Silicon radiation detectors

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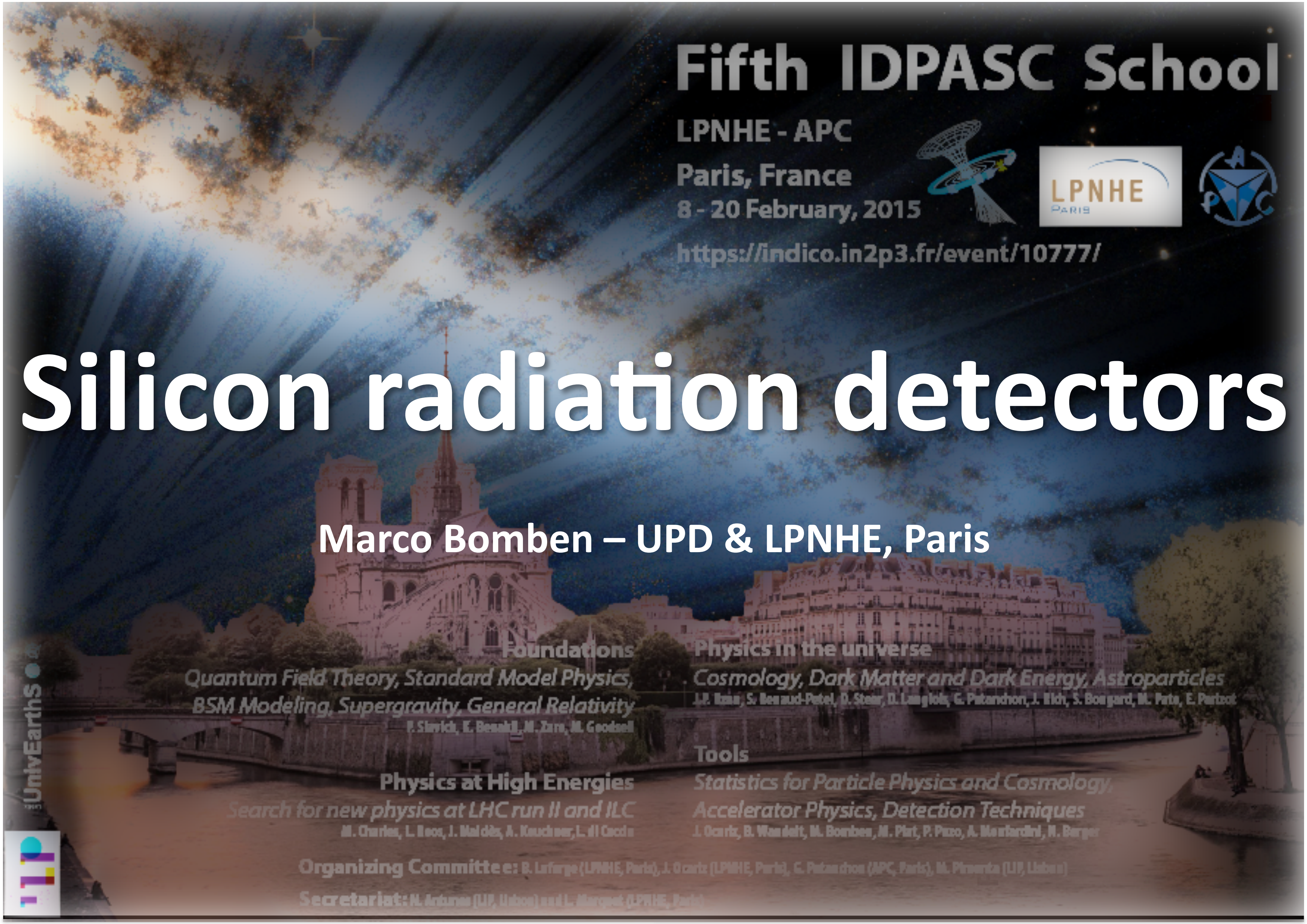

Acknowledgements

Thanks to: I. Abt, V. Bonvicini, G. Calderini, S. Holland, M. Krammer, M. Moll and P. Wells

- You can find great lectures here: http://www.hephy.at/fileadmin/user_upload/Lehre/Unterlagen/Praktikum/Halbleiterdetektoren.pdf
- And here: http://wwwusers.ts.infn.it/~bonvicin/Dottorandi08.pdf

References

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See also: http://www-physics.lbl.gov/~spieler/
•G. Lutz, Semiconductor Radiation Detectors: Device Physics , Springer (July 11, 2007)
•S.Sze, Physics of Semiconductor Devices, J.Wiley, 1981

•H. F.-W. Sadrozinski, Applications of Silicon Detectors, IEEE Trans. Nucl. Sci. Vol. 48 n.4 pp.933 –940, 2001.
•F. Hartmann, Silicon tracking detectors in high-energy physics, Nucl. Instr. and Meth. A666 (2012) 25-46
•D. Renker and E. Lorenz, Advances in solid state photon detectors, 2009 JINST 4 P04004

•K.A. Olive *et al.* (Particle Data Group), The Review of Particle Physics, Chin. Phys. C, **38**, 090001 (2014).

Disclaimer

- What this presentation doesn't cover:
  - Electronics
  - Infrastructures
  - Services
- Main focus on sensors
- Plus: The author has been working on Silicon Sensors for charged particles detectors at colliders for many years. Hence he has a slight bias for charged particle detectors

Outline

- History and motivations
- Semiconductors physics
- Silicon radiation detectors
- Perspectives

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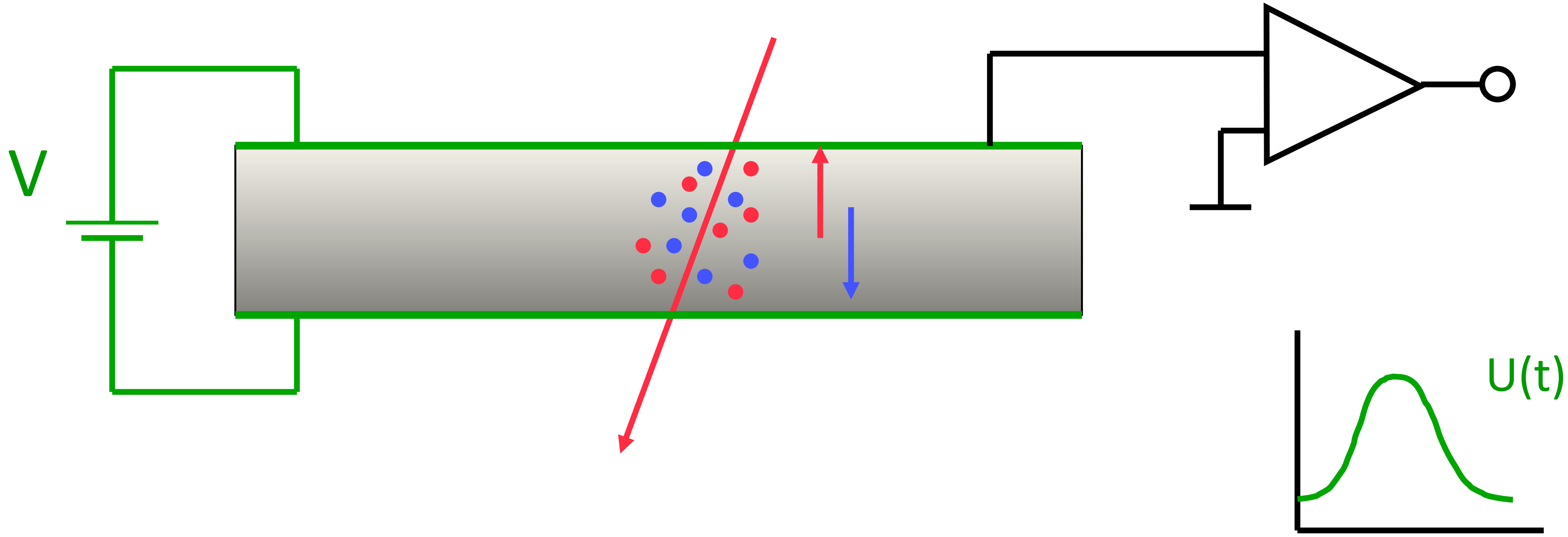
The basics



A solid state ionization chamber

Signal given by the drift of charges (electrons and holes) under the effect of the electric field

The signal is then amplified and shaped

Pre-history (1949-1951)

The first examples were mainly prototypes to demonstrate the feasibility of the principle

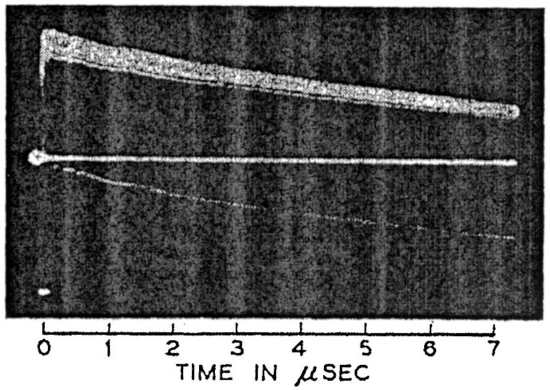


FIG. 3. Photograph of pulses from sixteen alpha-particles striking the $n-p$ barrier.

K.G. McKay, A Germanium Counter, Phys Rev 76 (1949), 1537

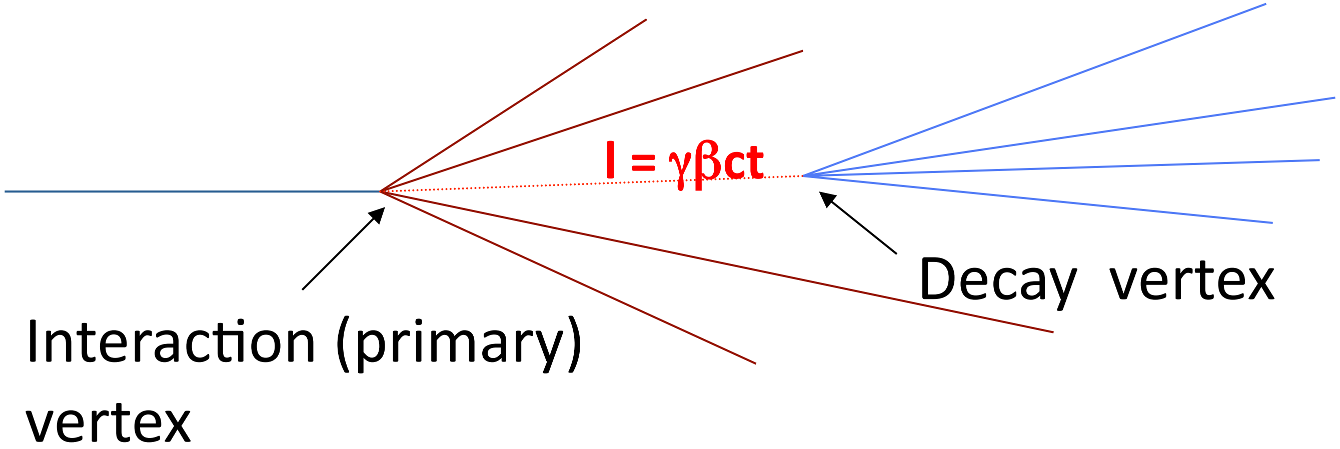
P.J. van Heerden et al., The Crystal Counter, Physica 16, (1950), 505

G.K. McKay, Electron-Hole Production in Germanium by Alpha-Particles, Phys.Rev. 84 (1951), 829

Motivations for semiconductor detectors

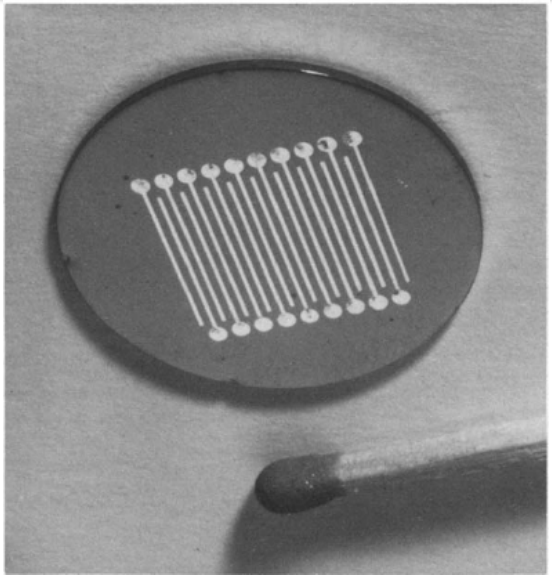
In High Energy Physics we want to reconstruct the particles produced in collisions and measure their characteristics, like: energy, momentum, charge, and their lifetime (if it applies)

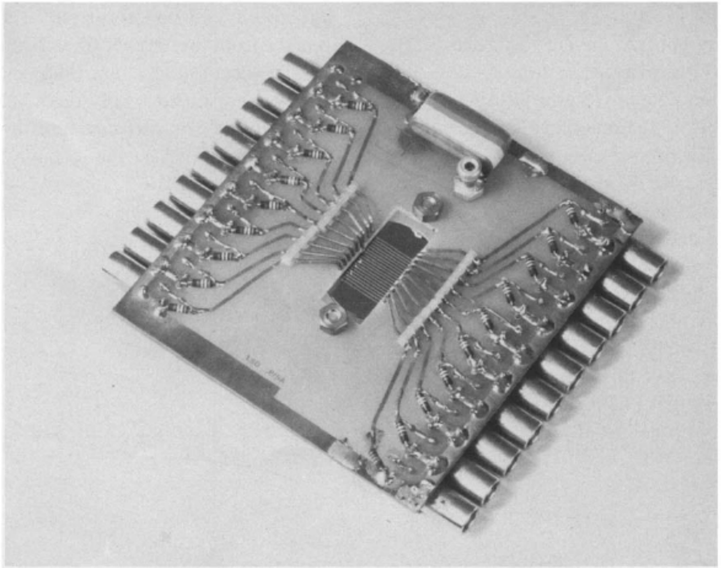
Lifetimes of tau leptons, charm and beauty hadrons: from 0.2 to 1.5 ps

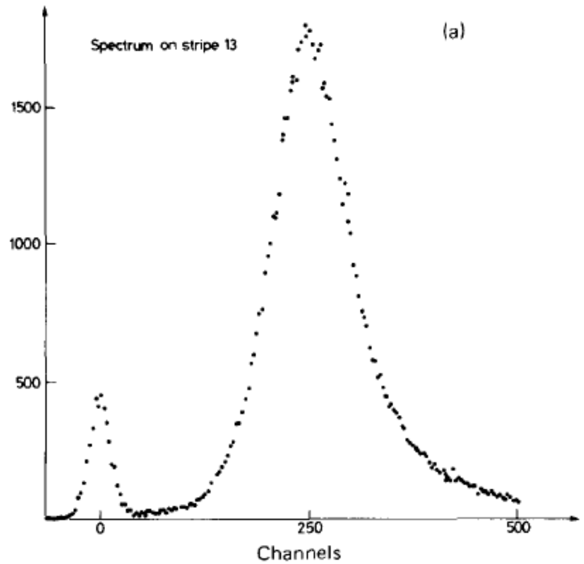


decay length $l = \gamma\beta ct$, so typically the decay vertex is at a distance of single millimeters from the interaction vertex

History – MESD by Pisa group (1980)







MESD featured 12 mm long 300 µm wide aluminium strips on a high resistivity Silicon wafer.

The signal was proportional to the energy released by the impinging particle.

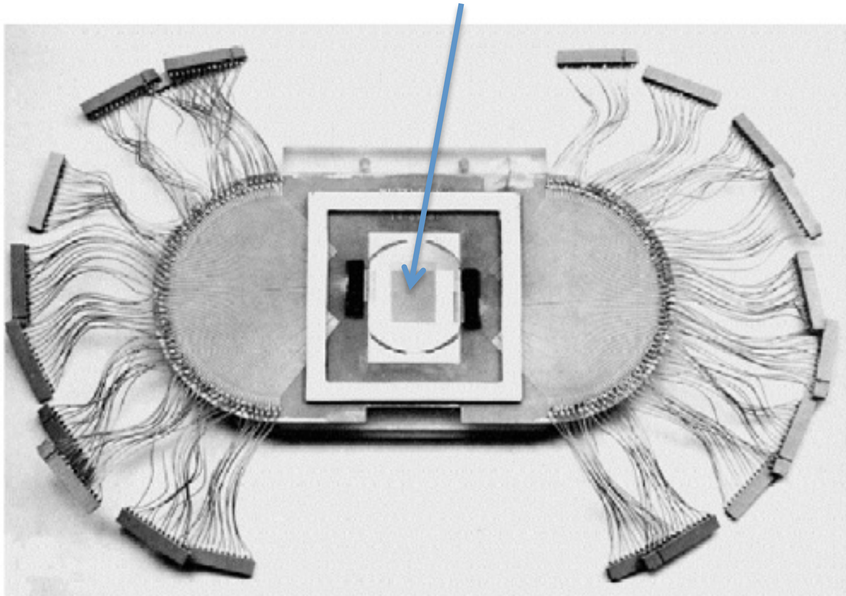
It assured good spatial resolution with low noise at room temperature.

All the desirable features of silicon detectors were already exploited by the first high energy physics detectors

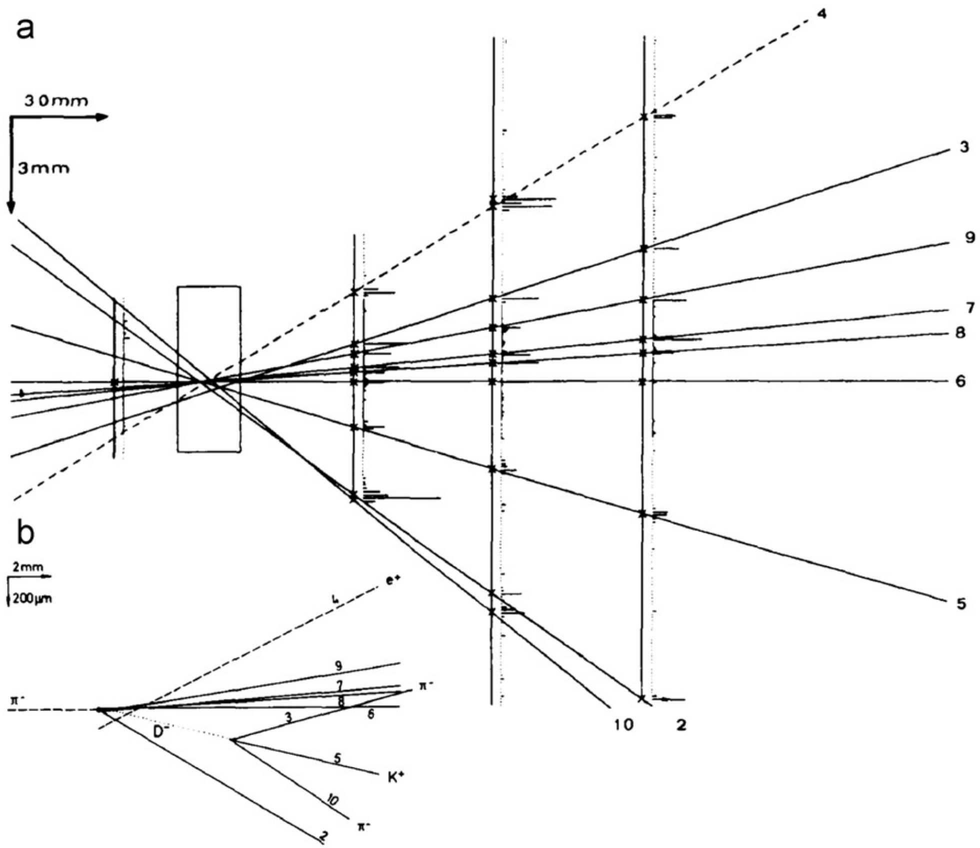
S. R. Amendolia et al., A Multi-Electrode Silicon Detector for High Energy Experiments, Nucl. Instr. Meth. 176 (1980)

History – NA11 detector (1980-1981)

Sensor ~ 24x36 mm^2



200 GeV/c π beam



- P-doped strips implanted on a high ohmic n-silicon wafer
- Rate capability: 10^6 Hz
- Vertex determination accuracy ~ 130 μm

E. Belau, et al., Nuclear Instruments and Methods in Physics Research Section A 217 (1983) 23

History – Munich group (1980-1981)

NUCLEAR INSTRUMENTS AND METHODS 169 (1980) 499-502, © NORTH HOLLAND PUBLISHING CO

FABRICATION OF LOW NOISE SILICON RADIATION DETECTORS BY THE PLANAR PROCESS

J KEMMER

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"Combining the techniques of oxide passivation, photo engraving and ion implantation, it's possible to get a large number of detector chips with only small tolerances in their geometrical and electrical properties"

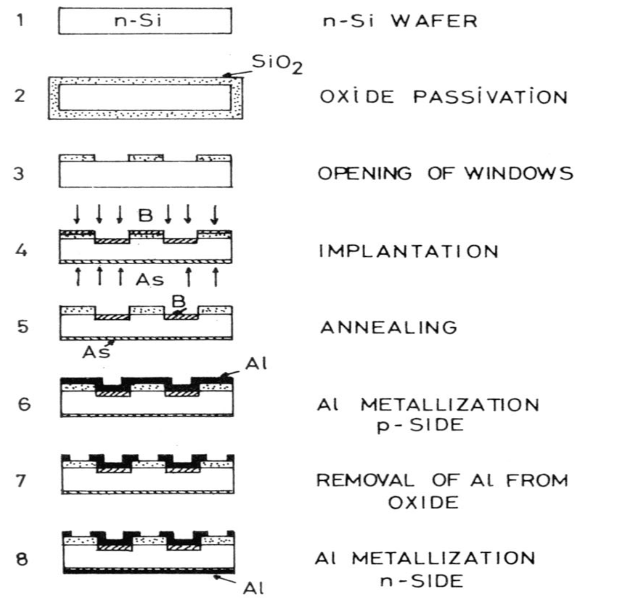

Fig. 1 : Successive steps of the manufacturing process of passivated ion-implanted silicon detectors

Performance:

✓ leakage current < 1 nA / cm^2/100 µm

✓ energy resolution of 100 keV for 5486 MeV alphas of ^{241}Am

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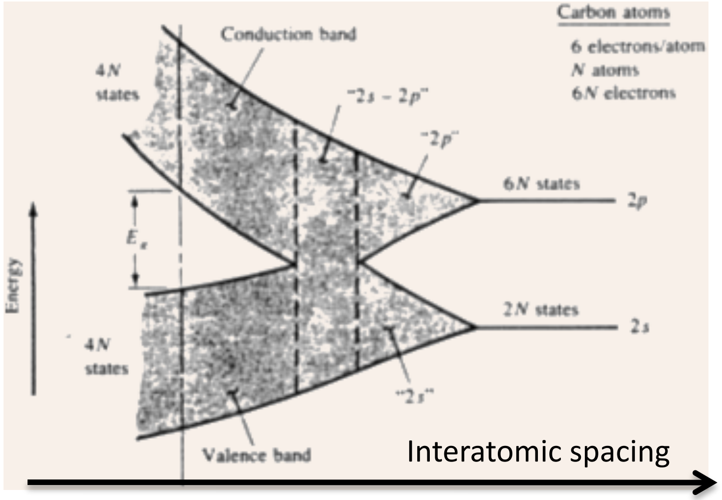
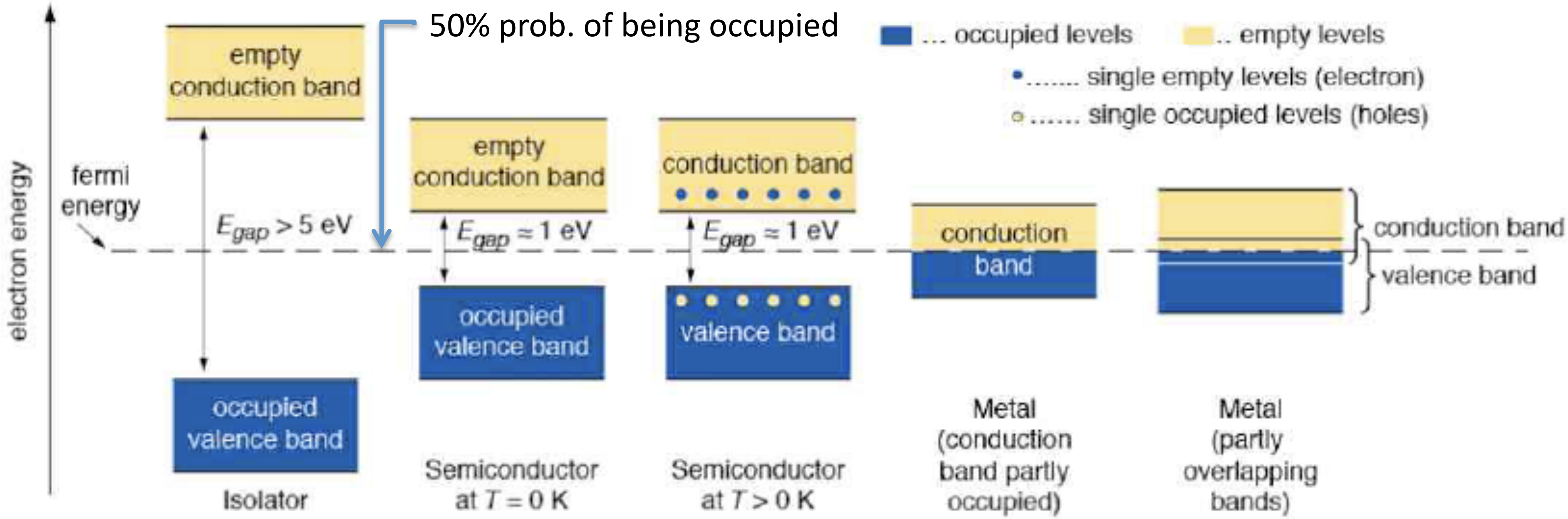
What is a semiconductor?

- In an isolated atom the electrons have only discrete energy levels. In solid state material the atomic levels merge to energy bands.
- In metals the conduction and the valence band overlap,
- whereas in isolators and semiconductors these levels are separated by an energy gap (band gap).
- In semiconductors this gap is large (compared to kT ~ 1/40 eV)





Semiconductors

Germanium: Used in nuclear physics, due to small band gap (0.66 eV) needs cooling (usually done with liquid nitrogen at 77 K)

Silicon: Standard material for vertex and tracking detectors in high energy physics, can be operated at room temperature, synergies with micro electronics industry.

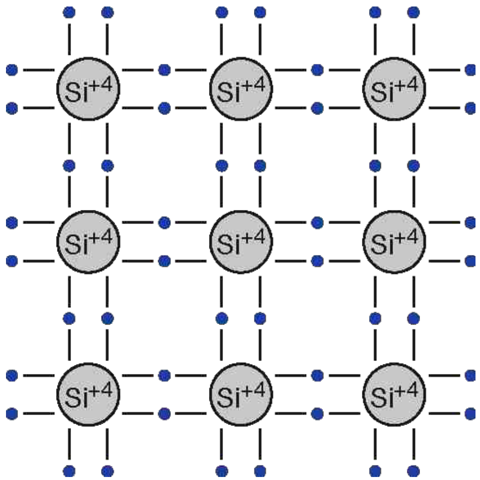
Diamond (CVD or single crystal): Large band gap (6 eV), requires no depletion zone, very radiation hard, drawback is a low signal and high cost

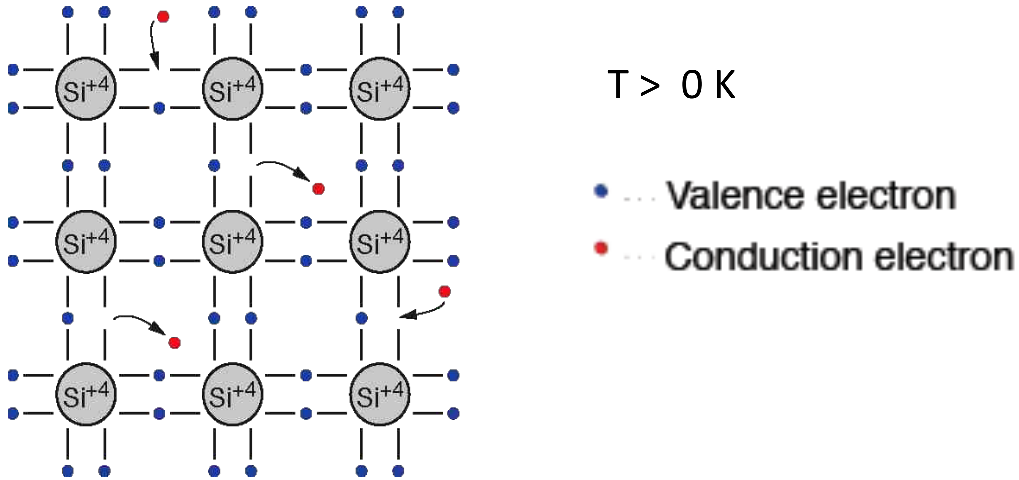
Compound semiconductors: GaAs (faster than Si, no good insulating layer), CdTe (large Z, hence efficient for photodection);

Bond model of semiconductors

Example of column IV elemental semiconductor (2dim projection)

T = 0 K





T > 0 K

Each atom has 4 closest neighbors, the 4 electrons in the outer shell are shared and form covalent bonds.

At low temperature all electrons are bound

At higher temperature thermal vibrations break some of the bonds ➔ free e- (n) cause conductivity (electron conduction)

The remaining open bonds attract other e- ➔ The “holes” (p) change position (hole conduction)

Intrinsic carrier concentration n_i: $n = p = n_i = 1.45\text{x}10^{10}\ \text{cm}^{-3}$ (T=300K)

Transport of charge carriers

Transport of charge carriers in a semiconductor: diffusion and drift

Diffusion: proportional to the gradient of the carrier density

Drift: proportional to the applied electric field

$$\boxed{\begin{aligned} \vec{J}_n &= \vec{J}_{n,drift} + \vec{J}_{n,diff} = q\left(\mu_n n \vec{E} + D_n \nabla n\right) \\ \vec{J}_p &= \vec{J}_{p,drift} + \vec{J}_{p,diff} = q\left(\mu_p p \vec{E} - D_p \nabla p\right) \end{aligned}}$$

D: diffusion coefficient [cm^2/s]

μ: mobility [$cm^2/(Vs)$]

Einstein's equation

$$D_n = \frac{kT}{q}\mu_n$$

$$D_p = \frac{kT}{q}\mu_p$$

$$\boxed{\vec{v}_{drift} = \mu \vec{E}}$$

Valid at low/moderate fields; for large fields (>~ 5×10^3 V/cm) the carriers velocities saturates (Si: v ~ 10^7 cm/s) ➔ 10-30 ns collection time

μ depends on doping and temperature.

For intrinsic silicon: μ_n~ 1350 $cm^2/(Vs)$, μ_p ~ 450 $cm^2/(Vs)$

Estimate SNR in an intrinsic silicon detector

Let's make a simple calculation for silicon:

Mean ionization energy I_0 = 3.62 eV, mean energy loss per flight path dE/dx = 3.87 MeV/cm, intrinsic charge carrier density at T = 300 K $n_i = 1.45 \cdot 10^{10}$ cm^{-3}.

Assuming a detector with a thickness of d = 300 μm and an area of A = 1 cm^2.

→ Signal of a mip in such a detector:

$$\frac{dE/dx \cdot d}{I_0} = \frac{3.87 \cdot 10^6\,\mathrm{eV/cm} \cdot 0.03\,\mathrm{cm}}{3.62\,\mathrm{eV}} \approx 3.2 \cdot 10^4\ \mathrm{e^-h^+{-}pairs}$$

→ Intrinsic charge carrier in the same volume (T = 300 K):

$$n_i\, d\, A = 1.45 \cdot 10^{10}\,\mathrm{cm^{-3}} \cdot 0.03\,\mathrm{cm} \cdot 1\,\mathrm{cm^2} \approx 4.35 \cdot 10^8\ \mathrm{e^-h^+{-}pairs}$$

→ Number of thermal created e^-h^+-pairs are four orders of magnitude larger than signal!!!

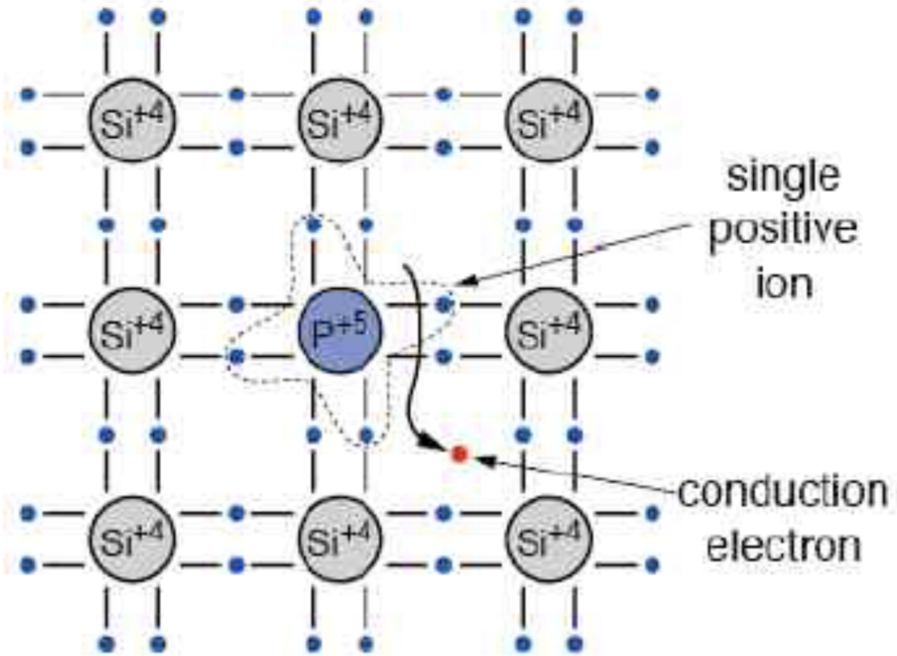
Have to remove the charge carrier!

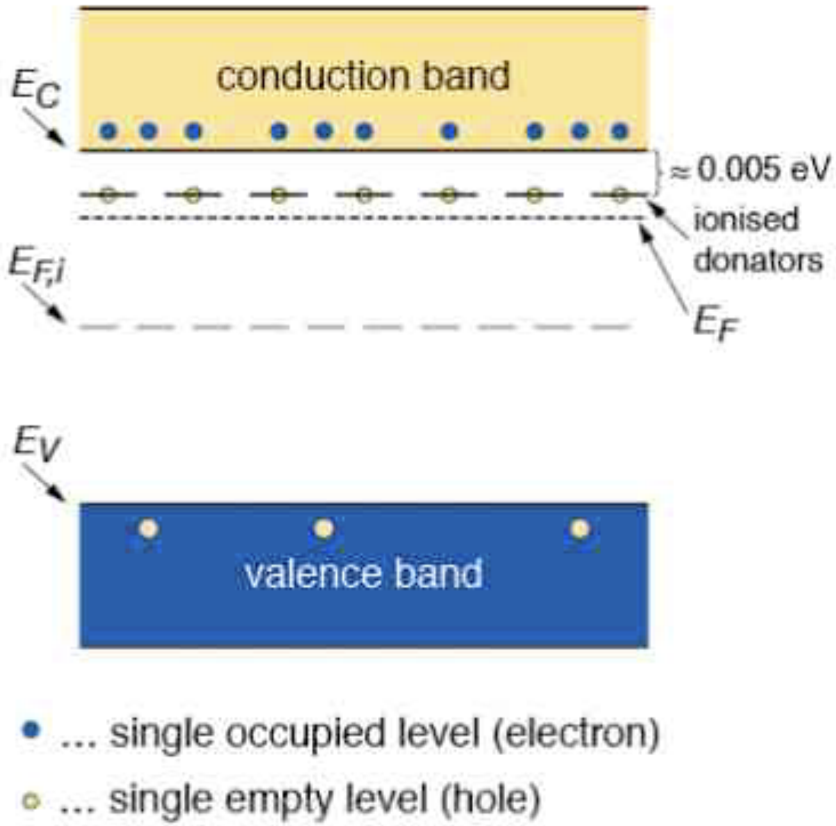
→ Depletion zone in reverse biased pn junctions

N-doping

Doping with an element 5 atom (e.g. P, As, Sb). The 5th valence electron is weakly bound.

The doping atom is called donor
The released conduction electron leaves a positively charged ion



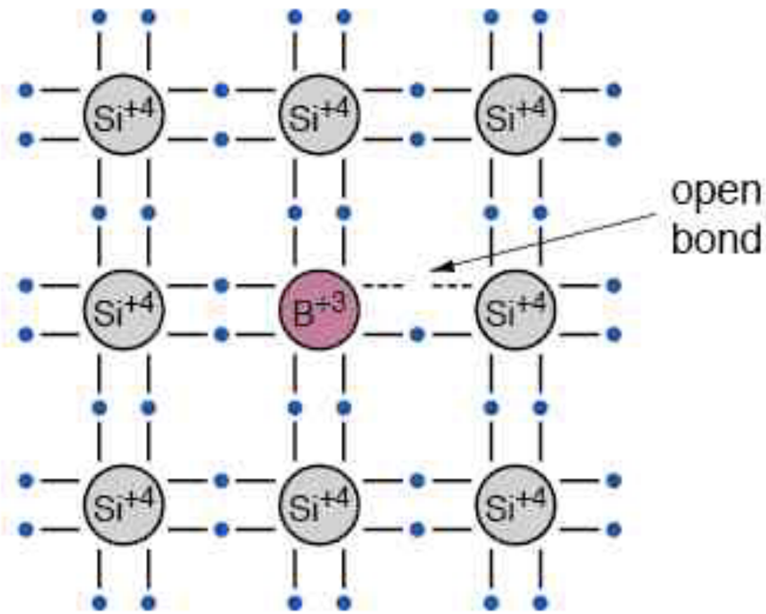


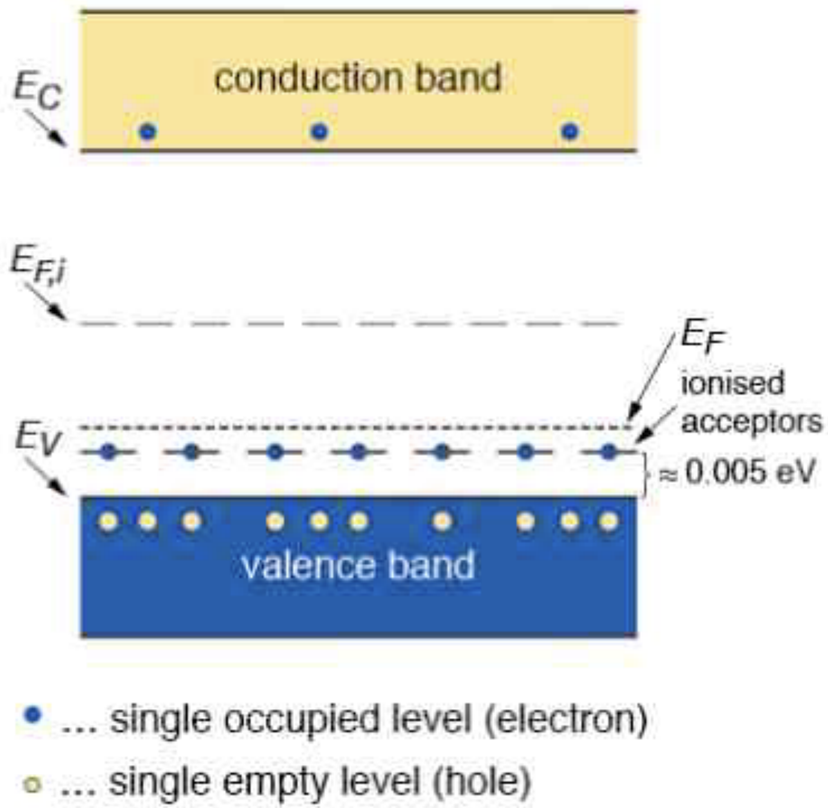
Electrons (holes) are called majority (minority) carriers.

P-doping

Doping with an element 3 atom (e.g. B, Al, Ga, In). One valence bond remains open

The doping atom is called acceptor
The acceptor atom in the lattice is negatively charged

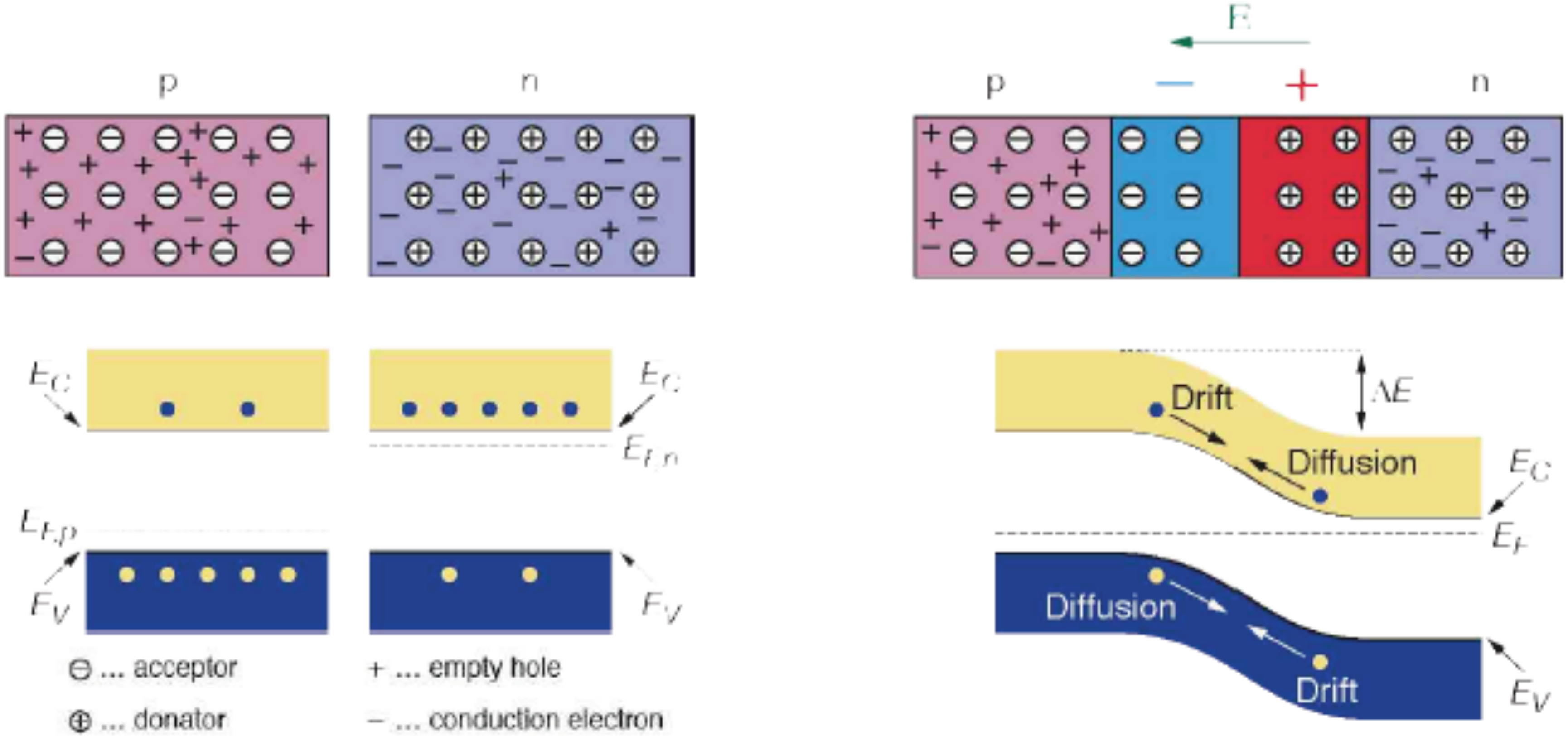




Holes (electrons) are called majority (minority) carriers.

The p-n junction

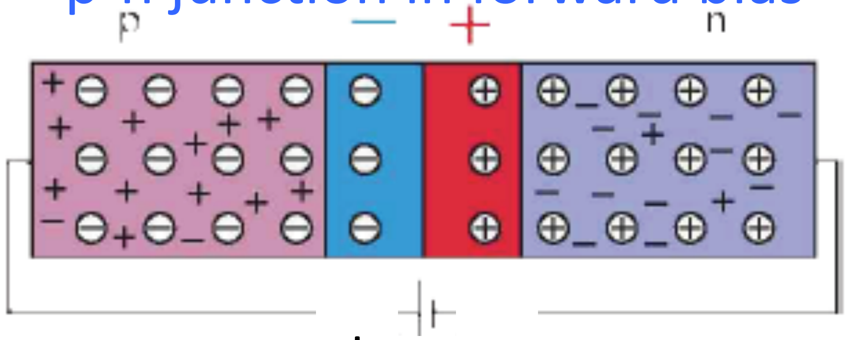
At n-type and p-type interface: diffusion of surplus carries to the other material until thermal equilibrium is reached.
The remaining ions create a space charge and an electric field stopping further diffusion.
The stable space charge region is free of charge carriers: the depletion zone.



The p-n junction – forward and reverse bias

Applying a forward bias voltage *V*,
e- and holes are refilled to the depletion zone.
The depletion zone becomes narrower

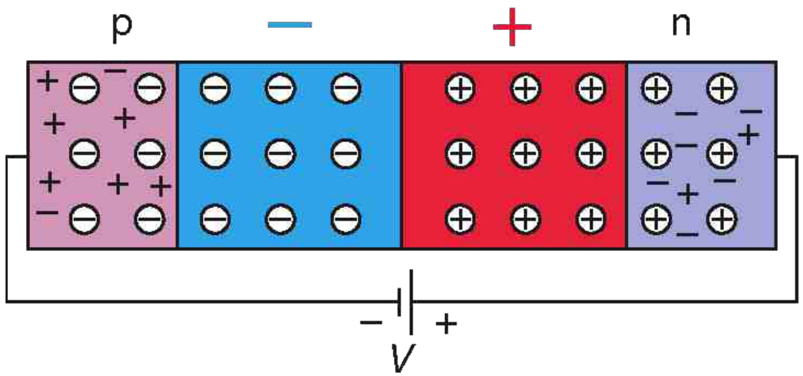
p-n junction in forward bias



That's not what we want!

Applying a reverse bias voltage *V*,
e- and holes are pulled out of the depletion zone.
The depletion zone becomes larger.

p-n junction in reverse bias



That's the way we operate our semiconductor detectors!

P-n junction – width of the depletion zone

Example of a typical p+-n junction in a silicon detector:

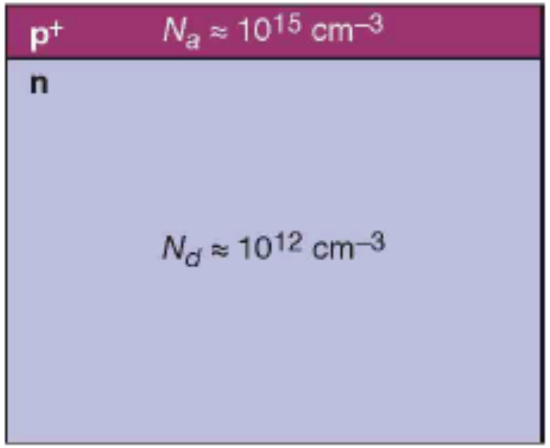
Effective doping concentration $N_a = 10^{15}$ cm^{-3} in p+ region and $N_d = 10^{12}$ cm^{-3} in n bulk.

Without external voltage:

$$W_p = 0.02\ \mu m$$
$$W_n = 23\ \mu m$$

Applying a reverse bias voltage of 100 V:

$$W_p = 0.4\ \mu m$$
$$W_n = 363\ \mu m$$



p+n junction

Width of depletion zone in n bulk:

$$\boxed{W \approx \sqrt{2\varepsilon_0\varepsilon_r\mu\rho|V|}} \quad \text{with} \quad \rho = \frac{1}{e\mu N_{eff}}$$

V ... External voltage
ρ ... specific resistivity
μ ... mobility of majority charge carriers
N_{eff} ... effective doping concentration

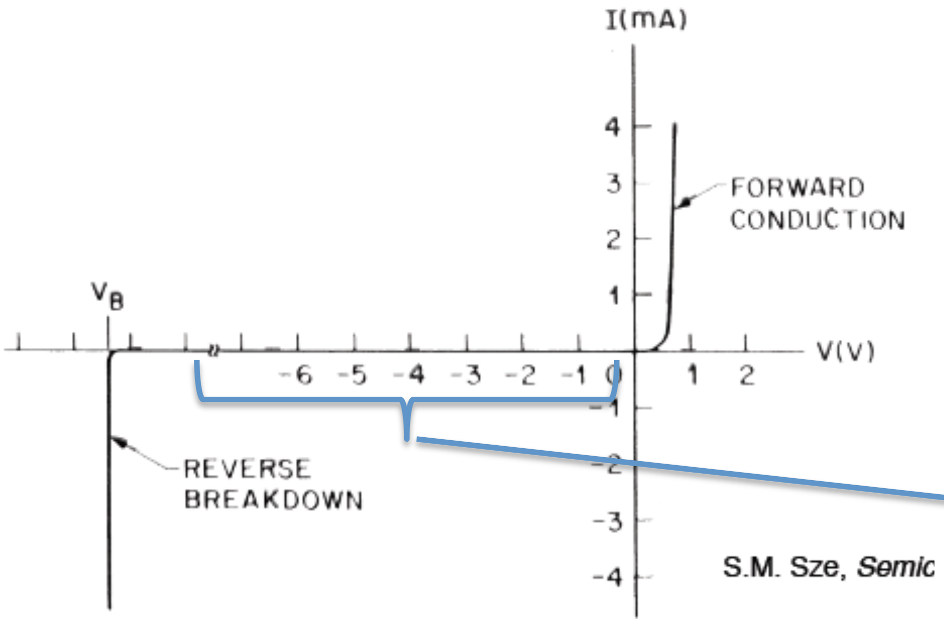
P-n junction – Current voltage characteristics

Typical current-voltage of a p-n junction (diode): exponential current increase in forward bias, small saturation in reverse bias.

Ideal diode equation:

$$I = I_0 \cdot \left[\exp\left(\frac{eV}{kT}\right) - 1\right]$$

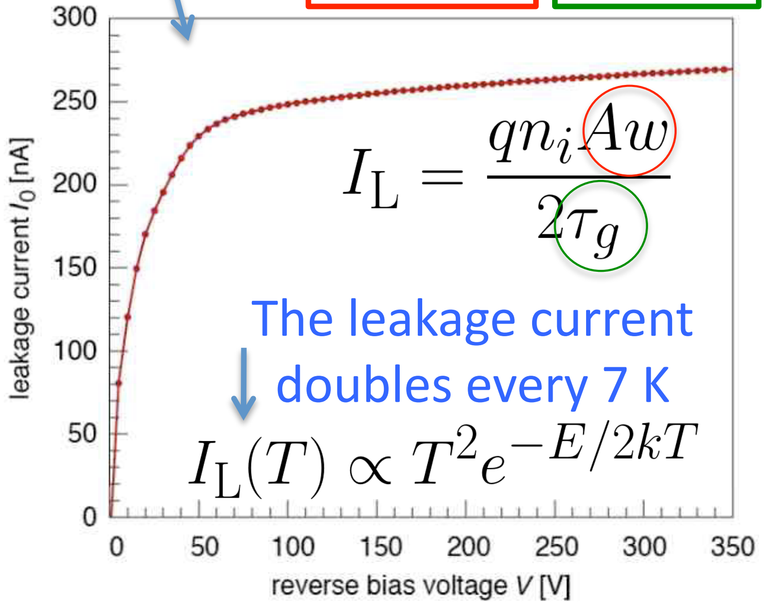
I_0 … reverse saturation current



Leakage current origin:
thermally generated carriers

Generation lifetime

Detector volume



$$I_{\mathrm{L}} = \frac{q n_i A w}{2\tau_g}$$

The leakage current doubles every 7 K

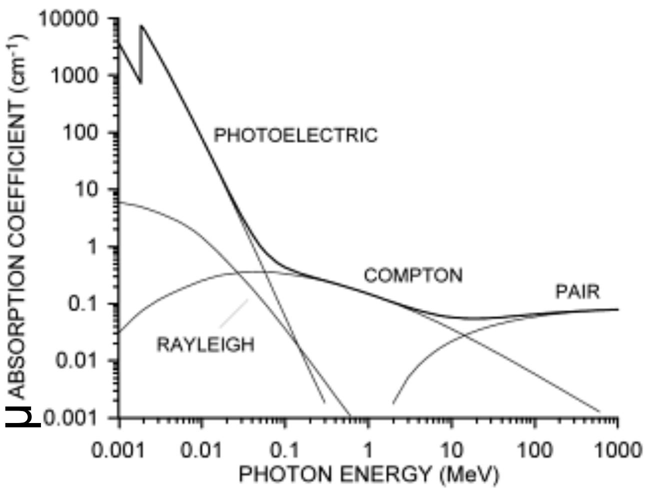
$$I_{\mathrm{L}}(T) \propto T^2 e^{-E/2kT}$$

Energy measurement

Photons

Point-like interaction

- Infinitesimal interaction probability: *dP=μdx*



- Photo: 1e-h pair per conversion
- e- from X-ray can trigger secondary emission

Charged particles

Charges created along the track

- 3.6 eV (E_i) to create an e-h pair
  ➔ 80 e-h / μm (most probable)
- Most probable charge (300 μm) ≈ 24000 e ≈ 4 fC

Energy *E* intrinsic resolution of a semiconductor detector:

$$\boxed{\Delta E_{FWHM} = 2.35 \cdot \sqrt{FEE_i}}$$

F the Fano factor; F ~ 0.1 for Si.

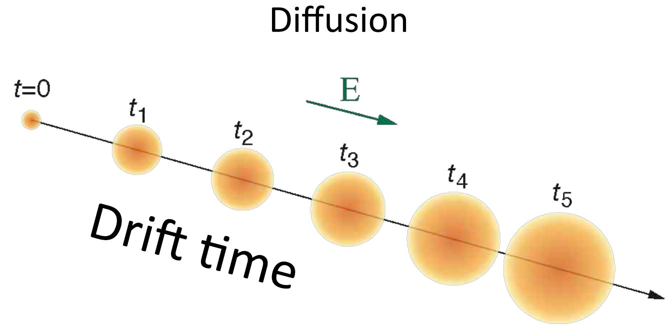
E.g. for photons of few keV a 100 eV resolution can be achieved

Position measurement

The position resolution depends on physical processes and on external parameters

Physical processes:

- statistical fluctuations in the energy loss
- diffusion: $\sigma_D = \sqrt{2Dt}$



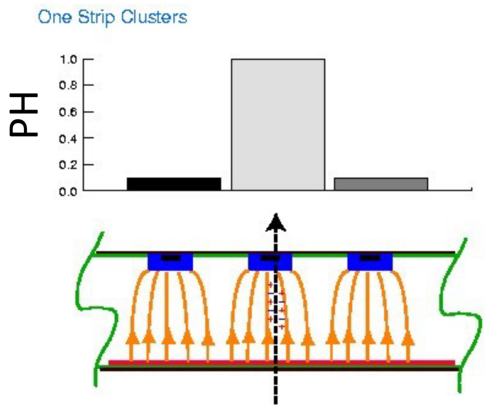
External parameters:

- analogue/binary signal readout
- detector segmentation ("pitch" *p*)
- signal-to-noise-ratio *SNR*

Single channel, binary r.o.

x = *strip position*

$\sigma = p/\sqrt{12}$



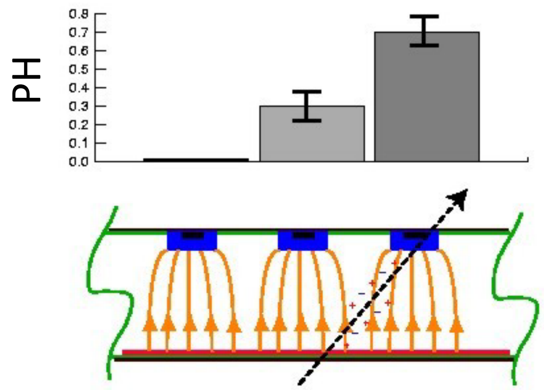
Analogue r.o.

$x = (x_1h_1+x_2h_2)/(h_1+h_2)$

x_i = *i-th* strip pos.

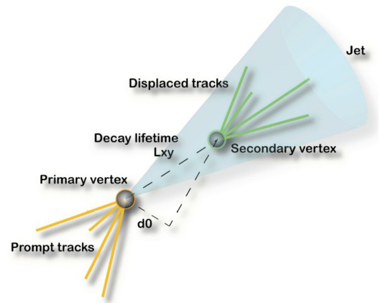
h_i = *i-th* strip PH

$\sigma \approx p/SNR$



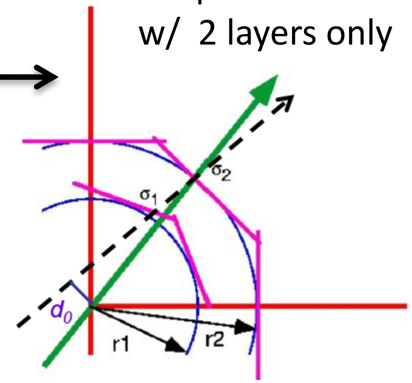
Vertexing resolution

Looking for significant impact parameter IP, d_0, and maybe form a reconstructed secondary vertex.

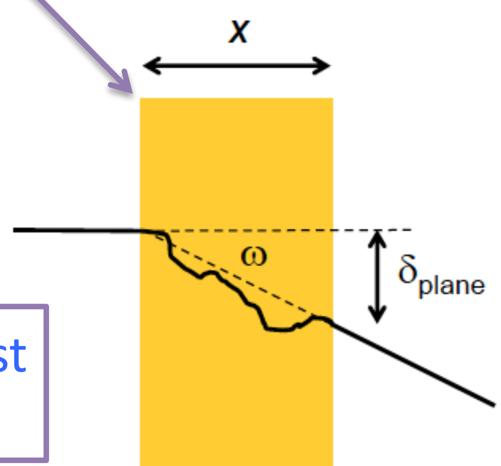


The IP resolutions depends on geometry, material and track momentum

Simplified model w/ 2 layers only



$$\sigma_{d_0} \approx \sqrt{\frac{r_2^2\sigma_1^2 + r_1^2\sigma_2^2}{(r_2 - r_1)^2}} \oplus \frac{r}{p\sin^{3/2}\theta} 13.6\text{MeV}\sqrt{\frac{x}{X_0}}$$



Geometry: use small r_1, large r_2, and small intrinsic spatial resolution σ_1 , σ_2

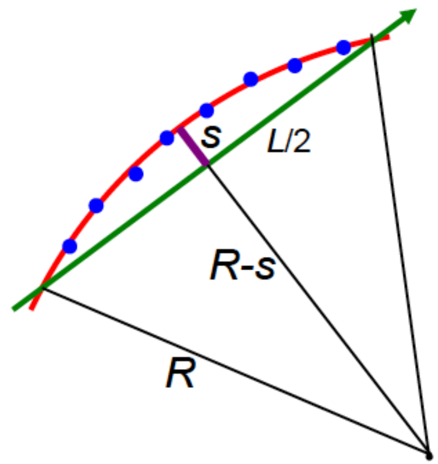
Multiple Scattering: important for low momentum tracks; best precision with small radius *r* and minimum thickness *x*

Momentum resolution

Charged particles: circular motion transverse to uniform B field

p_T [GeV/c] = 0.3 x B [T] x R [m]

Measuring the sagitta s we can measure the transverse momentum p_T



R=L²/2s

Transverse momentum resolution
Need strong B, long path length L
and excellent sagitta resolution σ_s

$$\boxed{\frac{\sigma_{p_T}}{p_T} = \frac{8 p_T}{0.3 B L^2} \sigma_s}$$

$$R = L^2/2s$$

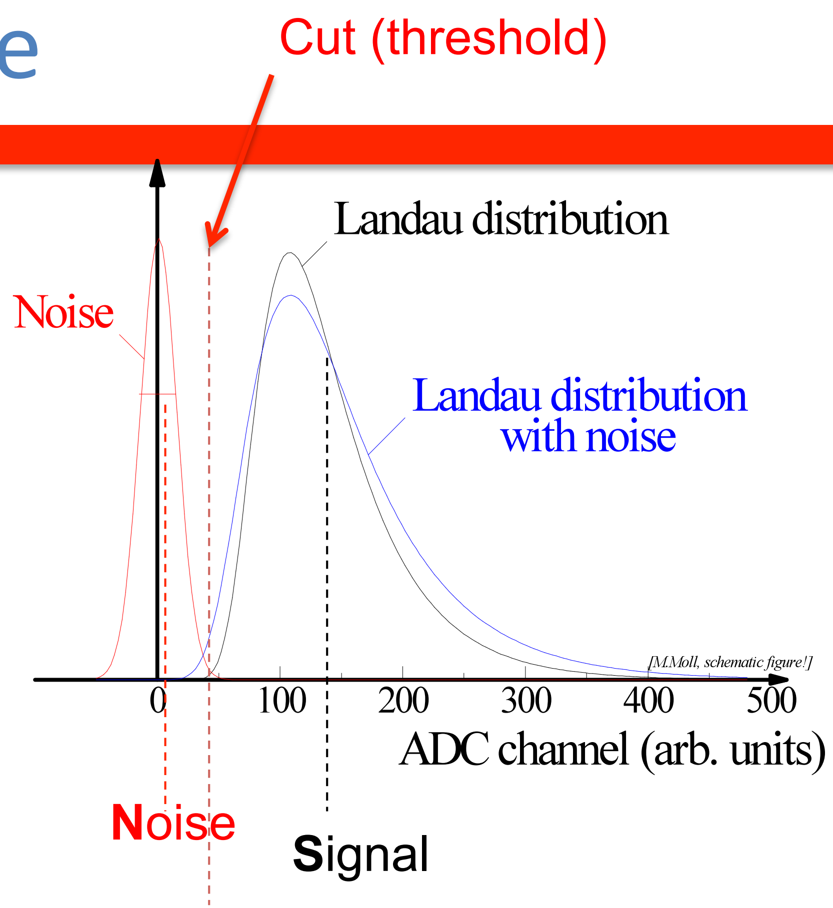
The sagitta resolution σ_s depends on the position resolution $\sigma_{\phi r}$ which depends on the sensor intrinsic resolution; $\sigma_{\phi r}$ is limited by multiple scattering

$$\boxed{\sigma_{r\phi} = \sigma_{int} \oplus \sigma_{MS}}$$

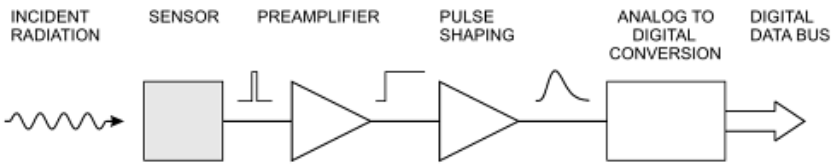
Requirement: best possible space point resolution, material at minimum

A quick word about noise

- Landau distribution has a low energy tail
  - becomes even lower by noise broadening
  - Noise sources: (ENC = Equivalent Noise Charge)
    - Capacitance
    - Leakage Current
    - Thermal Noise (bias resistor)
  - Figure of Merit: Signal-to-Noise Ratio S/N
  - Typical values >10-15, people get nervous if < 10. Radiation damage severely degrades the S/N.
  - If threshold is too high ➔ inefficiency
  - If threshold is too low ➔ noise occupancy



The complete detecting chain



Preamplifier: signals in silicon (0.05-4 fC) must be amplified. Minimize noise amplification!

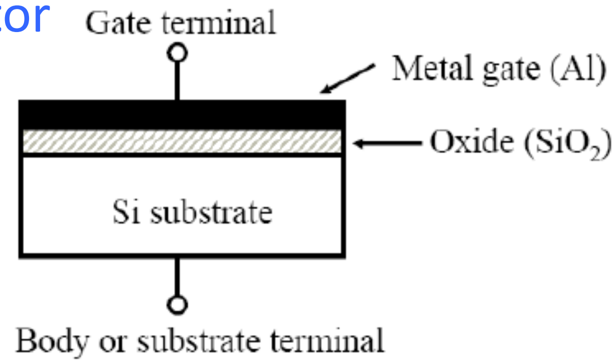
Pulse shaping: its primary function is to improve the signal-to-noise ratio. This is done by applying filters that tailor the frequency response
Typically bandwidth reduction which translates into an increase of the pulse duration (*"shaping time"*)

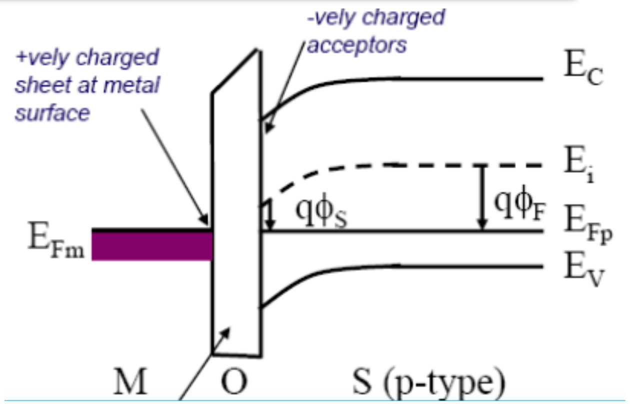
The MOS structure

MOS: Metal Oxide Semiconductor

Gate: Metal (or Polysilicon)

Oxide: SiO_2, grown on substrate

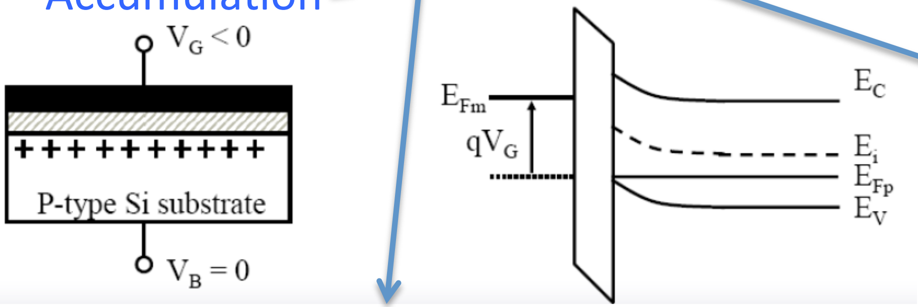




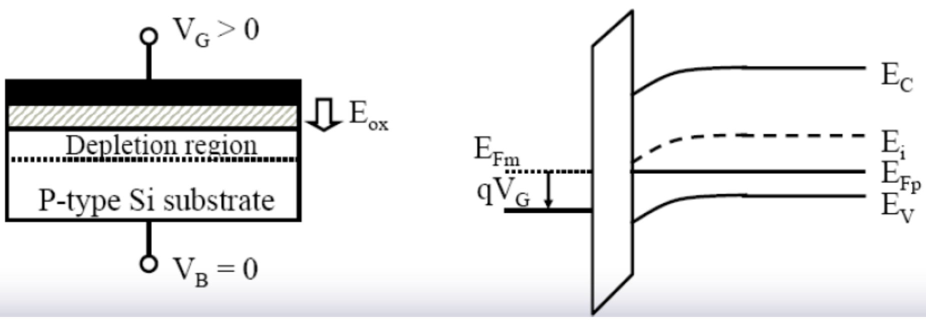
No applied voltage: a charged MOS capacitor

3 states

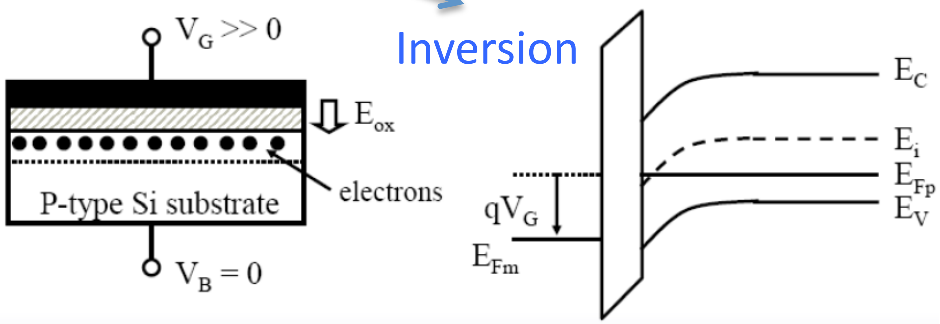
Accumulation



Depletion



Inversion



Silicon as detector material: summary

Reverse biased p-n junction as radiation detector: the depletion region is virtually free of mobile carriers ➔ in absence of radiation only the (small) diode reverse current flows in the junction

Energy deposition: creation of a e-h pair for E ~ 3.6 eV (gas: 15-30 eV)➔Large signals!

High electric field in the depleted bulk
➔ elec.s and holes drift very fast across the depletion zone: t_{coll} ~ 10-30 ns

Low doping concentration (high resistivity) of the bulk ➔ V_{depl} at low bias voltages (safely below V_{BD})
P-side of the junction: heavily doped
N+ implant on the n-side (ohmic side) of the detector to ensure a good ohmic contact.