# Introduction to silicon devices in HEP experiments & laboratory tests

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[100 m final Moscow 2013]

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- Silicon Devices in HEP experiments
  - Semiconductor basics:
    - Band theory, p-n junction, electrical properties, signal formation...
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# Introduction

- Silicon sensors are used in a wide variety of applications

- Nuclear physics
  - Energy measurement of charged particles & Gamma spectroscopy
  - Range of MeV
- Particle physics
  - As tracking devices: reconstruct trajectory of charged particles
    - Precise determination of particle properties
    - Vertex reconstruction
  - Momentum range of GeV
  - Impact parameters resolution: order of microns
- Satellite Experiments & Dark Matter
  - Tracking sensors
- Industrial applications
  - Security, medicine, biology

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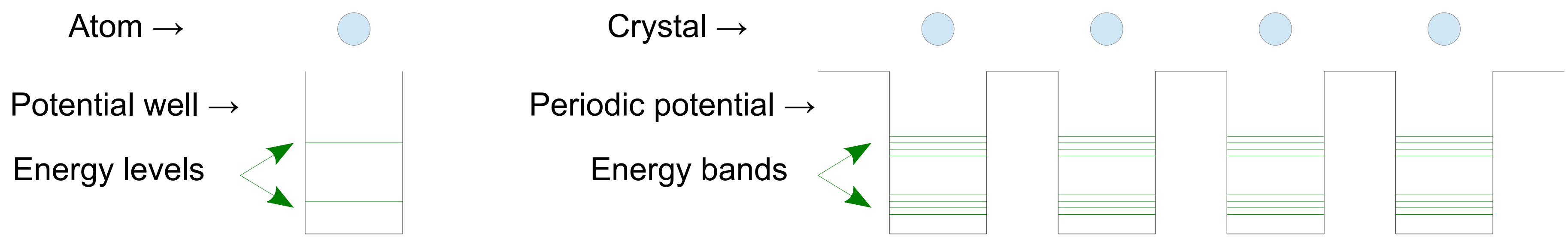
# Pros & Cons of semiconductors

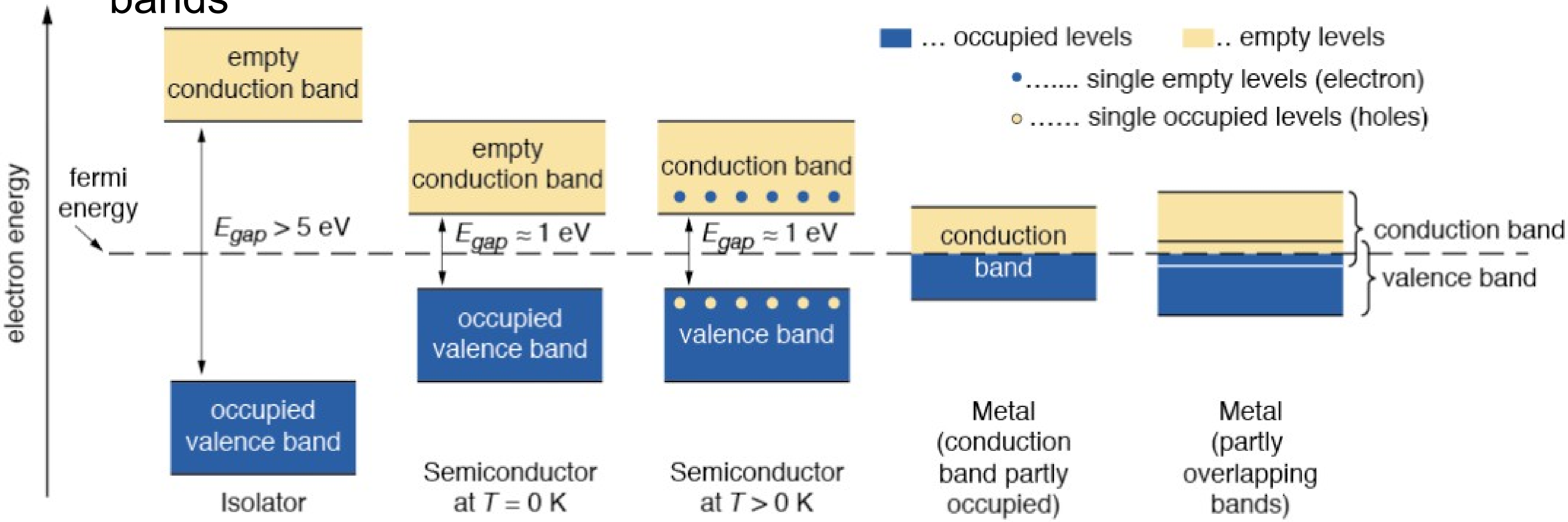
- Semiconductor detectors are quite dense
  - High energy loss in a small particle path
  - Miniaturisation & small scattering effects → good spatial resolution (μm)
- Ionisation energy is relatively low
  - 3.6 eV per e-hole pair:
    - Gas (>20 eV per e-ion pair) & Scintillators (>400 eV per photon)
  - Sizeable signals are produced in thin sensor layers. Typical size 300 μm
- Electronics industry: silicon technology is widely available
  - Large experience in silicon microchip manufactures → feasibility of complex designs
  - Same material as the readout electronics → integration of large number of channels
- Suitable for high radiation environments
  - For example: LHC & satellite experiments
- High cost
  - Power consumption → cooling system
  - Need of signal amplification (some exceptions)
  - Special laboratories → clean room

# Semiconductor basics

- Band structure of the electrons energy levels in the outermost layers




- Insulators, semiconductors & conductors
  - Classification depends on the energy gap between the valence and conduction bands

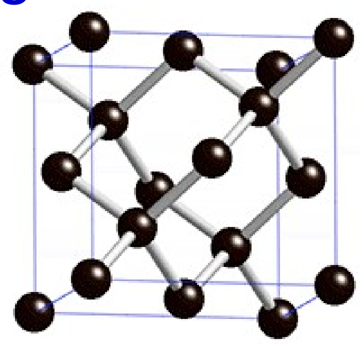


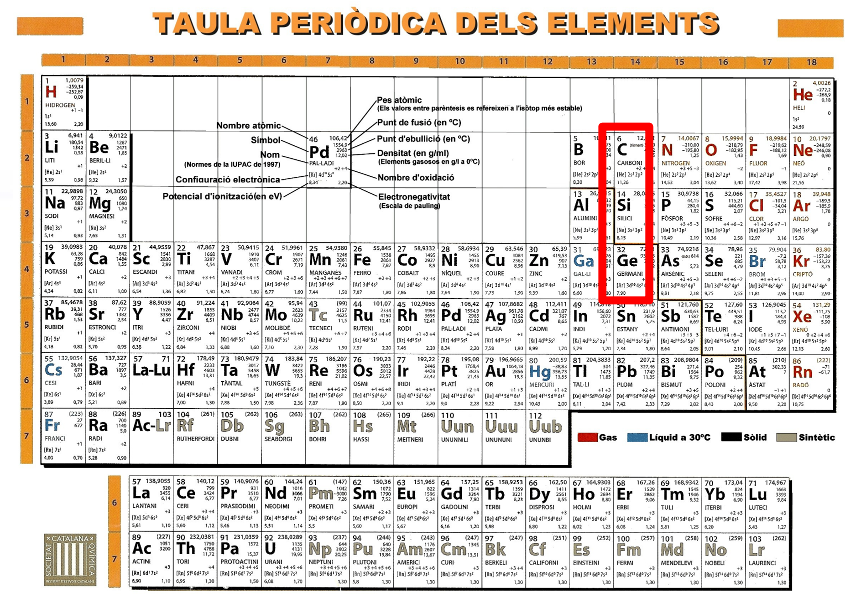
# Important aspects for sensor design

- Ideally sensors must have a large signal-to-noise ratio (SNR)
  - Large signals & Low noise
- In a semiconductor sensor demanding a large SNR leads to two contradictory requisites
  - Large signals: low ionisation energy (e-h pair formation) → small band gap
  - Low noise: few intrinsic charge carriers (e-h excitation) → large band gap
- Ideally the band gap energy should be around Eg ~ 5 eV
  - Small enough to convert particles ionizing energy loss into a sizeable signal
  - Large enough to avoid (at room T) many e-h pairs spontaneous formation and keep conduction band virtually empty → low noise
- Diamond has these properties
  - Artificial diamonds available in industry (CVD diamonds)
  - Unfortunately, diamonds sensors are too expensive for a large area detector (even artificial diamonds)
- Practical alternative: use Silicon
  - Eg ~1.12 eV (T dependent)
  - Low excitation (e-h pair) energy 3.6 eV
  - Fast signal collection (few ns)

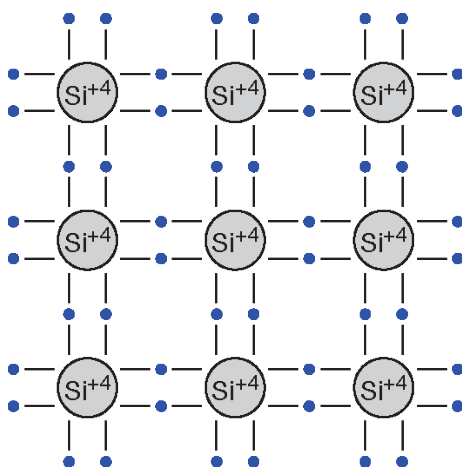
# Semiconductor basics

- Covalent bonds of electrons
  - Group IV: C, Si & Ge
  - 4 covalent bonds
  - 3D structure
  - Compounds: e.g. GaAs

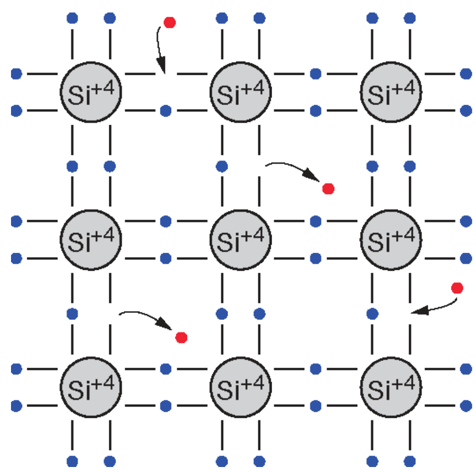





- Simplified 2D model




T = 0K




T > 0K

- Valence electron
- Conduction electron

- At T=0K all electrons are bound
  - No conductivity
- At T>0K thermal excitations break some bounds
  - Electrons free to move → electrical conductivity
  - Vacancies can be occupied by other electrons → hole conduction as a +ve charged particle

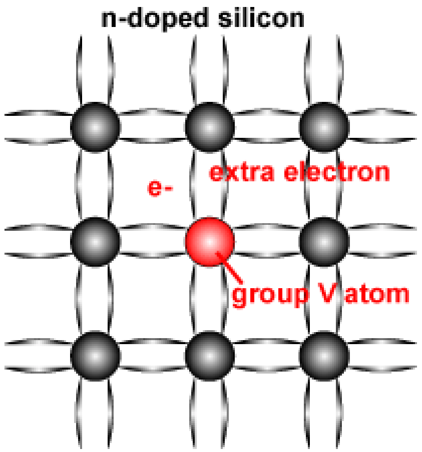
# Intrinsic and doped semiconductors

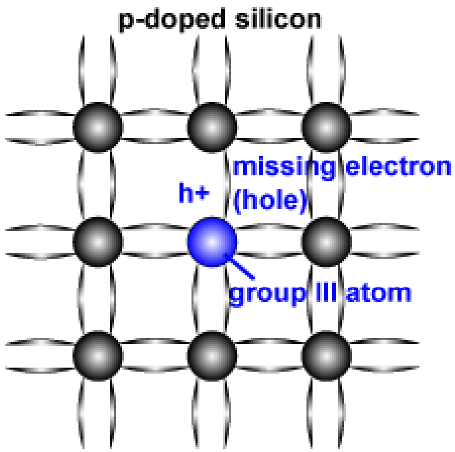
- At T>0K (e.g. room temperature) electrons in conduction band recombine with holes
  - Equilibrium is reached between excitation and recombination
  - Charge carrier concentration → intrinsic carrier concentration

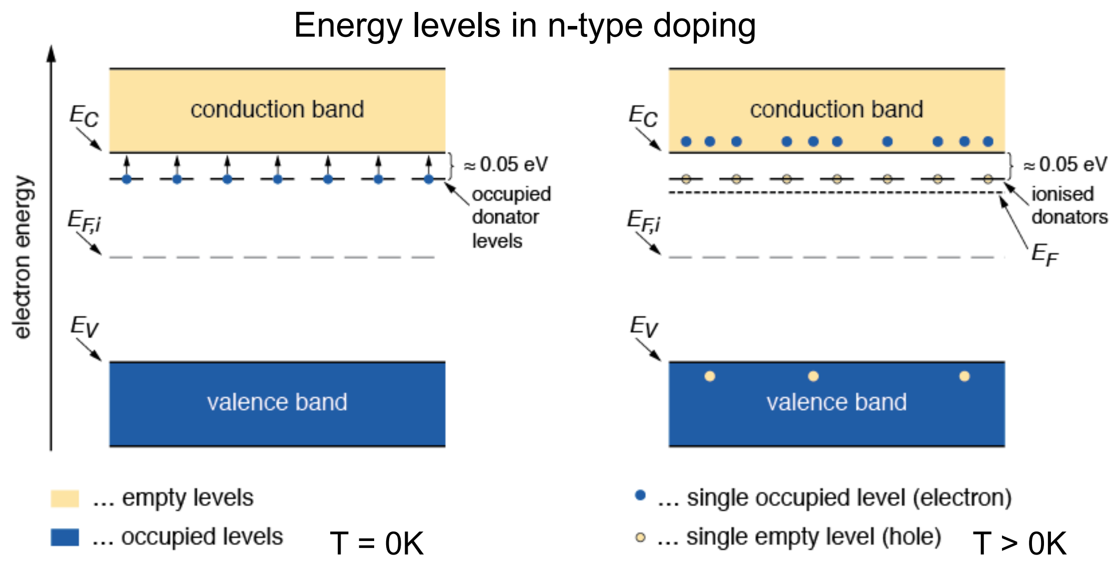
$$n_i = n_n = n_p \propto T^{3/2} \exp\left(-\frac{E_g}{2 k_B T}\right)$$

In Si, at room temperature
$n_i \sim 1.5 \cdot 10^{10}\ \mathrm{cm}^{-3}$

- Doping of silicon with group V elements (donor; P, As, Sb) adds a 5th electron weakly bound → electron ready for conduction → **n-type**
- Doping of silicon with group III elements (acceptor; B, Al, Ga, In) → a covalent bond is open → hole formed → **p-type**



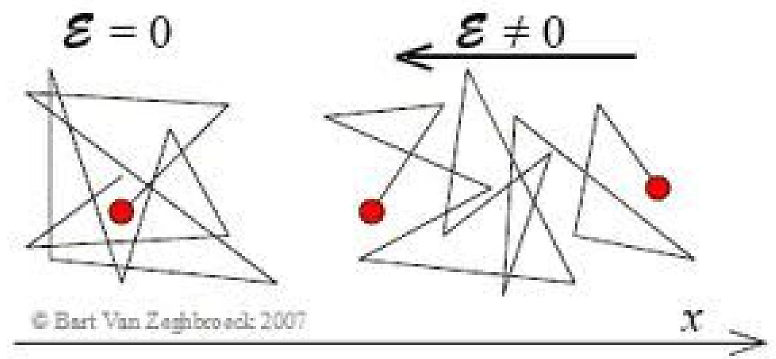



# Carriers mobility

- The motion of free carriers leads to a current that we may detect
  - Therefore the e-h mobilities are important parameters that influence the device design and manufacture
- Two kinds of carrier transport mechanisms
  - Drift: caused by an electric field (internal or external)
  - Diffusion: due to a carrier density gradient
- Due to thermal energy, carriers are permanently random moving
  - Electrons thermal velocity at room temperature ~$10^7$ cm/s = 100 μm/ns
  - Atoms in the crystal also vibrate more at high temperature
  - Electrons scatter with lattice atoms (loose energy & change direction) → random movement

In Si, at room temperature average time between collisions $2.6 \cdot 10^{-13}$ s




- Carriers move like a gas or wave packet with an effective mass (m*)

$$\frac{\hbar}{2m^*}\nabla^2\psi + V\psi = E\psi$$

# Carriers mobility

- Drift of charge carriers
  - An electric field (E) accelerates the carriers
  - The carriers collide with the atoms and lose their energy
  - A saturation drift velocity (v) is reached → mobility (μ)

$$\vec{v}_n = -\mu_n \cdot \vec{E} \qquad \vec{v}_p = \mu_p \cdot \vec{E}$$

$$\mu_n = \frac{e\tau_n}{m_n} \quad [cm^2/(V \cdot s)] \quad \mu_p = \frac{e\tau_p}{m_p}$$

τ is the average time between collisions

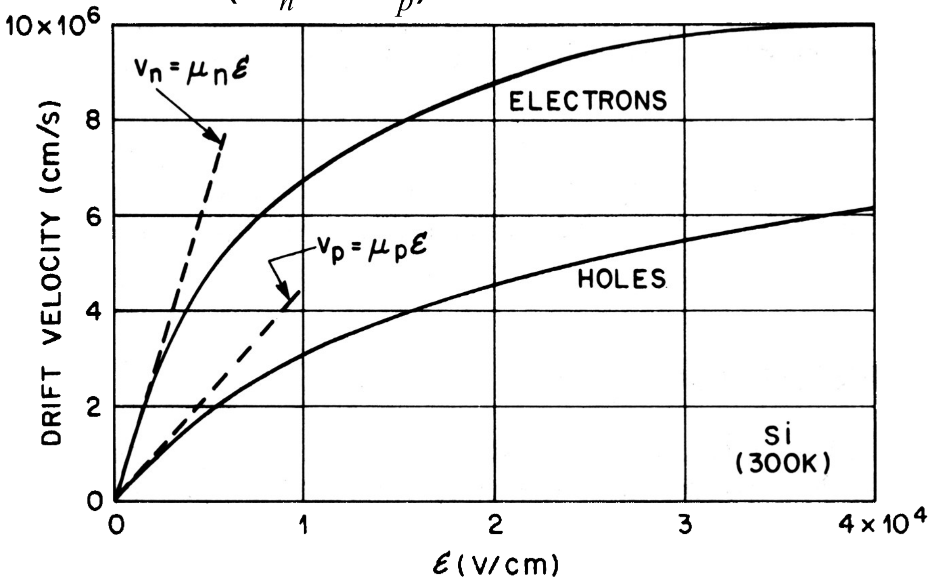
$\mu_n > \mu_p$ → electrons move faster

- This is an effective model for carriers drift
  - Effective mass applicable for electrons and holes ($m_n$ & $m_p$)

- Conductivity & Resistivity:
  - To avoid noise → high ρ is preferred

$$\sigma = e(\mu_n n_n + \mu_p n_p) \quad [(\Omega \cdot m)^{-1}]$$

$$\rho = \frac{1}{\sigma} = \frac{1}{e(\mu_n n_n + \mu_p n_p)}$$



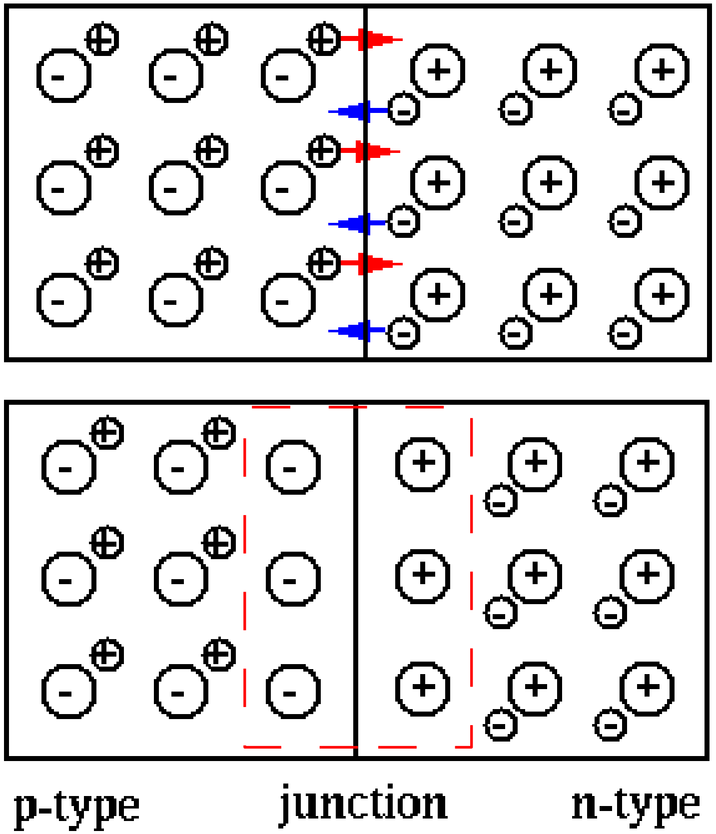

S.M. Sze: Semiconductor Devices
J. Willey & Sons, 1985

# The p-n junction

- A p-n junction is formed when two opposite doping type semiconductors are in contact
  - The excess of electrons in the n-type diffuses to the p-type and combine with the holes (majority) and vice-versa
  - A region free of charge carriers appears → depletion zone
  - The dopant atoms become permanently ionized → a net space charge region emerges → junction electric field (& built in potential $V_{bi}$)

Carriers diffusion →

Depletion zone →



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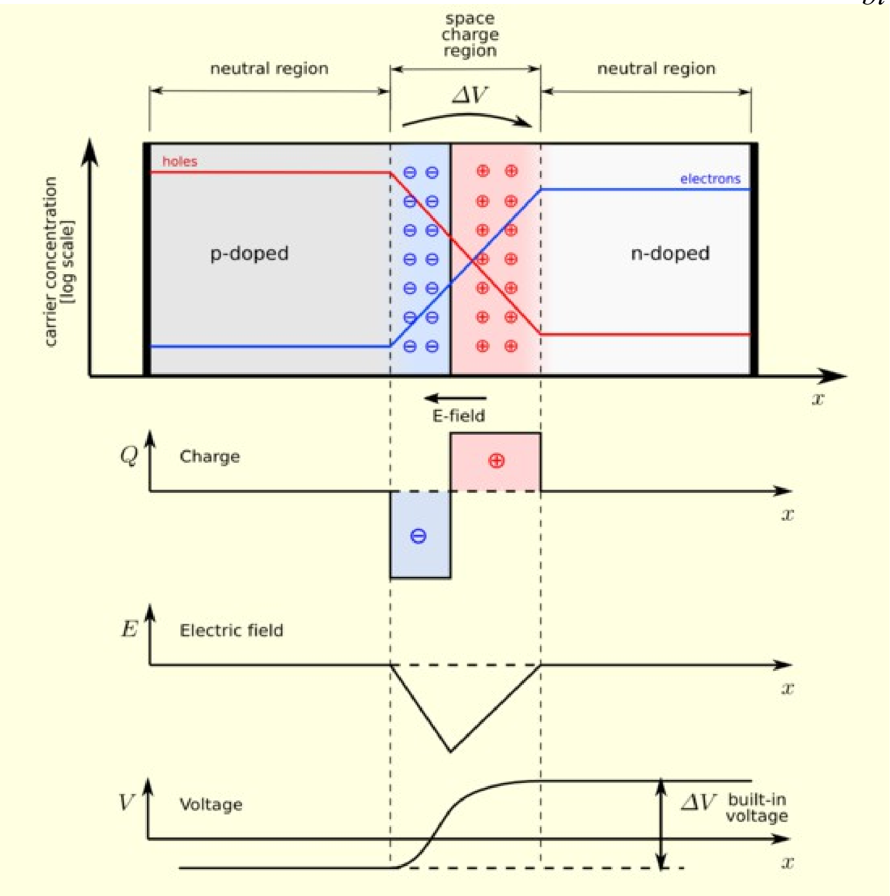
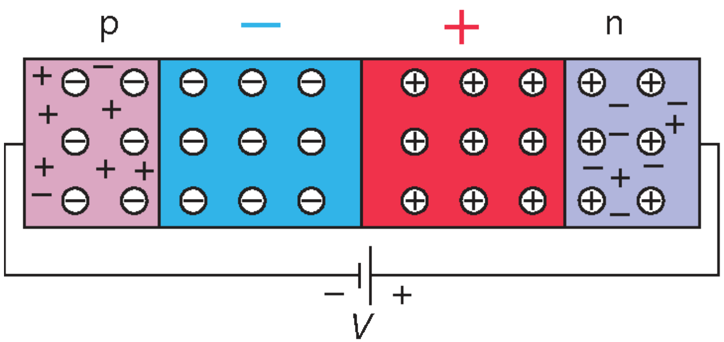



Still, thermal excitation creates e-h pairs in everywhere and of course in the depleted zone. The electric field there splits electrons and holes in opposite directions thus producing a LEAKAGE CURRENT

# Reverse biased p-n junction

- Apply an external (reverse bias) voltage
  - Electrons and holes may get enough energy to cross the barrier
  - The depletion zone grows (size depends on dopant concentrations)
  - The potential barrier becomes larger (by eV )
  - Diffusion across the barrier becomes more difficult (higher barrier)
  - Still there is a leakage current across the junction



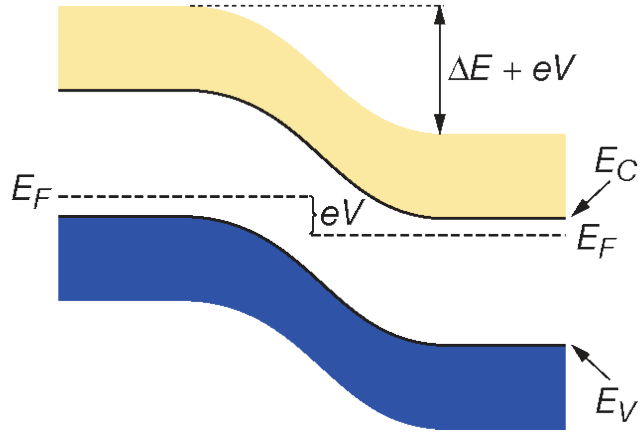

Width of the depletion zone:

$$W(V) \approx \sqrt{\frac{2\varepsilon_{Si}}{e|N_{eff}|}(V_{bi}+V)} \qquad N_{eff} = N_d - N_a$$

Capacitance:

$$C(V) = \frac{dQ}{dV} \approx A\sqrt{\frac{e\varepsilon_{Si}|N_{eff}|}{2V}}$$

$A \rightarrow$ Sensor area



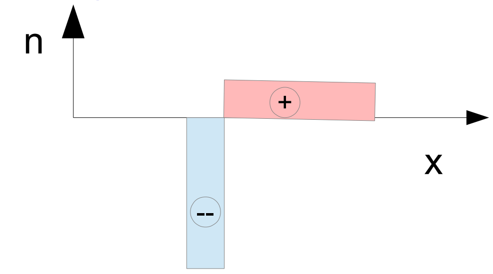

Leakage current (due to e-h pair generation):

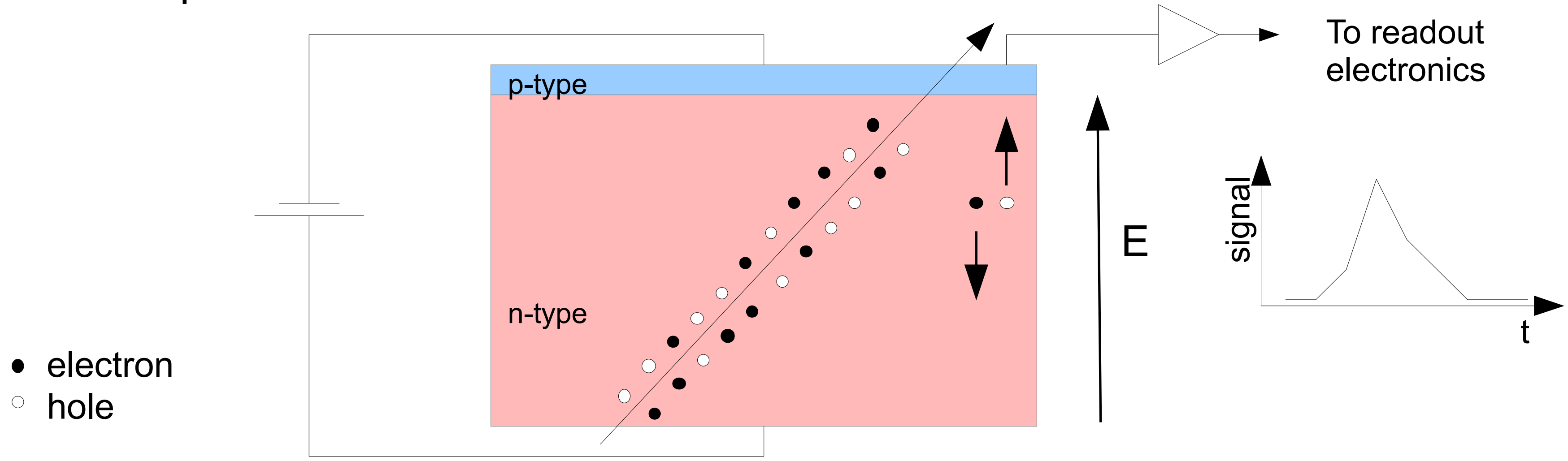
$$J(V) = \frac{e n_i W(V)}{2\tau_g} \propto \sqrt{V}$$

$$J(V,T) = \frac{e n_i W(V)}{2\tau_g(T)} \propto \frac{n_i}{\tau_g}(T) \propto T^2 \exp\left(-\frac{E_g}{2k_B T}\right)$$

# Basic silicon sensor scheme

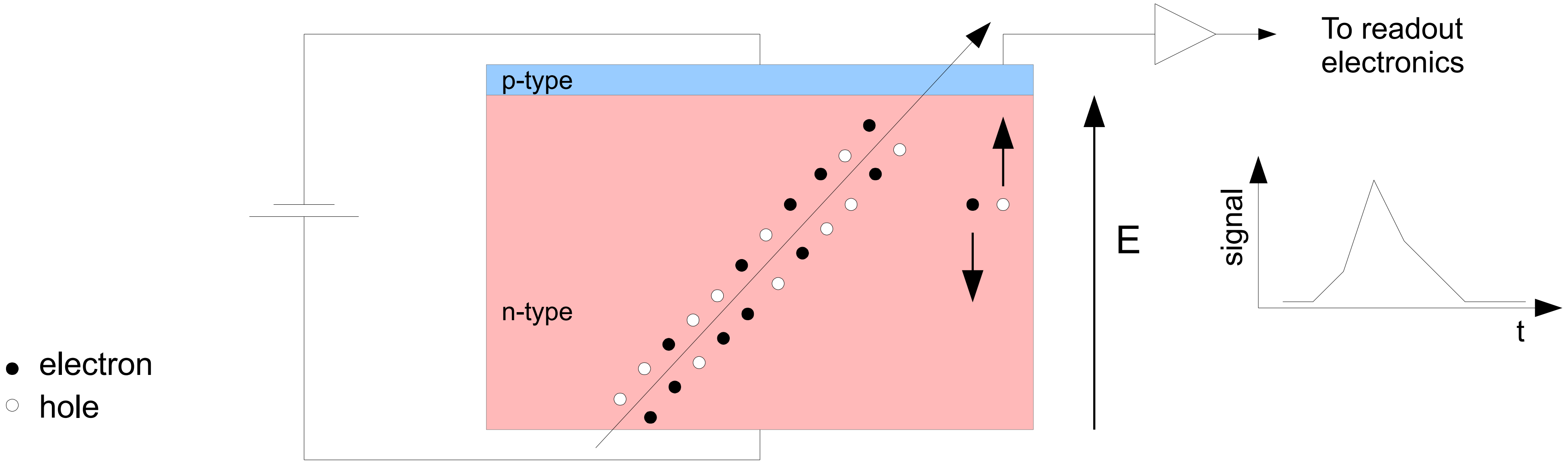
- Usually, sensors are operated via a reverse biased p-n junction
  - Very different dopant concentrations in p and n sides
    - Sensor bulk of a single type (either p- or n-type)
  - Depleted zone free of charge carriers
    - Except thermally generated e-h pairs → leakage current
  - Ionizing energy loss from incident particles releases e-h pairs (3.6 eV per e-h)
    - Minimum ionizing particles average energy loss in silicon: $(dE/dx)_{Si}$ = 3.88 MeV/cm
      - Average ~108 e-h pairs per micro-meter
      - Average ~32,000 e-h pairs in 300 μm thick silicon sensors
      - Average deposited charge ~5 fC
  - The electric field in depleted zone drifts away e-h pairs
    - Separation of e and h → current inducted



# Carriers motion and signal formation

- The movement of the charge carriers (e & h) leads to a current which can be detected → signal
  - Schockley-Ramo's Theorem (1938) relates the charge seen by the electrodes induced by a moving particle
- Signal like for **p-on-n** sensors
  - p-type connected to readout electronics
  - n-type bulk
  - Fully depleted sensor ($V_{bias} > V_{fd}$)



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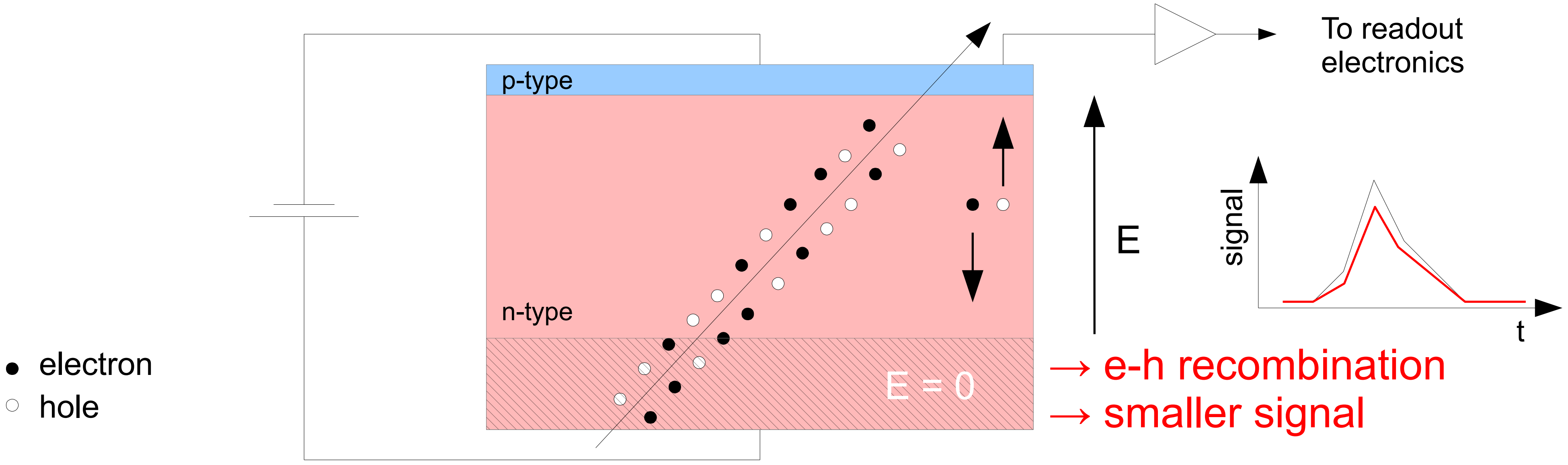

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- Signal like for **n-on-p** sensors
  - n-type connected to readout electronics
  - p-type bulk
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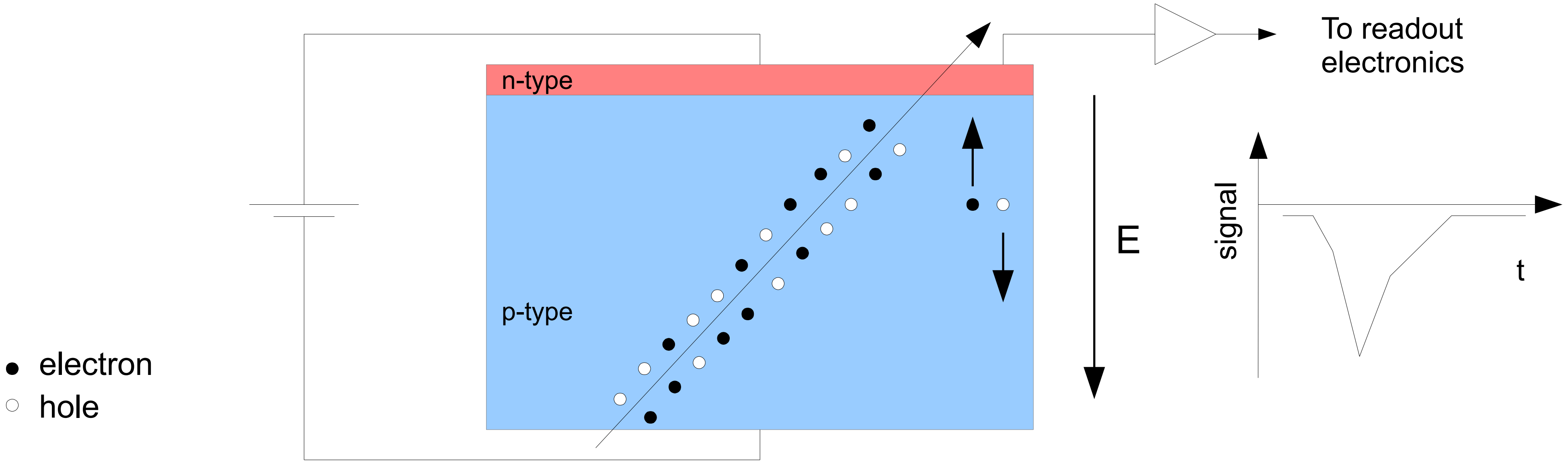


Advantage: electrons have factor 3 larger mobility → faster signal & smaller collection time

Still the holes contribute to the signal (they keep moving → current)

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- Signal like for **p-on-p** sensors
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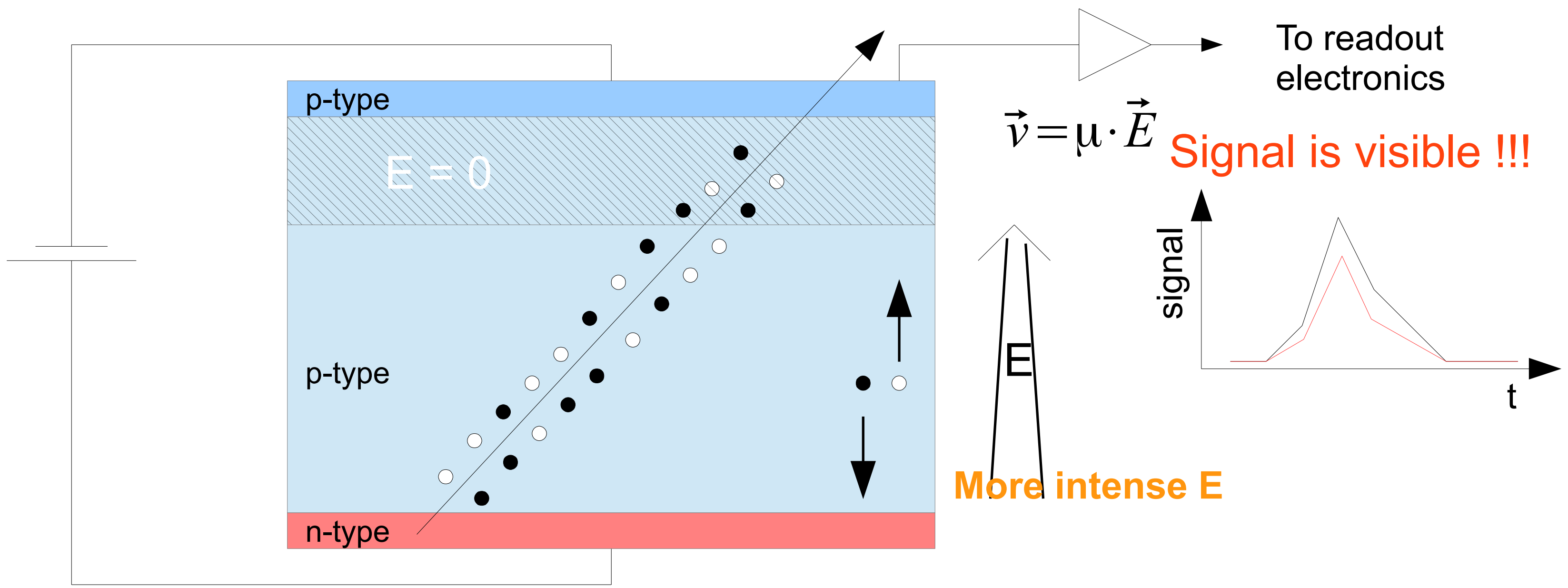
  - p-type bulk + n-type layer in the backplane → p-n junction
  - Partially depleted sensor ($V_{bias} < V_{fd}$)




- electron
- ○ hole

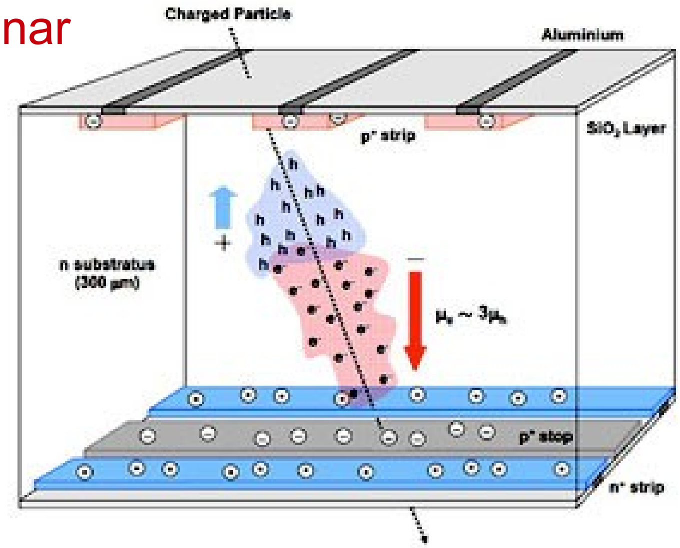
**In spite of the E=0 region near the readout channels signal is still visible because the charge carriers move in the depleted region → the current produces signal although spatial resolution degrades**

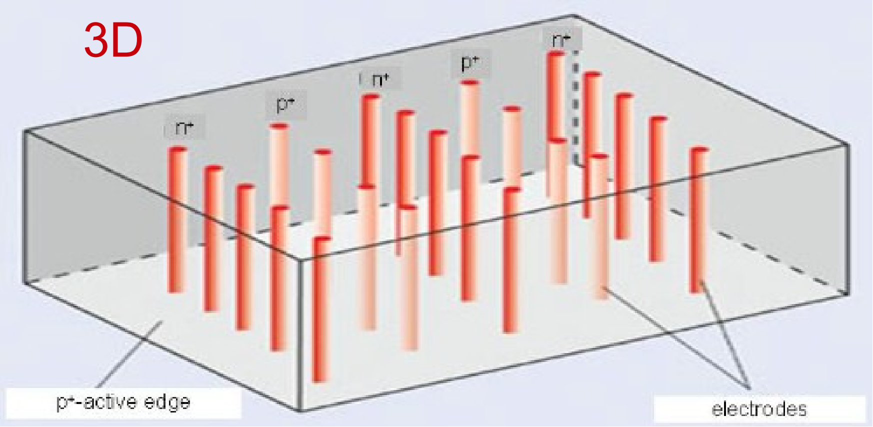
# Position sensitive: segmentation

- Silicon sensors can be used as position sensitive detectors via SEGMENTATION
  - Add many readout channels in the same sensor
  - Planar technology (most common)
  - 3D technology (recent development)

Silicon crystal ingot & wafers →

Planar



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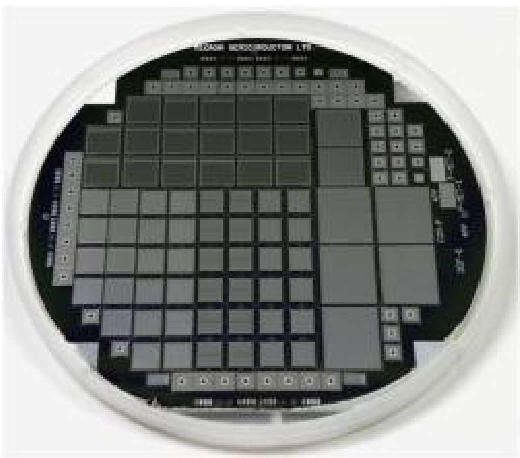
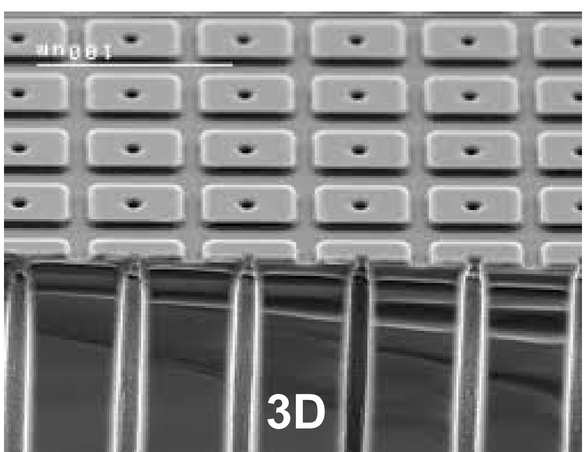
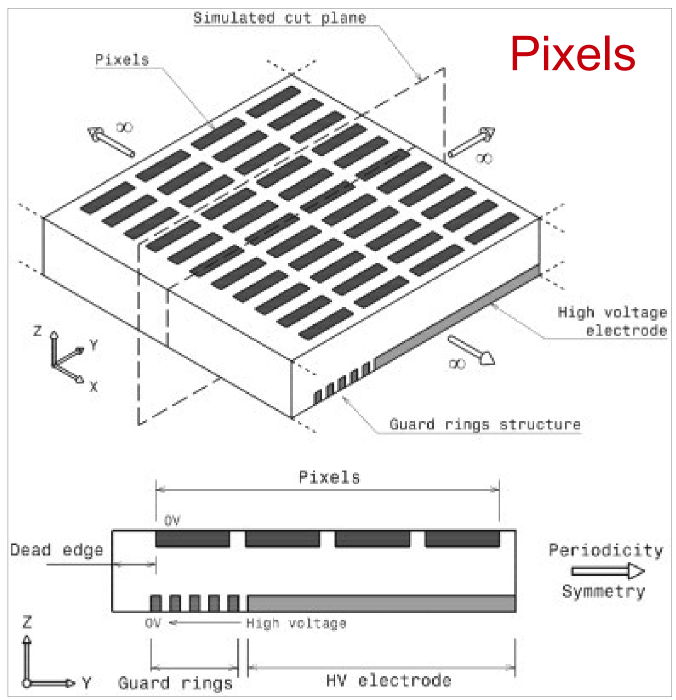
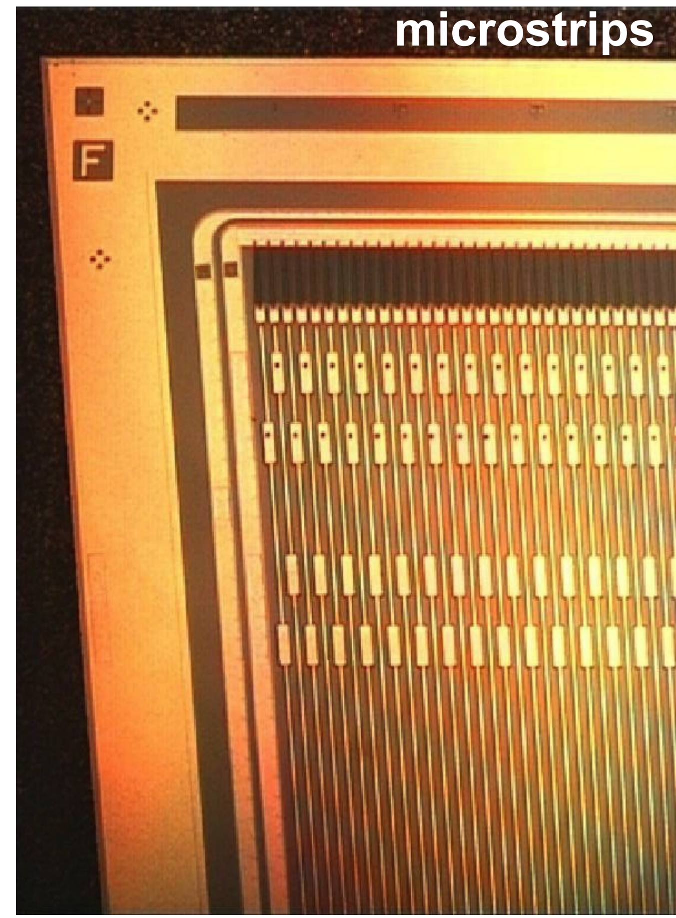
Silicon wafer with sensors





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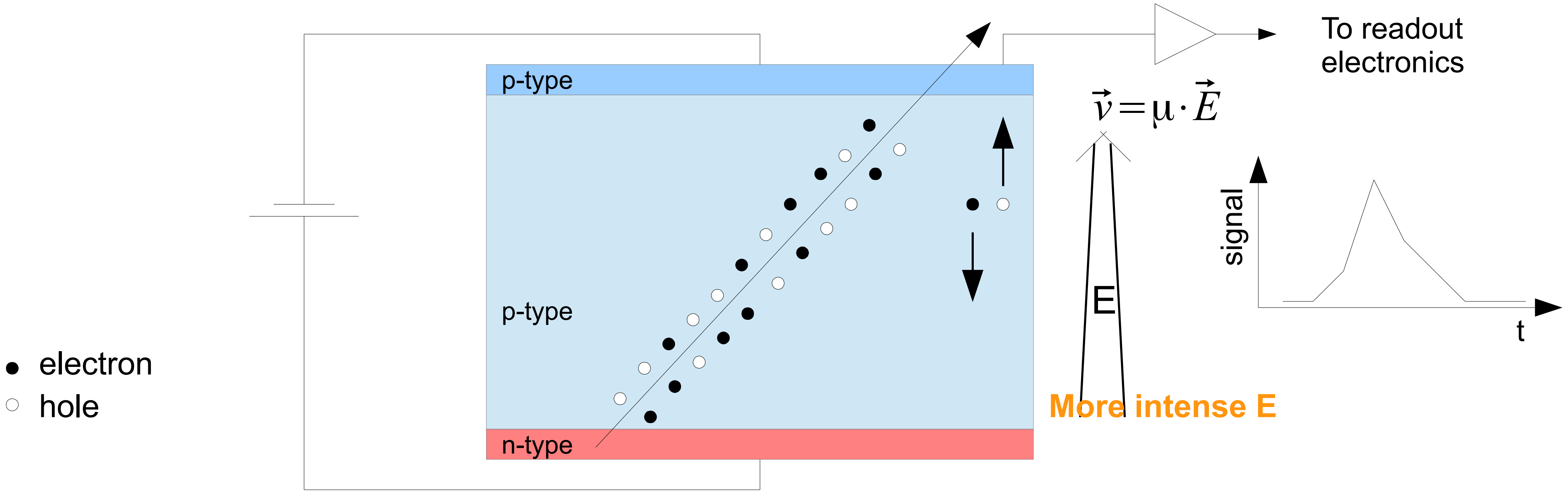
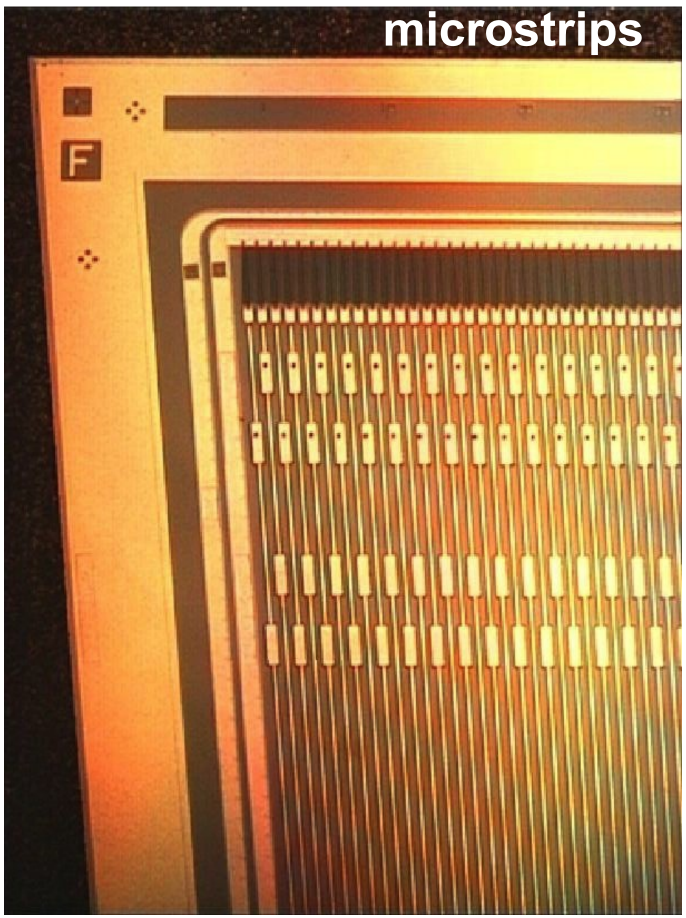


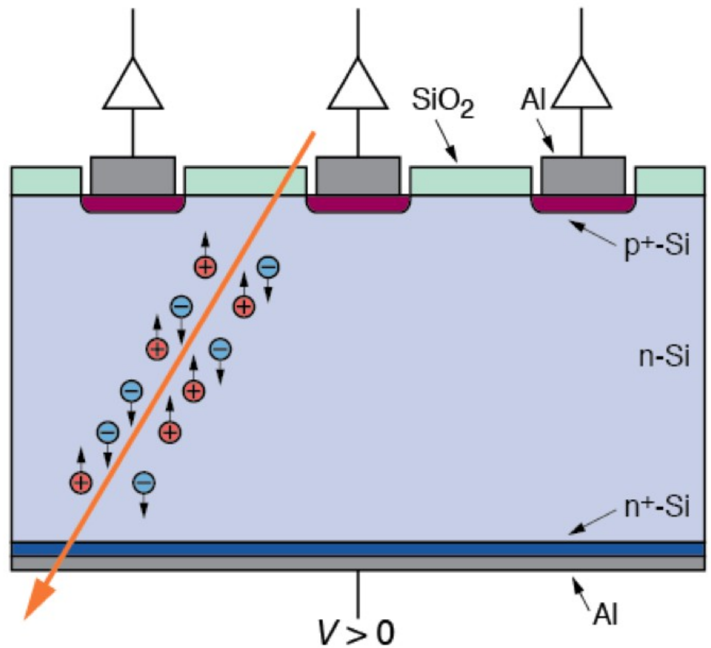

**The electric field is more intense at the p-n junction (backplane) → As carriers velocity is: v = μE → carriers slow down as they approach the readout contact**

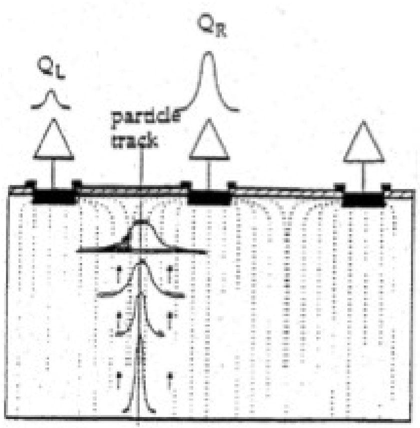
# Position sensitive: segmentation

- The measurement of the position depends on the fired channel
  - Many readout channels in the same sensor: channel ↔ position
  - Physics processes: distance between channels (pitch), signal-to-noise ratio, readout mode (analogue or binary), channel coupling, ...




← bias resistors

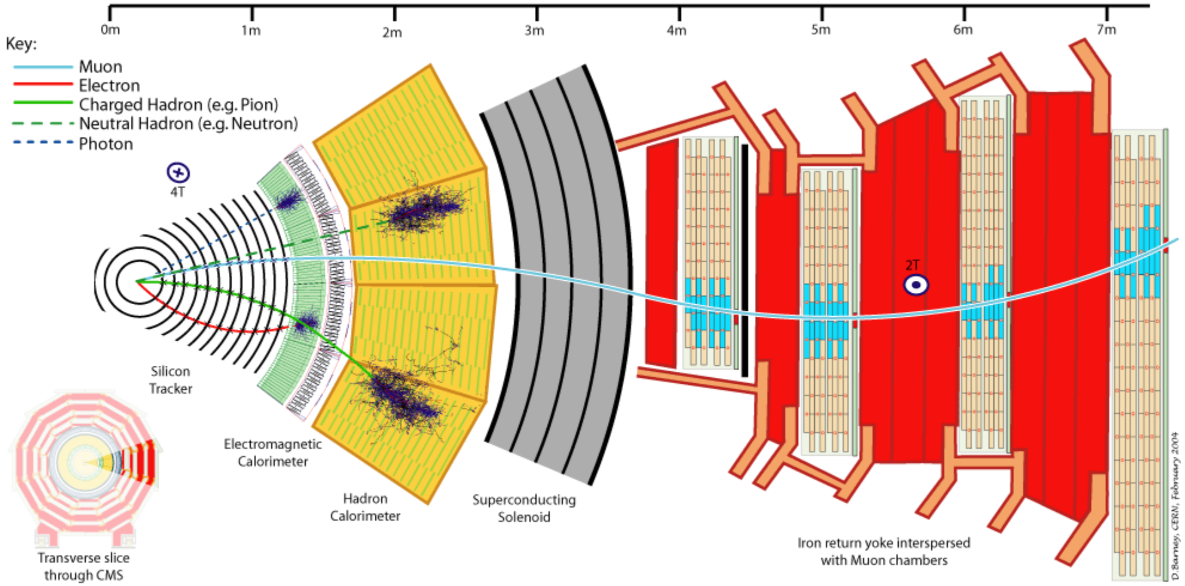



Naïve expectation of the resolution = pitch / √12
Although many effects may influence the final value

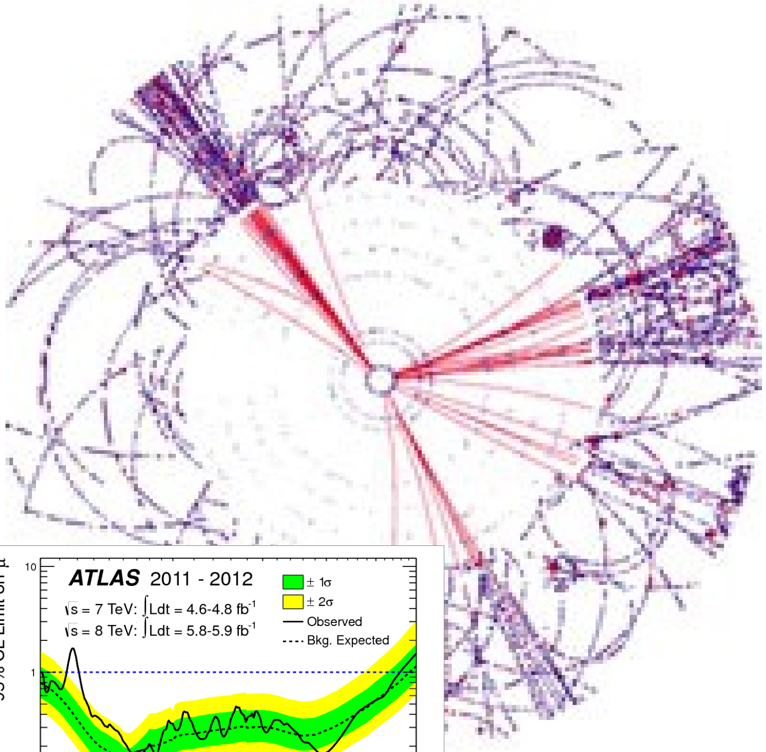
# Data acquisition in HEP experiments

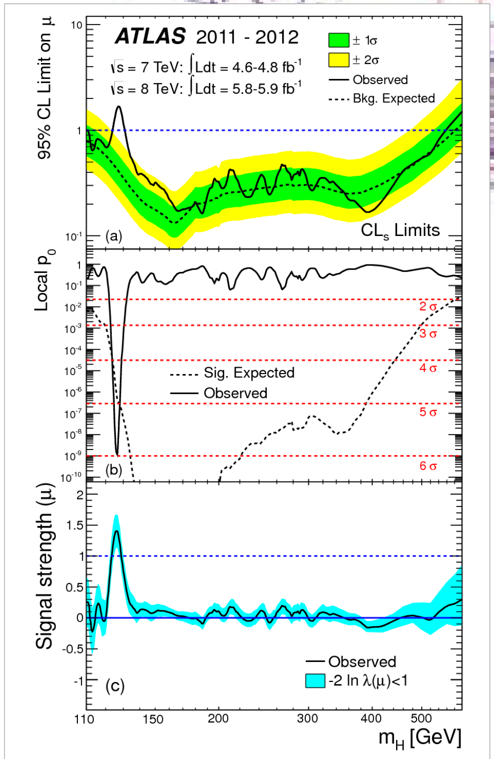
- Goal is to record the data registered by sensors when beams collide

# Data acquisition in HEP experiments

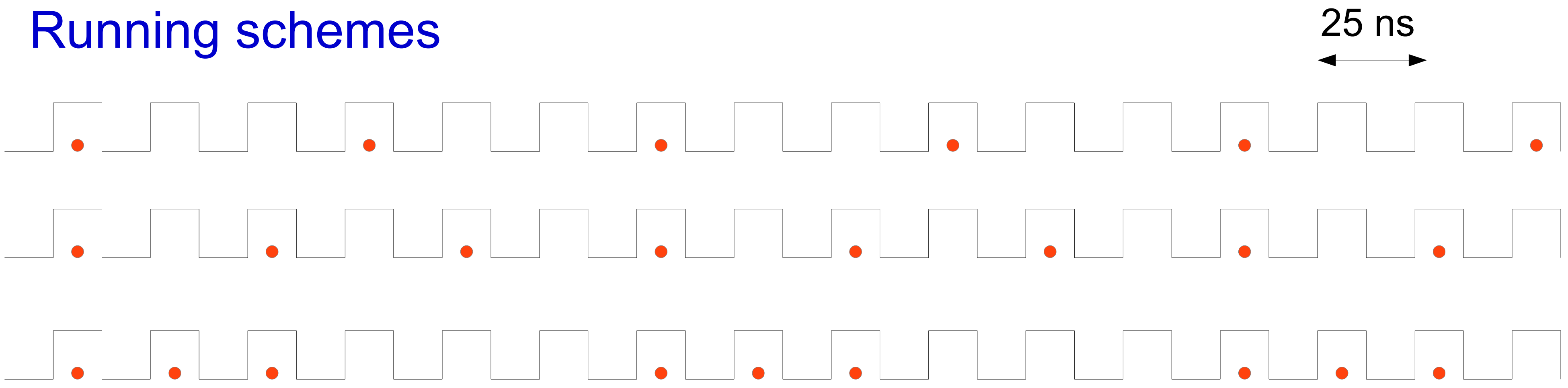
- Sensors react to the passage of particles and produce signals
  - Usually as electric pulses
  - Digitization: convert those pulse into digits
- Trigger
  - Whenever an interesting event happens
    - Whatever “interesting” means
- Record the data
  - In digital format
  - In disk or tape
- Event reconstruction
  - Tracker hits → tracks
  - Calorimetry → energy deposition
  - Bear in mind the calibration, geometry, etc.
- Event analysis & selection
  - According to the reconstructed objects
- Physics results
  - Eureka !



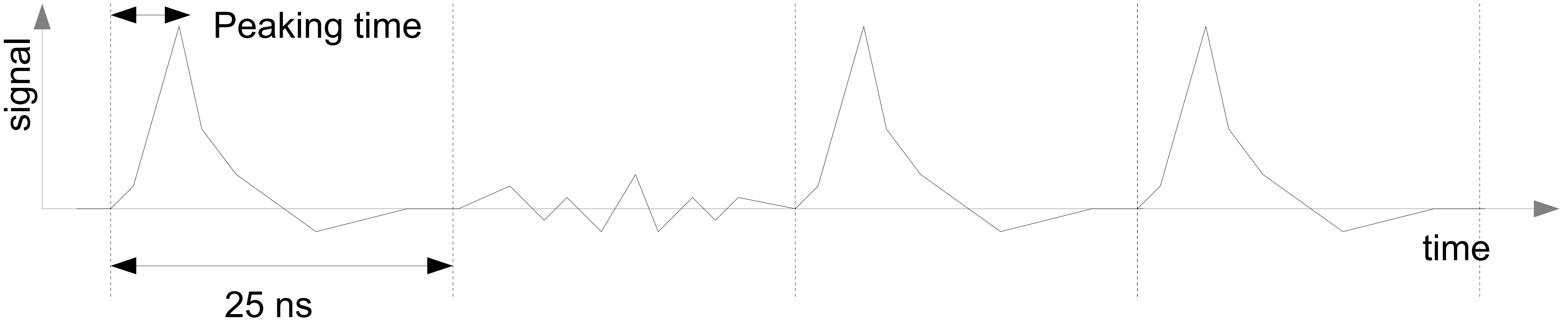


# LHC 40 MHz clock

- LHC works with a 40 MHz clock
  - It does not mean collisions happen at 40 MHz all day long
- Running schemes




- Electronics should be fast and be ready to record each 25 ns slot independently.
  - Otherwise signal pile-up may occur



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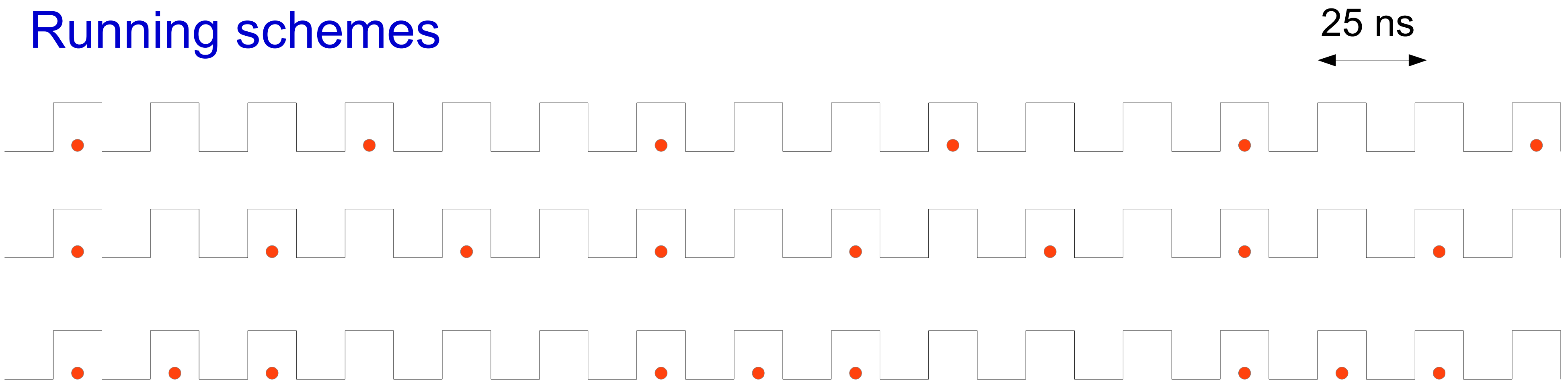


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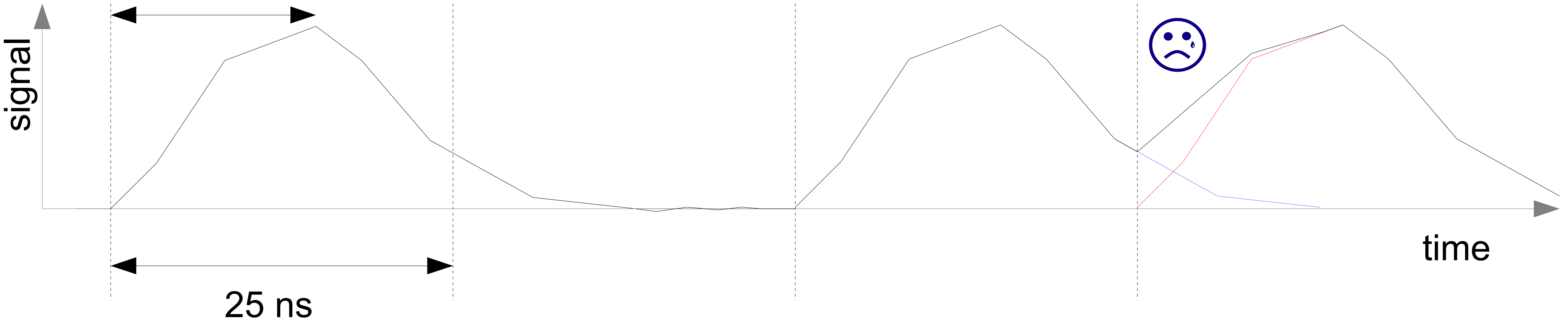
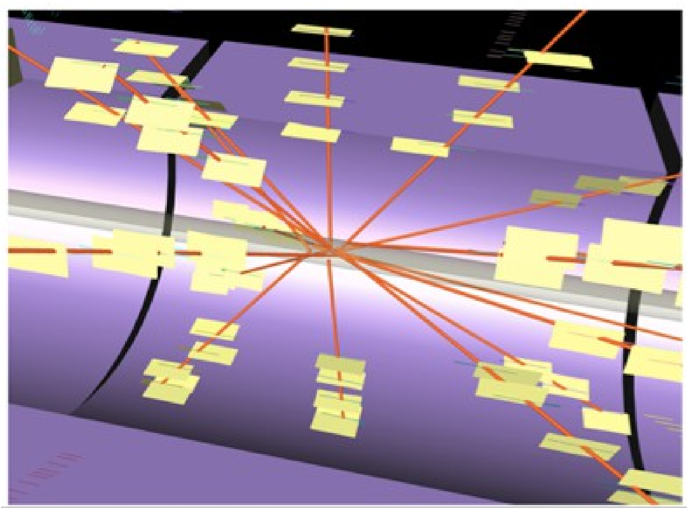
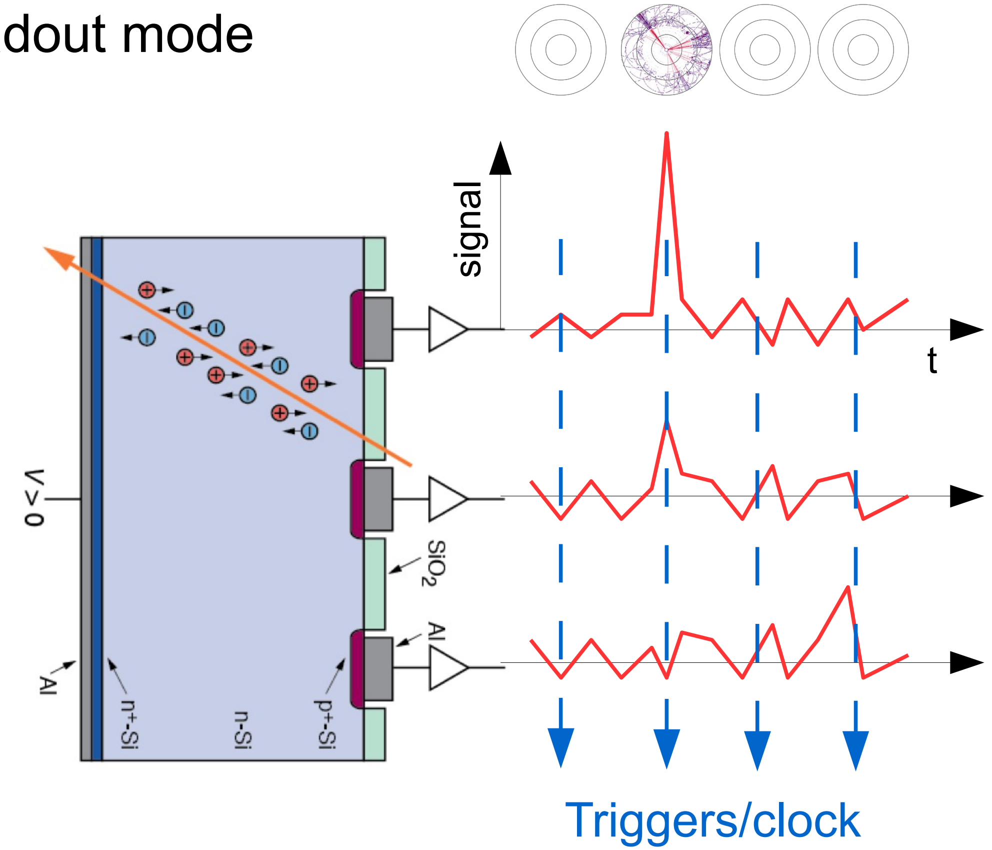


# Signal processing

- The sensors are operated continuously although data is read out only when acquisition is triggered
  - Output depends on readout mode






Analogue mode →
(arbitrary units)

| | | | |
|---|---|---|---|
| +1 | +8 | +1 | +1 |
| -1 | +3 | -1 | 0 |
| -1 | -1 | -1 | +4 |

Possibility to perform center of gravity calculations

Storing all data is not practical → zero suppression

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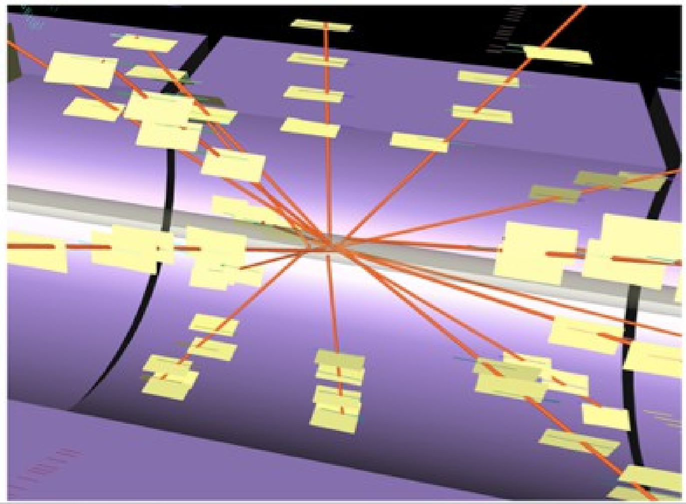
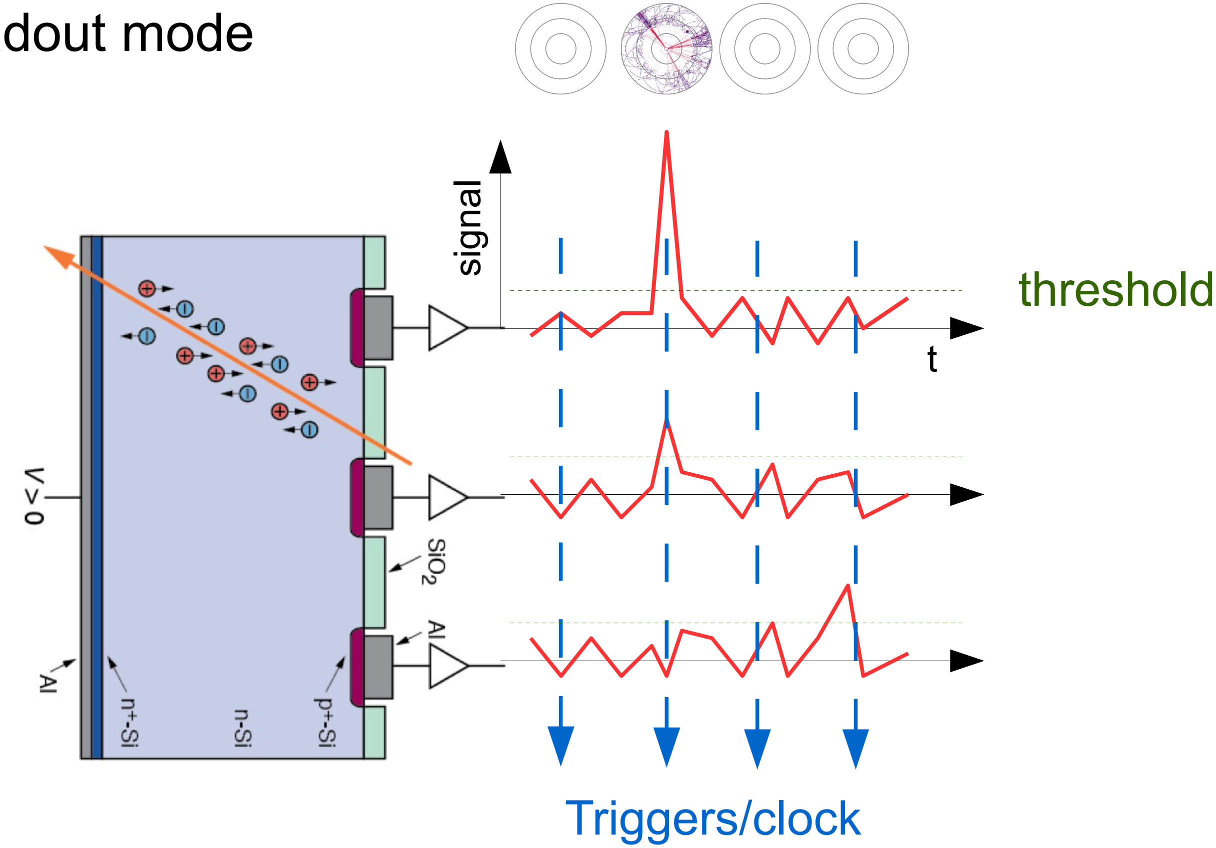
- The sensors are operated continuously although data is read out only when acquisition is triggered
  - Output depends on readout mode






**Binary mode** →

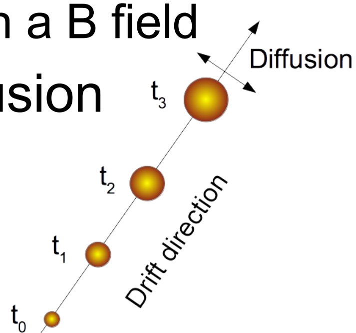
| | | | |
|---|---|---|---|
| 0 | 1 | 0 | 0 |
| 0 | 1 | 0 | 0 |
| 0 | 0 | 0 | 1 |

No center of gravity calculations

Very compact data format

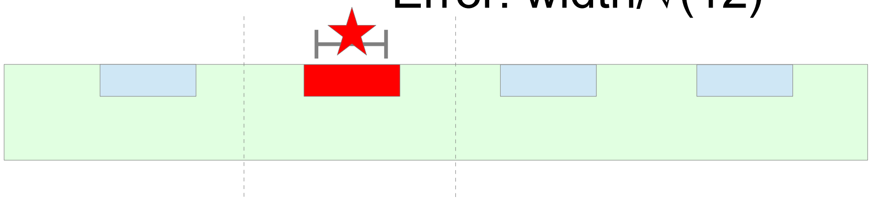
# Signal processing for track fitting

- Hit ↔ channel with signal
  - Detector specific
  - Channel ID & pulse height
- Cluster → group of channels
  - From 1 channel to many
  - 3D information:
  - Global or local coordinates
  - Position: (x, y, z)
  - Error: (δx, δy, δz) in a covariance matrix form
- Cluster position may depend:
  - Hit data: binary or analogue
  - Center of gravity
  - Lorentz angle corrections
    - Operation embedded in a B field
  - Charge carriers drift/diffusion
  - Track incident angle
  - MCS corrections



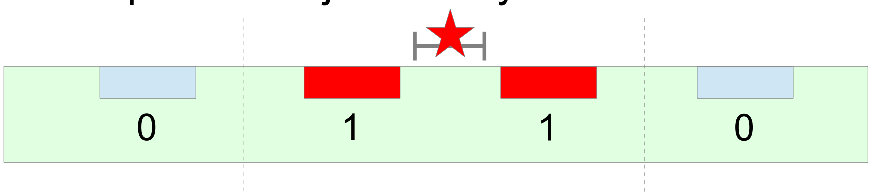

Single channel → Position: channel center

Error: width/√(12)

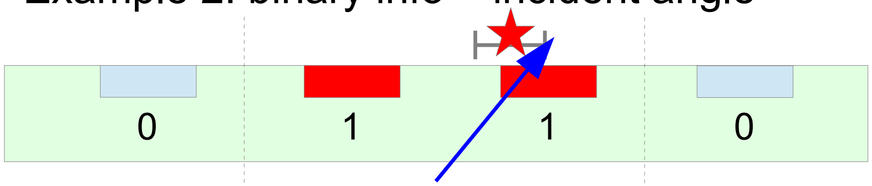


Many channels → Position and error depend on clustering algorithm, hit info (analog or binary), strategy and conditions

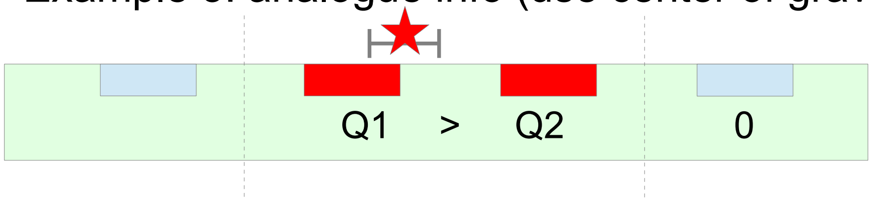
Example 1: use just binary info




Example 2: binary info + incident angle




Example 3: analogue info (use center of gravity)



# Signal processing for track fitting

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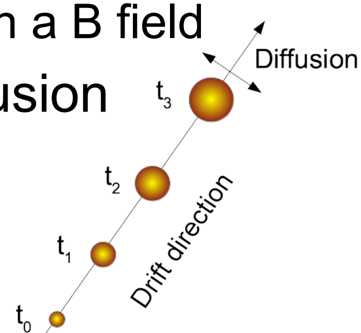
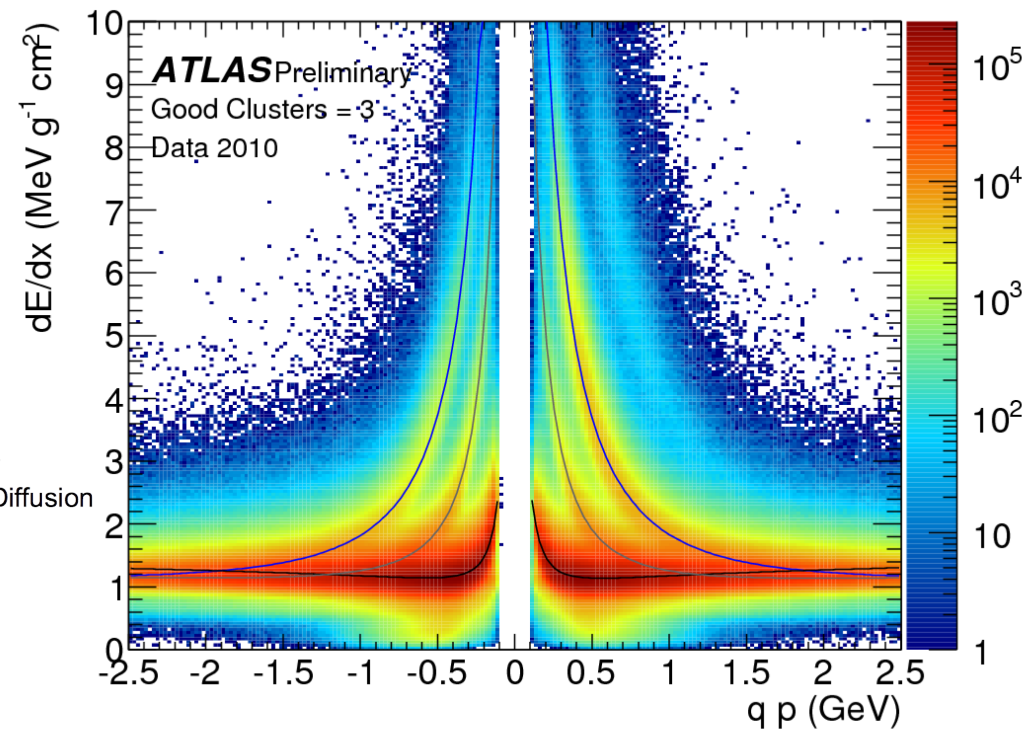


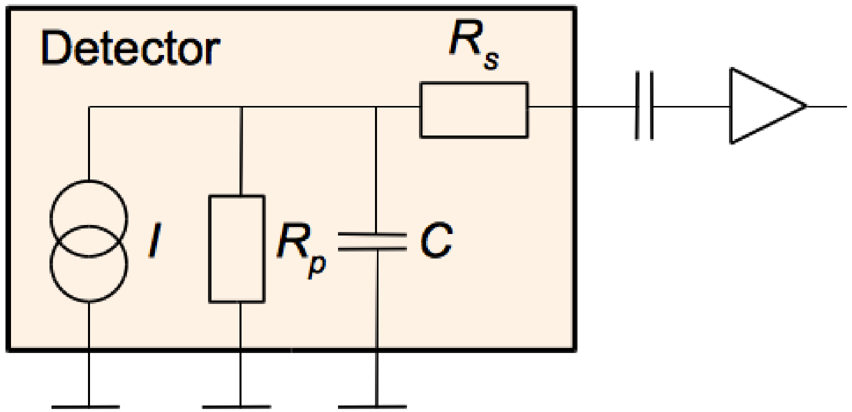

- Cluster charge (signal)
  - Computed from hits
  - Correct for:
    - gain & noise
    - Track path within tracking volume
- Allow to compute dE/dx
  - Analogue (pulse height) data



# Noise

- Noise degrades the tracking capabilities of silicon sensors
  - Genuine signals may be swamped by noise
  - Fake hits could spoil the track fitting

- Most important contributions to silicon sensors noise are:
  - Leakage current
  - Detector capacity
  - Detector parallel resistor
  - Detector series resistor




$$ENC = \sqrt{ENC_I^2 + ENC_C^2 + ENC_{Rp}^2 + ENC_{Rs}^2}$$

$ENC$ = Equivalent Noise Charge

# Noise

- Noise due to leakage current
  - Thermally generated e-h in depleted zone drift away → current
    - In a similar manner to the e-h pairs released by ionizing particles
    - Keep leakage current low
    - Radiation damage → increases the leakage current
- Noise due to detector capacitance
  - Usually the dominant source of noise
    - Keep capacity low
    - Use short strips or pixels (very low noise)
- Noise due to detector parallel resistor
  - Dominated by the bias resistors
    - Large value of the bias resistors are preferred
- Noise due to series resistor
  - Related with the coupling of the channel with the readout electronics
    - Low resistance in the aluminium layers is preferred → thick layers
    - Short connections → readout chips near the sensors
- Very close relation with amplifier's peaking time
  - Sampling time and peaking time dictated by the collision rate

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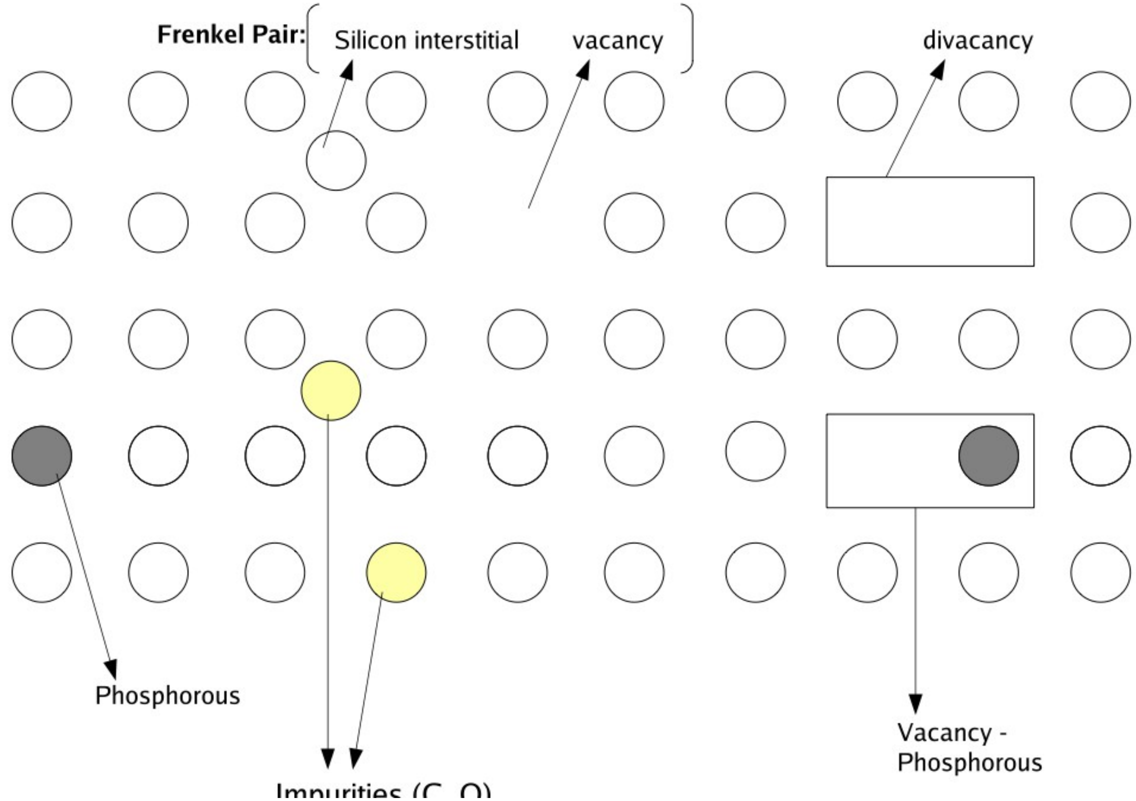
# Radiation damage

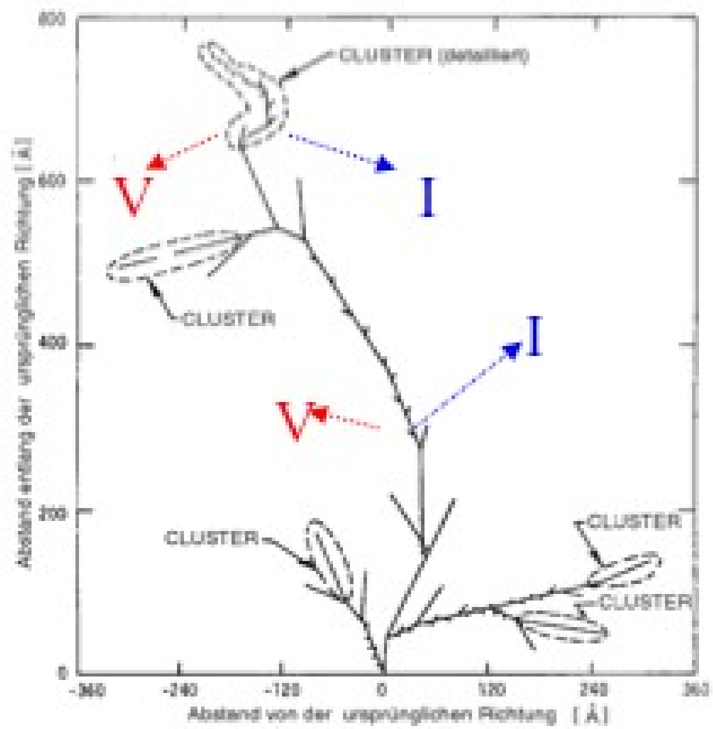
- Silicon atoms are structured in a crystal
- Particles crossing the sensors interact with the electron cloud an produce signal by ionizing the atoms (e-h pairs...)
- Those same particles (and neutral ones) can interact with the atoms
  - May produce displacement of the atoms of the lattice → crystal defects
  - Electrical properties depends on the crystal purity and defects can spoil them
- The rate at which crystal defects are introduced depends on:
  - Incident particle flow
  - Incident particle energy
  - NIEL
    - Non Ionizing Energy Loss
    - Which is used to expel Si atoms from their position in lattice & create defects




- Microscopic damage
  - Changes in the lattice
- Macroscopic effects
  - Sensor properties

# Radiation damage

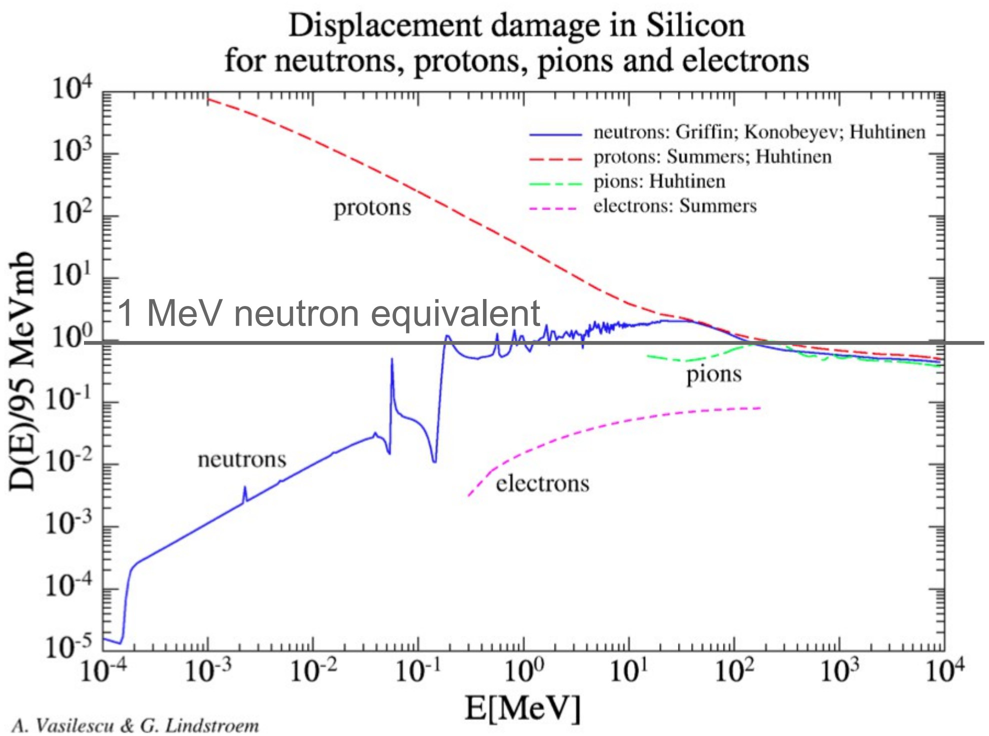
- Point defects:
  - Atoms leaving their position in the lattice leave a Vacancy (V)
    - 25 eV ! Energy necessary to remove a Si atom from its lattice location
  - They use to occupy an inter-lattice space (interstitial, I)
  - Frenkel defect: a vacancy – interstitial pair  (quite stable)
  - Otherwise: Annealing process
    - defects are mobile  at room T
- Cluster defects:
  - The primary knock-on atom may displace other atoms in the lattice
  - Clusters may involve hundreds of atoms
  - Produce amorphous silicon



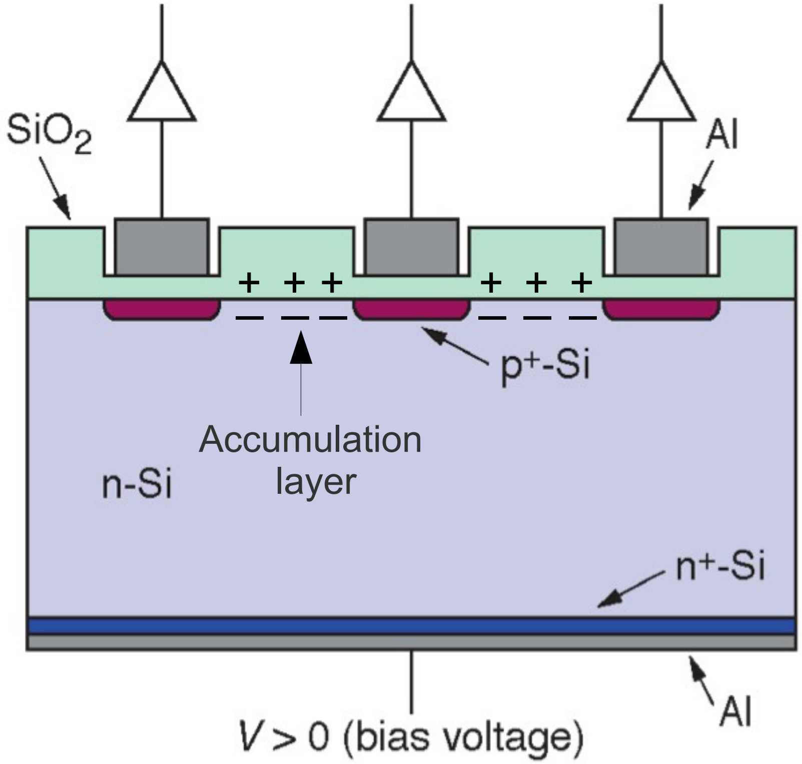

Schematic distribution of vacancies created
By a 50 KeV Si atom in silicon

# Radiation damage

- One can distinguish between damage in the bulk and in the surface
  - Bulk damage: dislocations caused by massive particles
    - defects create intermediate energy levels in the band gap
    - Doping concentration, leakage current and charge trapping
  - Surface damage: charge layer generated in the oxide caused by photons and charged particles
    - May affect the isolation between strips/channels → micro-discharges

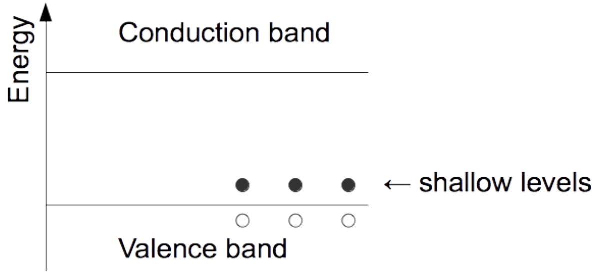


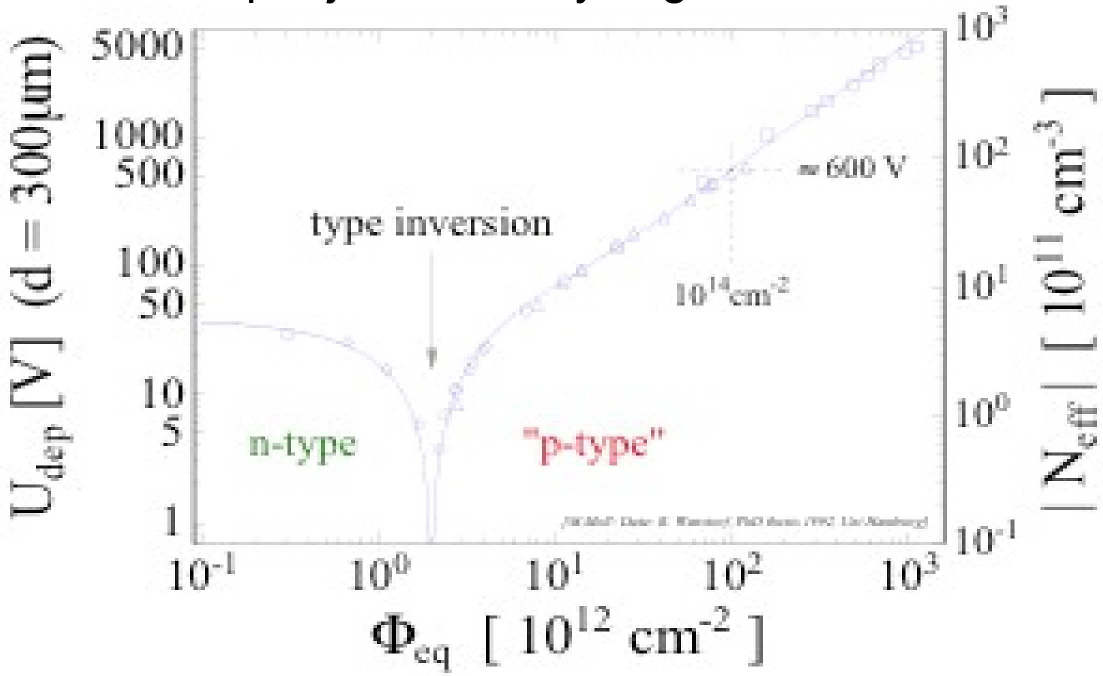

Damage hardness factor for different particles

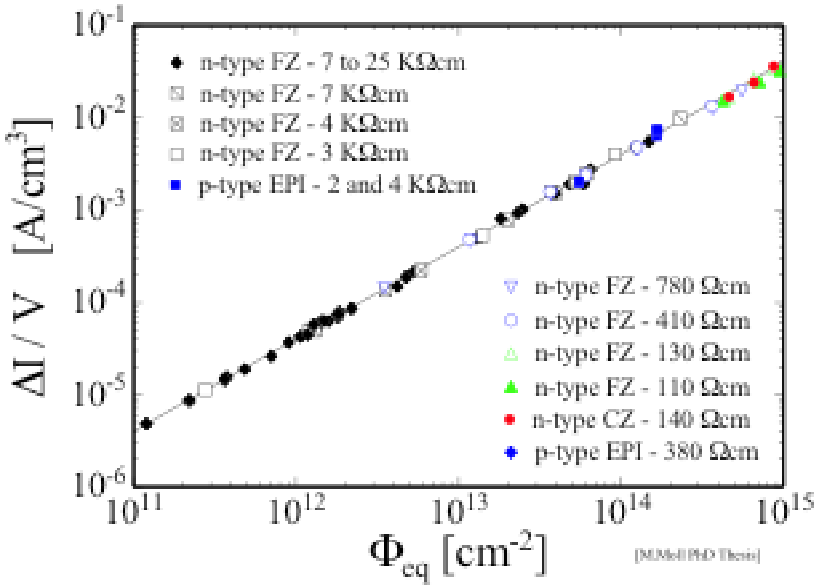


# Radiation damage: bulk damage

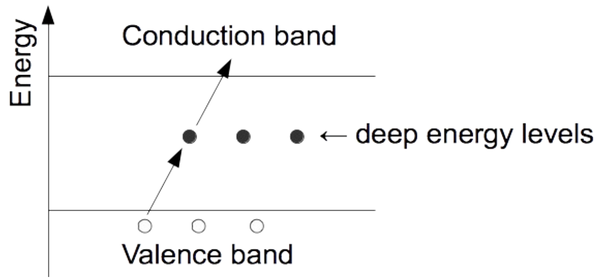
- Change of the effective doping concentration
  - New energy levels (defect) act as dopants (p-type)
  - Change in the depletion voltage
  - Eventual change of bulk type: from n-type to a p-type
    - p-n junction may migrate



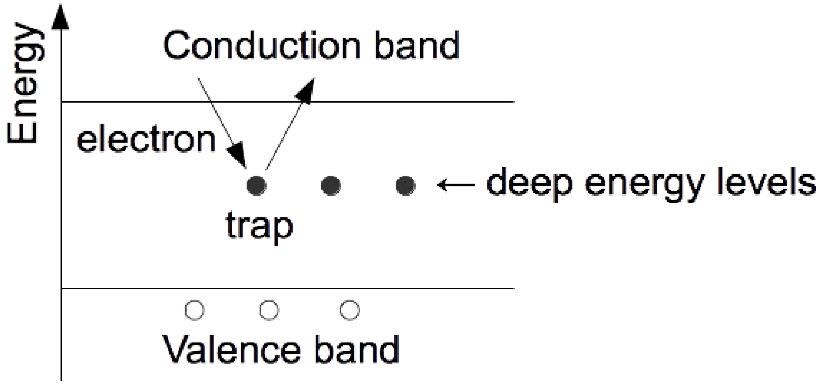

- Increase of the leakage current
  - Due to deep energy levels
  - Impact on sensors noise
  - Thermal runaway
    - Power dissipation & cooling system

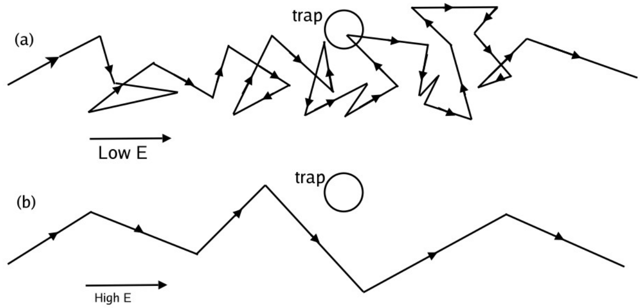


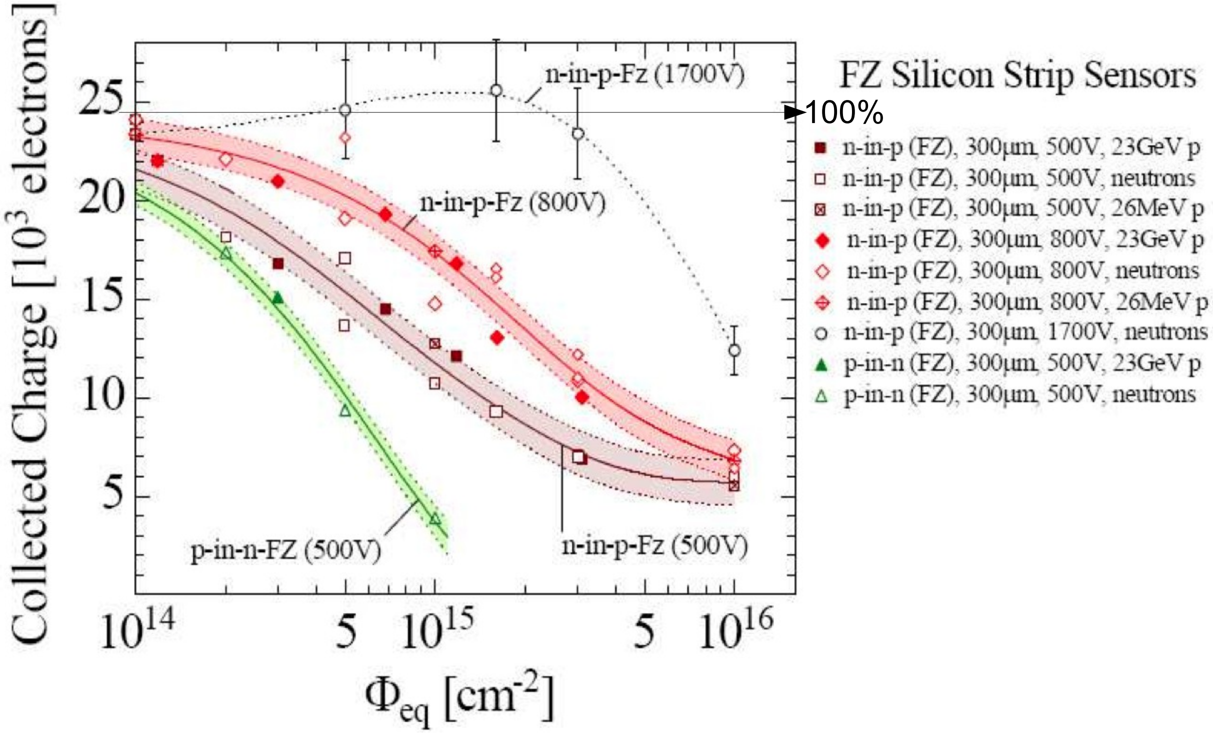
# Radiation damage

- Charge trapping: carriers may be caught during their drift
  - Later they will be released again
    - Although the net effect is: stop contributing to the current and therefore to the signal
- Trapping is due to deep levels
  - in the middle of the band gap
  - Trapping probability depends on carriers velocity
    - Mobility
    - Less trapping for electrons

[B. Rollings in 100 m hurdles final. Moscow 2013]

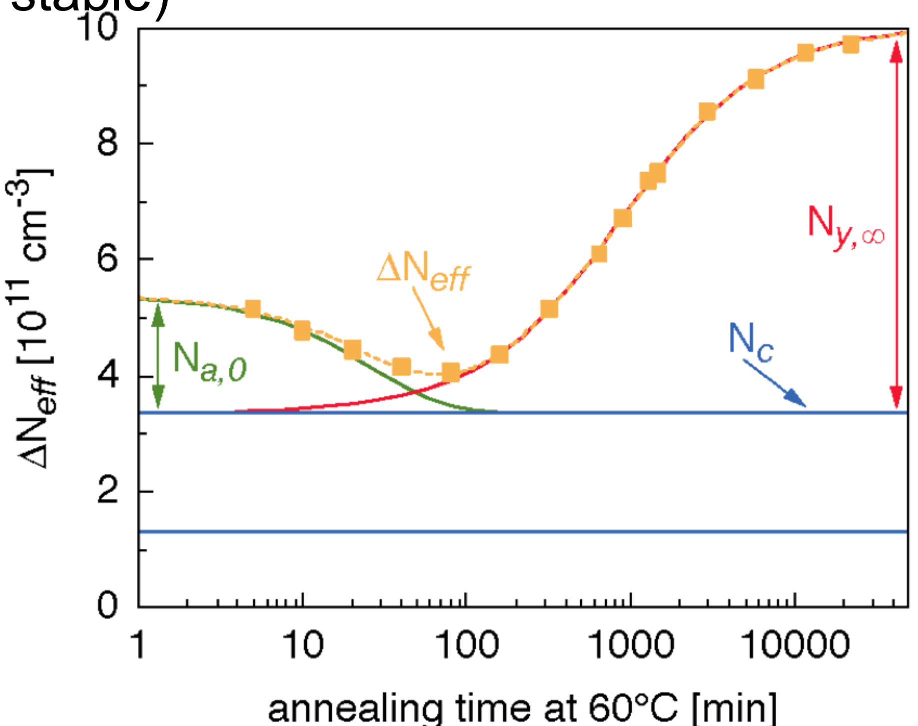


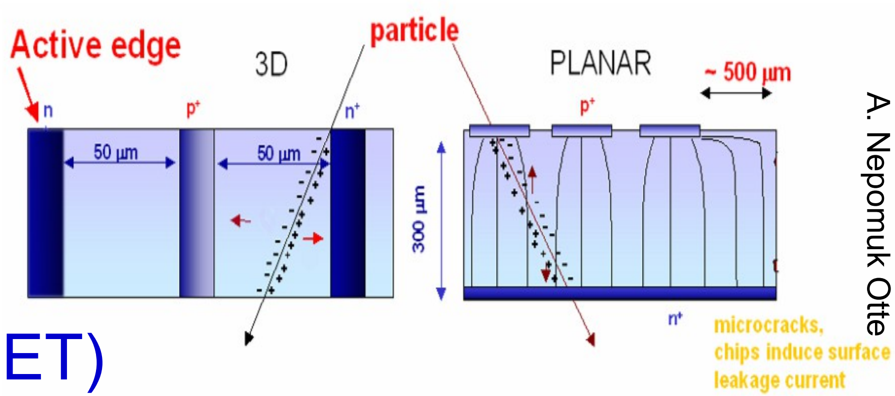
# Radiation damage: annealing

- Annealing: defects are mobile due to thermal excitation
  - Interstitial – vacancy may combine (lattice restoration → beneficial)
  - Form complex defects: di-vacancy (quite stable)
  - Temperature & time dependent
- 3 components of structural damage
  - Permanent damage
  - Beneficial annealing (short term)
  - Reverse annealing (long term)
- Effect clearly seen in effective doping
  - Evolves with time
- How to fight radiation damage
  - Defect engineering
    - Oxigenation of substrate (improves radiation hardness)
  - Device engineering
    - Substrate type (p-type does not inverts)
    - 3D (very low depletion, collection time, drift distance...)
  - New materials
    - MCZ, SiC, Monolithic devices, diamond

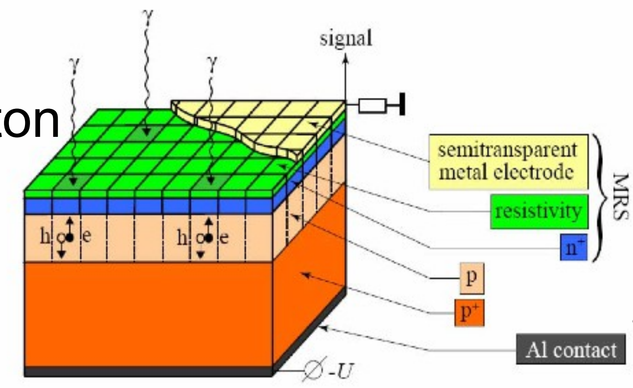


# Other semiconductor sensor types

- Charge Coupled Devices (CCD)
  - Slow device but with resolution equivalent to pixel sensors. Excellent SNR
- Silicon drift detectors
  - 2D information: segmentation and drift time
- Monolithic active pixels (MAPS)
  - All in one concept: detector+connection+readout
  - Great integration, low power consumption
- 3D detectors
  - Non planar, sideways depletion
  - Very low depletion voltages and very fast
- Depleted Field Effect Transistor (DEPFET)
  - Low capacitance, low noise & low power consumption
  - Combined function of sensor and amplifier
- Avalanche photodiodes (APD)
  - Operated in breakdown regime → detect single photon
  - Used in calorimetry & Cerenkov
- Silicon Photo-multipliers (SiPMs)
  - Matrices of APD (100 or 1000 per mm$^2$)




A. Nepomuk Otte




K Voloshoin. NIMA 539 (2005)

# Summary

- Silicon sensors operate thanks to:
  - Incident particle creates electron-hole pair by ionization
  - Electrons and holes (charge carriers) move → current to be detected
  - p-n junction

- Bibliography