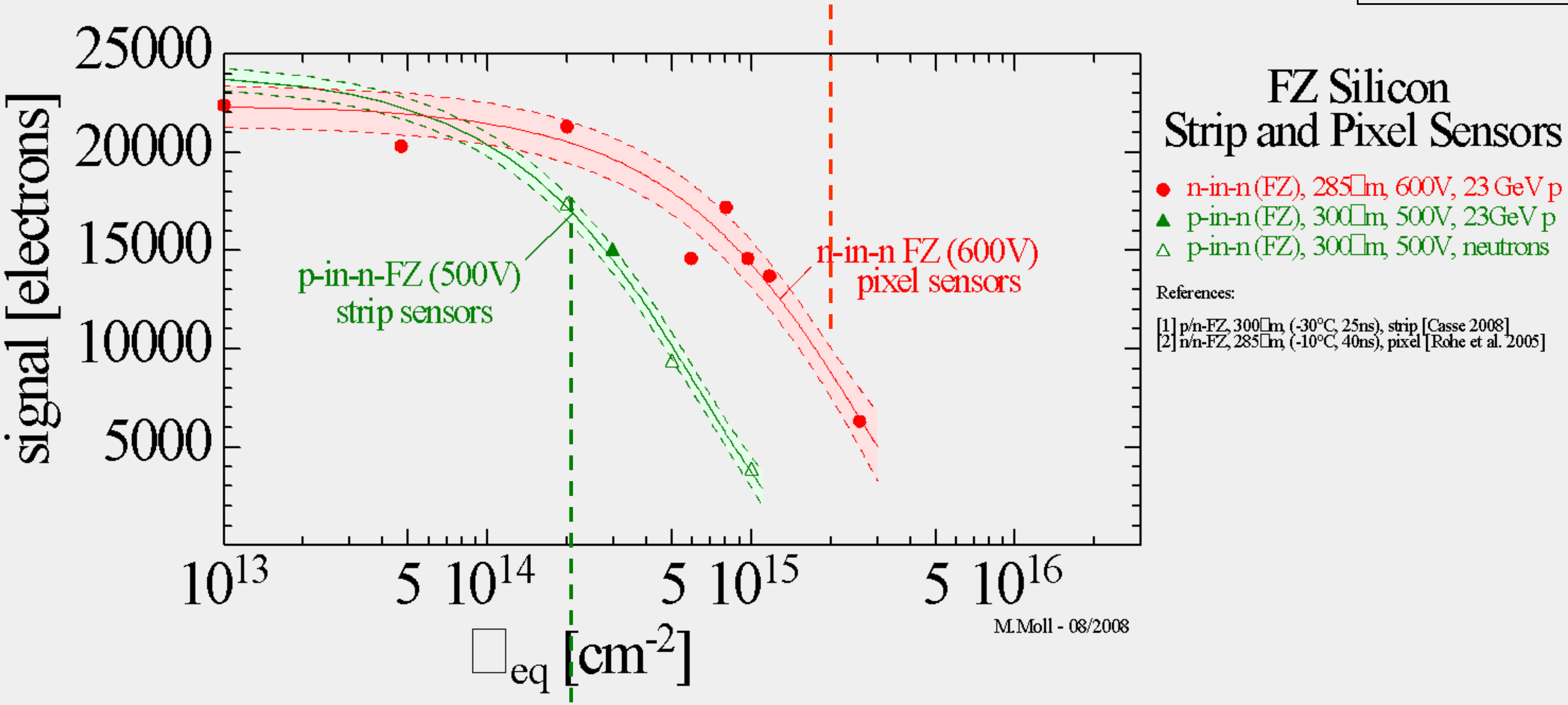
Mean charge



Signal degradation for LHC Silicon Sensors

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

Pixel sensors:
max. cumulated fluence for LHC



Situation in 2005

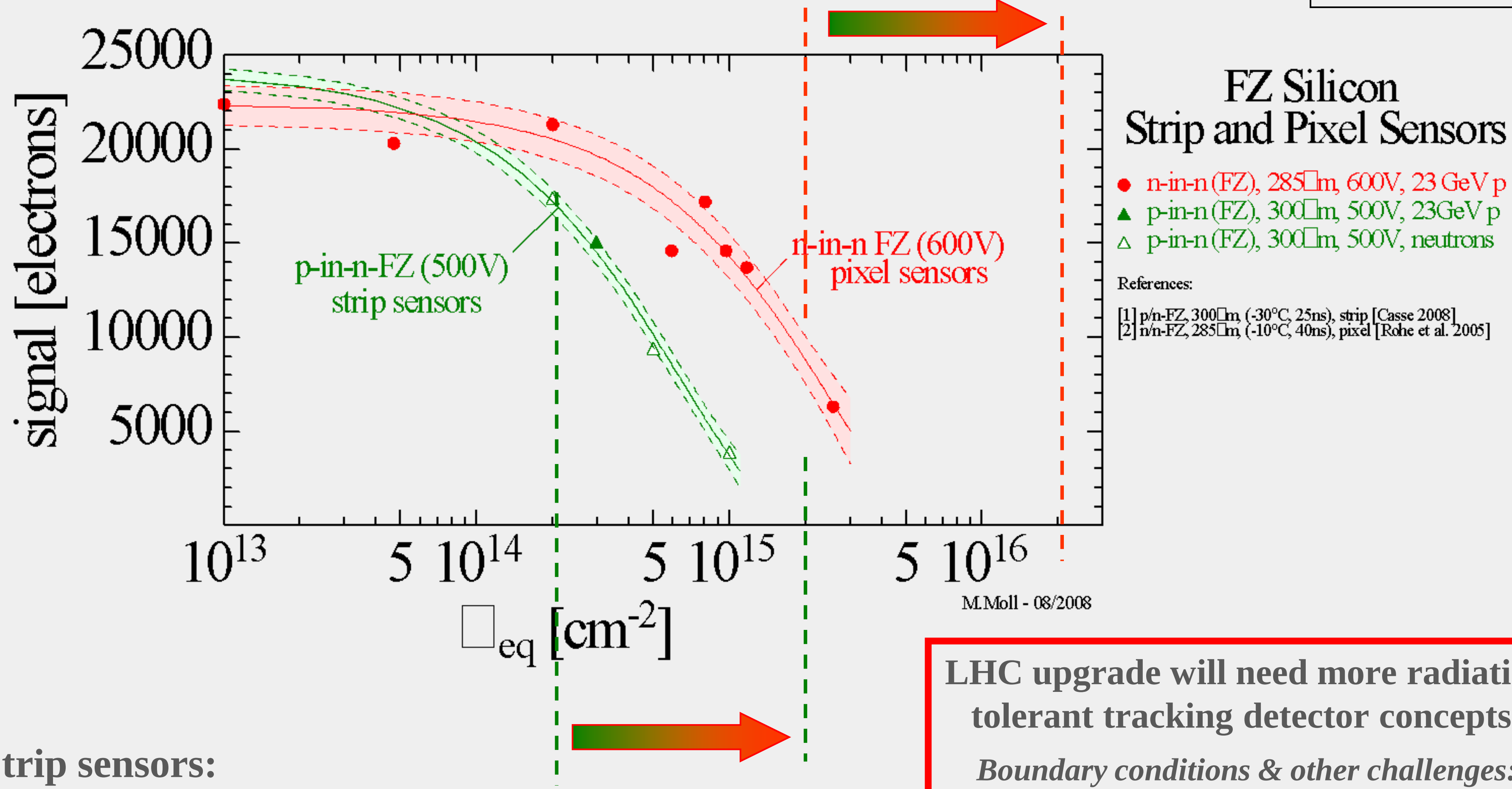
Strip sensors:
max. cumulated fluence for LHC

Signal degradation for LHC Silicon Sensors

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

Pixel sensors:

max. cumulated fluence for LHC and LHC upgrade



Strip sensors:

max. cumulated fluence for LHC and LHC upgrade

LHC upgrade will need more radiation tolerant tracking detector concepts!

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

Reverse biased abrupt p⁺-n junction

Poisson's equation

$$-\frac{d^2}{dx^2}\phi(x)=\frac{q_0}{\varepsilon\varepsilon_0}\cdot N_{eff}$$

w = depletion depth
d = detector thickness
U = voltage

N_{eff} = effective doping concentration

with
$$\frac{d}{dx}\phi(x=w)=0$$
$$\phi(x=w)=0$$

$$-\frac{d}{dx}\phi(x)=\frac{q_0}{\varepsilon\varepsilon_0}\cdot N_{eff}\cdot(x-w)$$

$$\phi(x)=\frac{1}{2}\cdot\frac{q_0}{\varepsilon\varepsilon_0}\cdot N_{eff}\cdot(x-w)^2$$

$$\boxed{C=\frac{dQ}{dU}=\frac{dQ\cdot dw}{dw\cdot dU}}$$

$$dQ=q_0\cdot|N_{eff}|\cdot A\cdot dw$$

$$dw=\sqrt{\frac{\varepsilon\varepsilon_0}{q_0|N_{eff}|2U}}\cdot dU$$

$$\boxed{w(V)=\sqrt{\frac{2\varepsilon\varepsilon_0}{q_0|N_{eff}|}\cdot V}}$$

depletion voltage

$$\boxed{V_{dep}=\frac{q_0}{2\varepsilon\varepsilon_0}\cdot|N_{eff}|\cdot d^2}$$

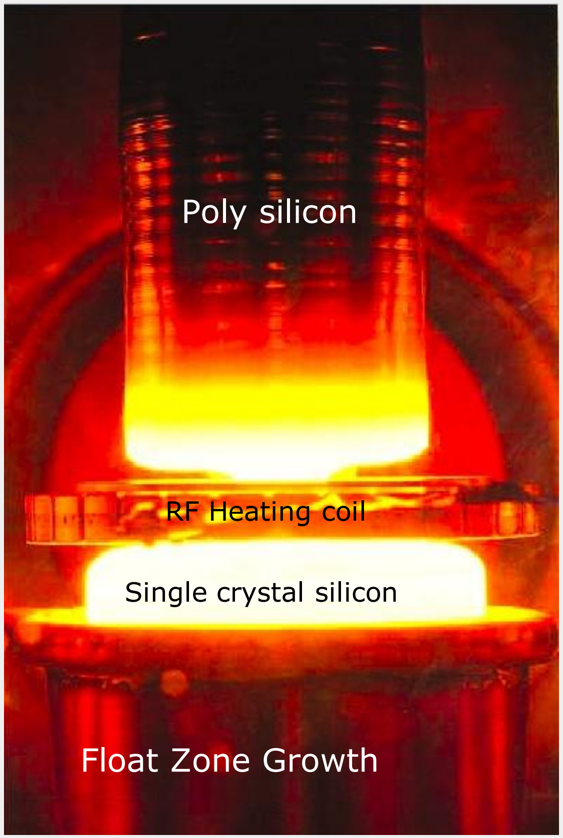
effective space charge density

$$\boxed{C(U)=A\cdot\sqrt{\frac{\varepsilon\varepsilon_0 q_0|N_{eff}|}{2U}}}$$

$$\boxed{C(w)=\frac{\varepsilon\varepsilon_0 A}{w}}$$

Silicon Growth Processes

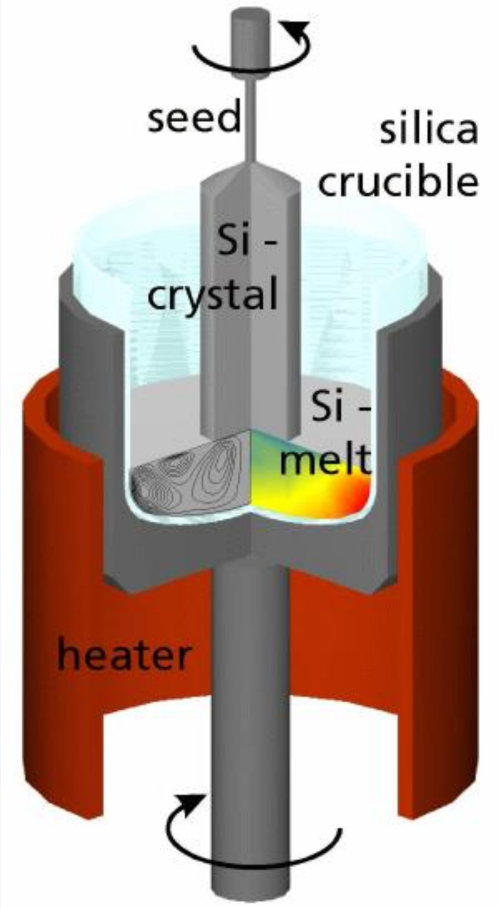
Floating Zone Silicon (FZ)



- Basically all silicon tracking detectors made out of **FZ** silicon $[O_i] < 5 \times 10^{16}$ cm^{-3}
- Some pixel sensors: Diffusion Oxygenated FZ (**DOFZ**)silicon $[O_i] \sim 1\text{-}2 \times 10^{17}$ cm^{-3}

Czochralski Silicon (CZ)

- The growth method used by the IC industry.
- Difficult to produce very high resistivity
- $[O_i] \sim 5 \times 10^{17}$ cm^{-3}

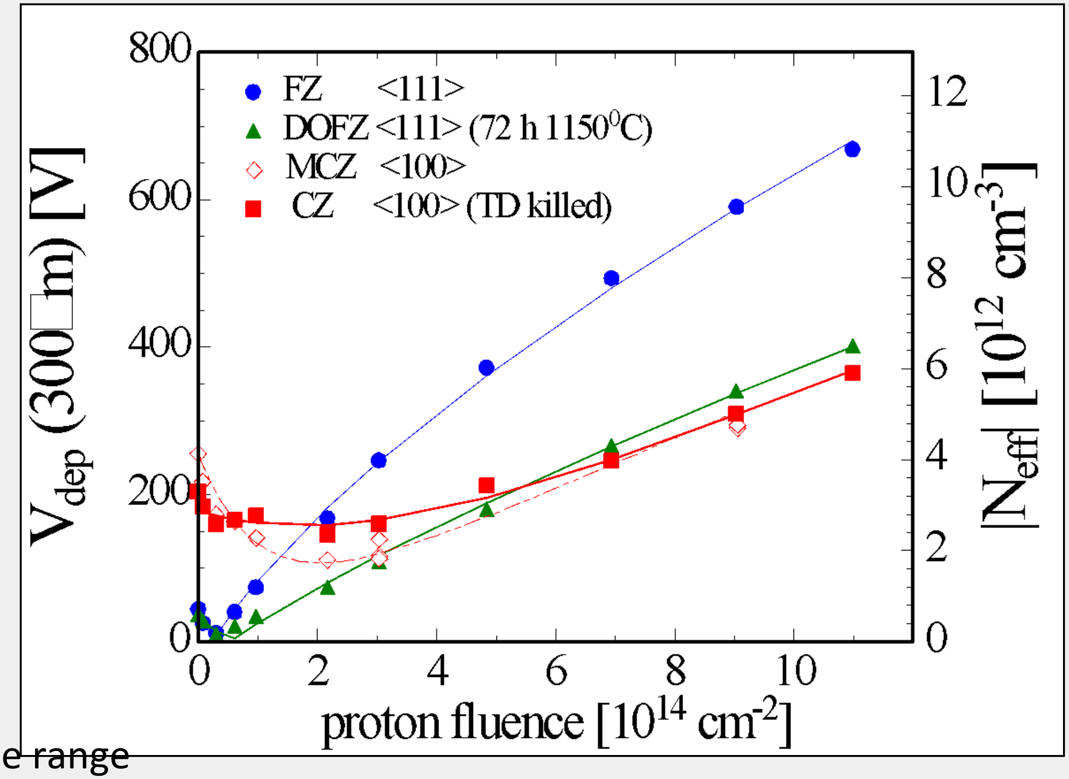


Epitaxial Silicon (EPI)

- Chemical-Vapor Deposition (CVD) of Si
- up to 150 µm thick layers produced
- growth rate about 1µm/min

Standard FZ, DOFZ, MCz and Cz Silicon

24 GeV/c proton irradiation



- **Standard FZ silicon**
  - type inversion at ~ 2×10^{13} p/cm^2
  - strong N_{eff} increase at high fluence
- **Oxygenated FZ (DOFZ)**
  - type inversion at ~ 2×10^{13} p/cm^2
  - 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)

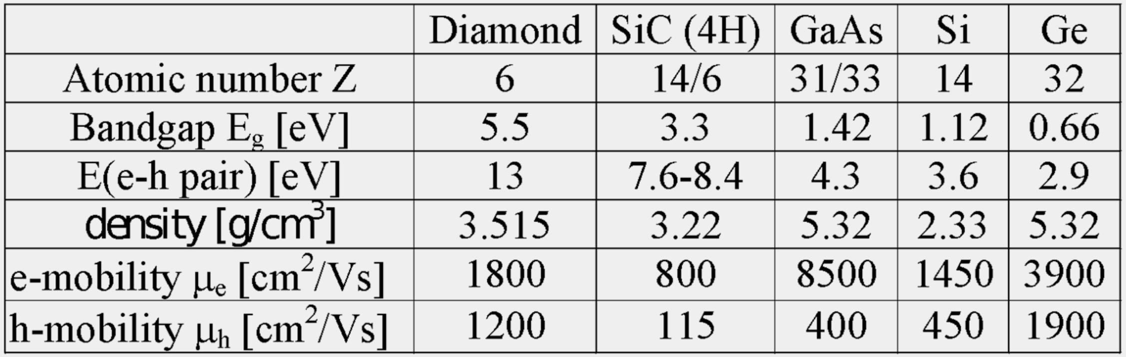
- **Common to all materials** *(after hadron irradiation, not after γ irradiation)*:
  - **reverse current increase**
  - **increase of trapping (electrons and holes) within ~ 20%**

Solid State Detectors – Why Silicon?

- **Some characteristics of Silicon crystals**
  - **Small band gap** E_g = 1.12 eV ⇒ E(e-h pair) = 3.6 eV (≈ 30 eV for gas detectors)
  - **High specific density** 2.33 g/cm^3 ; dE/dx (M.I.P.) ≈ 3.8 MeV/cm ≈ 106 e-h/µm (average)
  - **High carrier mobility** μ_e =1450 cm^2/Vs, μ_h = 450 cm^2/Vs ⇒ fast charge collection (<10 ns)
  - **Very pure** < 1ppm impurities and < 0.1ppb electrical active impurities
  - **Rigidity** of silicon allows thin self supporting structures
  - **Detector production by microelectronic techniques**

    ⇒ well known industrial technology, relatively low price, small structures easily possible

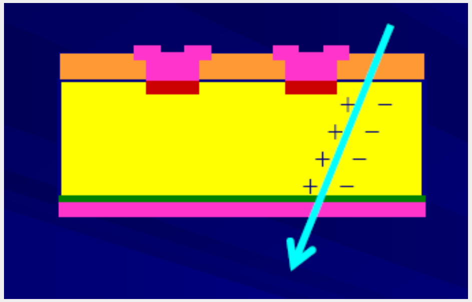
- **Alternative semiconductors**
  - Diamond
  - Gallium arsenide (GaAs)
  - Silicon Carbide (SiC)
  - Germanium (Ge)

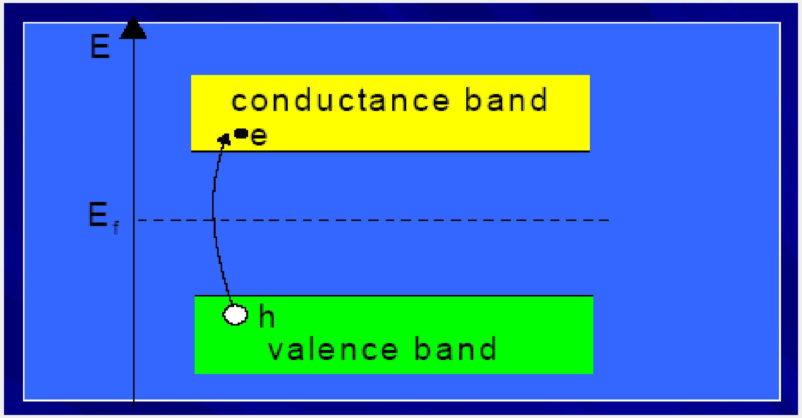


	Diamond	SiC (4H)	GaAs	Si	Ge
Atomic number Z	6	14/6	31/33	14	32
Bandgap E_g [eV]	5.5	3.3	1.42	1.12	0.66
E(e-h pair) [eV]	13	7.6-8.4	4.3	3.6	2.9
density [g/cm^3]	3.515	3.22	5.32	2.33	5.32
e-mobility μ_e [cm^2/Vs]	1800	800	8500	1450	3900
h-mobility μ_h [cm^2/Vs]	1200	115	400	450	1900

Principle of operation

- **Goal: precise charged particle position measurement**
- **Use ionization signal (dE/dx) from charged particle passage**
  (In a semiconductor, ionization produces electron hole (e-h) pairs



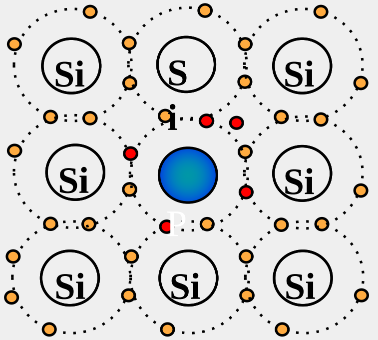


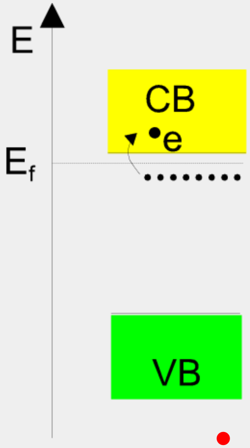
- **Problems:**
  - In pure intrinsic (undoped) silicon there are more free charge carriers than those produced by a charged particle
  - electron – hole pairs quickly re-combine
- **Solution:**
  - Deplete the free charge carriers and collect electrons or holes quickly by exploiting the properties of a p-n junction (diode)
  - electric field is used to drift electrons and holes to oppositely charged electrodes

Doping, resistivity and p-n junction

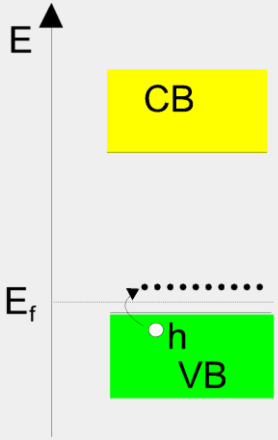
- **Doping: n-type silicon**
  - add elements from Vth group
    ⇒ donors (P, As,..)
  - electrons are majority carriers

e.g. Phosphorus





- **Doping: p-type silicon**
  - add elements from IIIrd group
    ⇒ **acceptors** (B, Ga,..)
  - holes are majority carriers



- resistivity ρ
  - carrier concentration n, p
  - carrier mobility μ_n, μ_p

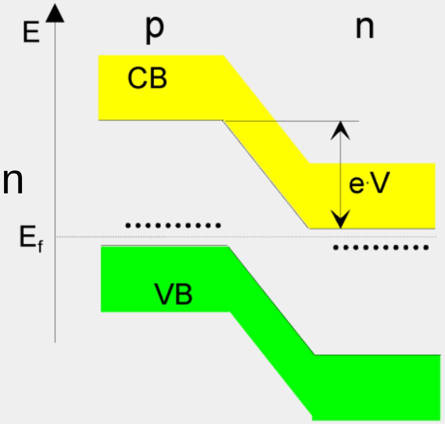
$$\rho = {}^{1}\!/_{q_0}\left(\mu_n n + \mu_p p\right)$$

	detector grade	electronics grade
doping	**≈ 10^{12} cm^{-3}**	**≈ 10^{17} cm^{-3}**
resistivity ρ	**≈ 5 kΩ·cm**	**≈1 Ω·cm**

- p-n junction

  There must be a single Fermi level!

  ⇒ band structure deformation
  ⇒ potential difference
  ⇒ depleted zone

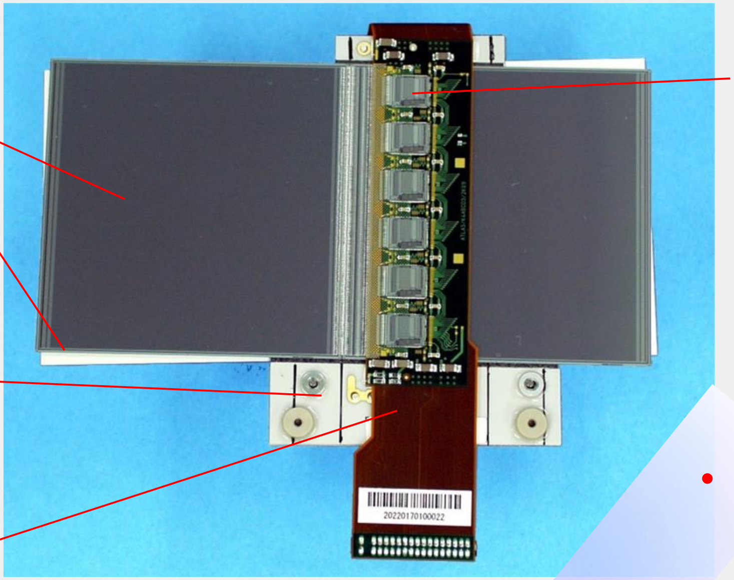


Detector Module

- **Detector Modules** **“Basic building block of silicon based tracking detectors”**
  - **Silicon Sensors**
  - **Mechanical support (cooling)**
  - **Front end electronics and signal routing (connectivity)**

SCT = SemiConductor Tracker
ASICS = Application Specific Integrated CircuitS
TPG = Thermal Pyrolytic Graphite

- **Example: ATLAS SCT Barrel Module**



- **Silicon sensors (x4)**
  - 64 x 64 mm^2
  - p-in-n, single sided
  - AC-coupled
  - 768 strips
  - 80µm pitch/12µm width
- **Mechanical support**
  - TPG baseboard
  - BeO facings
- **Hybrid (x1)**
  - flexible 4 layer copper/kapton hybrid
  - mounted directly over two of the four silicon sensors
  - carrying front end electronics, pitch adapter, signal routing, connector
- **ASICS (x12)**
  - ABCD chip (binary readout)
  - DMILL technology
  - 128 channels
- **Wire bonds (~3500)**
  - 25 µm Al wires

σ(rφ) ~ 16 µm, σ(z) ~ 850µm [NIMA538 (2005) 384]

- **ATLAS – SCT**
  - 15.552 microstrip sensors
  - 2.112 barrel modules
  - 1.976 forward modules

TCT example: diode

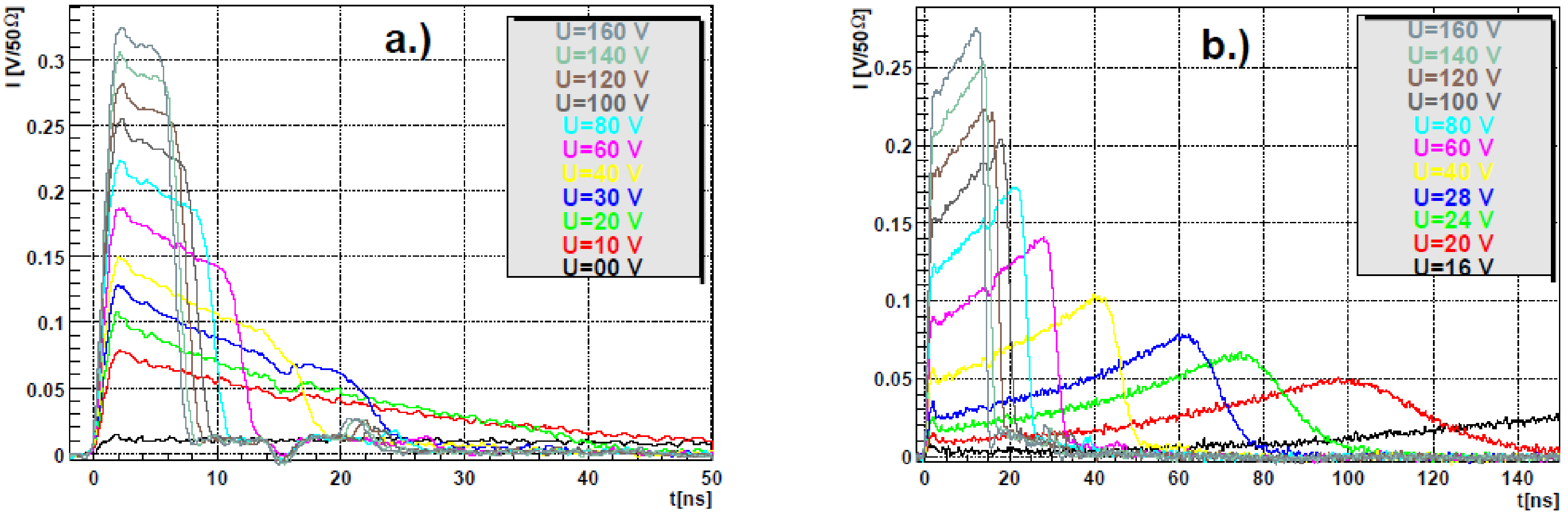


Figure 4.13 : Current pulse shapes measured at $T = 293$ K at different bias voltages after a.) electron and b.) hole injection in an non-irradiated $p^+ - n - n^+$ pad detector ($V_{FD} = 14$ V). Electrons and holes were generated by a short (1 ns) 670 nm laser pulse.

G. Kramberger,PhD thesis, Un. Ljubljana, 2001