Detector Physics 2022/2023, Lecture 7

Semiconductor detectors

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Additional references

- NPAC lectures by J. Bolmont, 2019 (→ thanks!)

https://npac.lal.in2p3.fr/wp-content/uploads/2019/Cours-S1/Detectors/NPAC_Detector_Physics_Part5_JB_light.pdf

- Lectures on Detectors for CERN Summer Students:

Daniela Bortoletto 2015

https://indico.cern.ch/event/243648/attachments/415356/577104/daniela_l4_post.pdf

Marco Bomben 2015

https://indico.in2p3.fr/event/10777/contributions/3166/

Werner Riegler 2019

https://indico.cern.ch/event/817555/

- M. Krammer and F. Hartmann, Silicon Detectors, EDIT20111

https://indico.cern.ch/event/124392/contributions/1339904/attachments/74582/106976/IntroSilicon.pdf

- G. Lutz, Semiconductor radiation detectors: device physics. Springer, Berlin, 1999

Motivation

Introduced in the 1960's for spectroscopy

→ dramatic improvement of energy resolution

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

FABRICATION OF LOW NOISE SILICON RADIATION DETECTORS BY THE PLANAR PROCESS

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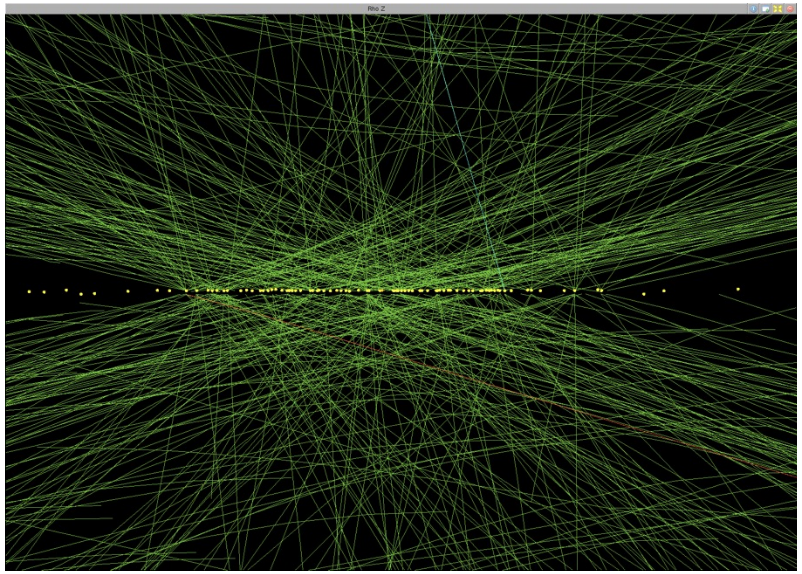
Received 30 July 1979 and in revised form 22 October 1979

Dedicated to Prof Dr H -J Born on the occasion of his 70th birthday

By applying the well known techniques of the planar process oxide passivation, photo engraving and ion implantation, Si pn-junction detectors were fabricated with leakage currents of less than 1 nA cm^{-2}/100 μm at room temperature Best values for the energy resolution were 10 0 keV for the 5 486 MeV alphas of ^{241}Am at 22°C using 5×5 mm^2 detector chips

From the 1980's : need to determine position of primary interaction vertex and/or secondary decays

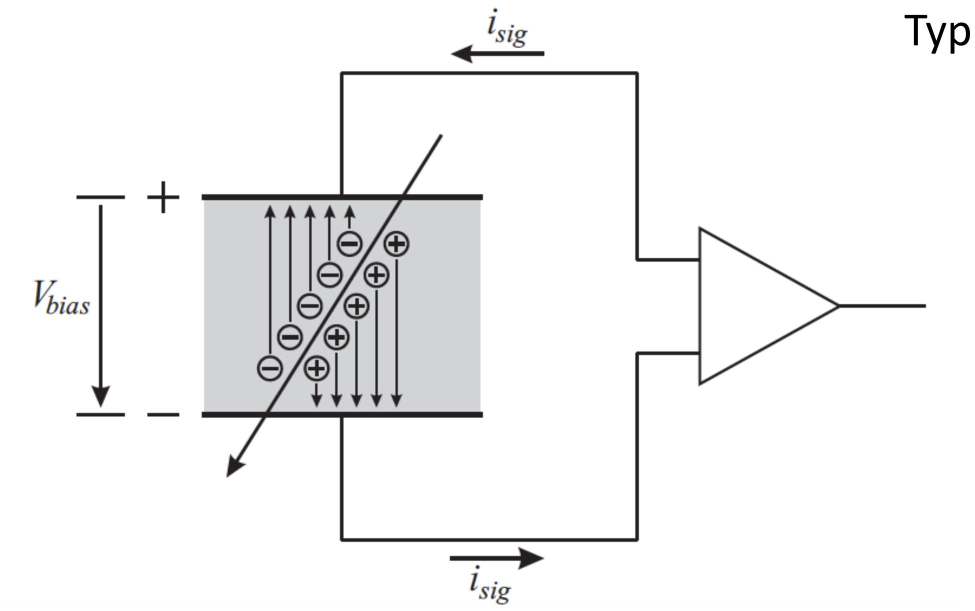


Semiconductor detectors provide

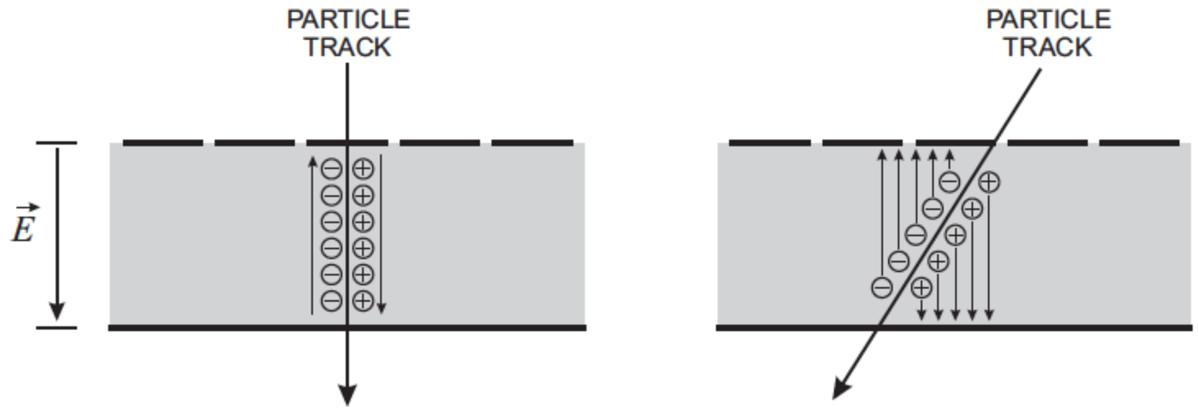
- high segmentation
- high density => small size

Semiconductor sensors : principle

- Fundamental information carriers : e$^-$-hole pairs produced along the path of the charged particle
- Detection signal formed by collecting the e$^-$-hole pairs (basically a ionization chamber)



Typically : Si, Ge



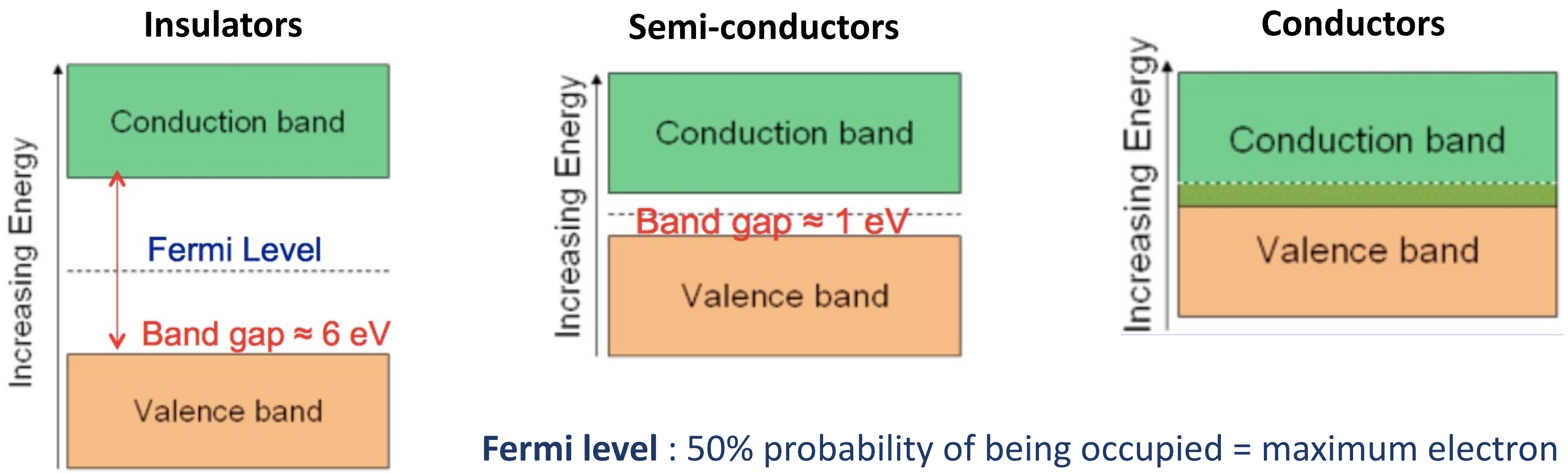
Fast time response, (<20 ns)

Segmenting the sensor electrodes provides position information

H. Spieler, Semiconductor Detector Systems, Clarendon Press Oxofrd

Semiconductor properties

- Crystals : periodic lattice of atoms
- Electron energy levels are smoothed into ”bands” due to reciprocal interaction of atoms close to each-other



Fermi level : 50% probability of being occupied = maximum electron energy at T=0K

- In semi-conductors, E_{gap} ~ $E_{thermal}$: with thermal energy, electrons can cross the band gap and reach the conduction band. A vacancy is created in the valence band : electron-hole pair

Semiconductor properties

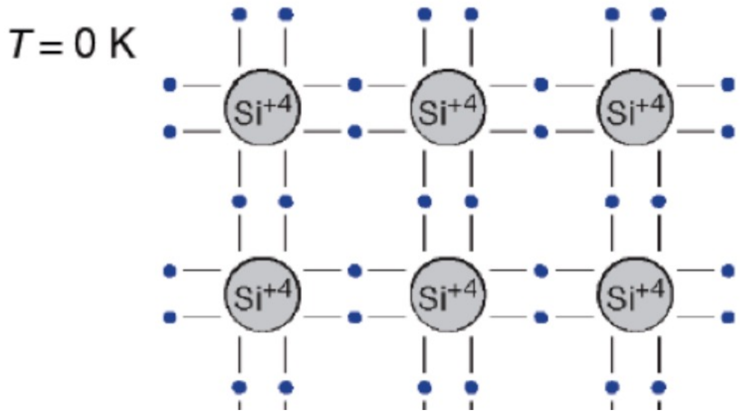
- Probability for an electron to move from the valence to the conduction band

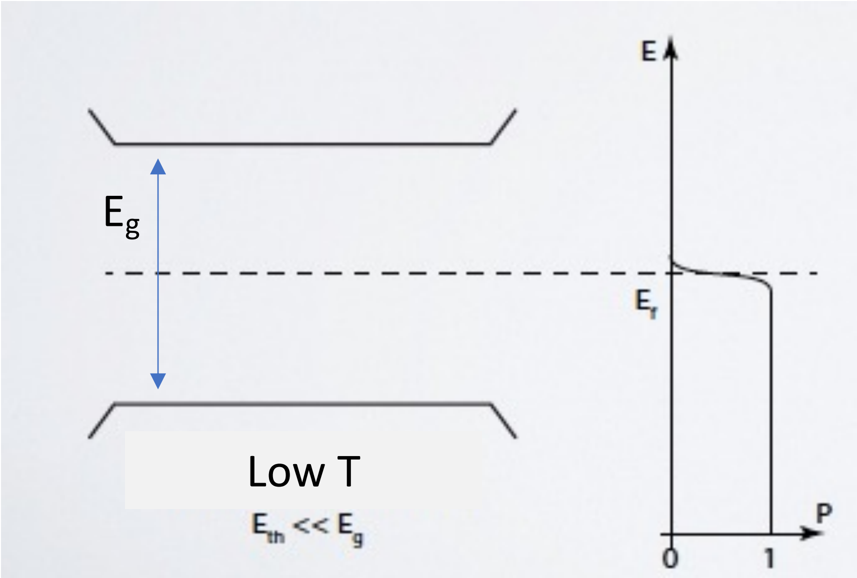
$$P(T) = cT^{3/2} exp\left(-\frac{E_g}{2k_B T}\right)$$

T : absolute temperature
c : proportionality constant characteristic of material
E_g : band gap energy
k_B : Boltzmann constant

Example : Silicon (tetravalent : 4 nieghbours)

- At very low temperature, all the electrons participate in bonds between the atoms





Semiconductor properties

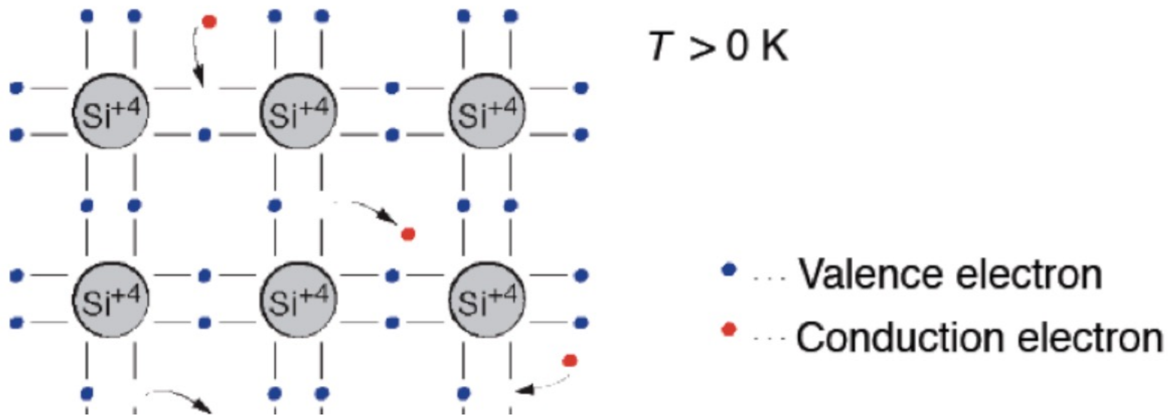
- Probability for an electron to move from the valence to the conduction band

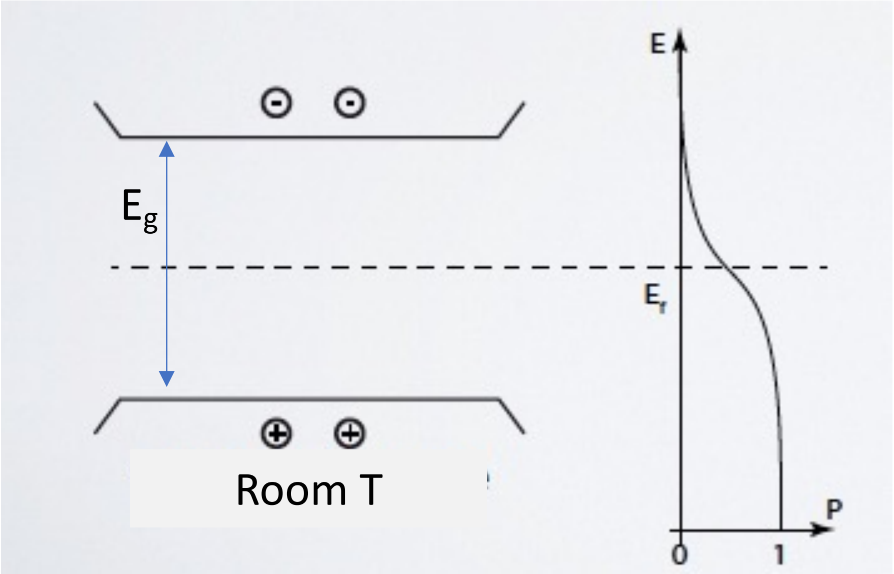
$$P(T) = cT^{3/2} exp\left(-\frac{E_g}{2k_BT}\right)$$

T : absolute temperature
c : proportionality constant characteristic of material
E_g : band gap energy
k_B : Boltzmann constant

Example : Silicon (tetravalent : 4 nieghbours)

- At room temperature, some bonds are broken by thermal energy → electron-hole pair creation





Intrinsic semiconductors

- Thermal equilibrium is reached between excitation and recombination when the number of free electrons equals that of free holes : <u>intrinsic carriers</u>

$$n_e = n_h = n_i$$

Typical values : n_i=1.5 10^{10} cm^{-3} in Si, 2.4 10^{13} cm^{-3} in Ge

- Compare with the signal from a MIP :

  dE/dx = 3.87 MeV/cm

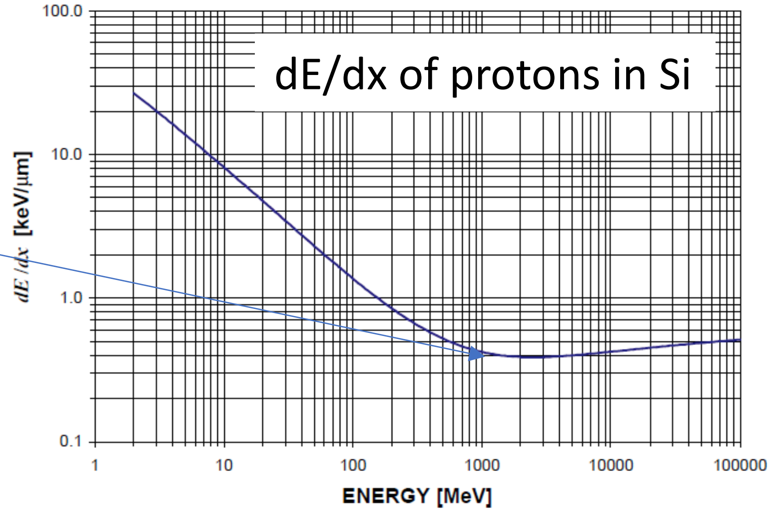
  assume detector thickness Δ = 300 μm, area A=1cm^2

  mean energy to form a e-h pair in Si : w = 3.63 eV

e-h pairs from MIP $= \frac{(dE/dx)\cdot\Delta}{w} = 3.2\ 10^4$

e-h pairs from thermal noise = n_i A Δ = 4.35 10^8 >> signal

→ need to deplete the free charge carriers

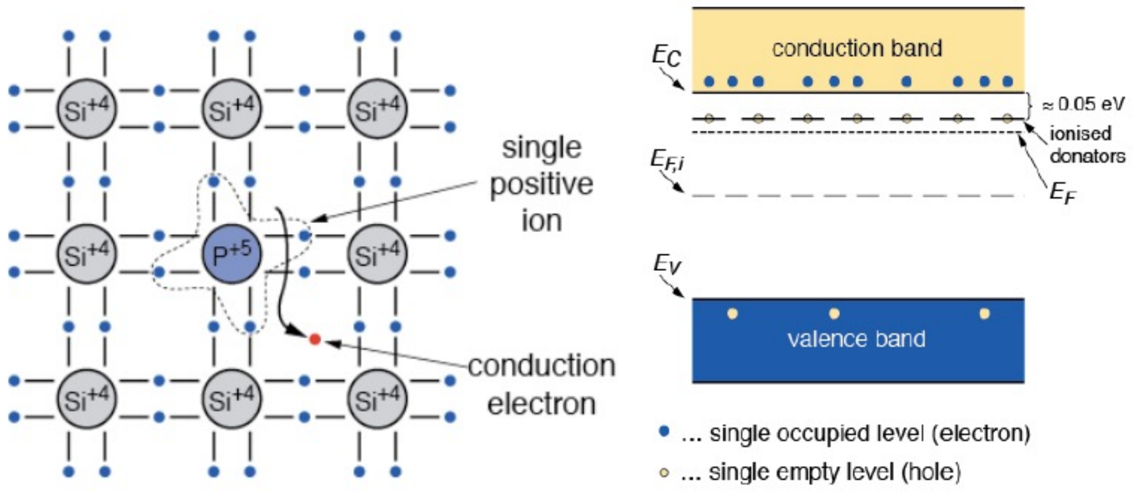


Doped semiconductors

- Add impurities with different number of valence electrons
- Create additional levels in the bandgap, to be occupied by charge carriers
- Very small concentrations : 10^{12}-10^{15} cm^{-3}, vs 10^{20} cm^{-3} atoms of Si or Ge

Donor impurities (<u>n-type doping</u>) : As, P, Sb

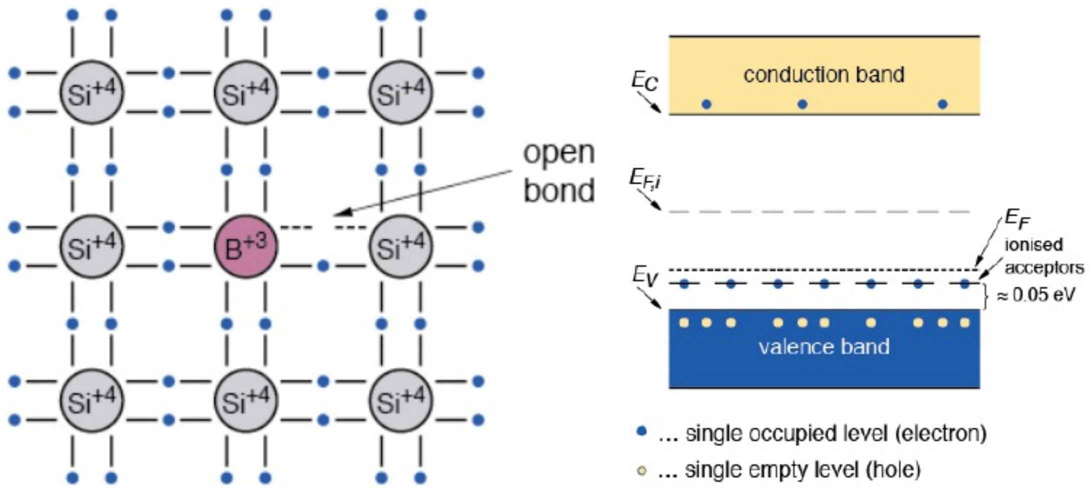
5 valence electrons



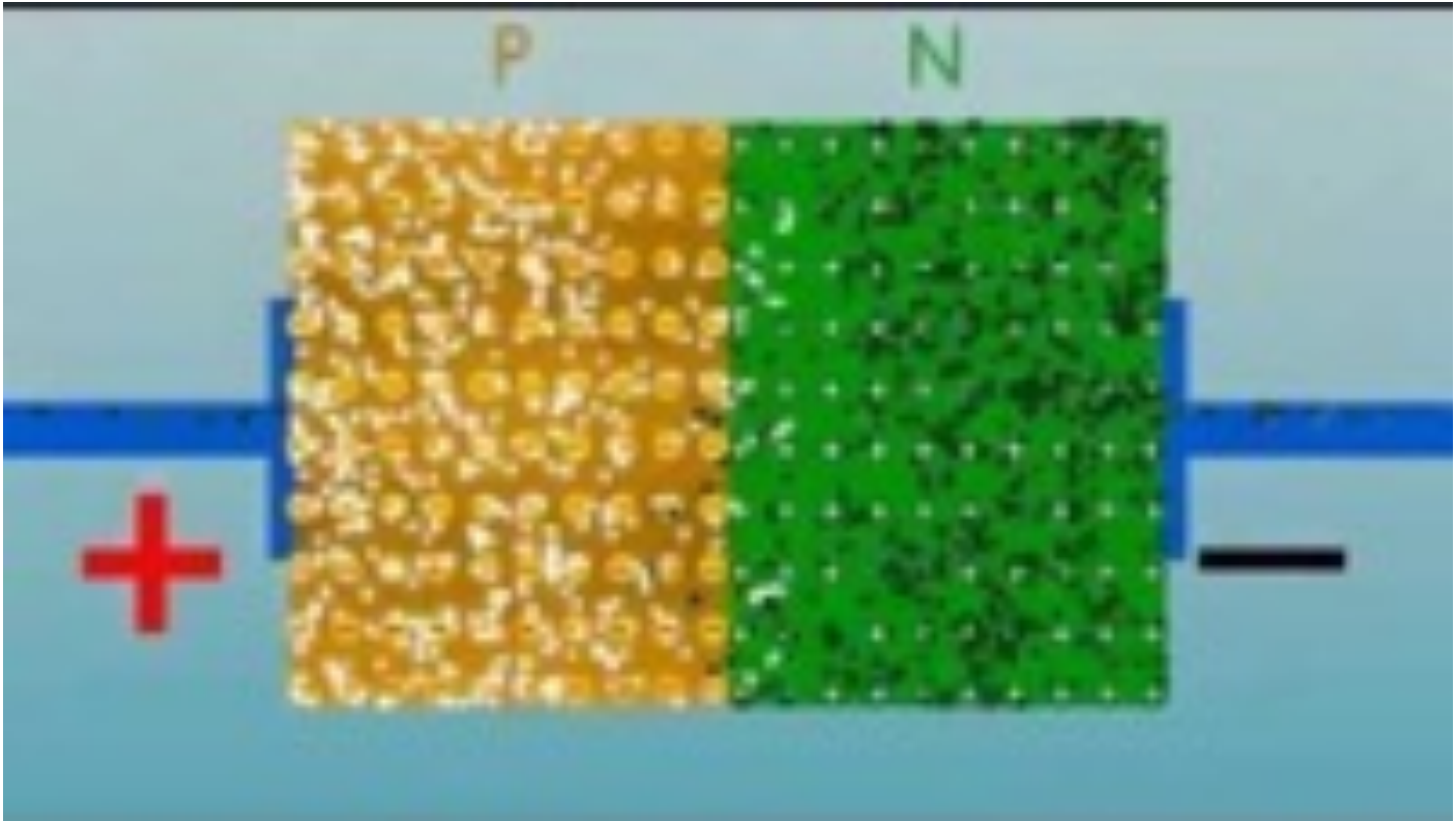
all the e- in excess in the donor level are transferred to the conduction band because of thermal energy

Acceptor impurities (<u>p-type doping</u>) : Ga, B, In

3 valence electrons



the acceptor level is filled with e- from the valence band because of thermal energy



https://youtu.be/JBtEckh3L9Q

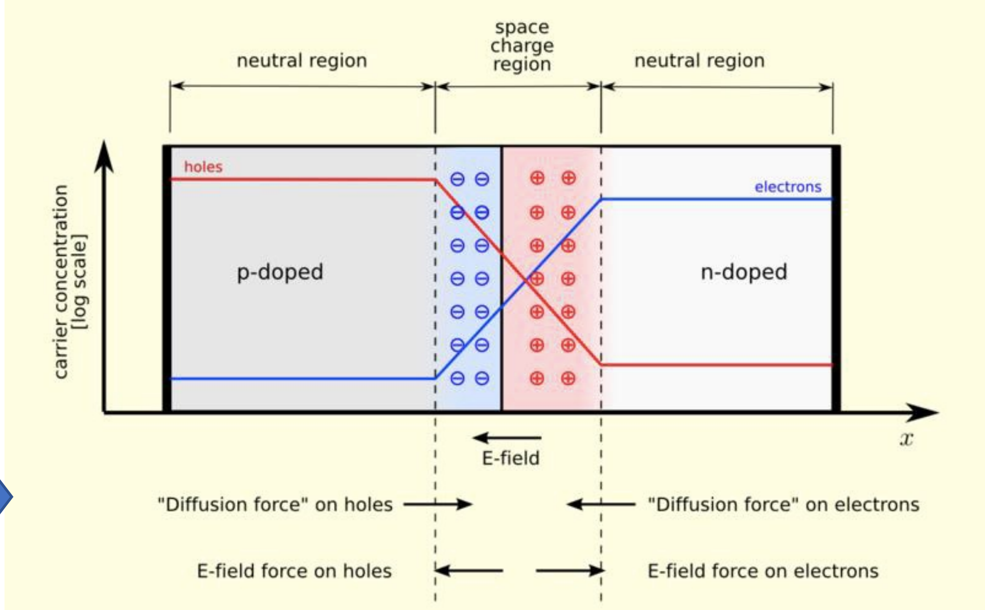
The PN Junction. Developed under Teaching Innovation Project 11-293 of Universidad de Granada (Spain) Creative Commons By-NonCommercial-NonDerivs. English version. All the themes in the soundtrack were released under Creative Commons licenses by their respective authors.

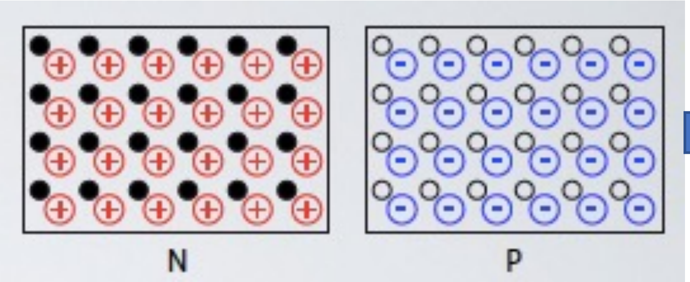
p-n junction

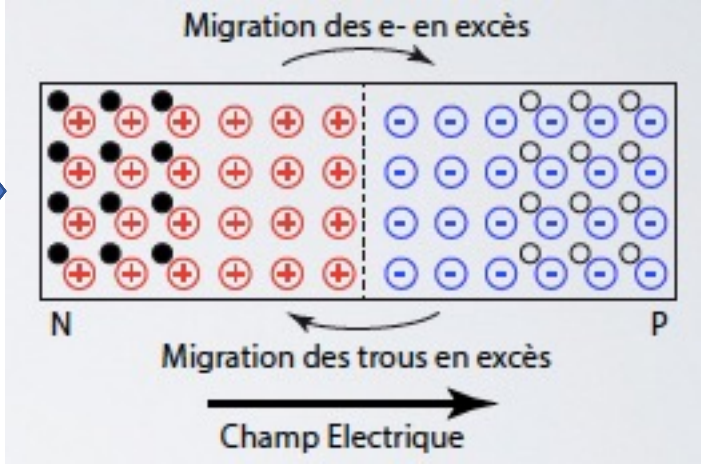
Obtained by diffusing p-type impurities on one side of a n-type Si bar (”bulk”)

- (free) electrons migrate to the p side and fill the holes
- (free) holes migrate to the n side and capture electrons

- creation of a depletion region with no charge carriers
- the n side is now charged +, the p side is charged - :
- creation of an electrical potential (built-in potential)
- this balances the chemical potential : equilibrium







p-n junction: depletion depth

suppose uniform charge density *ρ(x)* on both sides

charge conservation $N_A x_p = N_D x_n$

solve Poisson equation $\frac{d^2V}{dx^2} = -\frac{\rho(x)}{\epsilon}$

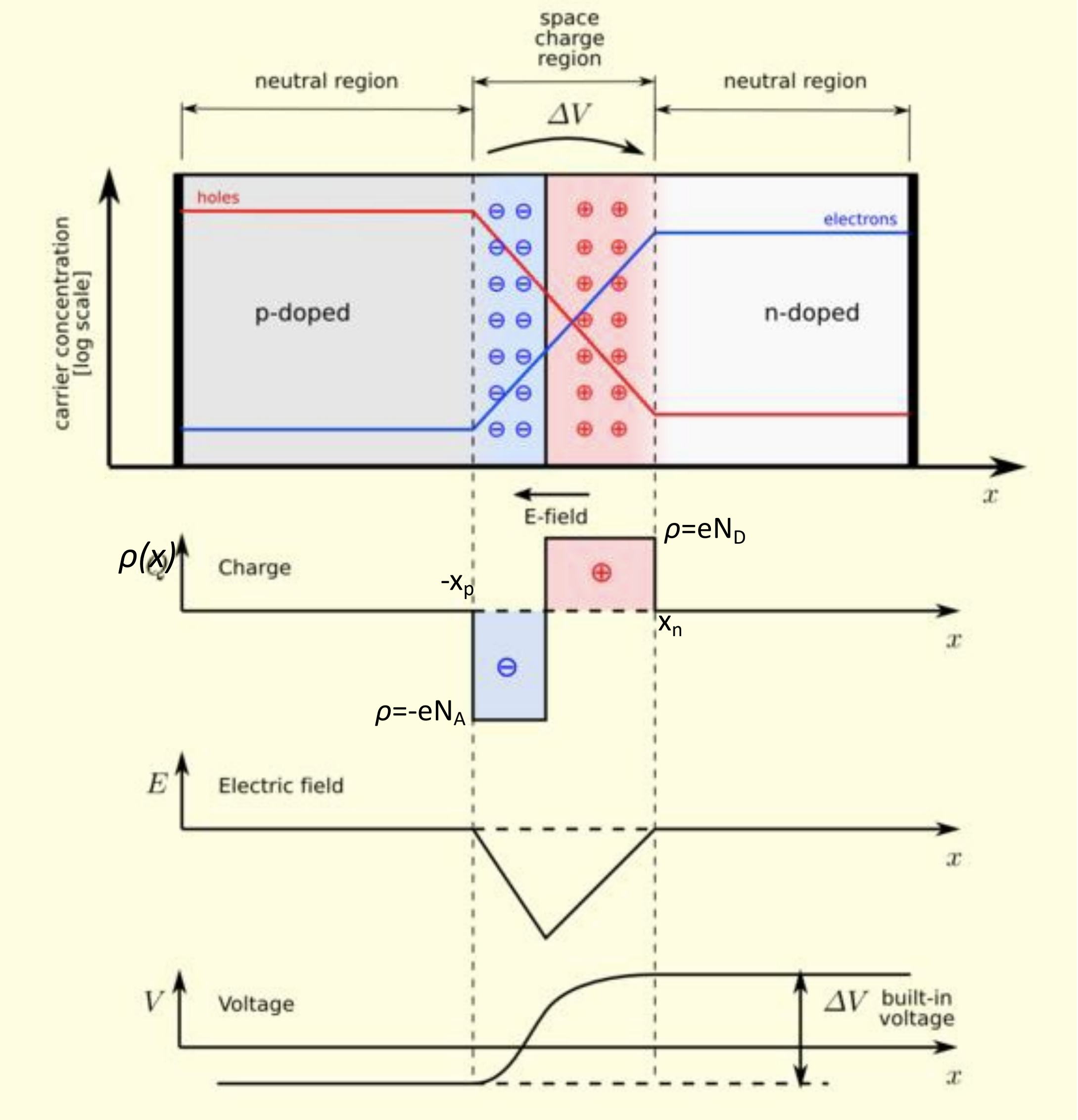
using boundary conditions $E(-x_p)=E(x_n)=0$

(Exercise1)

→ $\Delta V = \frac{e}{2\epsilon}\left(N_A x_p^2 + N_D x_n^2\right)$

→ $x_p = \left(\frac{2\epsilon\,\Delta V}{e\,N_A\,(1+N_A/N_D)}\right)^{1/2}$ $x_n = \left(\frac{2\epsilon\,\Delta V}{e\,N_D\,(1+N_D/N_A)}\right)^{1/2}$

→ $d = x_p + x_n = \left(\frac{2\epsilon\,\Delta V}{e}\frac{N_A+N_D}{N_A N_D}\right)^{1/2}$



p-n junction: depletion depth

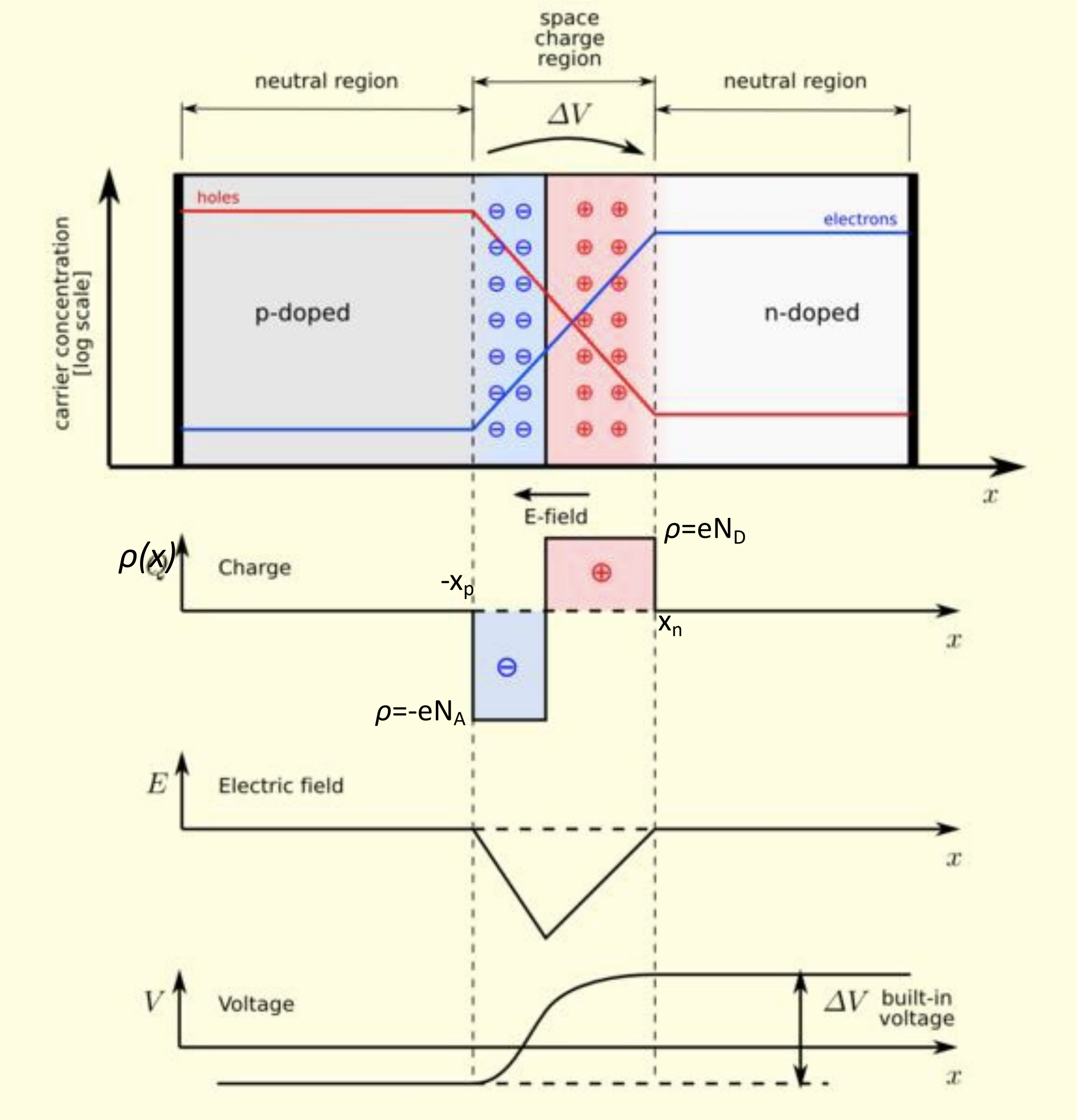
- Typical values in Si P-N junctions :
  - $N_A = 10^{15}$ cm^{-3} in p+ region , $N_D = 10^{12}$ cm^{-3} in n bulk << N_A
  - → x_p=0.02 µm and x_p=23 µm

$$d = x_p + x_n \approx x_n \approx \left(\frac{2\epsilon\,\Delta V}{e\,N_D}\right)^{1/2}$$

can be expressed as a function of mobility μ

and resistivity $\rho = (eN_D\mu_e)^{-1}$

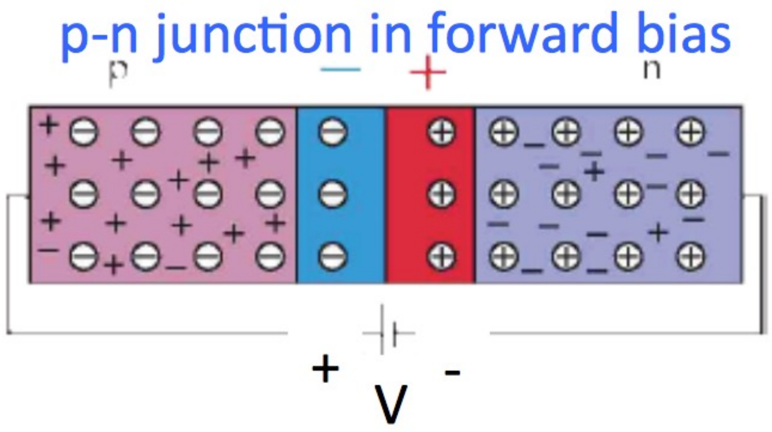
$$d \approx (2\,\epsilon\,\rho\,\mu_e\,\Delta V)^{1/2}$$



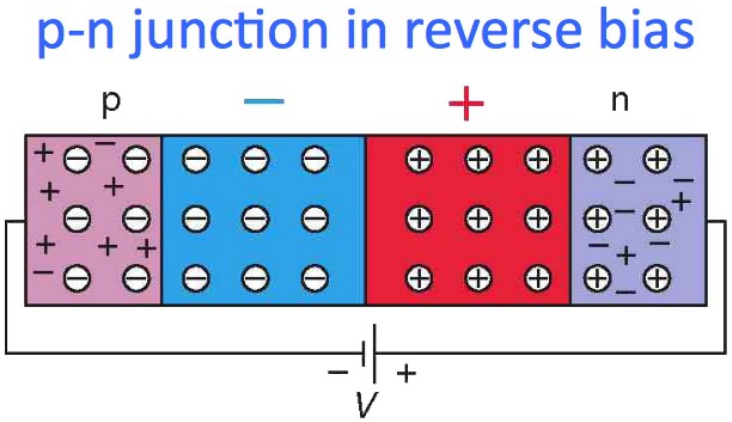
p-n junction: forward and reverse bias

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

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.



That's the way we operate our semiconductor detectors!

M. Bomben - Silicon Radiation Detectors, section A - 5th IDPASC School, LPNHE, 19/2/2015 22

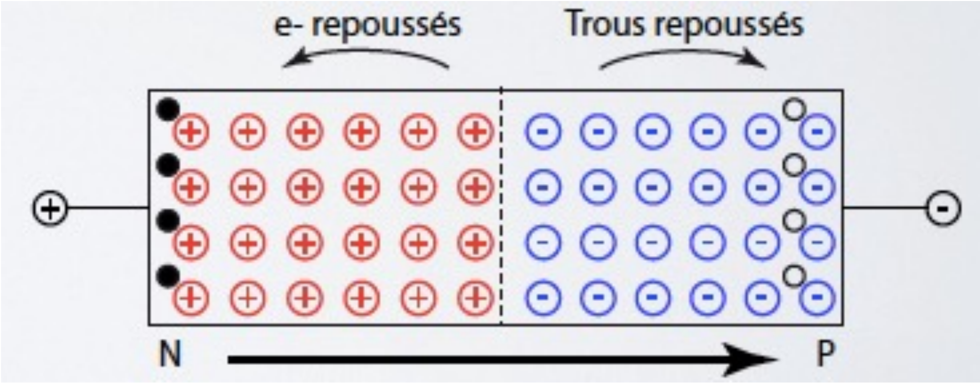
From the p-n junction to the detector

- Revers bias junction

ΔV -> $\Delta V+V_B$ in the formula

($V_B >> \Delta V$, so $\Delta V+V_B \sim V_B$)

example : d=1mm V_B=300V



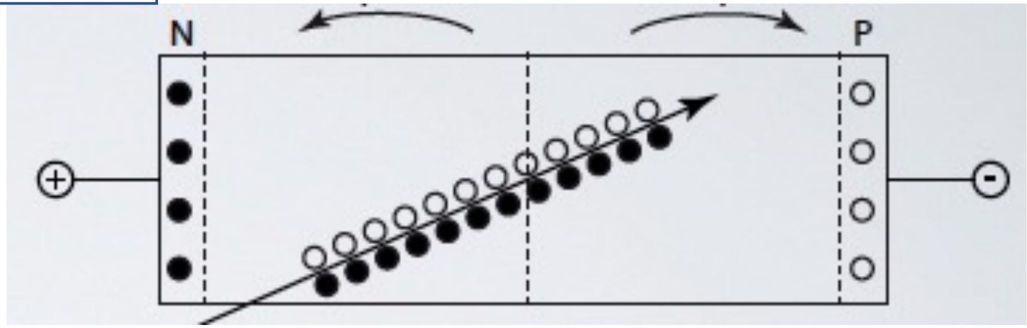
The voltage V needed to fully deplete a device of thickness d is called the depletion voltage V_d

- The depleted region is the useful volume for detection

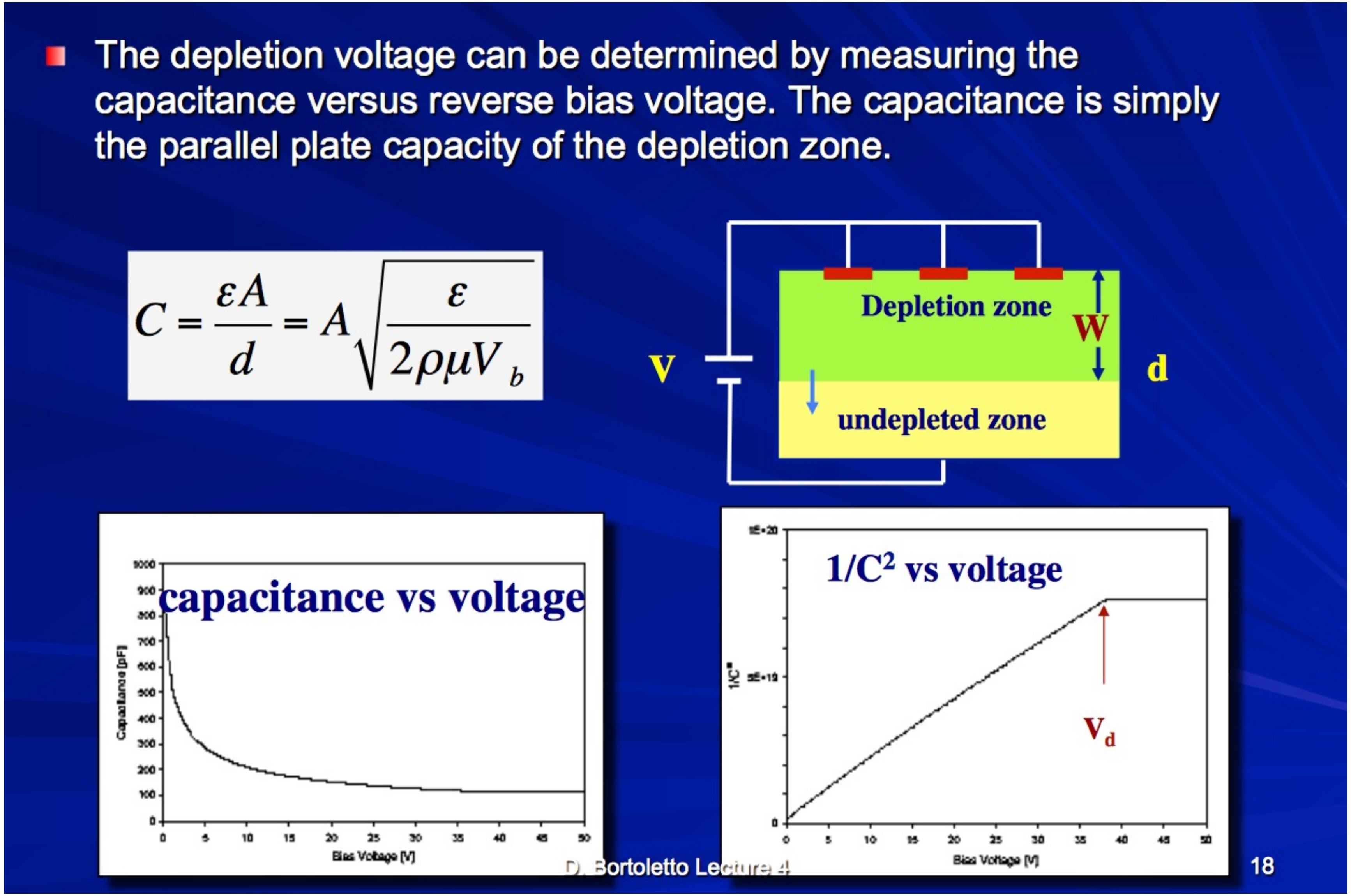
ionizing particles produce e^--hole pairs

e- (holes) drift to the n (p) side → current pulses

proportional to the energy deposit



Depletion region and capacitance



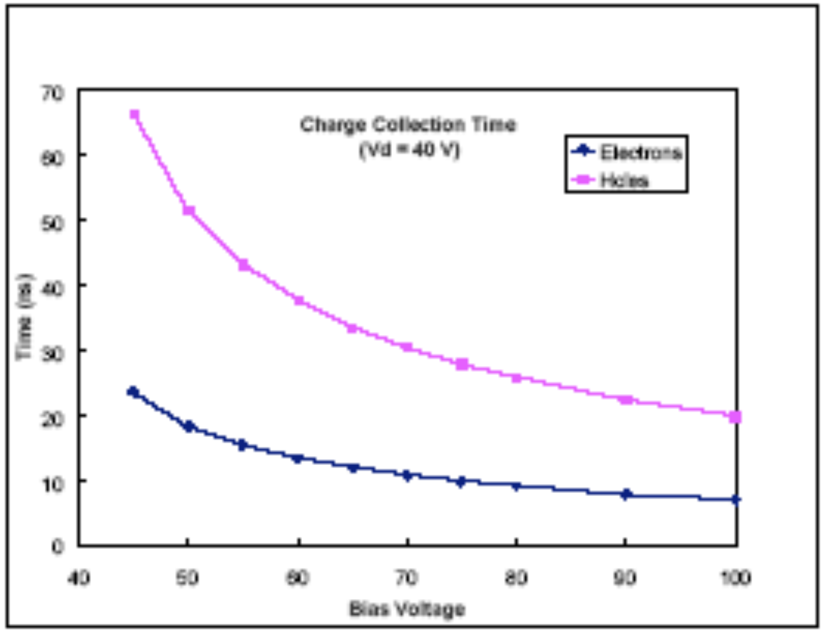
Semiconductor detector characteristics

- Charge collection

  the drift velocity of electron/holes is $v_e = \mu_e E$, $v_h = \mu_h E$ respectively

  The mobility μ depends on T and E. (Attention! Here E is the electric field)

  Charge collections times O(10ns) → fast!



- Linearity

  the depleted region has a capacitance C=εA/d

  the observed voltage on the electrodes is then $V = \frac{Q}{C} = n\frac{E}{wC}$

  → linear with the deposited energy

  A,d : detector area and thickness
  n : collection efficiency
  E : deposited energy
  w : average energy for e-h pair creation

- Energy resolution

  the intrinsic energy resolution depends on the number of carriers *E/w* and the Fano Factor F~0.12

$$R = 2.35\sqrt{\frac{Fw}{E}}$$

(Attention! Here E is the deposited ennergy)

  (+ contributions from other sources, e.g. electronics)

(parenthesis: the Fano Factor)

- Assume the formation of charge carriers to be a Poisson process:
- if N carriers generated, the statistical fluctuation on that number is $\sqrt{N}$
- since N is usually large, the detector response will follow a Gaussian distribution with mean = N and standard deviation = $\sqrt{N}$
- For a linear detector, where the response *E* is proportional to N, *E=kN*, the resolution is

$$R = \frac{FWHM}{\langle E \rangle} = \frac{2.35\,\sigma(E)}{E} = \frac{2.35\,k\sqrt{N}}{kN} = \frac{2.35\,\sqrt{N}}{N}$$

- This is the intrinsic limit from statistical fluctuations. Better values are found from measurements in some detectors.
- Processes leading to the formation of charge carriers are probably not completely independent: departure from Poisson statistics, quantified by **the Fano Factor F**

$$F = \frac{observed\ variance\ on\ N}{Poisson\ predicted\ variance\ (= N)}$$

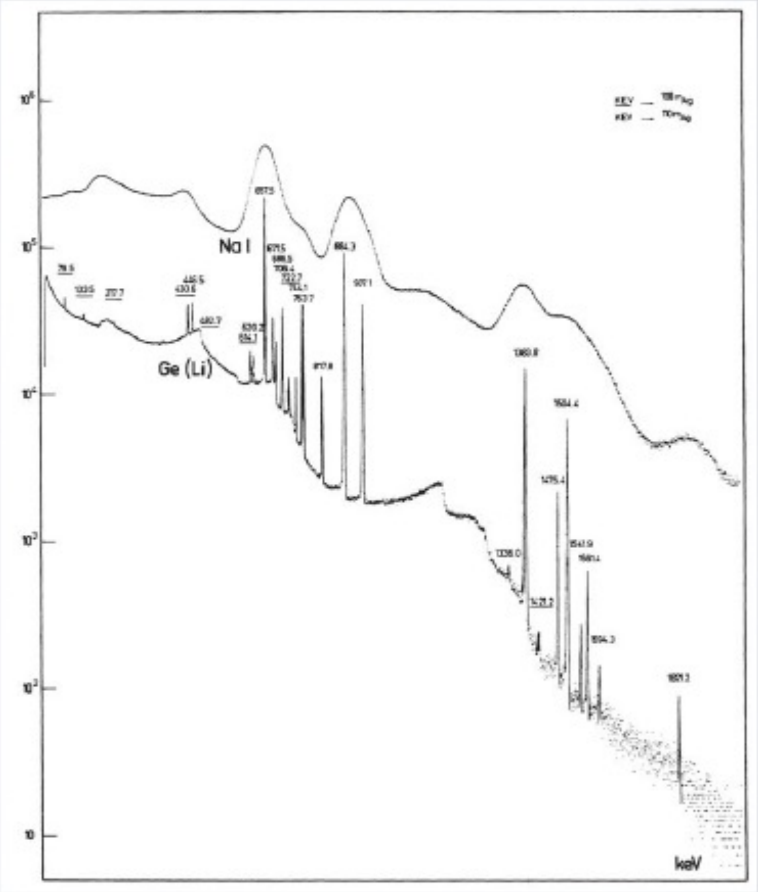
- so the resolution is $R = \frac{2.35\,k\sqrt{N}\sqrt{F}}{kN} = 2.35\sqrt{\frac{F}{N}} = 2.35\sqrt{\frac{F\,w}{E}}$

in scintillators F~1
in Si/Ge F~0.1

Semiconductor detector characteristics

RESOLUTION

- For a 1 MeV photon
- Nal(Tl):
  - 40000 photons/MeV
  - Light collection efficiency ~ 0,2
  - QE ~ 0,25
  - Np.e. ~ 2000
  - σ(E)/E = 1/sqrt(2000) ~ 2%
- Si:
  - 300000 e-/holes pairs per MeV
  - Essentially all carriers collected
  - For F = 0.1,
    σ(E)/E = sqrt(0,1/300000) ~ 0,06%



Semiconductor detector characteristics

- <u>Leakage current</u>

  Small fluctuating current flowing when V_B is applied, although a reverse bias diode is ideally non-conducting.

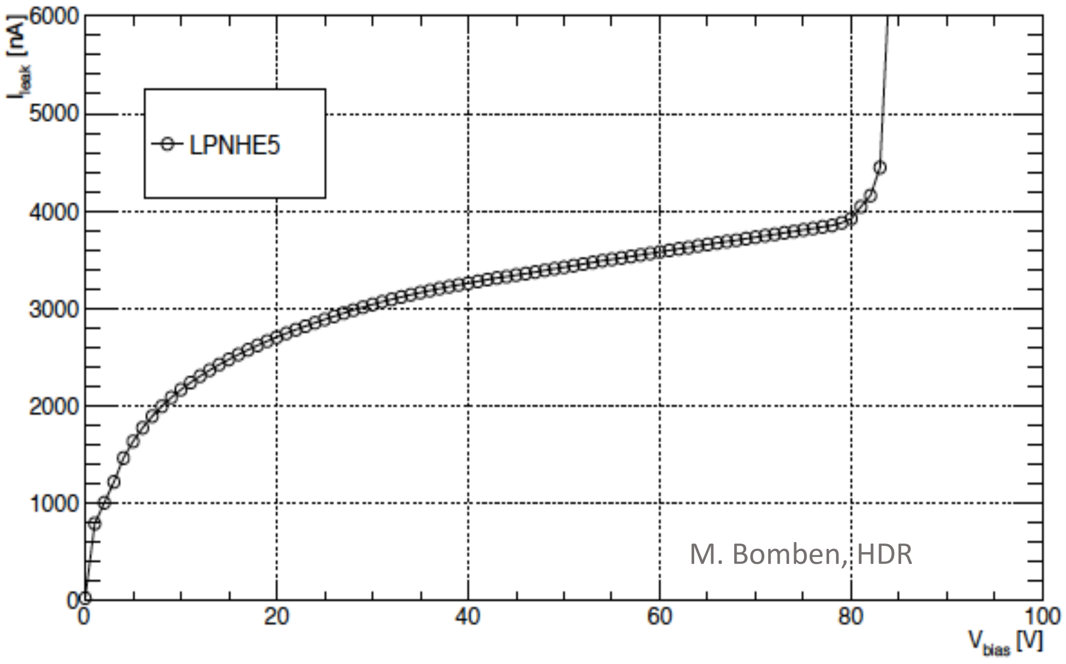
  It <u>limits the smallest signal pulse height</u> that can be observed.

  Several sources:

  - Generated current: thermally generated e-h pairs, separated by the electric field and collected at the ends of the semiconductor volume

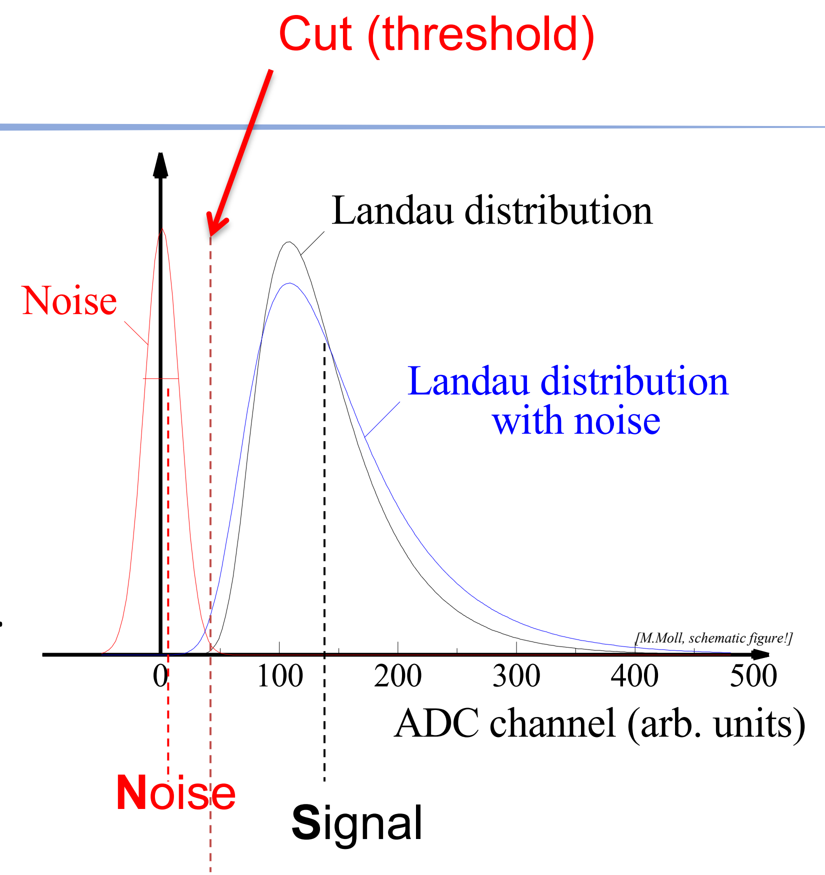
    → reduced by using pure and defect-free materials with high carriers lifetime, operate at low T

  - Diffusion current: movement of minority charge carriers

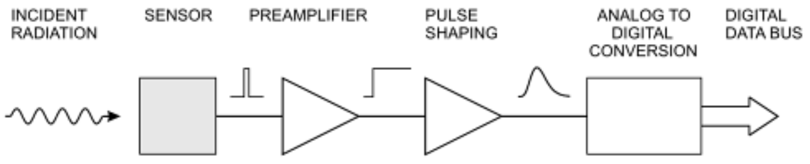


A quick word about noise

- 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”*)

Some properties of Si and Ge as detectors

	Silicon (Si)	Germanuim (Ge)
Z, A	14 , 28.1	32, 72.6
ρ [g/cm^2]	2.33	5.32
E_g (T=300K) [eV]	1.1	0.7
E_g (T=0K) [eV]	1.21	0.785
w (T=300K) [eV]	3.62	-
w (T=77K) [eV]	3.81	2.96
μ_e (T=300K) [cm^2/Vs]	1350	3900
μ_h (T=300K) [cm^2/Vs]	480	1900

only ~1/3 of deposited energy goes into production of e-h pairs

- Low ρ: good for charged particles

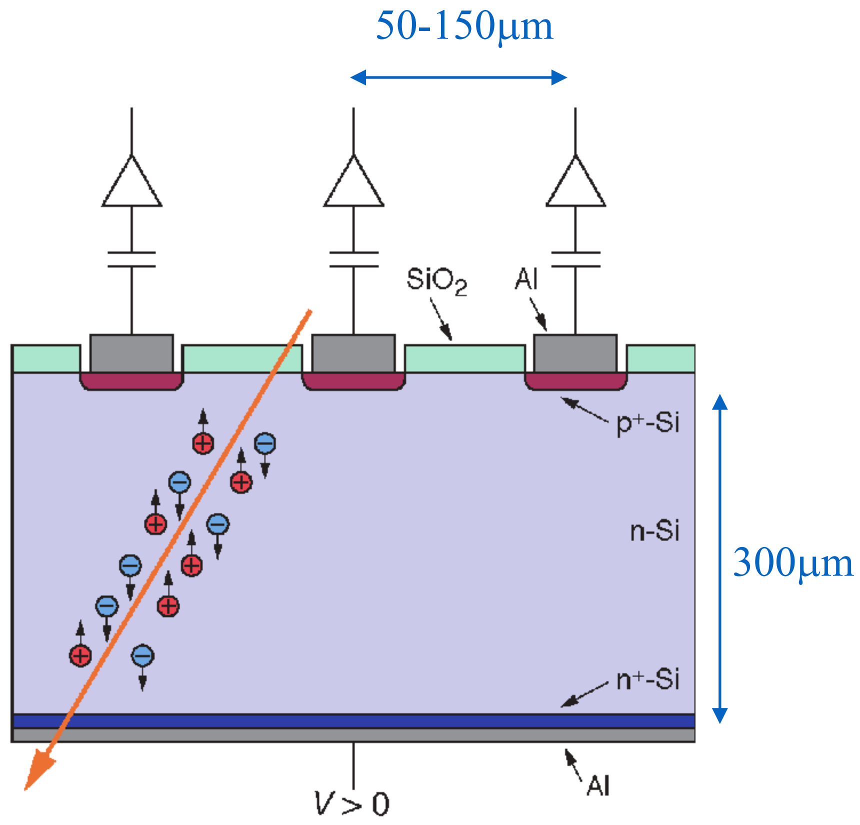
- High Z: good for γ detection (σ for photoelectric effect x60 Si)
- Needs cooling

Position measurement: Microstrip detectors

By segmenting the implant, the position of the traversing particle can be reconstructed in 1 dimension

A typical n-type Si strip detector:

- ★ p^+n junction:
  $N_a \approx 10^{15}$ cm^{-3}, $N_d \approx 1–5 \cdot 10^{12}$ cm^{-3}
- ★ n-type bulk: $\rho > 2$ kΩcm
  → thickness 300 μm
- ★ Operating voltage < 200 V.
- ★ n^+ layer on backplane to improve ohmic contact
- ★ Aluminum metallization



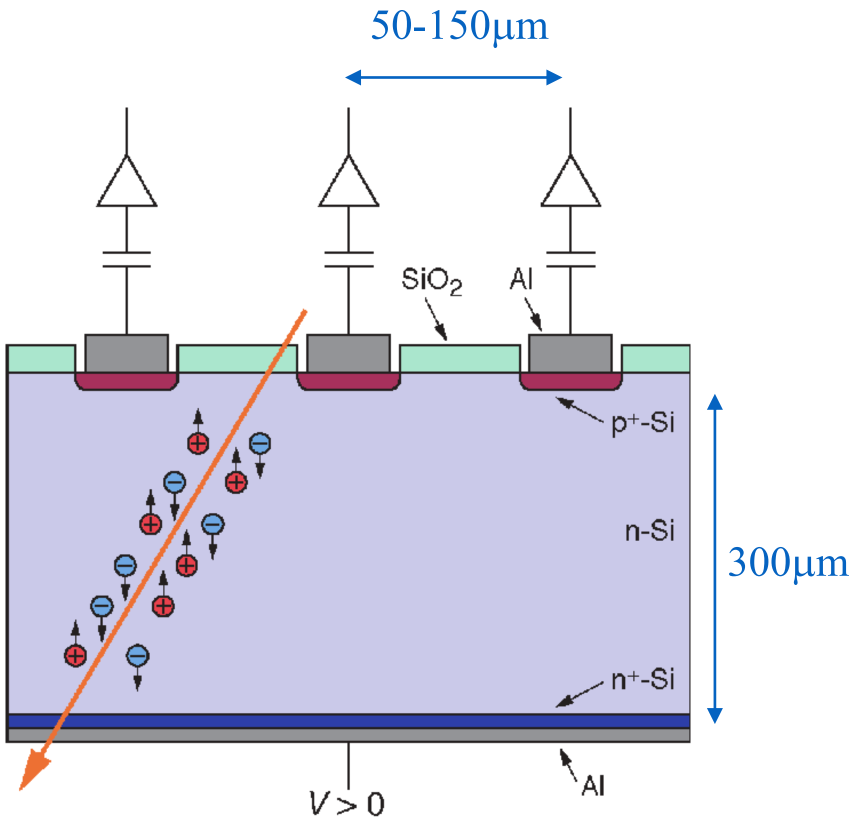
- An amplifier is connected to each strip.
- AC coupling blocks leakage current from the amplifier

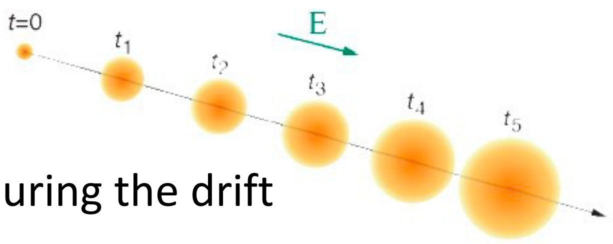
Position measurement: Microstrip detectors

By segmenting the implant, the position of the traversing particle can be reconstructed in 1 dimension

→<u>position resolution</u> = pitch/sqrt(12)

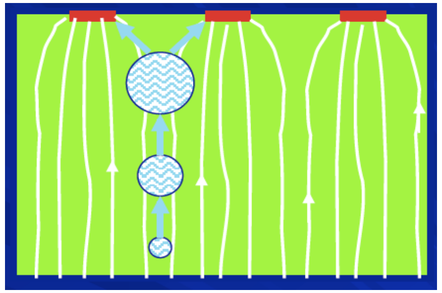
~ O(10-50µm)





Diffusion:

- caused by random motion during the drift
- width of charge cloud $\sigma_D = \sqrt{2Dt}$ with $D = kt\mu/e$
- typical σ_D = 8µm after 300µm drift
- can be used to improve position resolution (sharing of signal between adjacent strips)

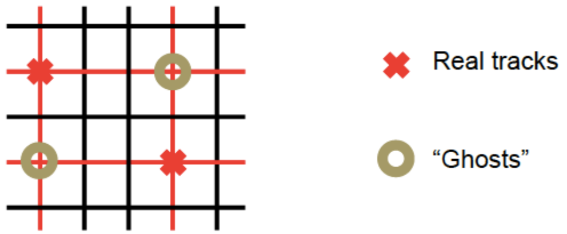


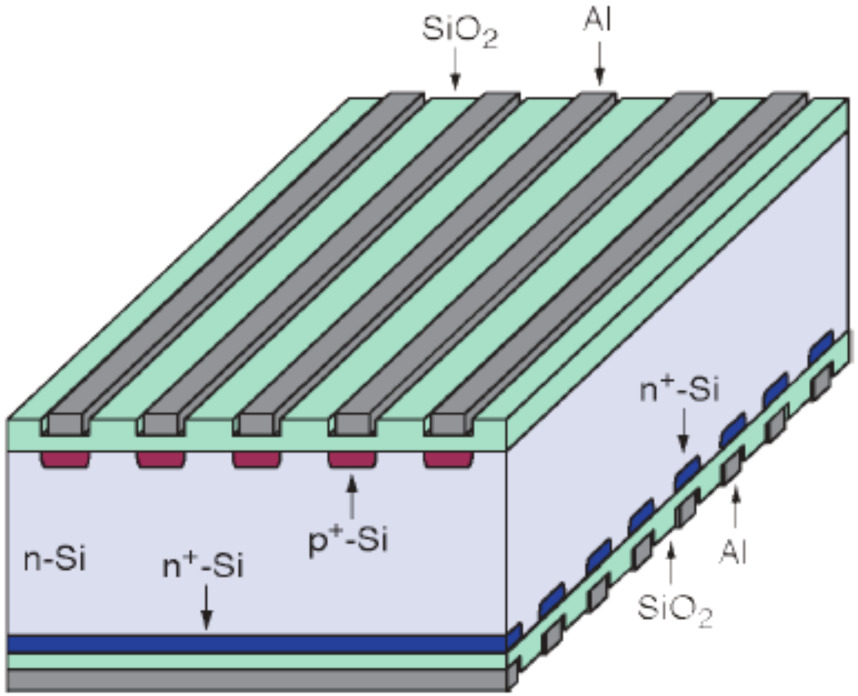
Double-Sided Silicon Detectors

- Reconstruction of two coordinates with one detector layer

+ Advantage: minimize multiple scattering

- Disadvantage: ”ghost hits” at high particle multiplicity





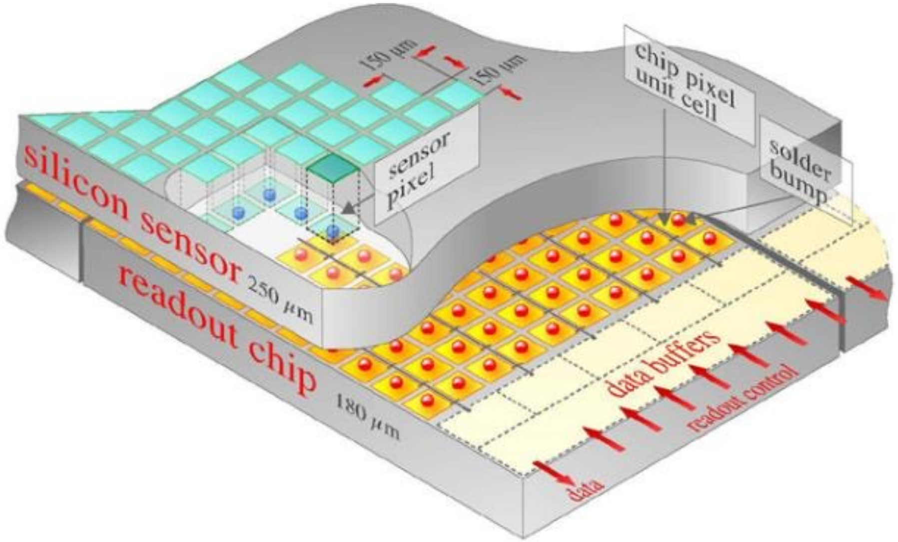
Scheme of a double sided strip detector (biasing structures not shown)

The solution: Pixel detectors…

Pixel Detectors

- Two-dimensional arrays of p-n diodes organised in a matrix
- Each p-n junction is readout by a dedicated readout integrated circuit
- Sensor and readout electronics are physically separated and linked by a bump bonding

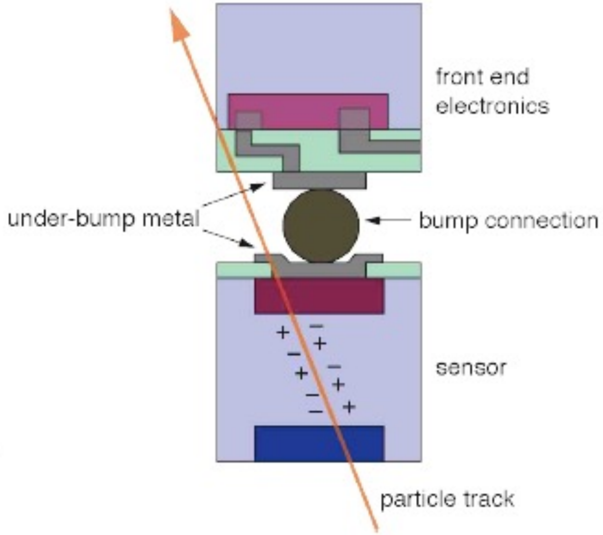
→ Hybrid Pixel Detectors (HPDs)



+ Unambiguous 2D position measurement, pitch ~50µm

+ Smaller leakage currents than DSSD

- Large number of readout channels: complex solutions, large power consumption

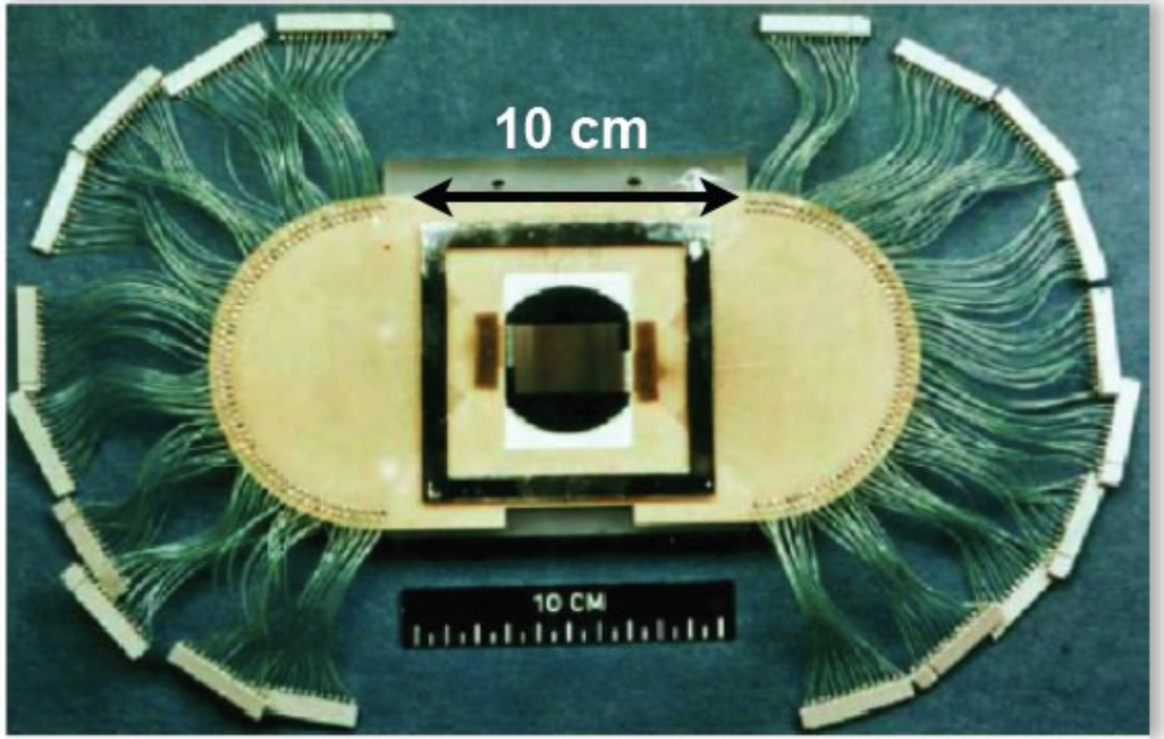


Examples

NA11 at CERN, 1983

First use of a position-sensitive Si detector in HEP

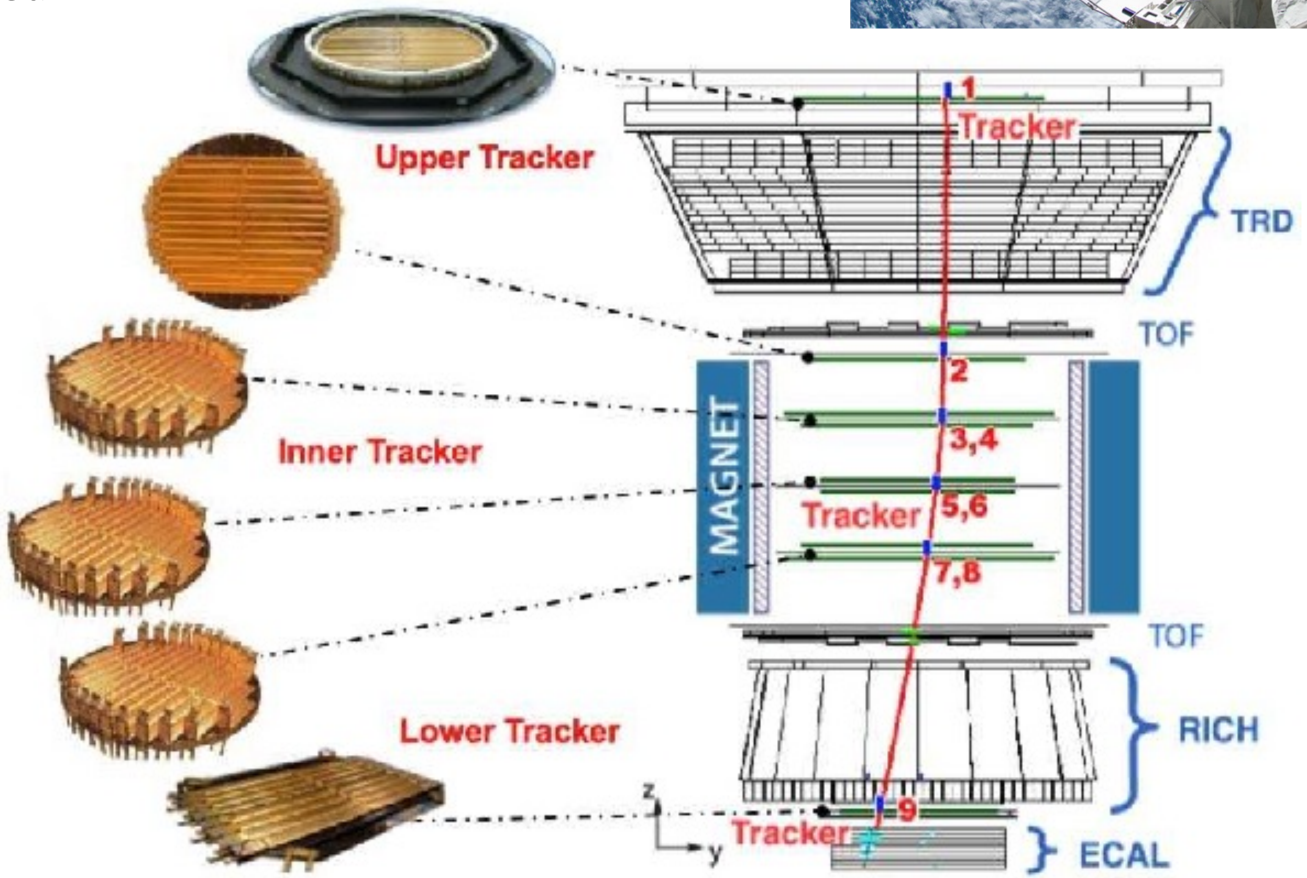
- To measure lifetimes of charmed mesons
- Surface: 24 cm^2 (2” wafer) 1200 strip, 20 µm pitch. Every 3rd/6th strip connected. Precision 4,5 µm !
- 8 Si detectors (2 in front, 6 behind the Target)



Examples

AMS-02

Large-acceptance spectrometer on the ISS, since 2011.
To perform precise measurements of charged cosmic rays fluxes in a wide energy range



Silicon Tracker Detector (STD):
9 layers of double-sided Si sensors (2300)

- Total instrumented surface area: 6.45 m^2 with 196 k readout channels
- Position resolution: 8.5 µm (30 µm) in the bending (non-bending) plane
- particle rigidity measurement (p/Z) of 1.5% at 10 GeV and a maximum detectable rigidity above 1 TeV for protons
- Charge separation of nuclei up to Z=26 (by dE/dx measurement)

Examples

The 4 main LHC experiments (ATLAS, CMS, ALICE, LHCb) have Si trackers

CMS

the world largest silicon tracker

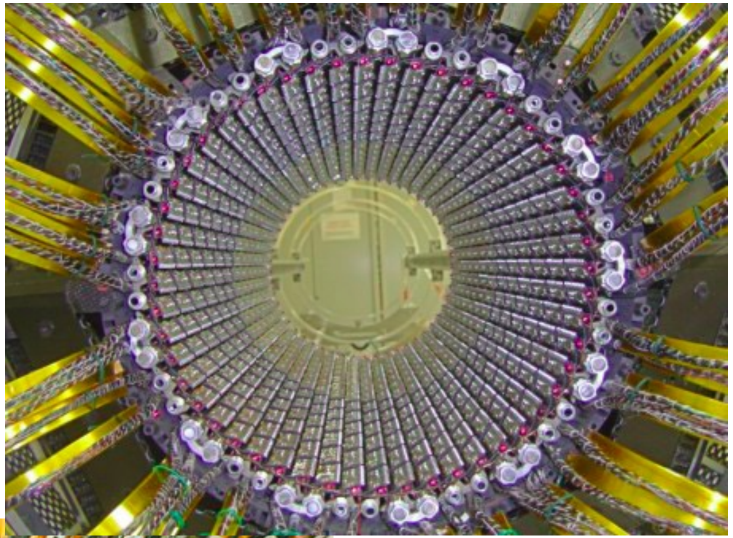
~1m^2 of pixel sensors,
60x106 channels,
hit resolution 10x17 μm^2

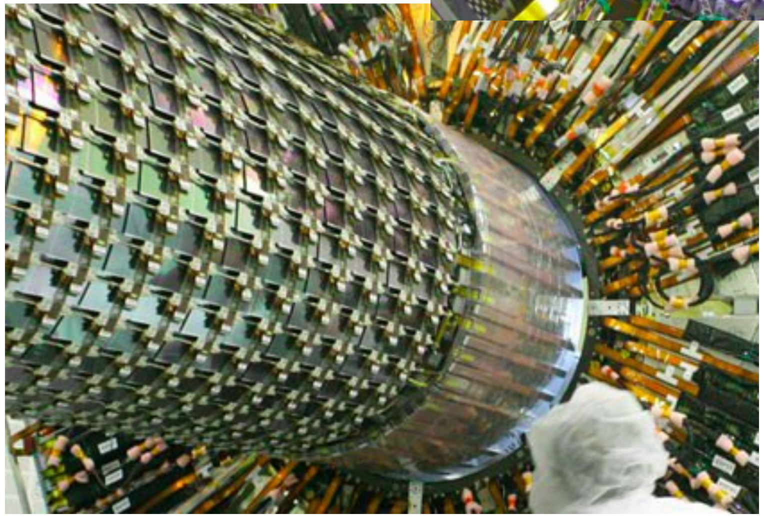
200 m^2 of strip sensors (single sided)
11 x 106 readout channels, hit resolution 40-60 µm

ATLAS

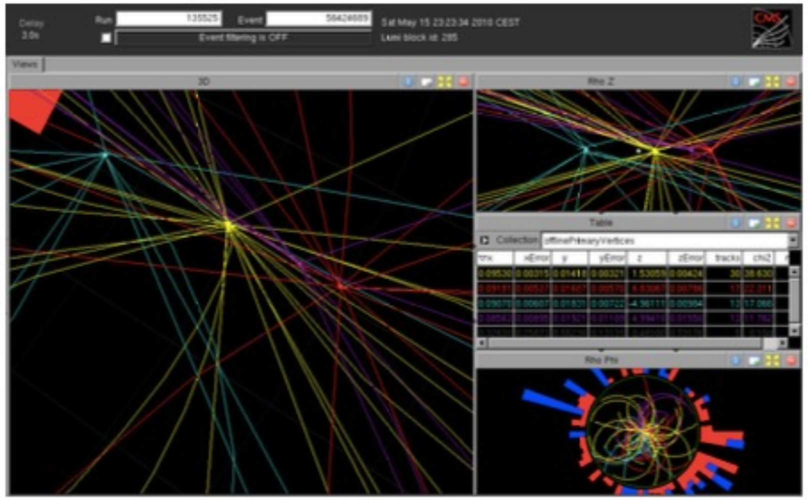
Pixels: 1744 modules,
80 x 106 channels.
Pixel size 50 x 400μm^2 .
Resolution 14 x 115μm^2

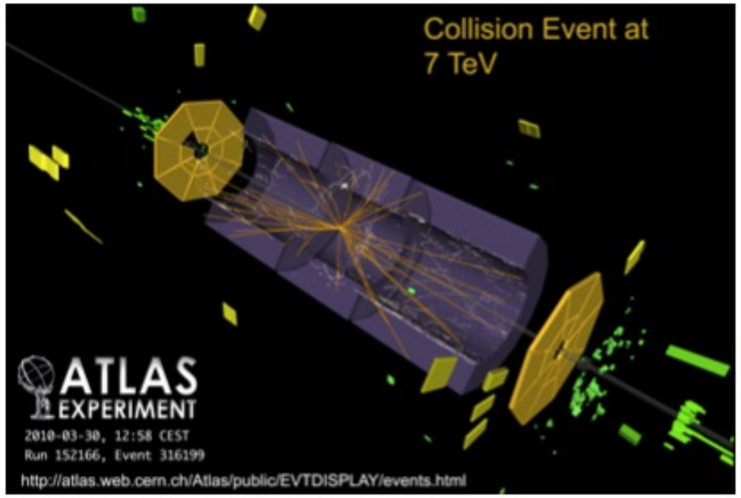
Strips: 61 m^2 of silicon ,
4088 modules,
6x106 channels
Readout pitch 80 µm, hit resolution 17 µm

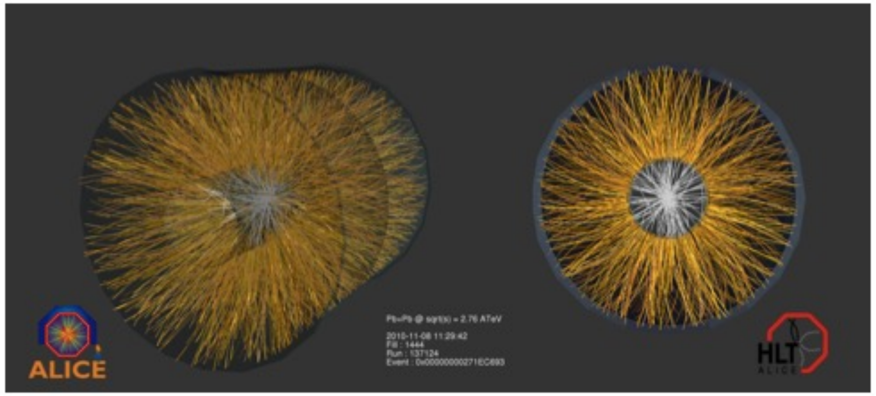




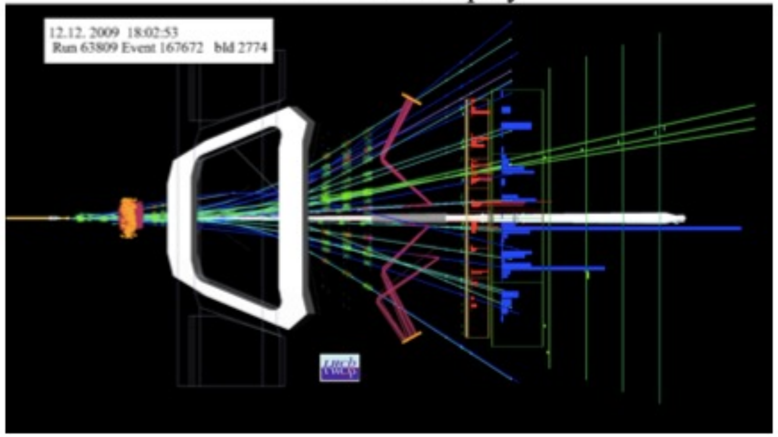
Examples







LHCb Event Display



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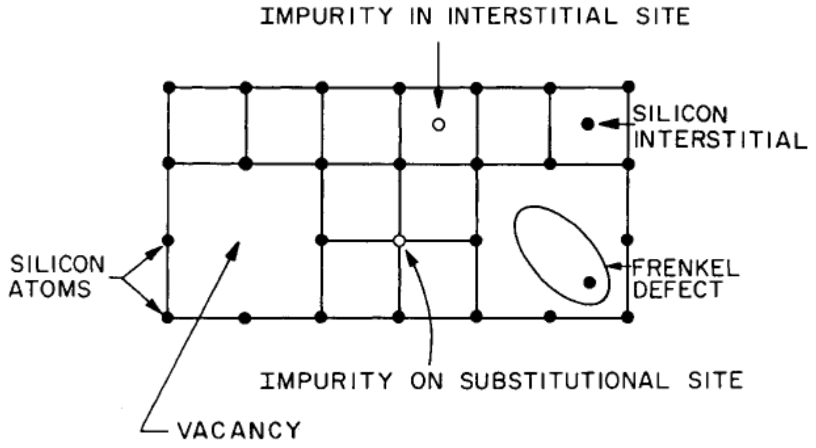
Radiation damage

- Inelastic collisions of impinging particles on Si cause displacement of a Si atom from its lattice site → point defects
- several defects grouped together can form a cluster the probability depends on the particle type and energy. The amount increases with particle fluence.



→ Macroscopic effects ("ageing"):

- increase of leakage current
- change in operation voltage
- reduction of signal amplitude

- → R&D for radiation-hard sensors

Challenges for the future

- High Luminosity LHC
  – Radiation tolerance (~$10^{16}/cm^2$ for pixels, $10^{15}/cm^2$ for strips; ~20 x current)
  – High hit rate (up to 1.5 GHz/cm^2 in pixels)
  – High track density (200 or more spectator events)
- e^+e^- colliders
  – Extremely low material (minimize multiple scattering)
  – Requires very low average power
  – Extremely good position resolution (ILC goal is ~3 microns)

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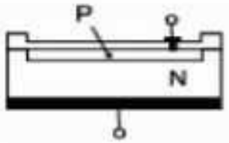
Some other Si detectors

Hamamatsu photodiodes can be classified by manufacturing method and construction into five types of silicon photodiodes and two types each of GaAsP and GaP photodiodes.

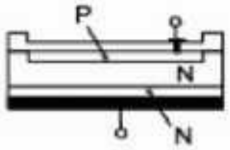
Planar Diffusion Type

An SiO2 coating is applied to the P-N junction surface, yielding a photodiode with a low level dark current.



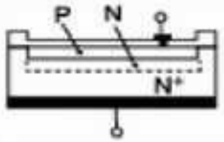
Low-Capacitance Planar Diffusion Type

A high-speed version of the planar diffusion type photodiode. This type makes use of a highly pure, high-resistance N-type material to enlarge the depletion layer and thereby decrease the junction capacitance, thus lowering the response time to 1/10 the normal value. The P layer is made extra thin for high ultraviolet response.



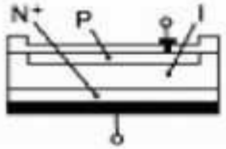
PNN+ Type

A low-resistance N+ material layer is made thick to bring the NN+ boundary close to the depletion layer. This somewhat lowers the sensitivity to infrared radiation, making this type of device useful for measurements of short wavelengths.



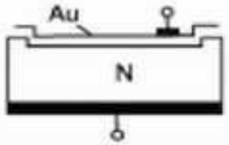
PIN Type

An improved version of the low-capacitance planar diffusion device, this type makes use of an extra high-resistance I layer between the P- and N-layers to improve response time. This type of device exhibits even further improved response time when used with reversed bias and so is designed with high resistance to breakdown and low leakage for such applications.



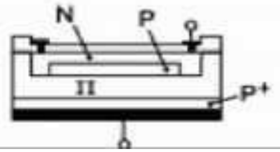
Schottky Type

A thin gold coating is sputtered onto the N material layer to form a Schottky Effect P-N junction. Since the distance from the outer surface to the junction is small, ultraviolet sensitivity is high.



Avalanche Type

If a reverse bias is applied to a P-N junction and a high-field formed within the depletion layer, photon carriers will be accelerated by this field. They will collide with atoms in the field and secondary carriers are produced, this process occurring repeatedly. This is known as the avalanche effect and, since it results in the signal being amplified, this type of device is ideal for detecting extremely low level light



Photodetectors: Avalanche PhotoDiodes (APD)

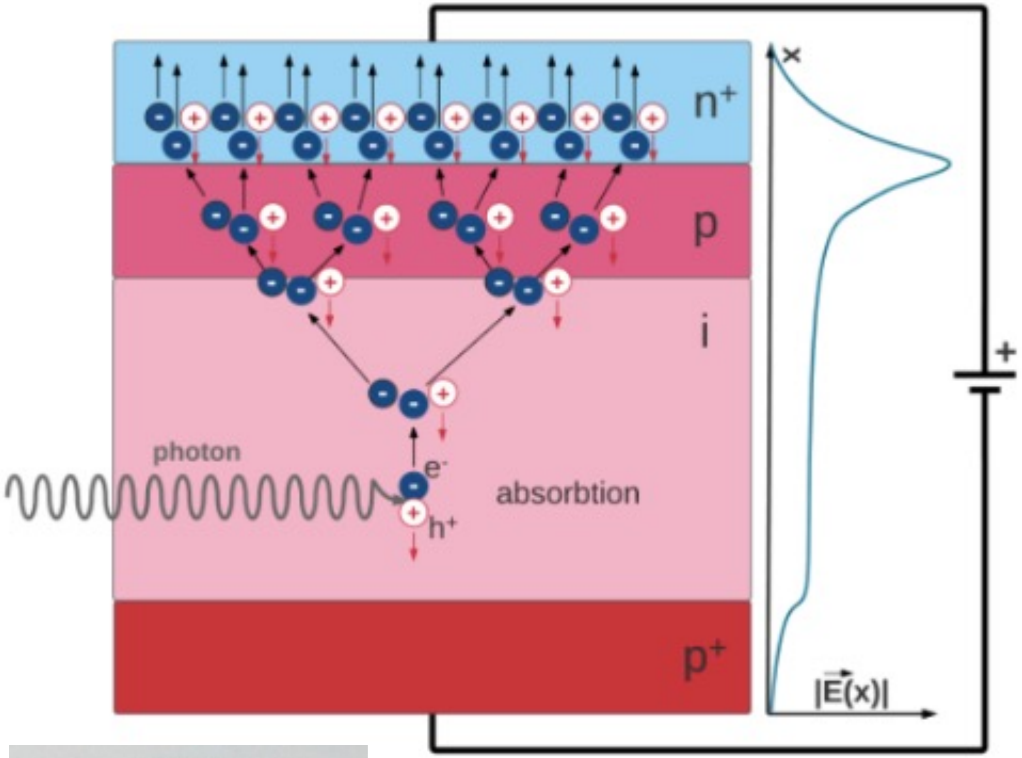
Conversion of photons into a charge current :

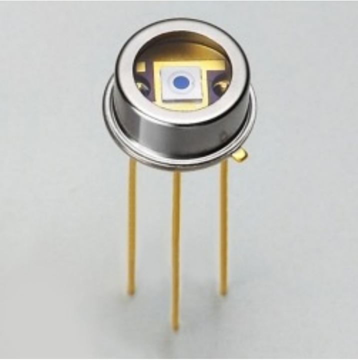
e-h pair creation + avalanche multiplication

+ Gain O(100)

+ Fast response times
(formation of avalanche <ns)

- Large operation voltage (E > 10^5 V/cm)
- Poor energy resolution (fluctuations in the avalanche), extremely sensitive to voltage changes

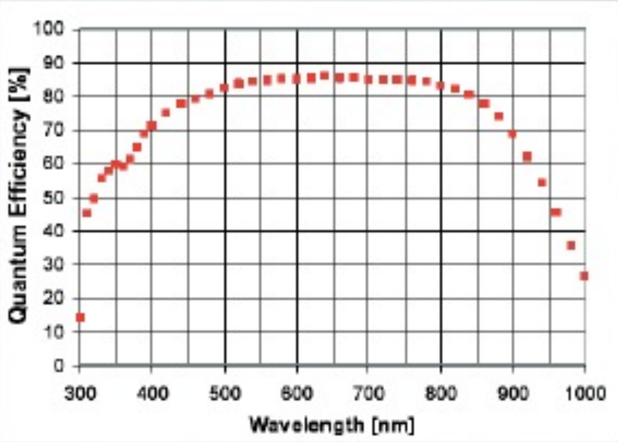


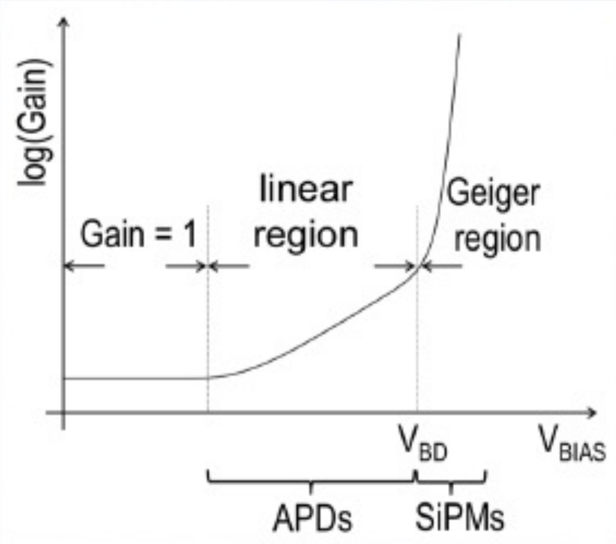


Hamamatsu Si APD S8890-10

Photodetectors: Avalanche PhotoDiodes (APD)

- QE ~ 80% at 500-800 nm → the scintillator must be chosen accordingly
- Log(gain) linear with the biais voltage between 150 et 350 V
  - Exponential increase
- Above, Geiger region

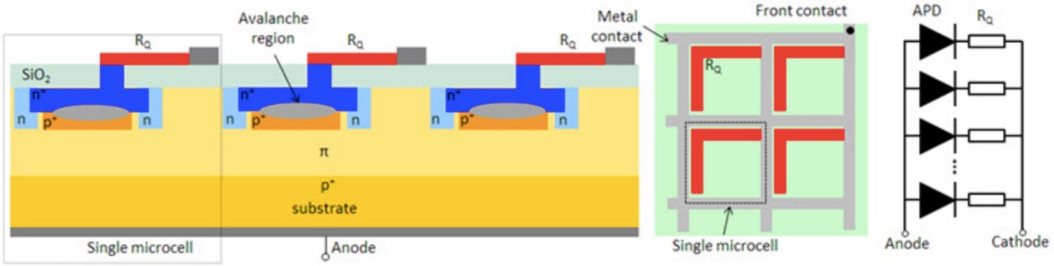




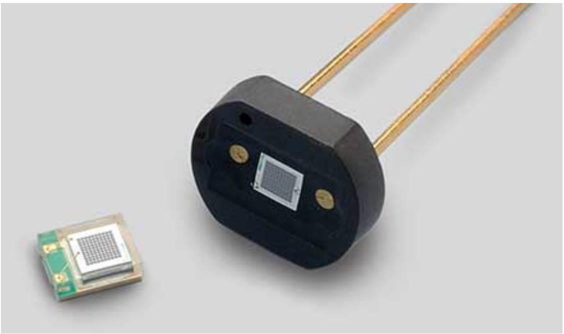
MU5PYN03 146 J. Bolmont

Photodetectors: Silicon PhotoMultipliers (SiPM)

Matrices of 100s-1000s APDs operated in Geiger mode



- The signal in each cell is not proportional to energy: on/off
- Count number of hit cells → measure the photon flux



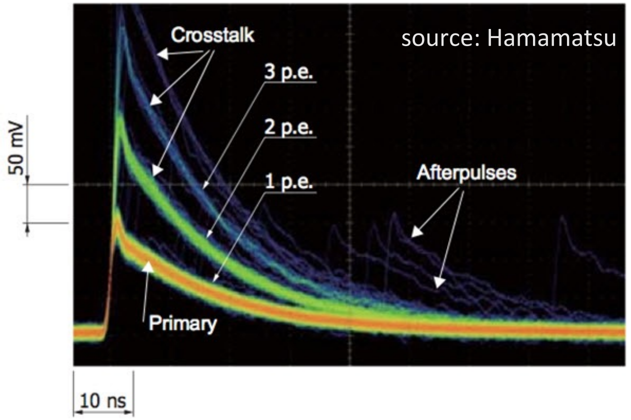
+ Gain ~10^5-10^7 (cfr PMTs)

+ Good charge resolution

+ No need for HV

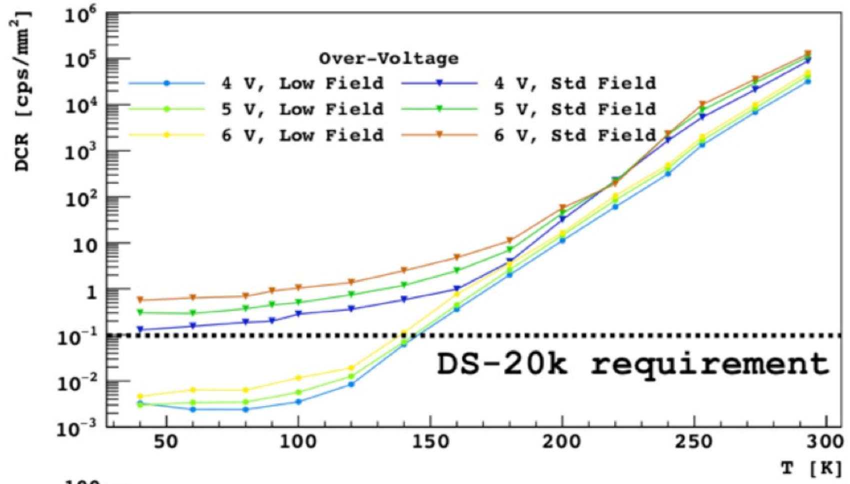
+ Not sensitive to magnetic field

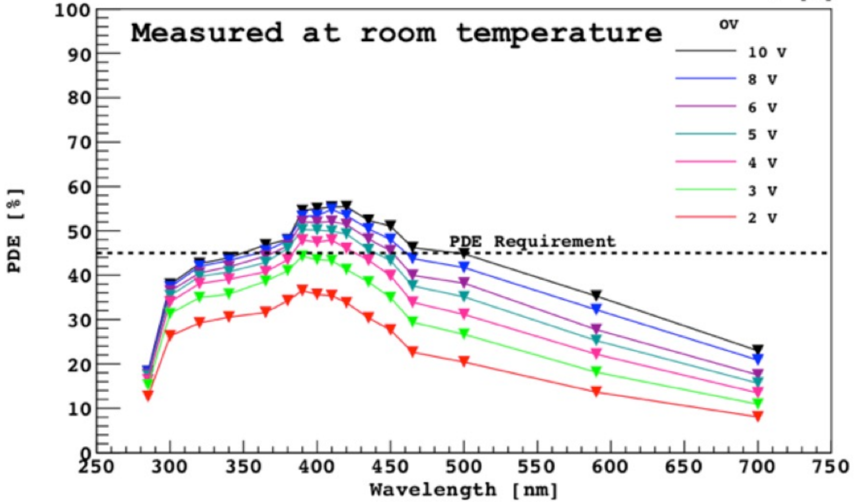
- Dark noise, crosstalk, afterpulses, …



SiPM at cryogenic temperatures

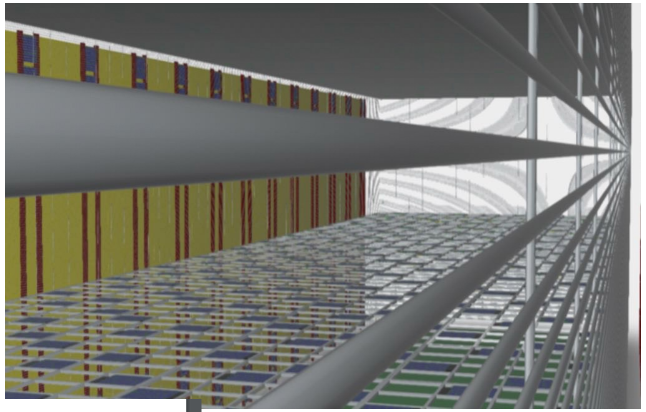
Dark count rate decreases with temperature

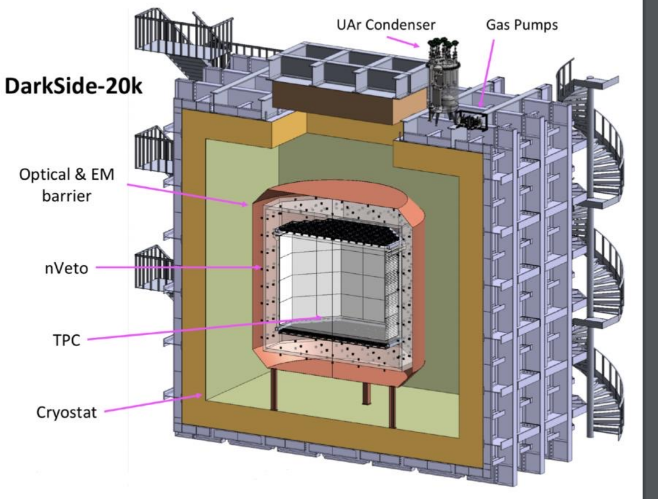




Interesting for applications in future large-scale TPCs based on noble liquids (Ar, Xe)

DUNE
(Deep Underground Neutrino Experiment)





DarkSide-20k
(direct search for dark matter)

→ see Lecture 9

Exercises

Exercise 1

Compute the solution to Poisson’s equation to obtain the depth of the depletion region (slide 11).

Exercise 2

Consider two Si diode detectors, A and B, with the same level of the impurity concentration.

The cross- sectional area of detector A is 1 cm^2 while that of detector B is 4 cm^2.

The detectors are biased to 200 V (A) and 100 V (B) and both are in partial depletion.

(a) Which detector has a larger depletion depth ? By how large a factor ?

(b) Which detector has a higher capacitance ?

(c) Which do you expect to have a better energy resolution ? Why ?

Semiconductor detectors: key notions

- Crystals with band-gap ~ 1 eV + doping p or n
- p-n junction: depletion region + bias voltage to increase depth
  - the depleted region is the useful volume for detection
  - $d \sim (V/N_{imp})^{-1/2}$
- Energy resolution $R = 2.35\sqrt{Fw/E}$ with Fano Factor F ~0.12
  - Example: σ_E/E ~ 0.06% for 1 MeV photons in Ge
- Position measurement via readout segmentation (microsrtip, pixels)
  - resolution 10-50 µm
- Drawbacks: leakage current, noise, ageing
- Light detectors: APD, SiPM