Silicon Radiation Detectors for High Energy Physics:

A very short introduction

M. Bomben
LPNHE & U. de Paris – Paris, France

Acknowledgements and disclaimer

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

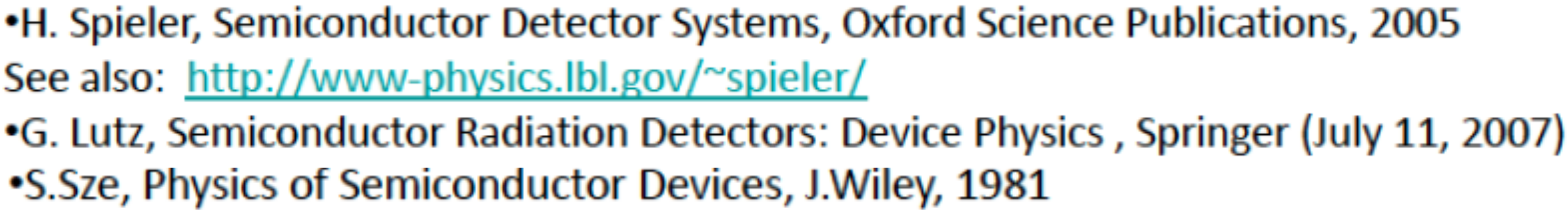
You can find great lectures here:

http://www.hephy.at/fileadmin/user_upload/Lehre/Unterlagen/Praktikum/Halbleiterdetektoren.pdf

And here: http://wwwusers.ts.infn.it/~bonvicin/Dottorandi08.pdf

Disclaimer: 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

References



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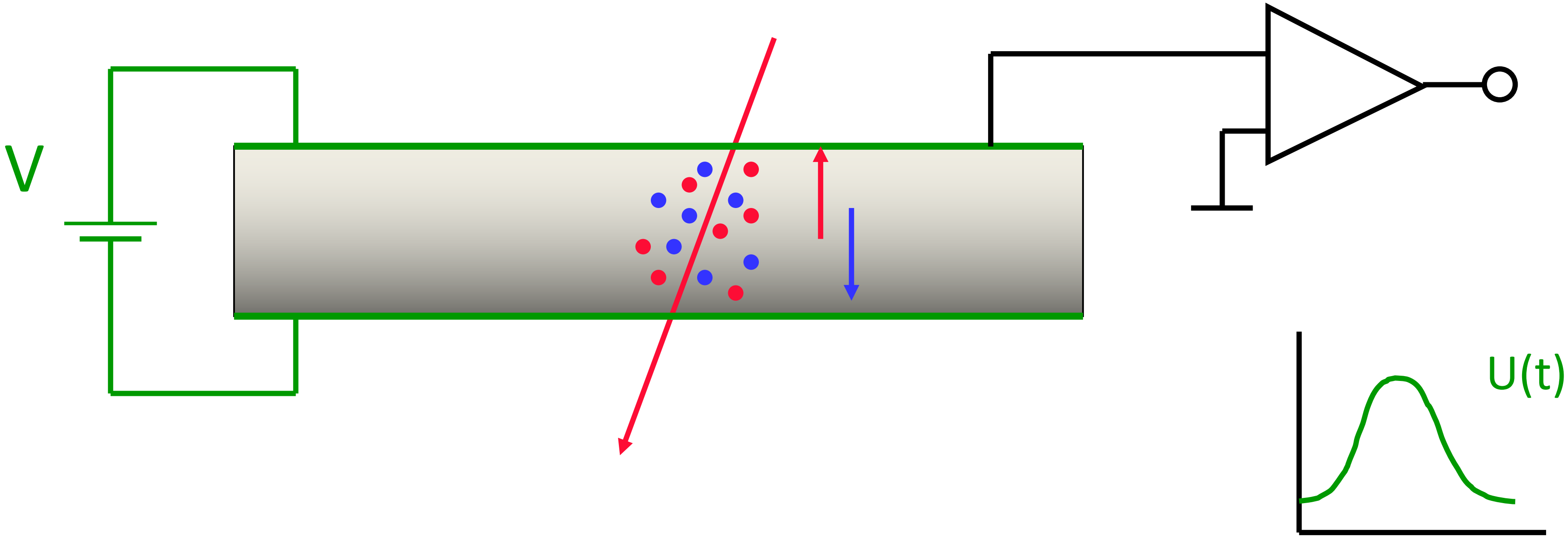
- M. Bomben - https://indico.in2p3.fr/event/10777/timetable/#20150219
- M. Bomben - https://tel.archives-ouvertes.fr/tel-01824535

The basics



A solid-state ionization chamber

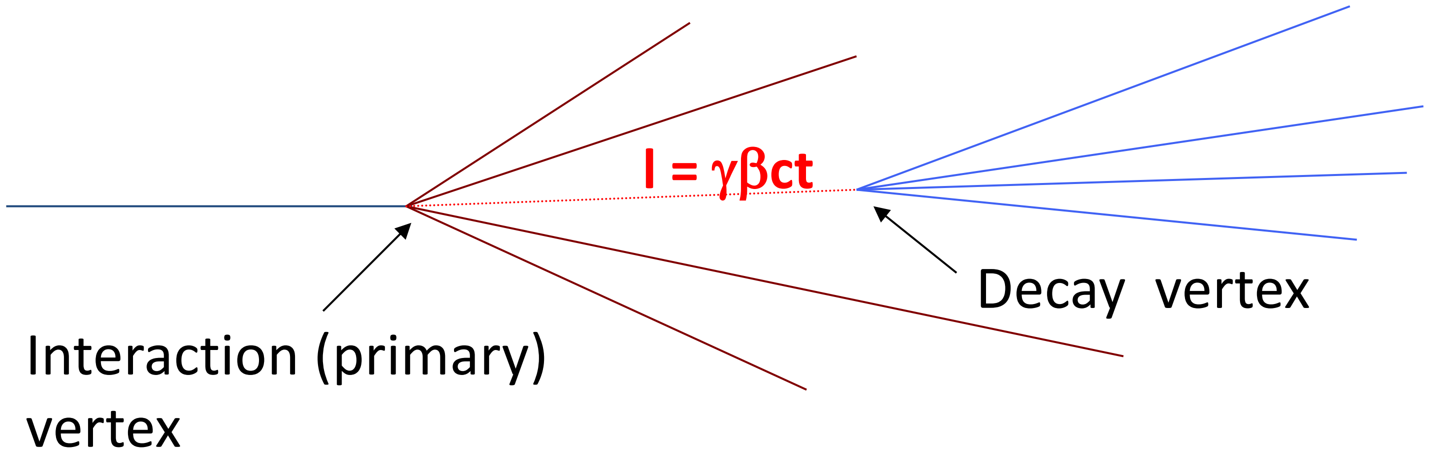
Signal given by the drift of charges (electrons and holes) under the effect of the electric field

The signal is then amplified and shaped

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



$l = \gamma\beta ct$

Decay vertex

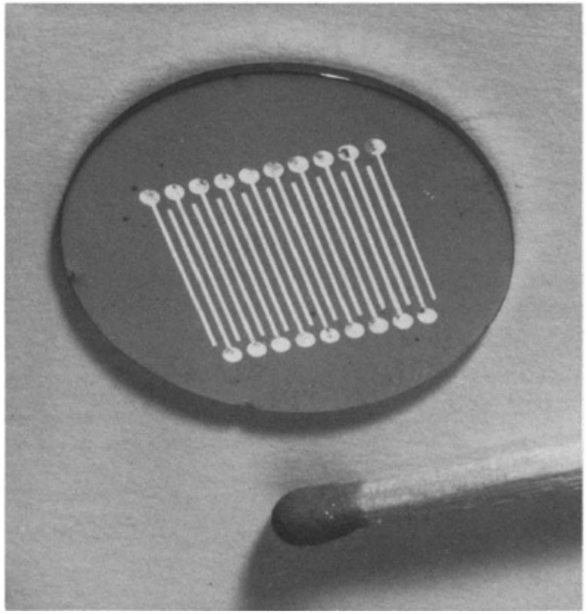
Interaction (primary) vertex

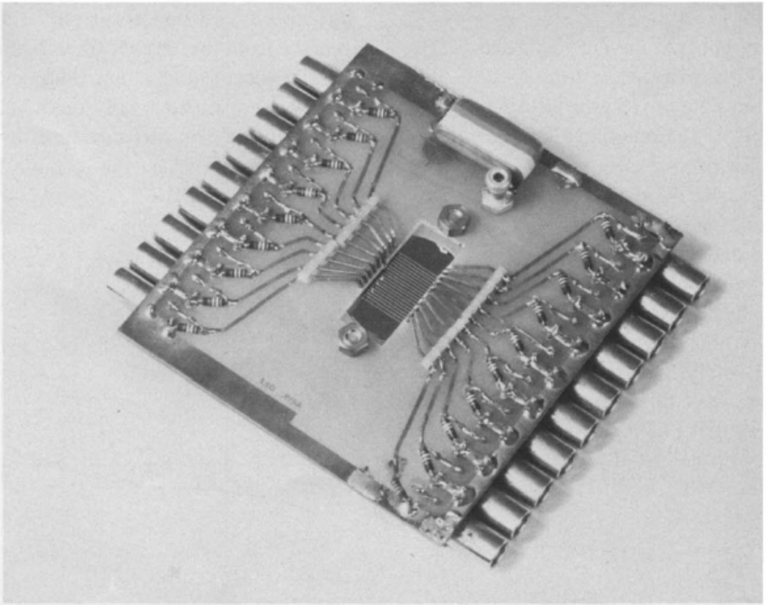
decay length $l = \gamma\beta ct$, so typically the decay vertex is at a distance **of single millimeters** from the interaction vertex

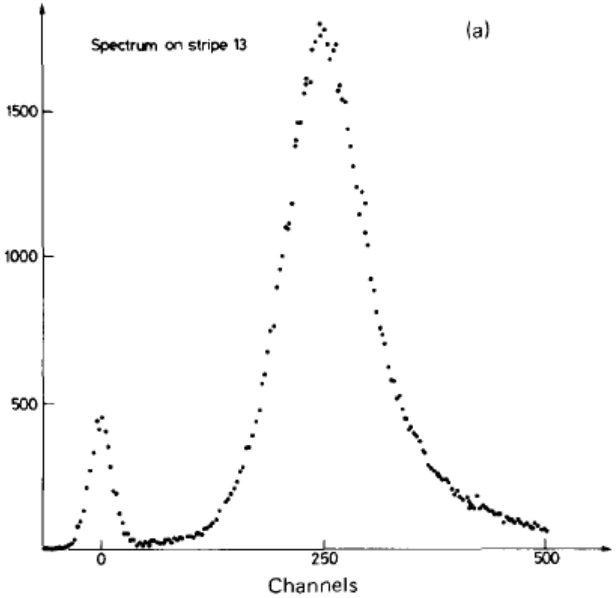
⇒ place detectors as close as possible

⇒ **detector with submillimeter precision is needed**

History – MESD by Pisa group (1980)







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

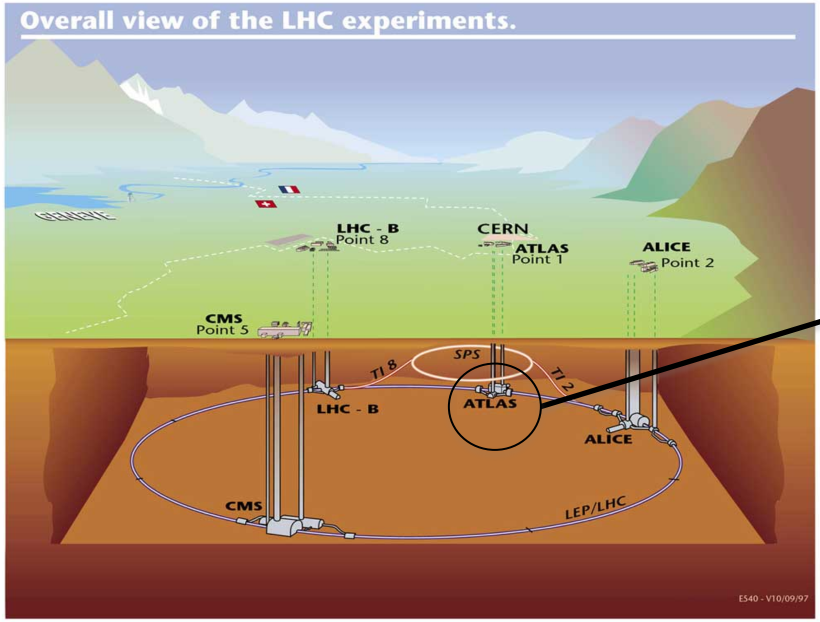
The signal was proportional to the energy released by the impinging particle.

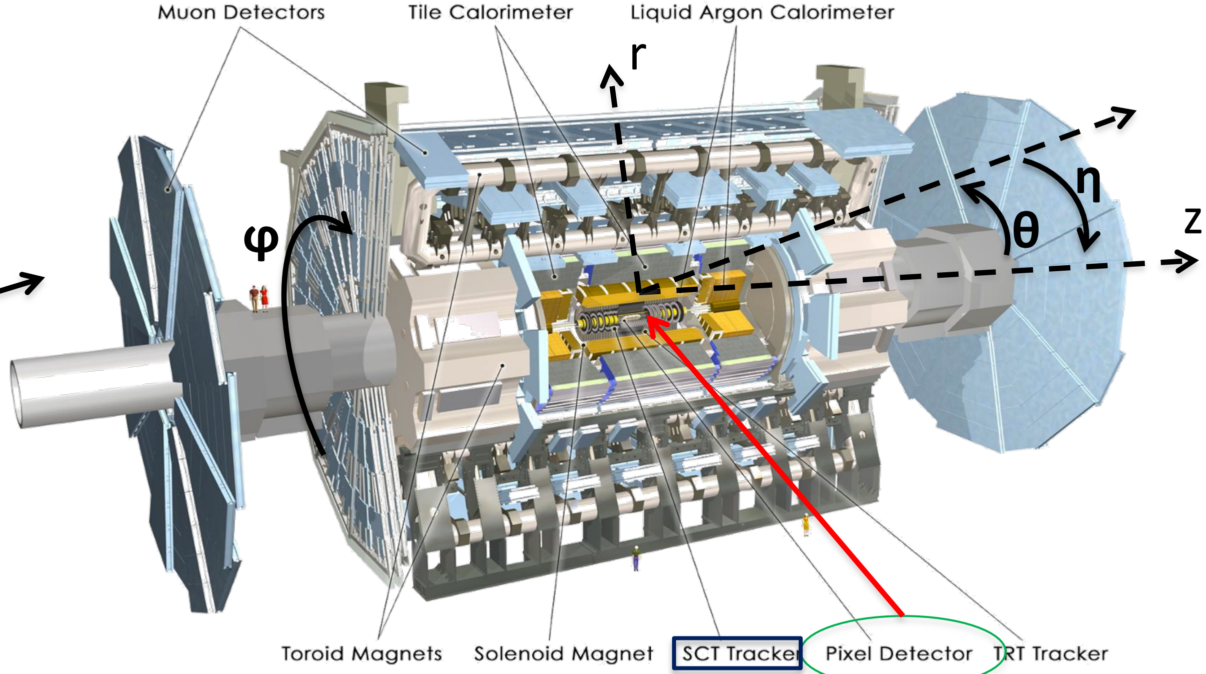
It assured **good spatial resolution** with low noise at room temperature.

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

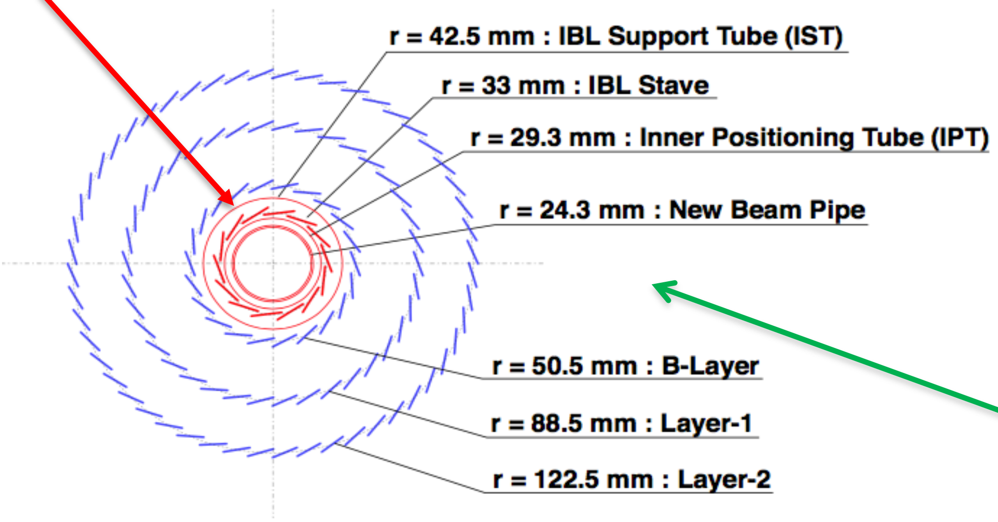
S. R. Amendolia et al., A Multi-Electrode Silicon Detector
for High Energy Experiments, Nucl. Instr. Meth. 176 (1980)

Today: ATLAS detector @ CERN LHC





3.3 cm from the interaction point



r = 42.5 mm : IBL Support Tube (IST)

r = 33 mm : IBL Stave

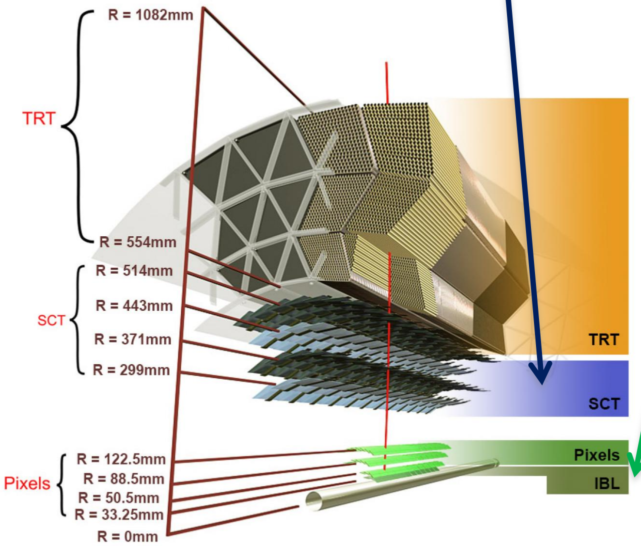
r = 29.3 mm : Inner Positioning Tube (IPT)

r = 24.3 mm : New Beam Pipe

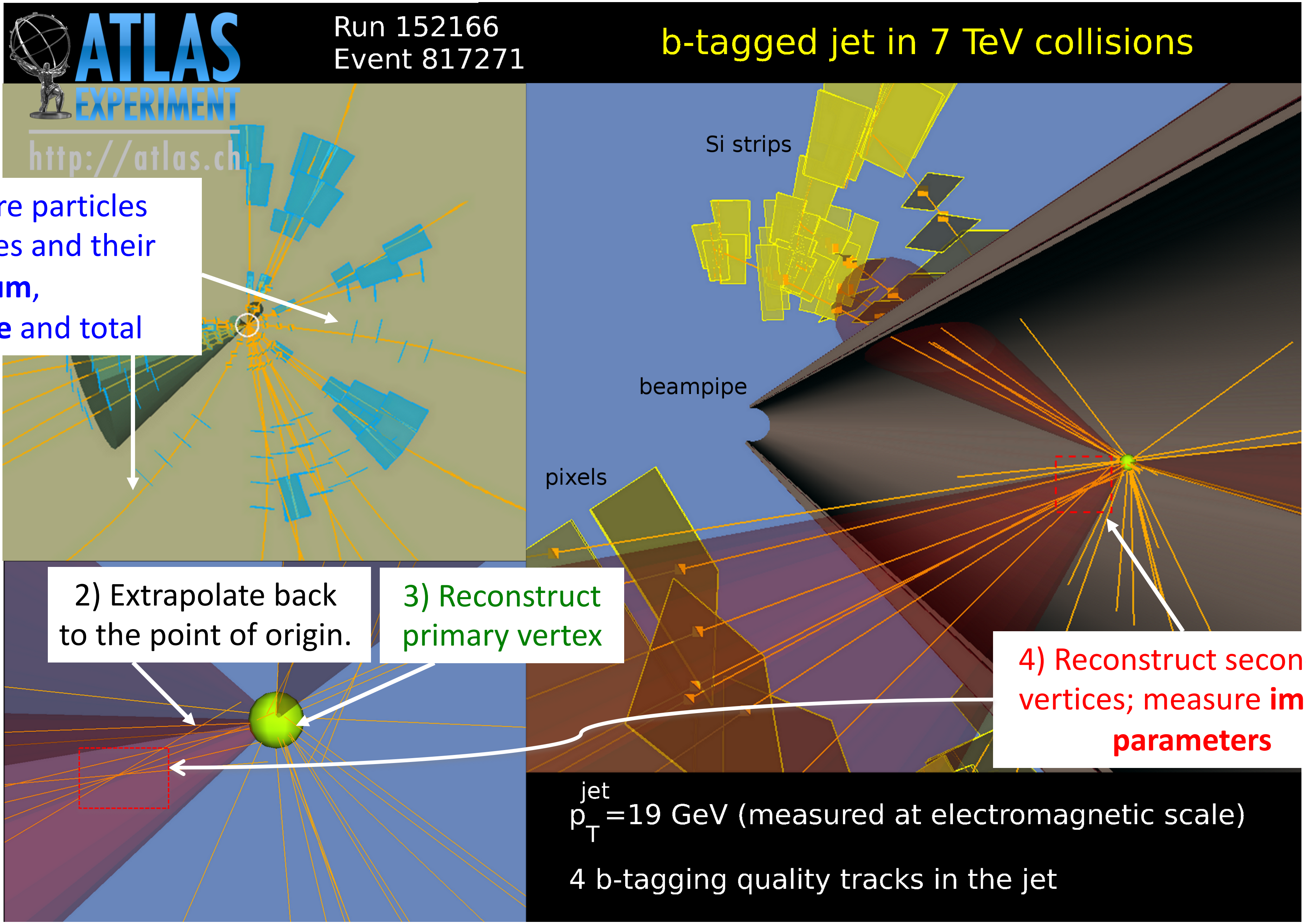
r = 50.5 mm : B-Layer

r = 88.5 mm : Layer-1

r = 122.5 mm : Layer-2



Role of trackers in HEP experiments



1) Measure particles trajectories and their **momentum**, **transverse** and total

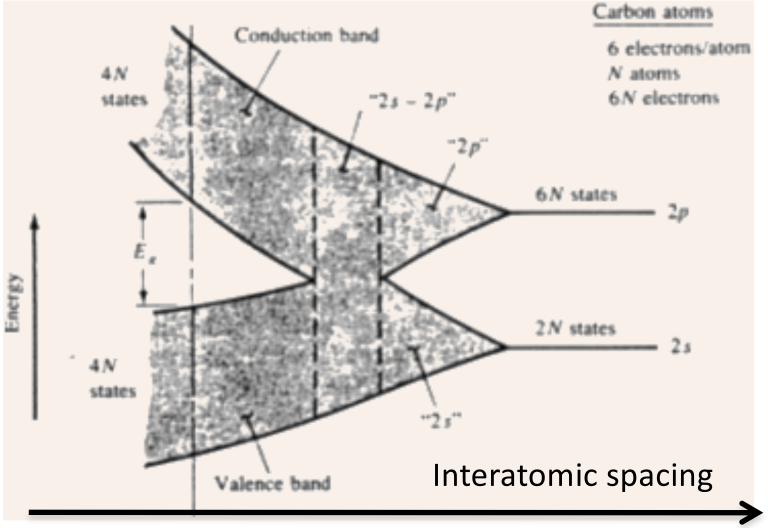
2) Extrapolate back to the point of origin.

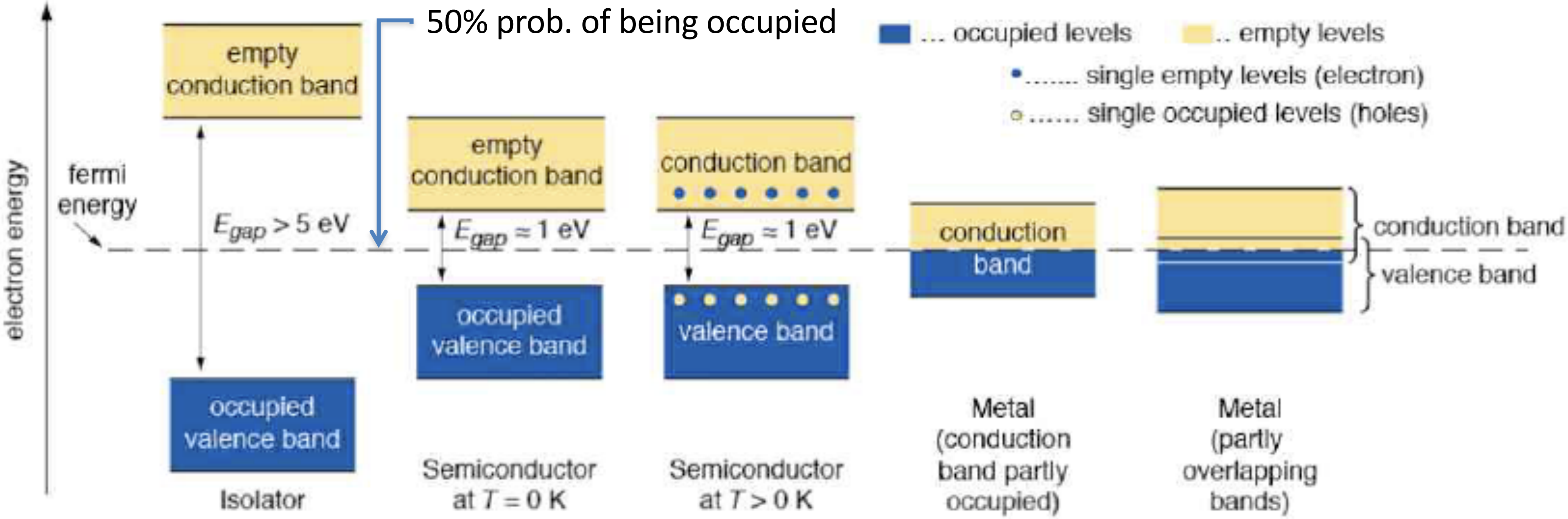
3) Reconstruct primary vertex

4) Reconstruct secondary vertices; measure **impact parameters**

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)




50% prob. of being occupied

Semiconductors

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

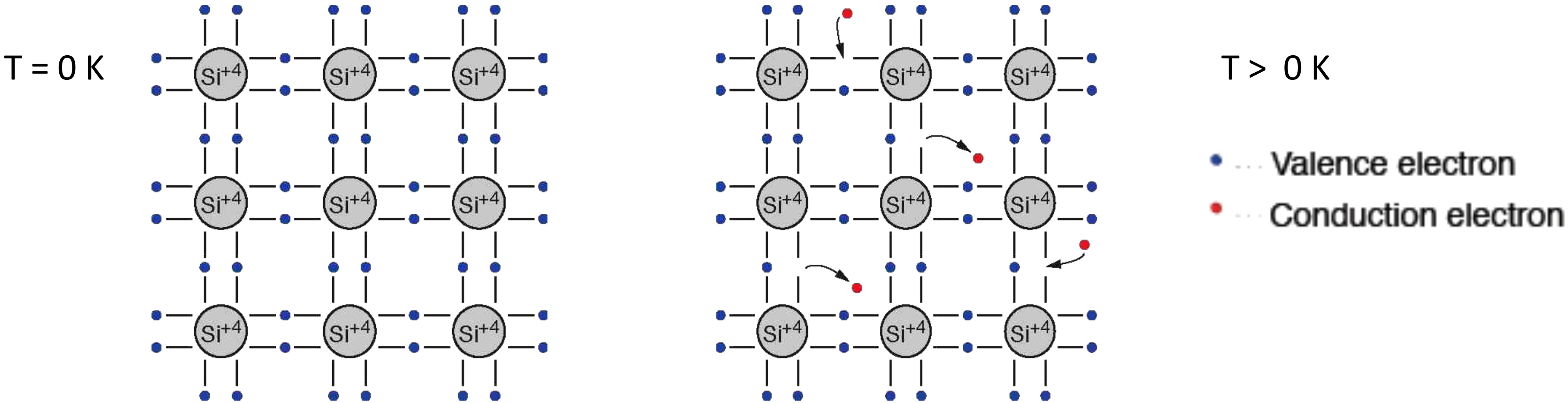
Silicon: Standard material for vertex and tracking detectors in high energy physics, can be operated at room temperature, synergies with micro electronics industry.

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)



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: $n = p = n_i \sim 1\times10^{10}$ cm^{-3} (T=300K) (In contrast, in metals ~ 10^{22}/cm^{3})

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

$$\vec{J}_n = \vec{J}_{n,drift} + \vec{J}_{n,diff} = q\left(\mu_n n \vec{E} + D_n \nabla n\right)$$

$$\vec{J}_p = \vec{J}_{p,drift} + \vec{J}_{p,diff} = q\left(\mu_p p \vec{E} - D_p \nabla p\right)$$

D: diffusion coefficient [cm^2/s]
μ: mobility [cm^2/(Vs)]

Einstein's equation

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

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

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

Valid at low/moderate fields; for large fields (>~ 5x10^3 V/cm) the carriers velocities saturates (Si: v ~ 10^7 cm/s) ➔ 10-30 ns collection time

FAST!

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 $d = 300\ \mu$m 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!

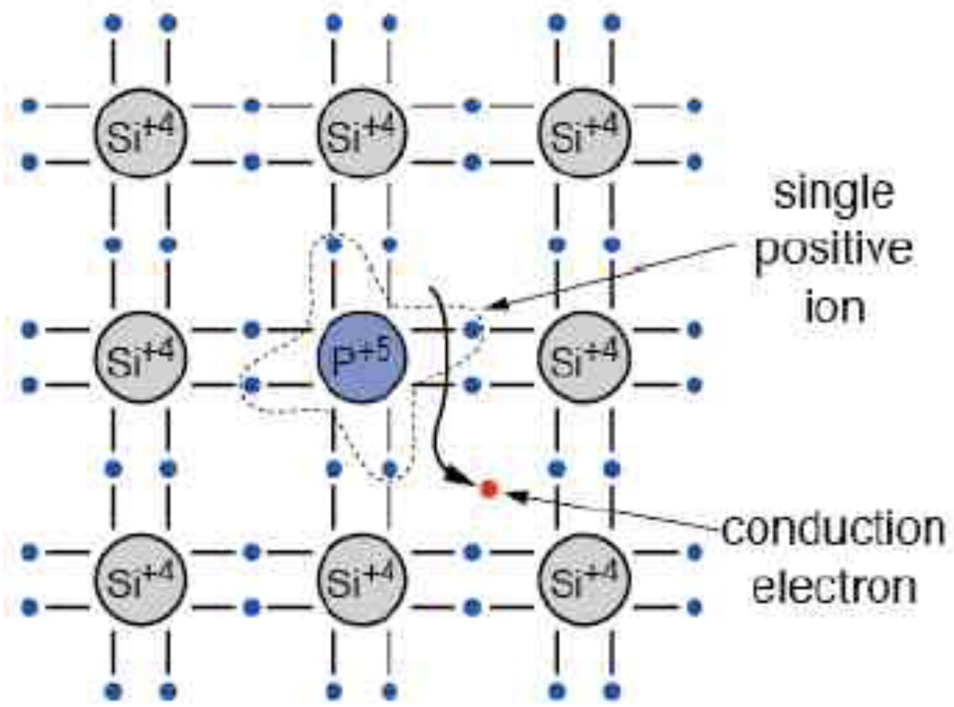
→ Depletion zone in reverse biased pn junctions

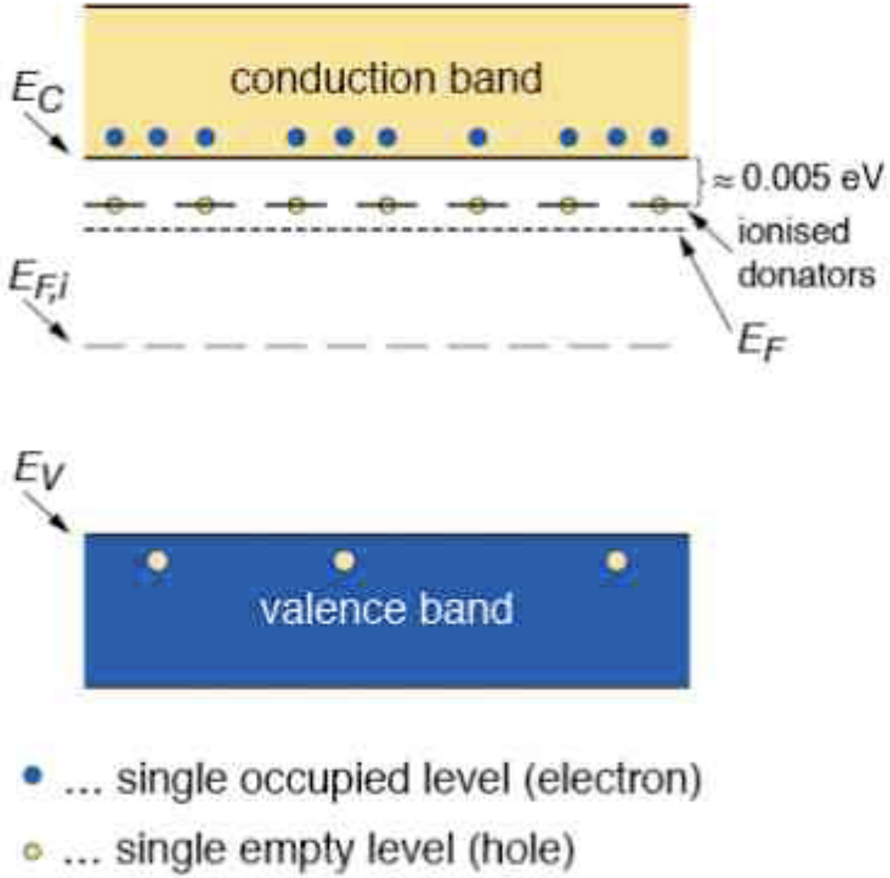
N-doping

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





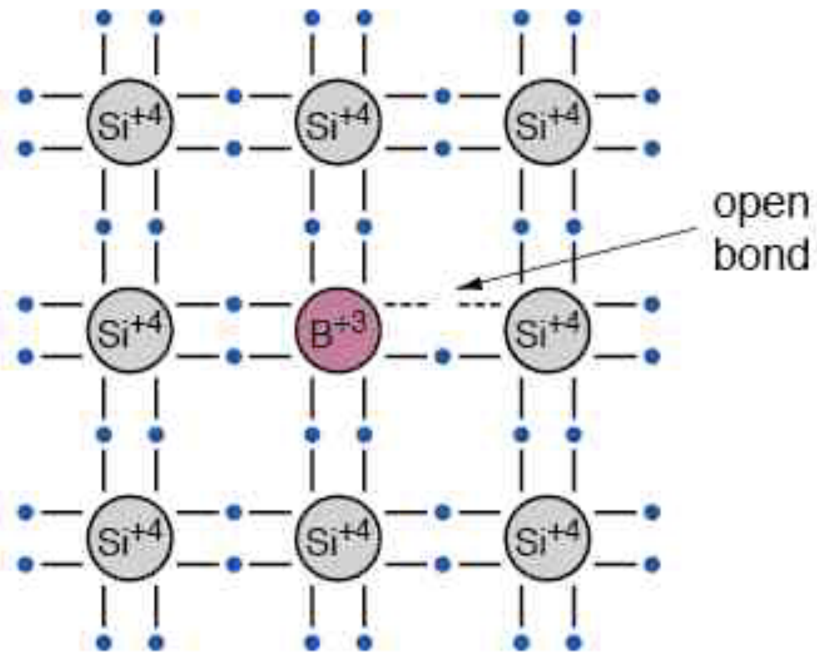
Electrons (holes) are called majority (minority) carriers.

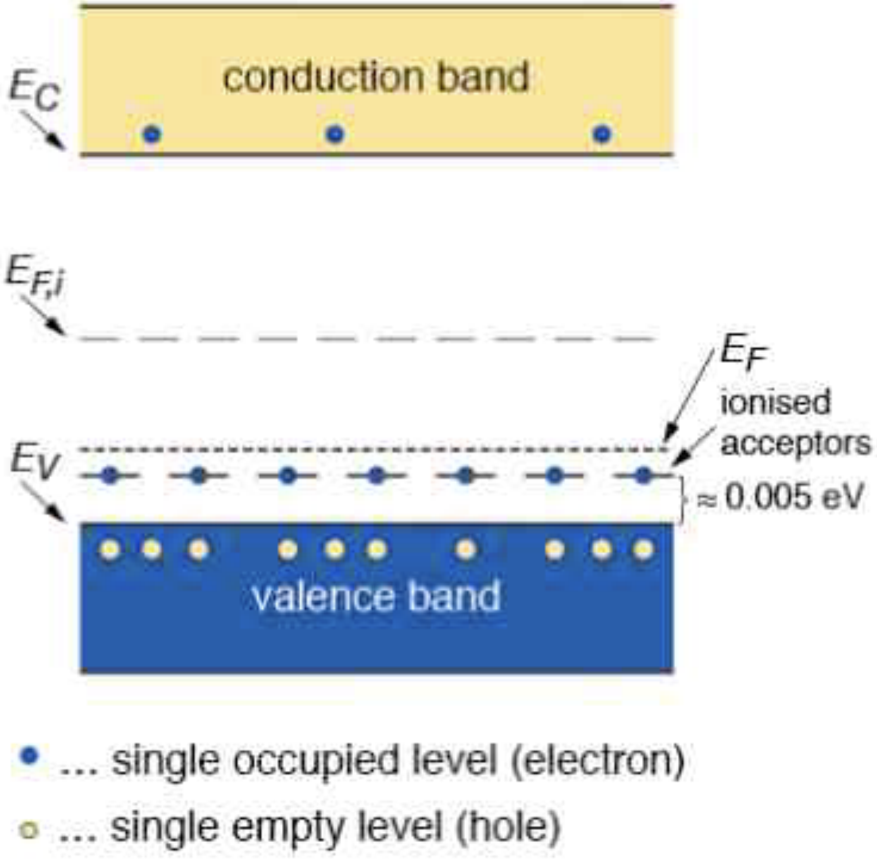
P-doping

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





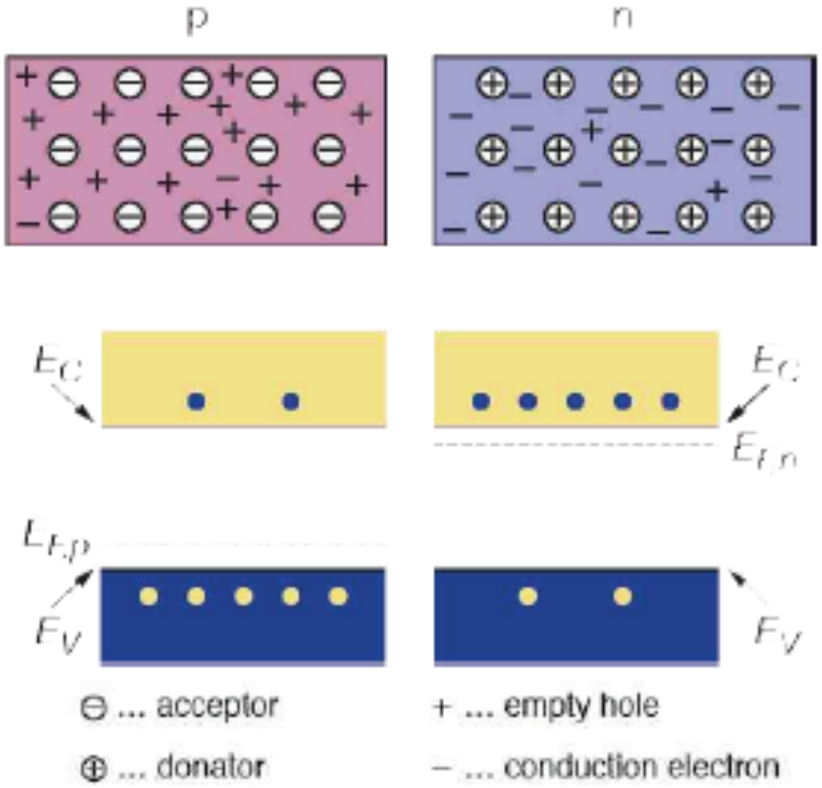
Holes (electrons) are called majority (minority) carriers.

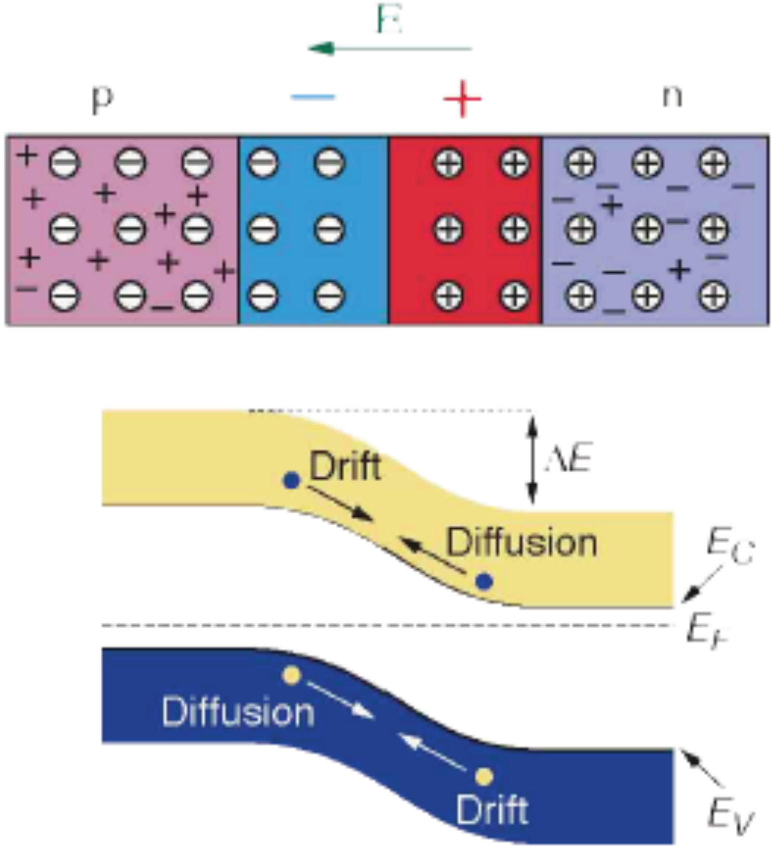
The p-n junction

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.

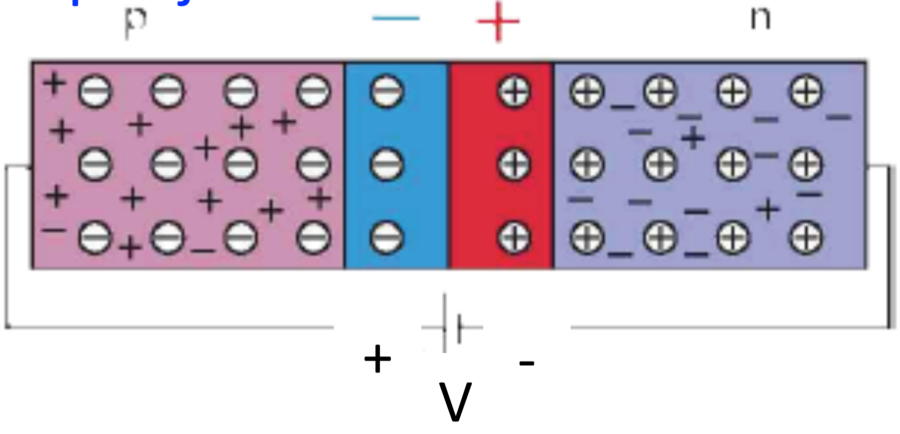




The p-n junction – forward and reverse bias

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

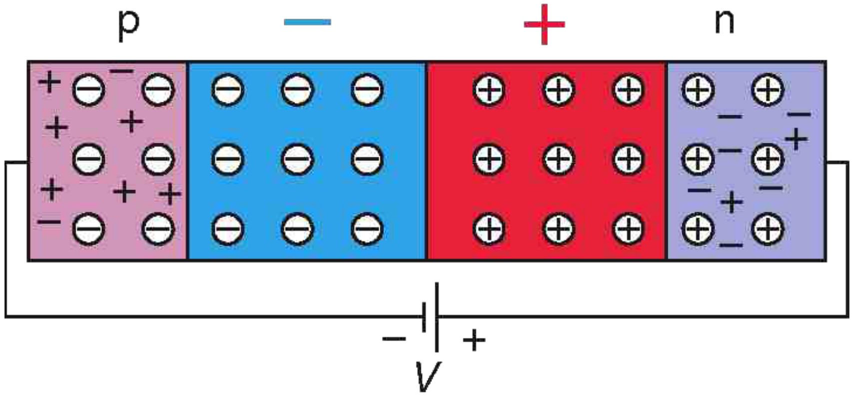
p-n junction in forward bias



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.

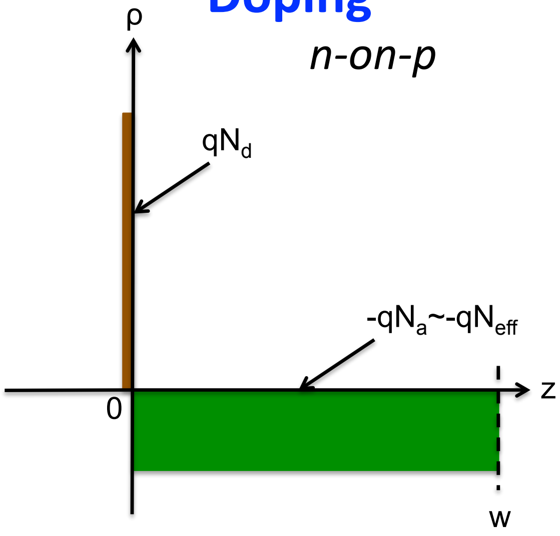
p-n junction in reverse bias



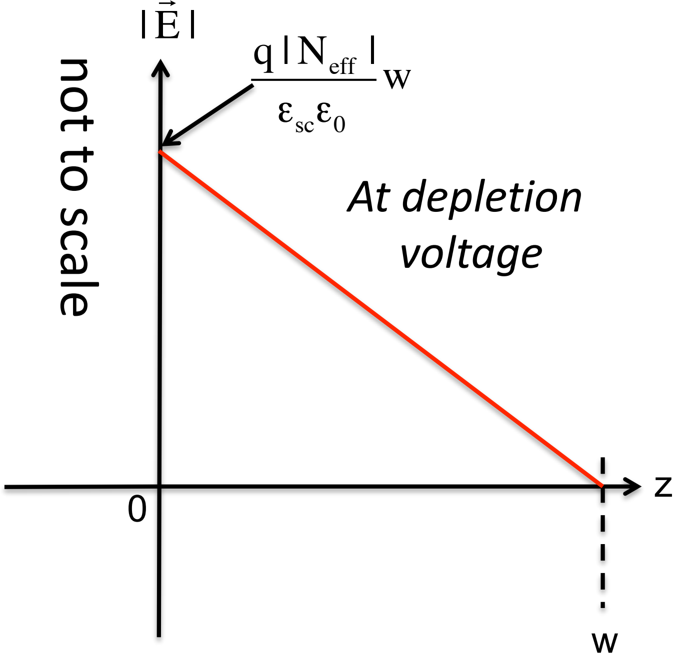
That’s the way we operate our semiconductor detectors!

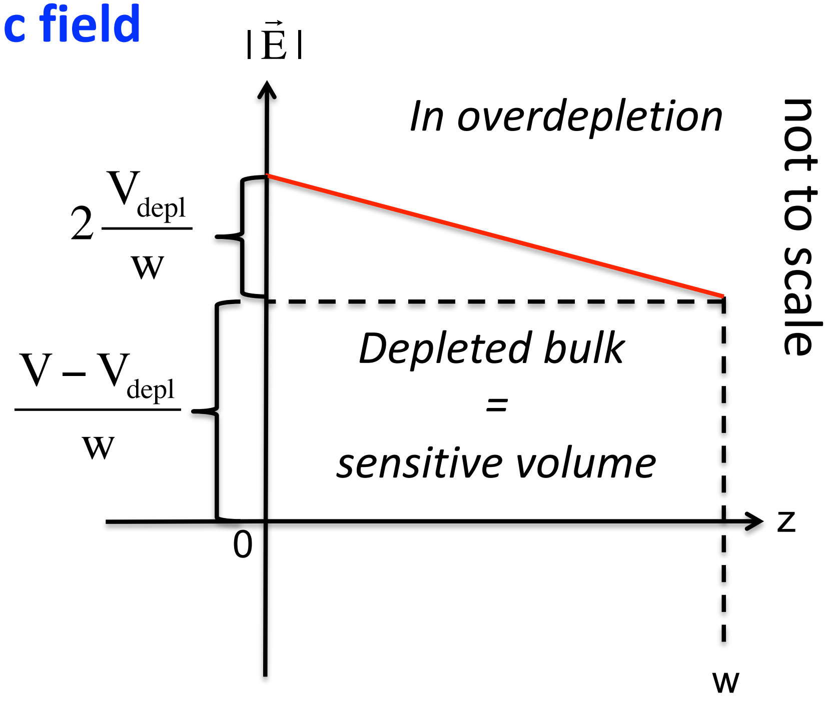
Electric field and carriers speed

Doping



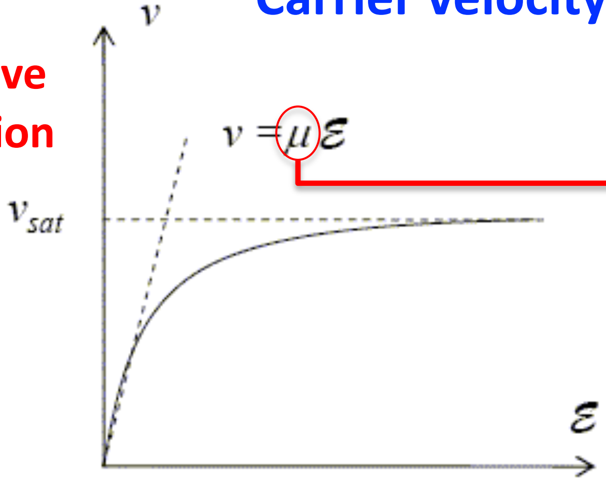
Electric field





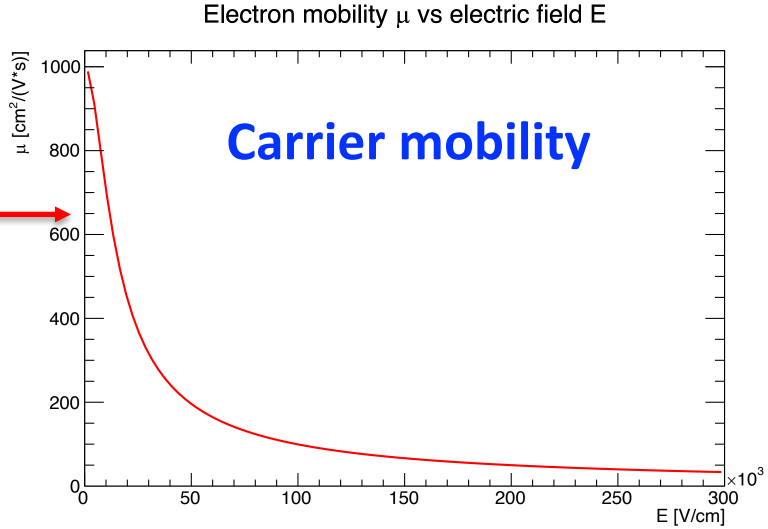
We want large electric field to have fast charge collection

Carrier velocity



https://ecee.colorado.edu/~bart/book/book/title.htm

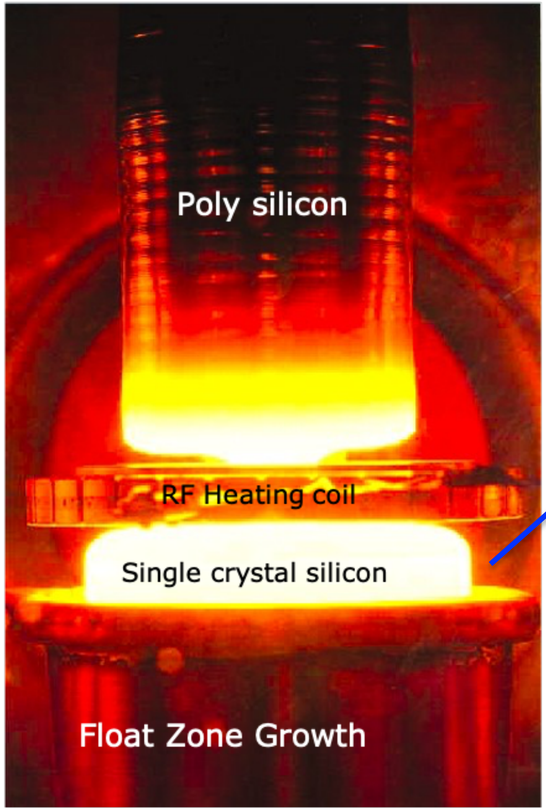
Carrier mobility



HEP silicon detector production

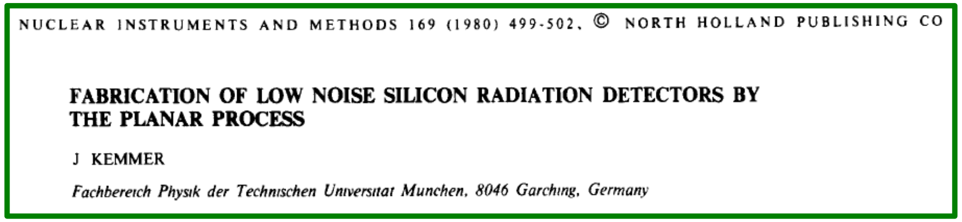
Detectors produced on **wafers**

- **Floating Zone Silicon (FZ)**



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

M. Moll, Bethe Forum on Particle Detectors, Bonn – April 2014


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

Fachbereich Physik der Technischen Universitat Munchen, 8046 Garching, Germany

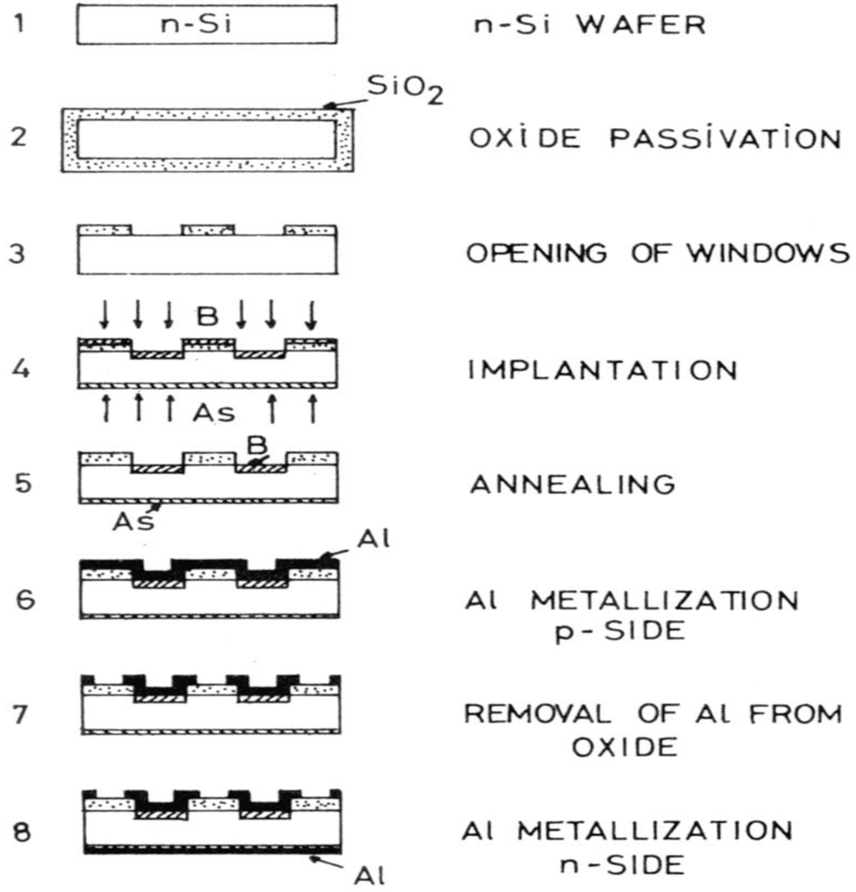
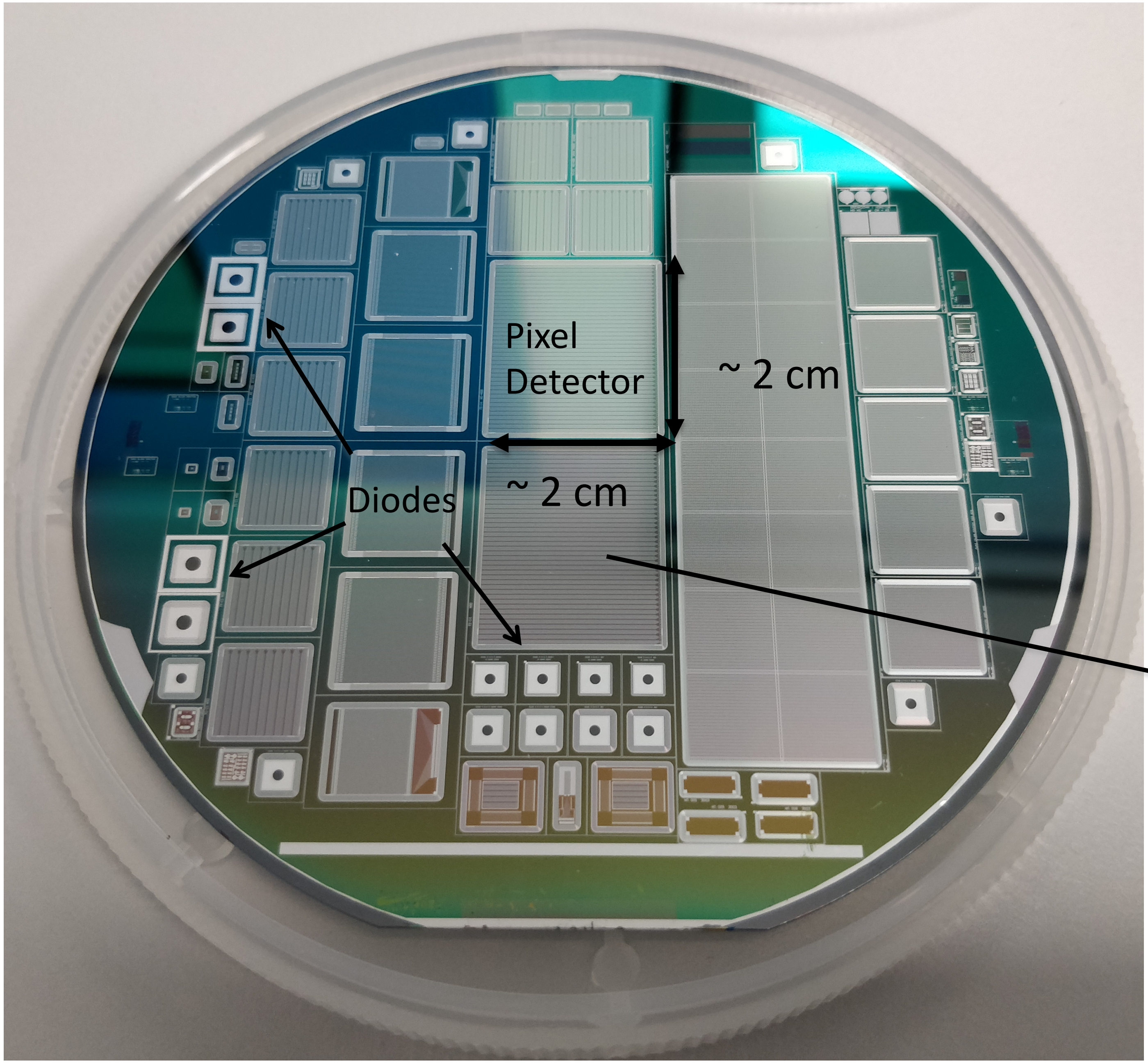


Fig. 1 : Successive steps of the manufacturing process of passivated ion-implanted silicon detectors

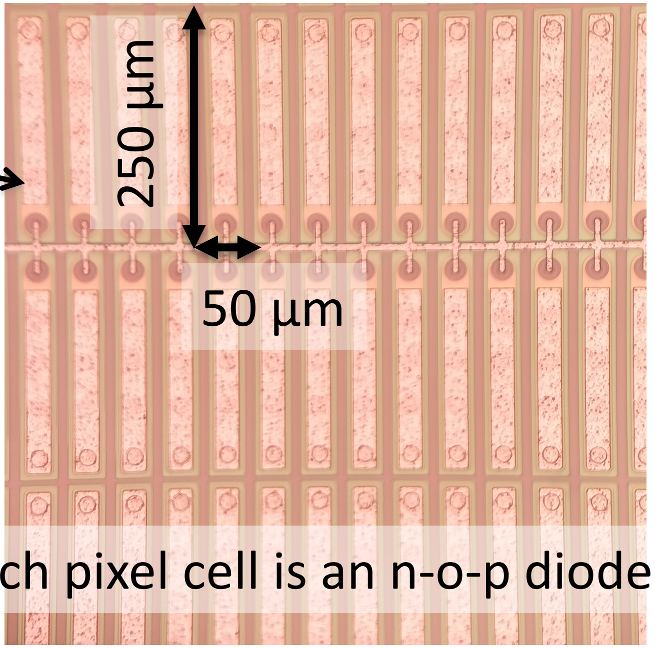
HEP silicon detector production



Detectors produced on **wafers**

Diameters: from 10 cm (picture) to 20 cm (depending also on industry trust)

Thicknesses: 300 µm down to 100 µm or less (most recent I tested: 50 µm)



Each pixel cell is an n-o-p diode

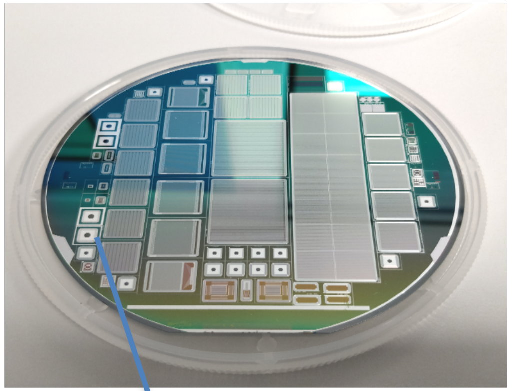
Simplest silicon sensors: the pad diode

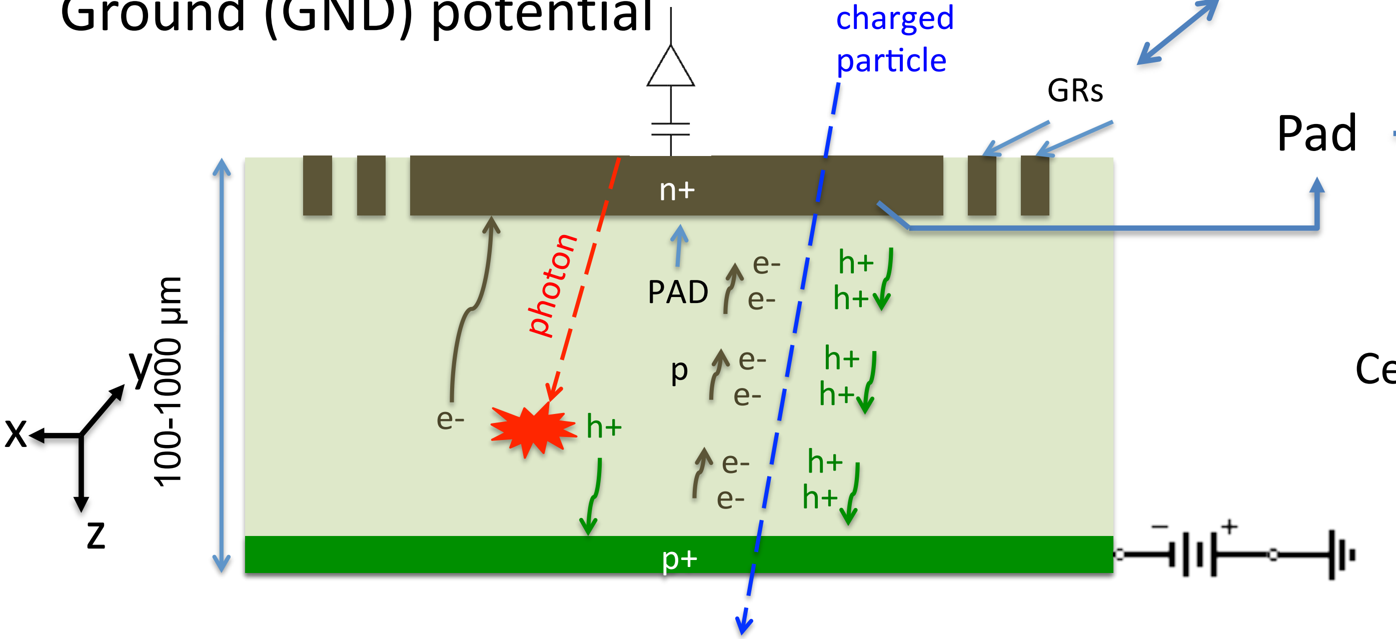
A single p-n junction diode in reverse bias is the simplest silicon radiation detector

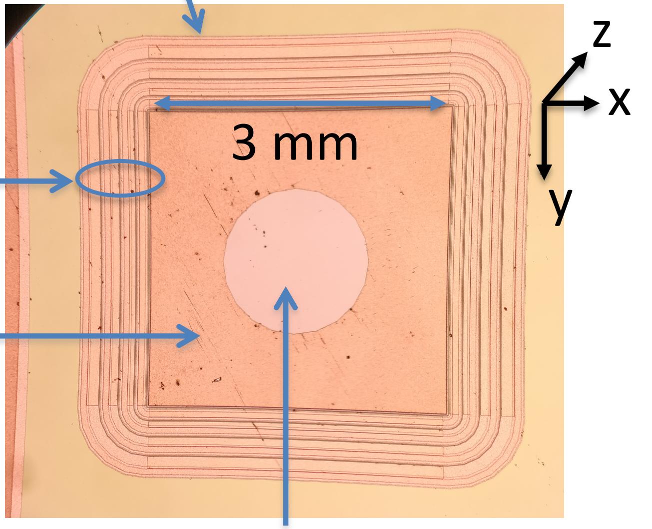
Often it is called pad diode

The size varies between few mm^2 to few cm^2

Guard Rings (GRs) assure a smooth transition between the High Voltage (HV) and the Ground (GND) potential







Central openings in the aluminium layer for visible/IR photon detection

P-n junction – width of the depletion zone

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

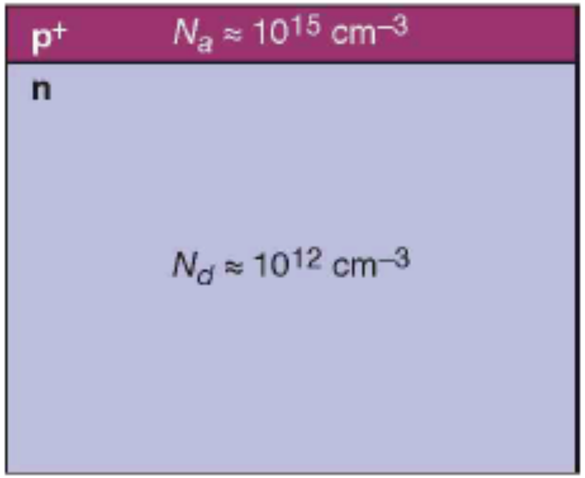
Effective doping concentration $N_a = 10^{15}\ \mathrm{cm}^{-3}$ in p+ region and $N_d = 10^{12}\ \mathrm{cm}^{-3}$ in n bulk.

Without external voltage:

$$W_p = 0.02\ \mu\mathrm{m}$$
$$W_n = 23\ \mu\mathrm{m}$$

Applying a reverse bias voltage of 100 V:

$$W_p = 0.4\ \mu\mathrm{m}$$
$$W_n = 363\ \mu\mathrm{m}$$



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

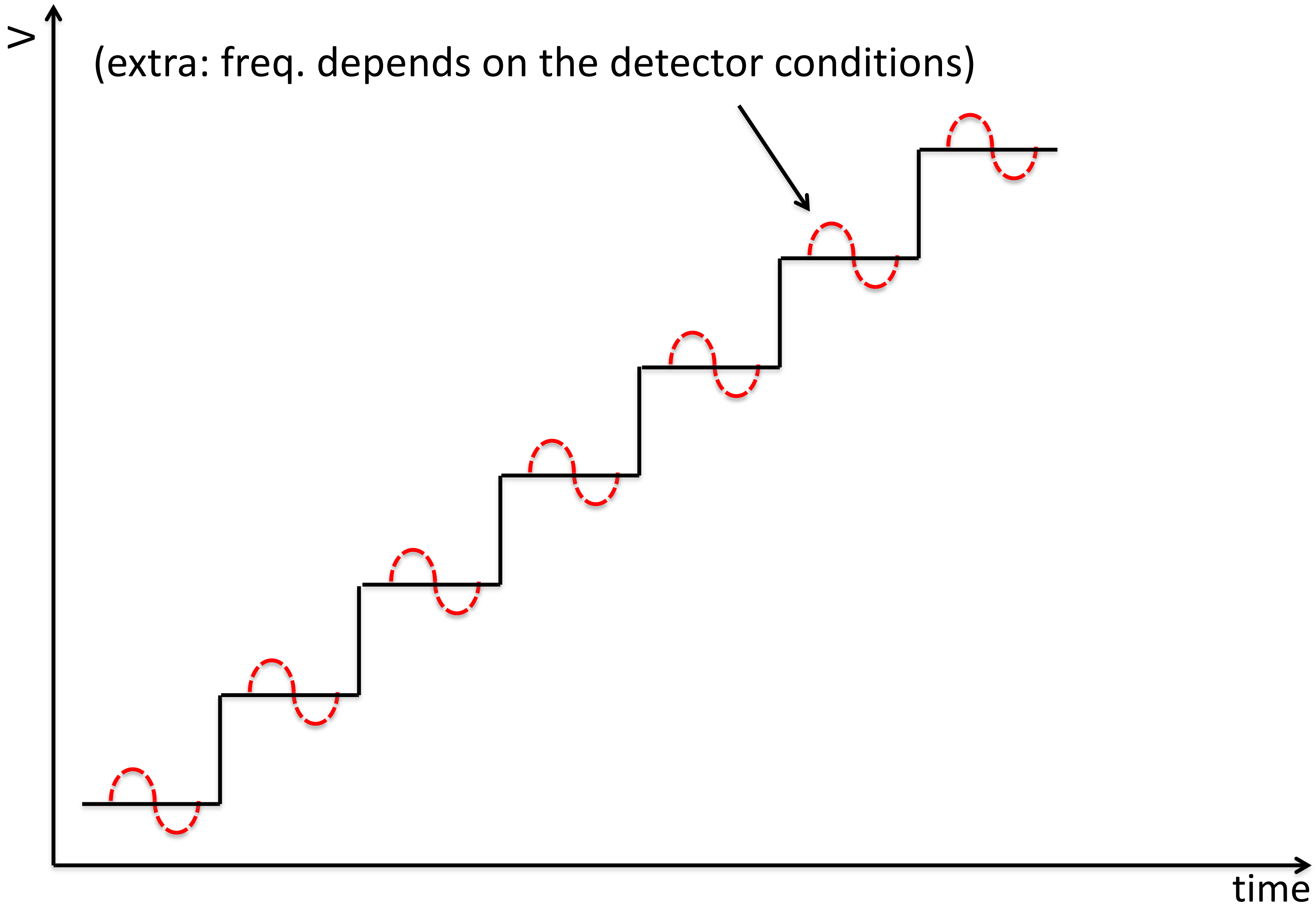
Depletion voltage: howto

- By definition, differential capacitance is the change in charge (Q) in a device that occurs when it also has a change in voltage (V):

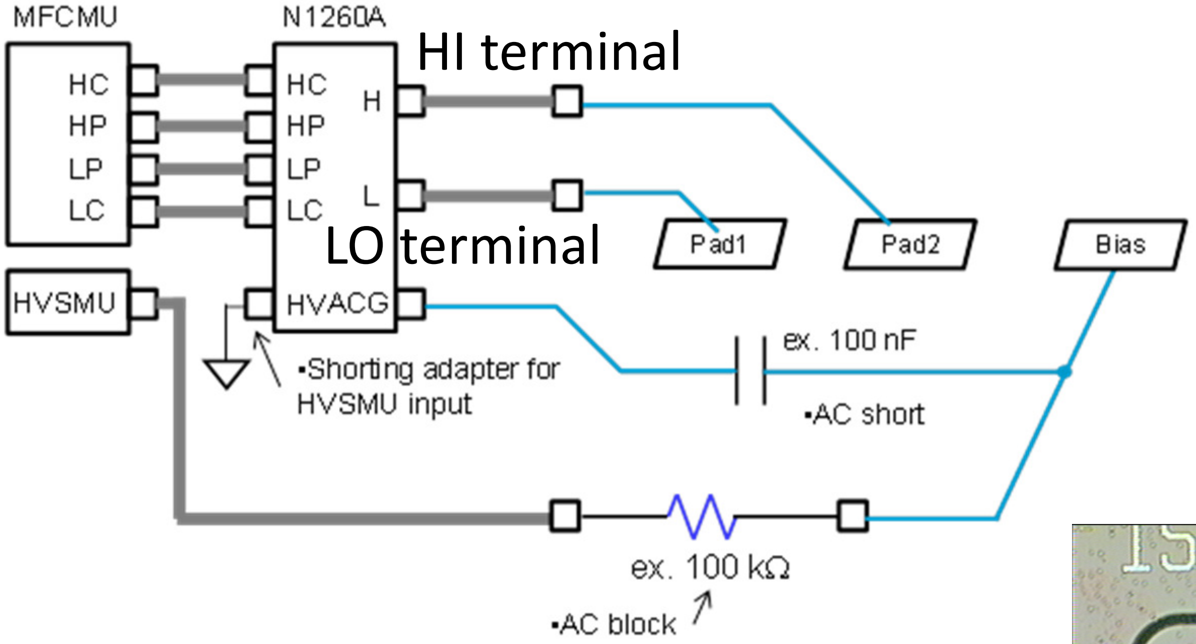
$$C=\Delta Q/\Delta V$$

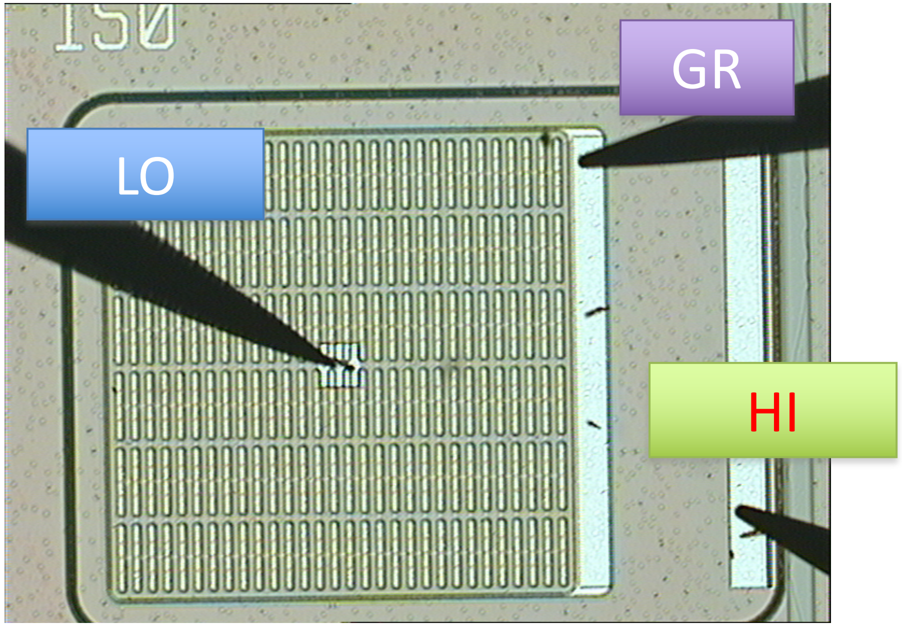
- One general practical way to implement this is to apply a small AC voltage signal (millivolt range) to the device under test, and then measure the resulting current. Integrate the current over time to derive Q and then calculate C from Q and V.
- C-V measurements in a semiconductor device are made using two simultaneous voltage sources: an applied AC voltage signal (dVac) and a DC voltage (Vdc) that is swept in time, as illustrated in the next slide.

Voltage ramp for CV analysis



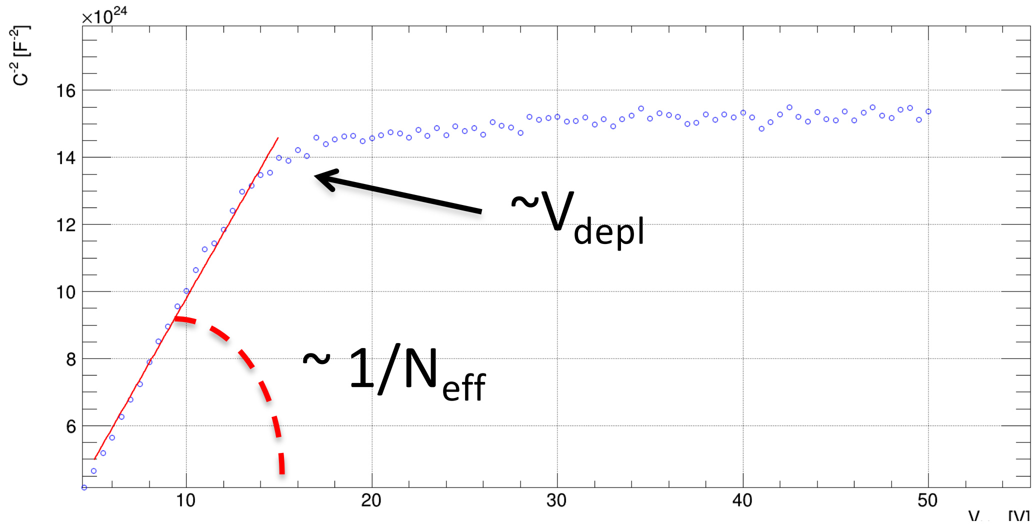
Connections for CV analysis





CV analysis: observables

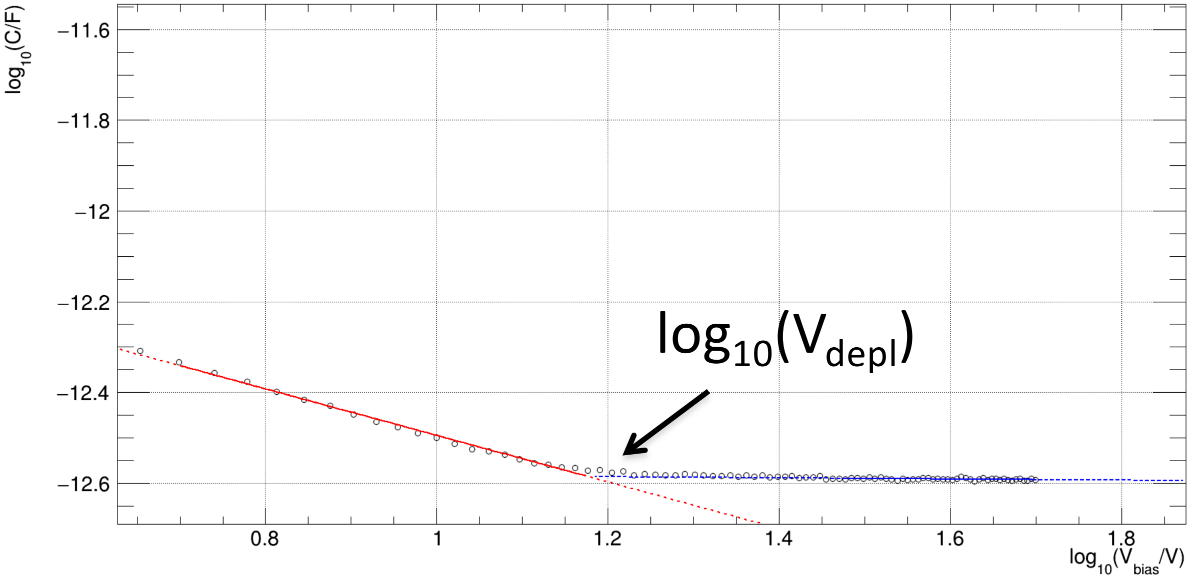
C^{-2} vs V



$$C = \frac{A\epsilon_0\epsilon_{sc}}{w}\sqrt{\frac{V_{depl}}{V}} = A\sqrt{\frac{qN_{eff}\epsilon_0\epsilon_{sc}}{2}\frac{1}{V}}$$

$$N_{eff} = 2\frac{\left(\frac{d(C^{-2})}{dV}\right)^{-1}}{q\epsilon_0\epsilon_{sc}A^2}$$

log10(C) vs log10(V)

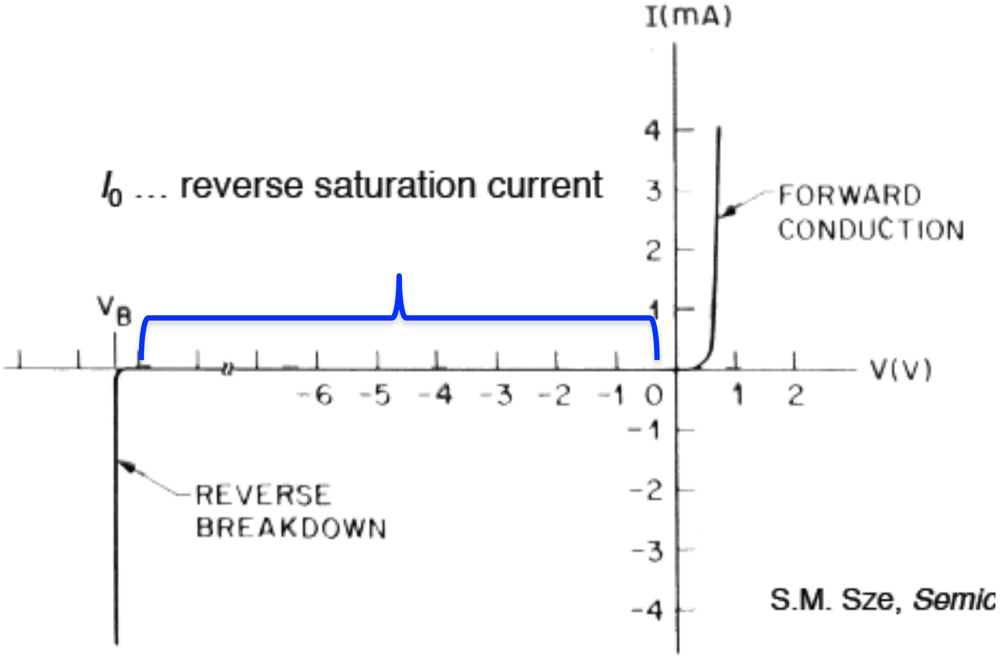


P-n junction – Current voltage characteristics

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

Ideal diode equation:

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



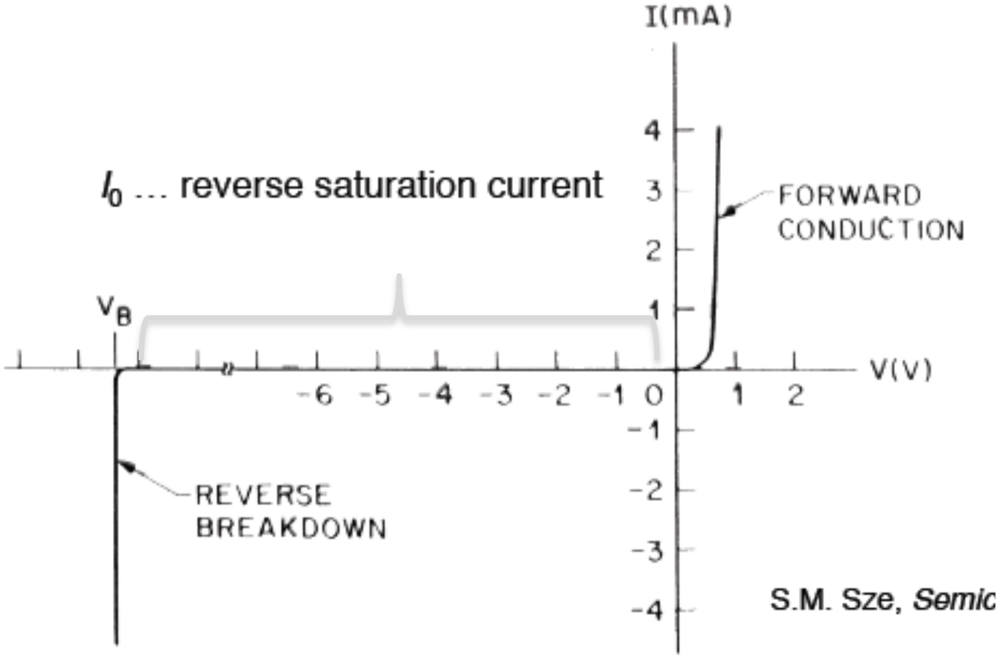
S.M. Sze, *Semic*

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

In reverse bias:
extra contribution
from bulk generated current



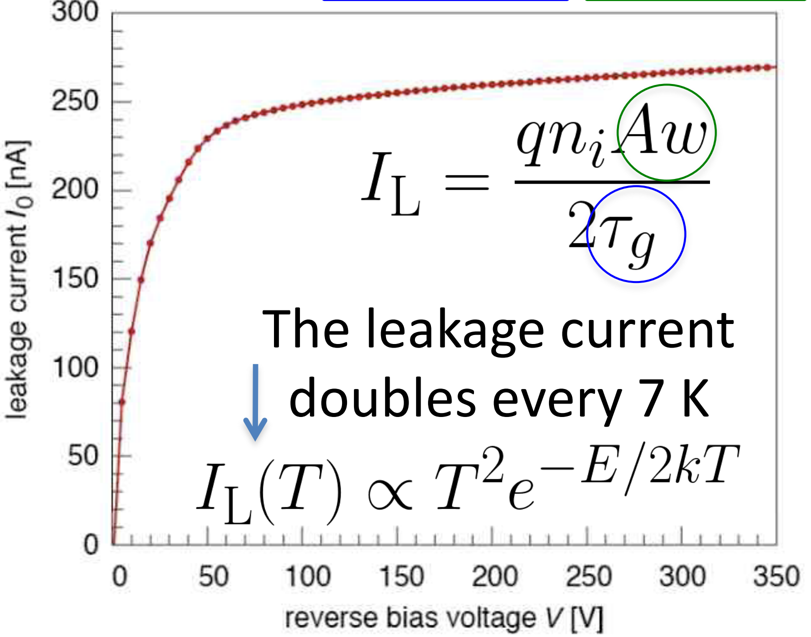
I_0 … reverse saturation current

S.M. Sze, *Semic*

Leakage current origin:
thermally generated carriers

Generation lifetime

Detector volume

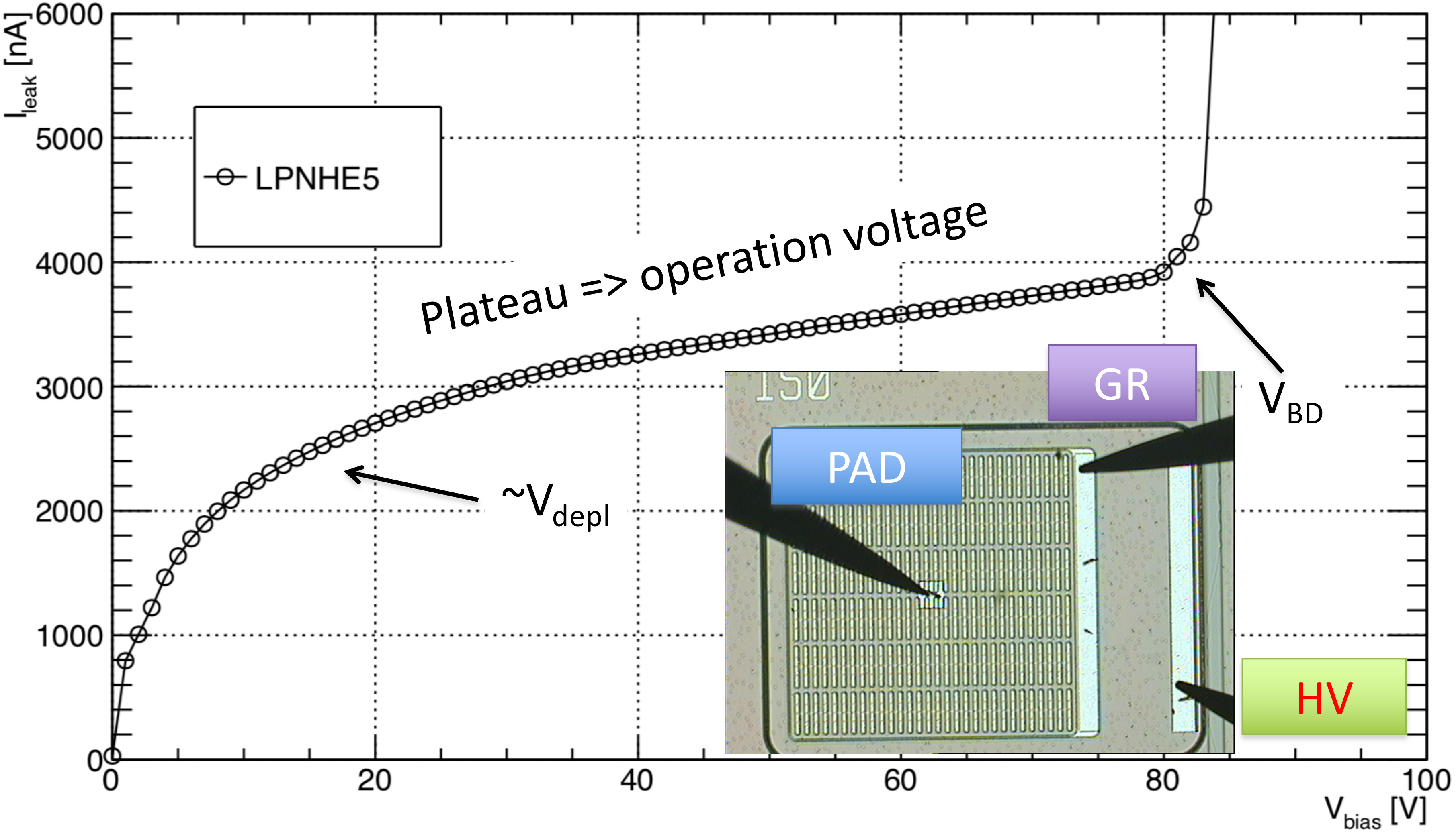


$$I_{\mathrm{L}} = \frac{q n_i A w}{2\tau_g}$$

The leakage current doubles every 7 K

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

IV in real life



Plateau => operation voltage

~V_{depl}

V_{BD}

Silicon as detector material: summary

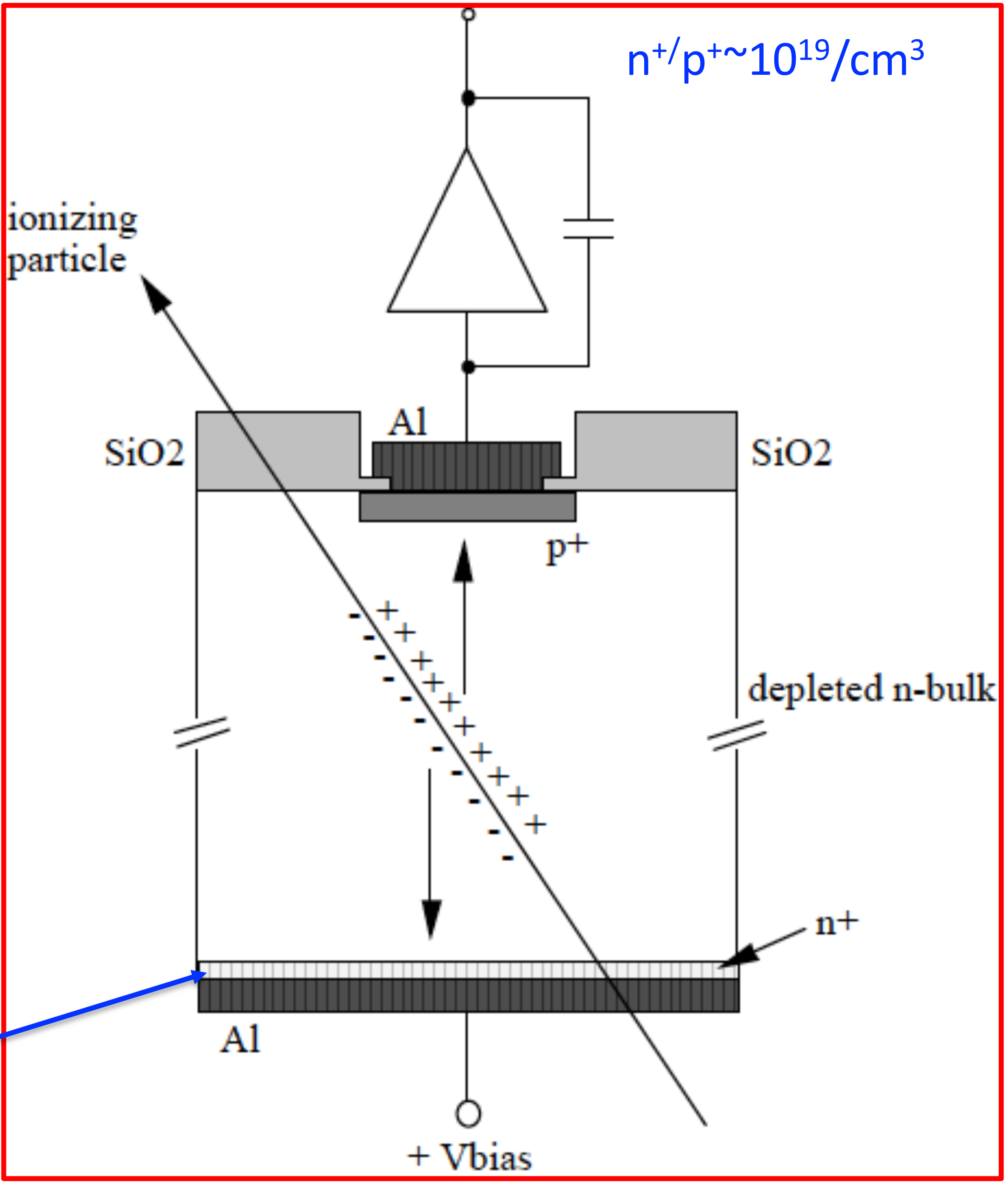
Reverse biased p-n junction as radiation detector: the **depletion region** is virtually **free of mobile carriers** ➔ in absence of radiation only the (small) diode reverse current flows in the junction

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})

N-side of the junction: heavily doped N+ implant on the n-side (ohmic side) of the detector to ensure a good ohmic contact.



Backup

How to “see” particles?

- The goal is to measure position in space, charge, speed, mass and energy of the particles produced in collisions
- In order to achieve this, HEP experiments are made of several layers, each one with a specific task in the reconstruction of the collision event