



# Detector Physics 2023/2024, Lecture 7

## Semiconductor detectors

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# Additional references

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- 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](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](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

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

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

## FABRICATION OF LOW NOISE SILICON RADIATION DETECTORS BY THE PLANAR PROCESS

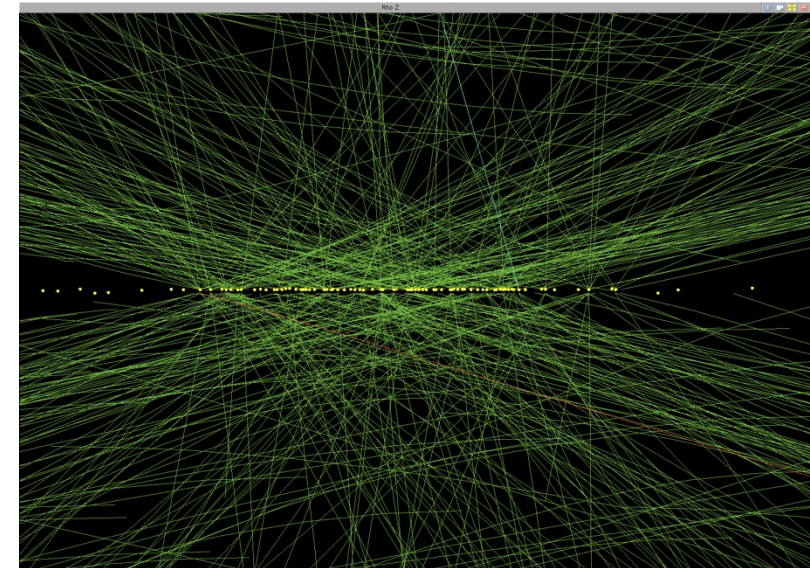
J KEMMER

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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  $1 \text{ nA cm}^{-2}/100 \mu\text{m}$  at room temperature. Best values for the energy resolution were 10.0 keV for the 5.486 MeV alphas of  $^{241}\text{Am}$  at 22°C using  $5 \times 5 \text{ mm}^2$  detector chips

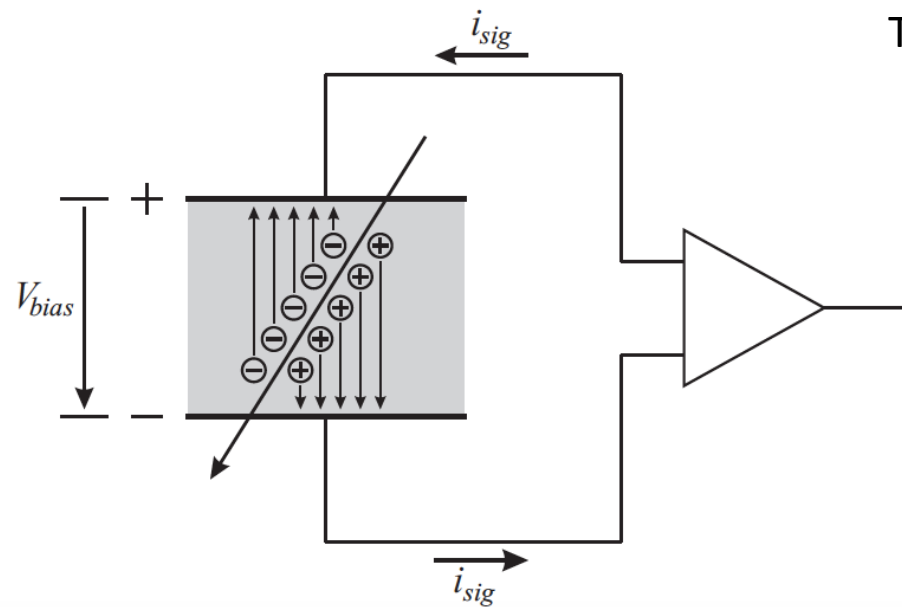


Semiconductor detectors provide

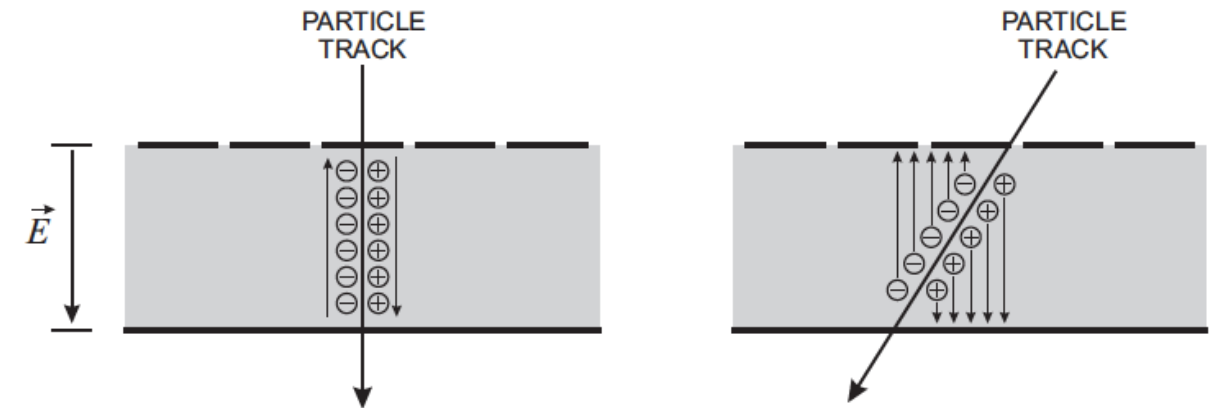
- high segmentation
- high density => small size

# Semiconductor sensors : principle

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



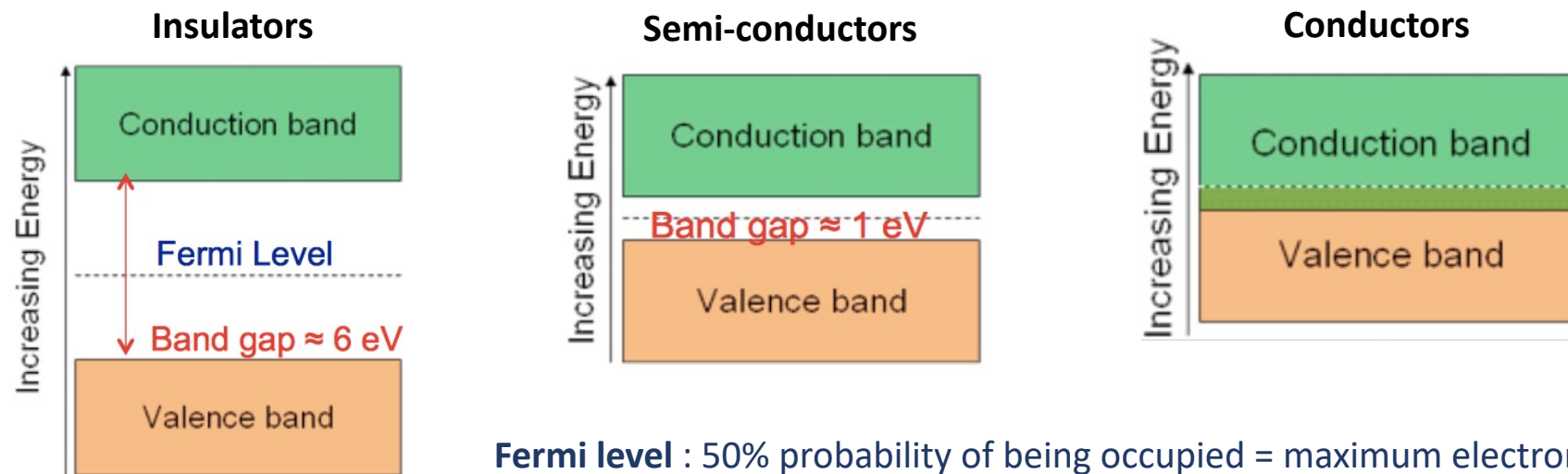
Fast time response, (<20 ns)



Segmenting the sensor electrodes provides position information

# Semiconductor properties

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



- In semi-conductors,  $E_{\text{gap}} \sim E_{\text{thermal}}$  : 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

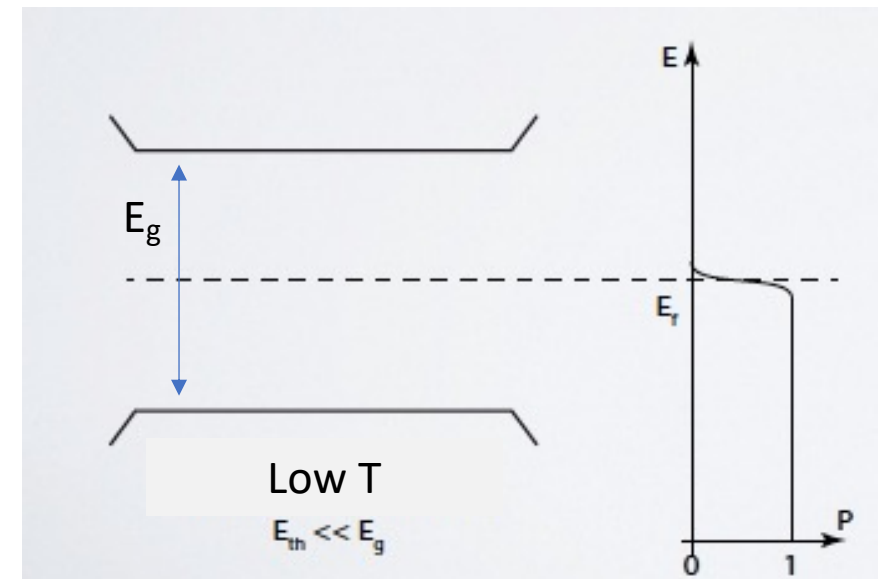
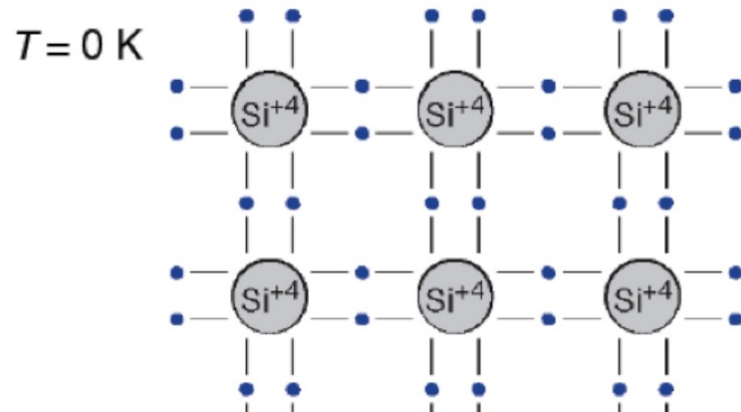
- Probability for an electron to move from the valence to the conduction band

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

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

Example : Silicon (tetravalent : 4 neighbours)

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



# Semiconductor properties

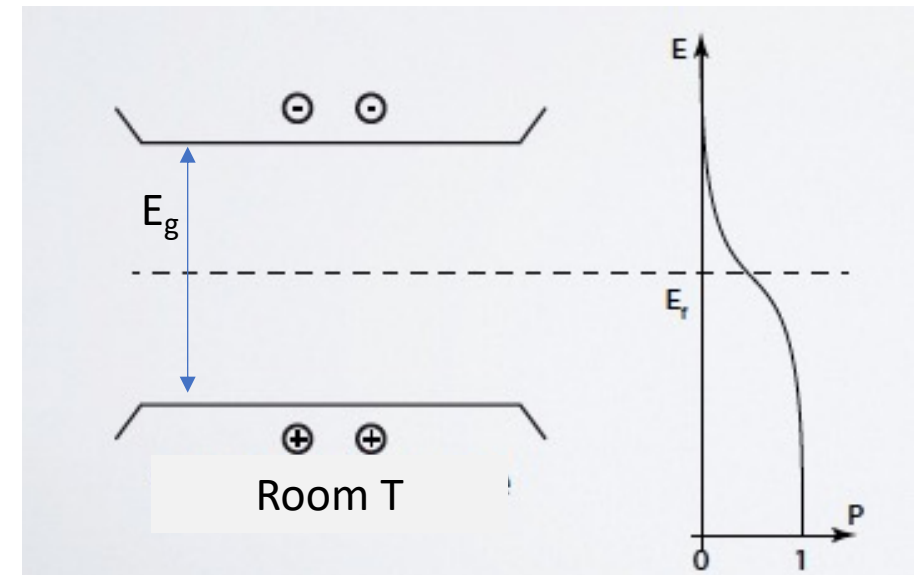
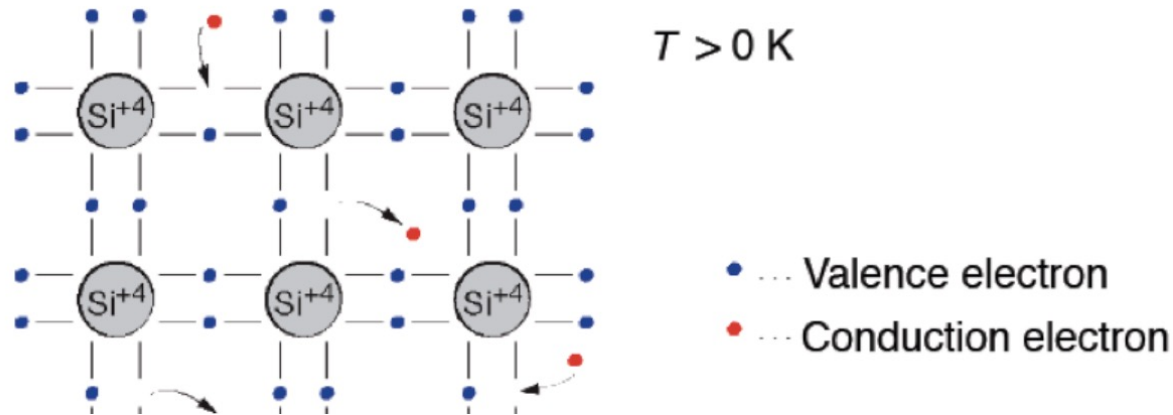
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T : absolute temperature  
 c : proportionality constant characteristic of material  
 $E_g$  : band gap energy  
 $k_B$  : Boltzmann constant

Example : Silicon (tetravalent : 4 neighbours)

- 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 : intrinsic carriers

$$n_e = n_h = n_i$$

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

- Compare with the signal from a MIP :

$$dE/dx = 3.87 \text{ MeV/cm}$$

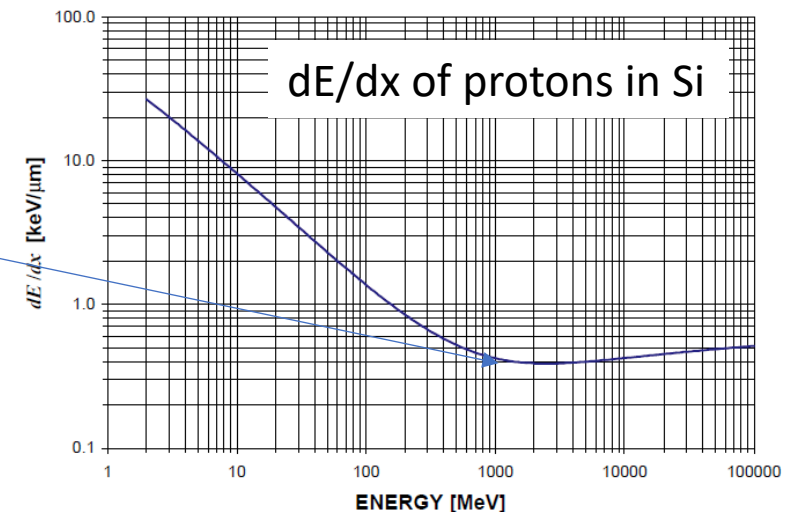
assume detector thickness  $\Delta = 300 \text{ }\mu\text{m}$ , area  $A = 1 \text{ cm}^2$

mean energy to form a e-h pair in Si :  $w = 3.63 \text{ eV}$

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

$$\text{e-h pairs from thermal noise} = n_i A \Delta = 4.35 \cdot 10^8 \gg \text{signal}$$

→ need to deplete the free charge carriers



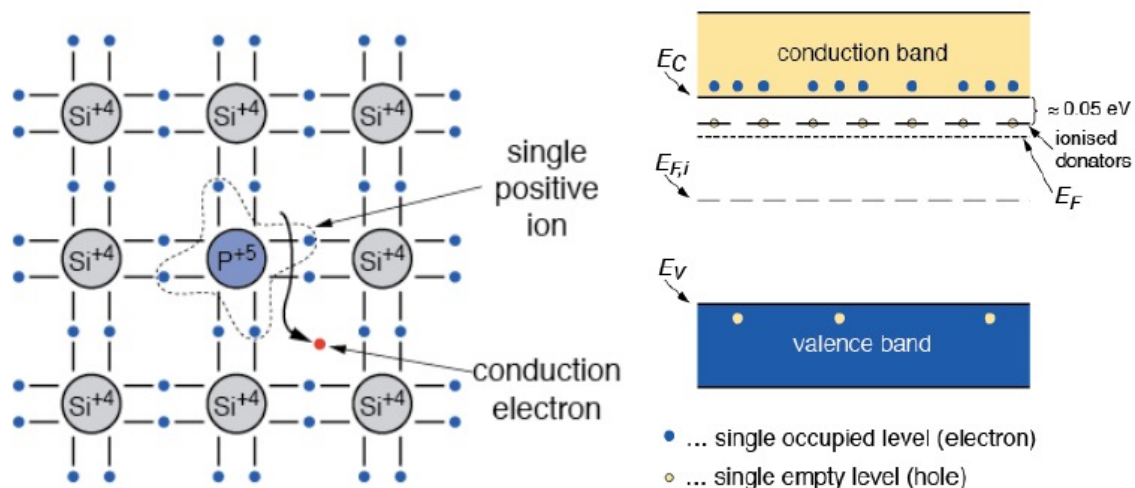


# Doped semiconductors

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

## Donor impurities (n-type doping) : As, P, Sb

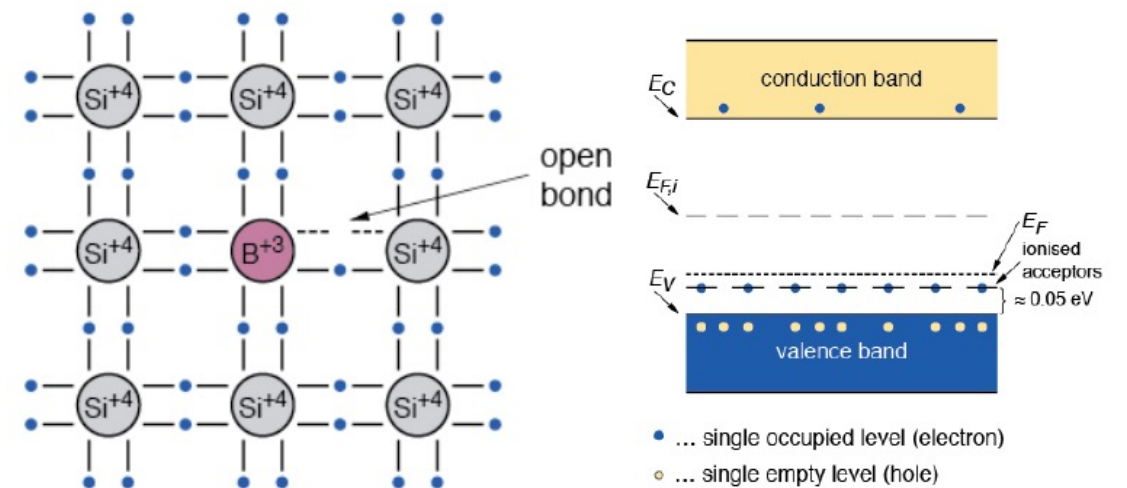
5 valence electrons



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

## Acceptor impurities (p-type doping) : Ga, B, In

3 valence electrons

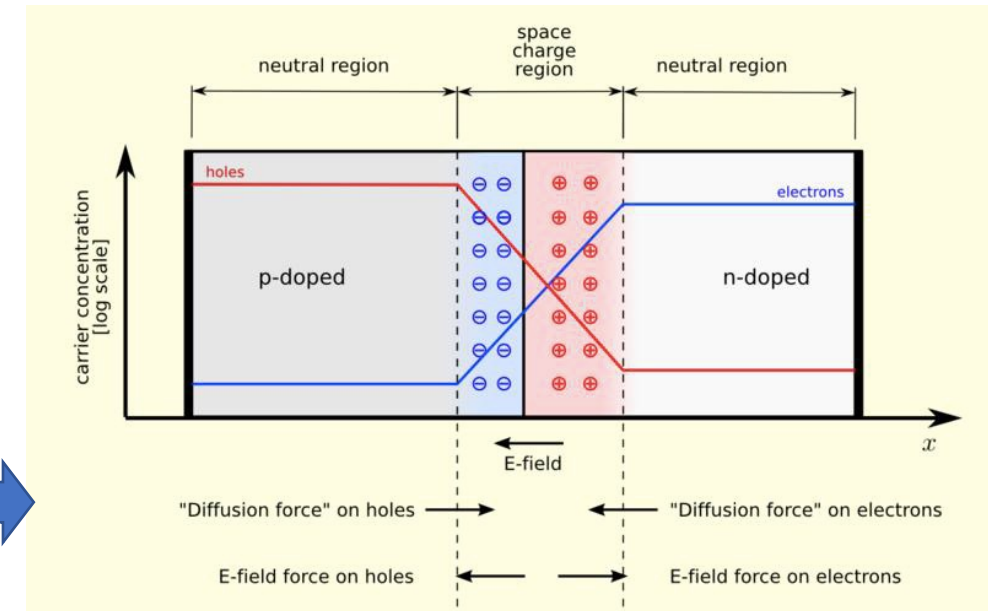
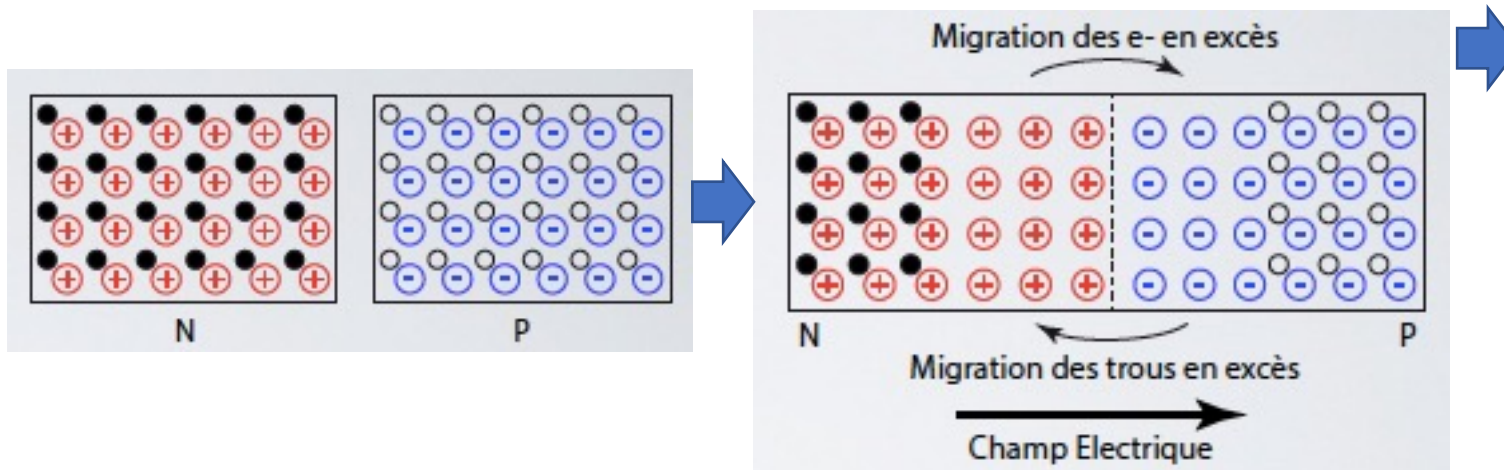


the acceptor level is filled with e- from the valence band because of thermal energy

# 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  $\rho(x)$  on both sides

charge conservation  $N_A x_p = N_D x_n$

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

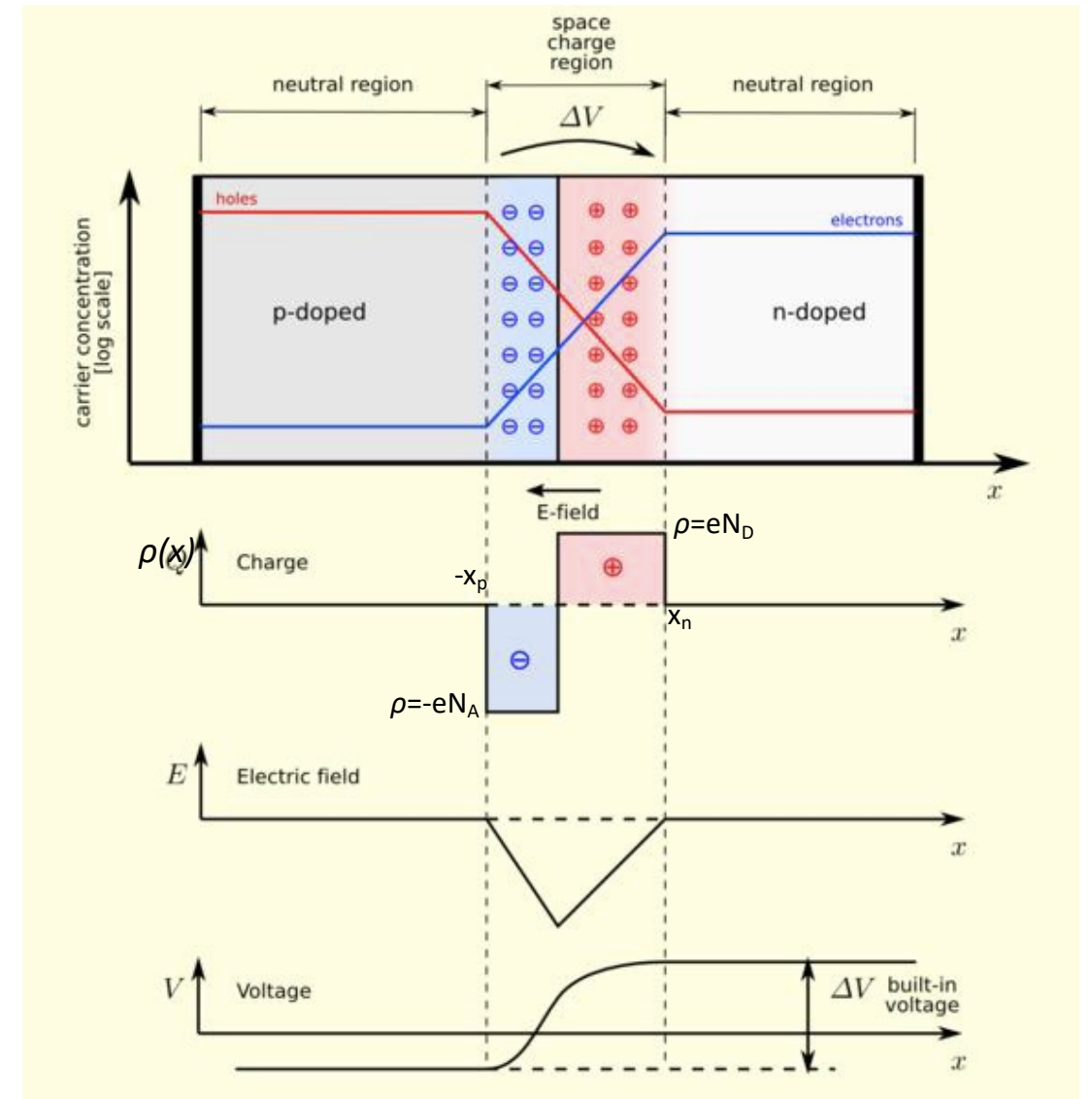
using boundary conditions  $E(-x_p) = E(x_n) = 0$

(Exercise1)

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

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

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



# p-n junction: depletion depth

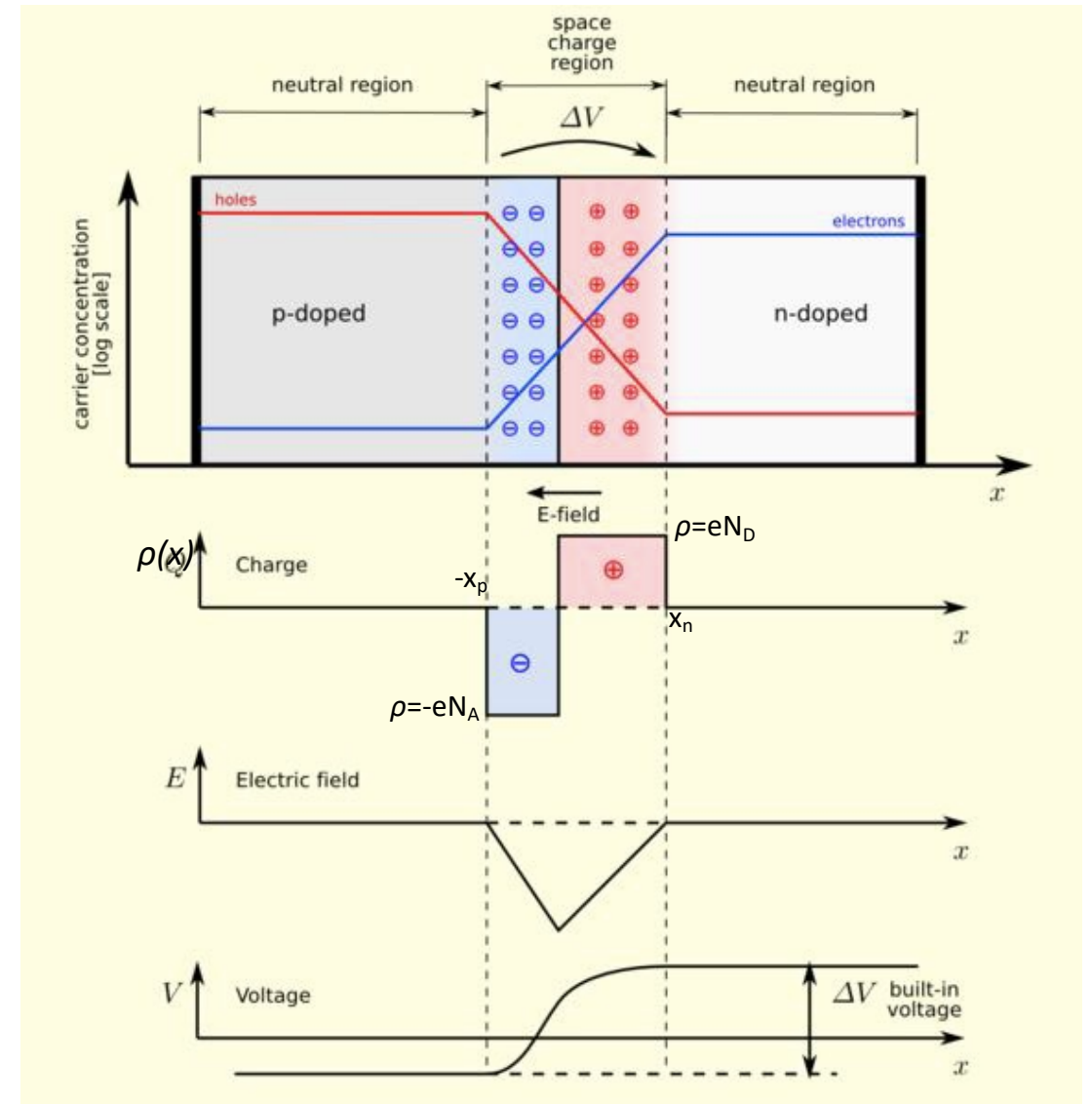
- Typical values in Si P-N junctions :
  - $N_A = 10^{15} \text{ cm}^{-3}$  in p+ region ,  $N_D = 10^{12} \text{ cm}^{-3}$  in n bulk  $\ll N_A$
  - $\rightarrow x_p = 0.02 \text{ } \mu\text{m}$  and  $x_n = 23 \text{ } \mu\text{m}$

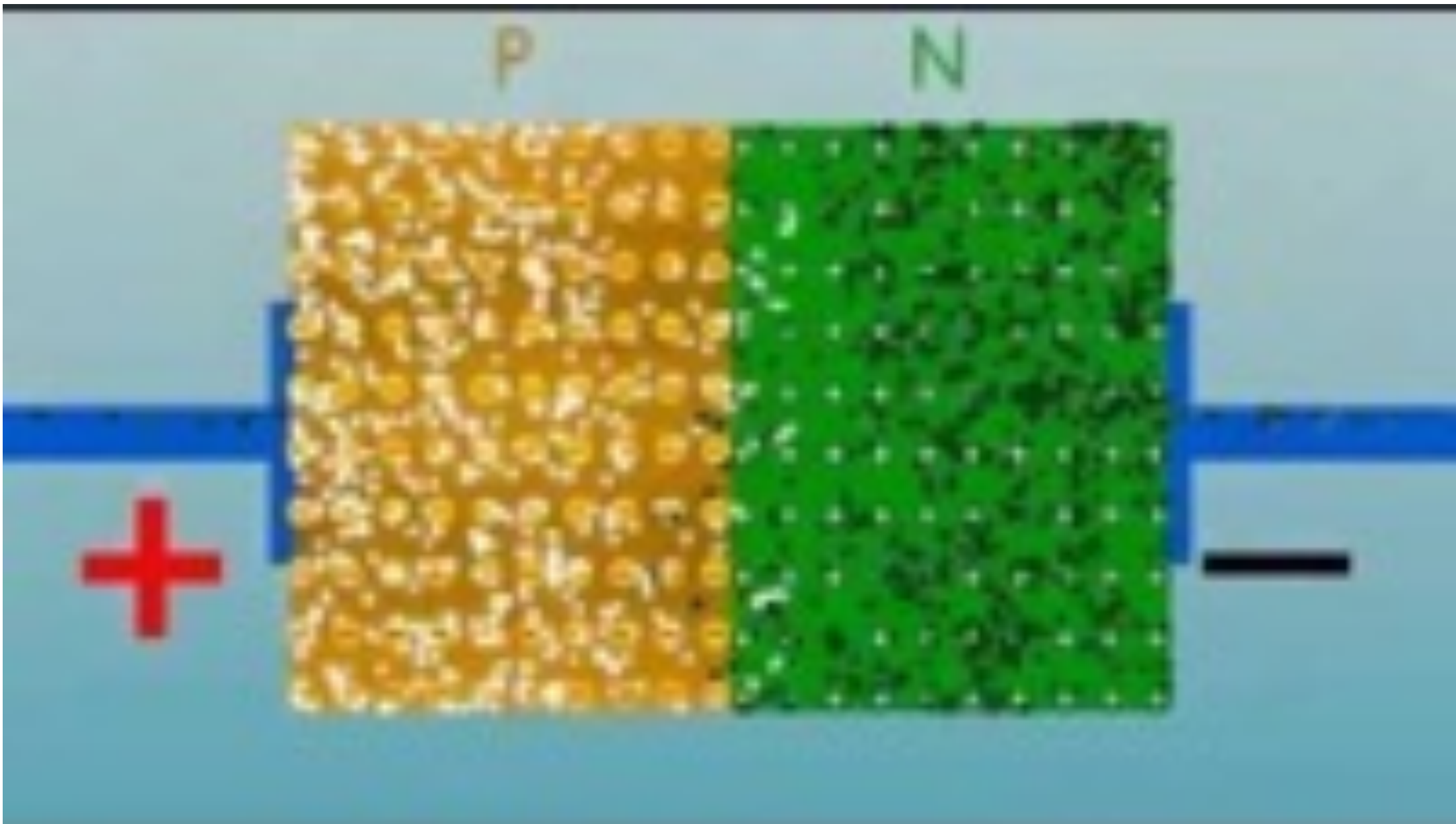
$$d = x_p + x_n \approx x_n \approx \left( \frac{2\epsilon \Delta V}{e N_D} \right)^{1/2}$$

can be expressed as a function of mobility  $\mu$

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

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





<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: forward and reverse bias

Applying a forward bias voltage  $V$ ,  
e- and holes are refilled to the depletion  
zone.

The depletion zone becomes narrower

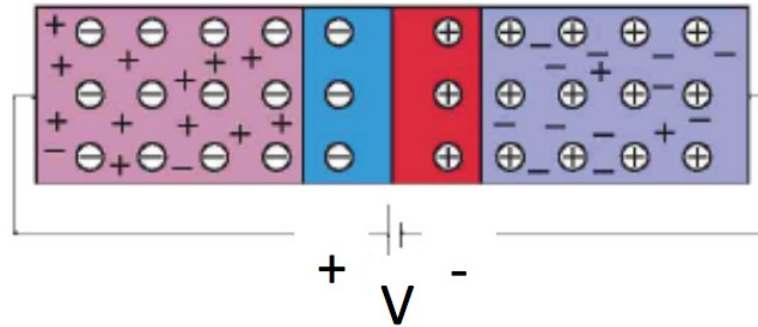
That's not what we want!

Applying a reverse bias voltage  $V$ ,  
e- and holes are pulled out of the  
depletion zone.

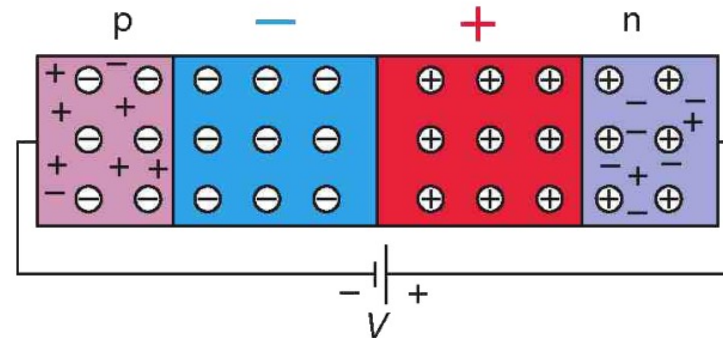
The depletion zone becomes larger.

That's the way we operate our semiconductor detectors!

p-n junction in forward bias



p-n junction in reverse bias



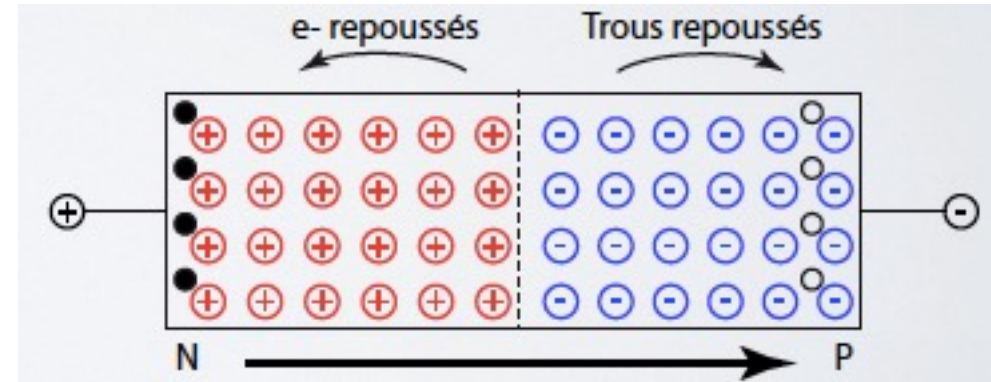
# From the p-n junction to the detector

- Revers bias junction

$\Delta V \rightarrow \Delta V + V_B$  in the formula

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

example :  $d=1\text{mm}$   $V_B=300\text{V}$



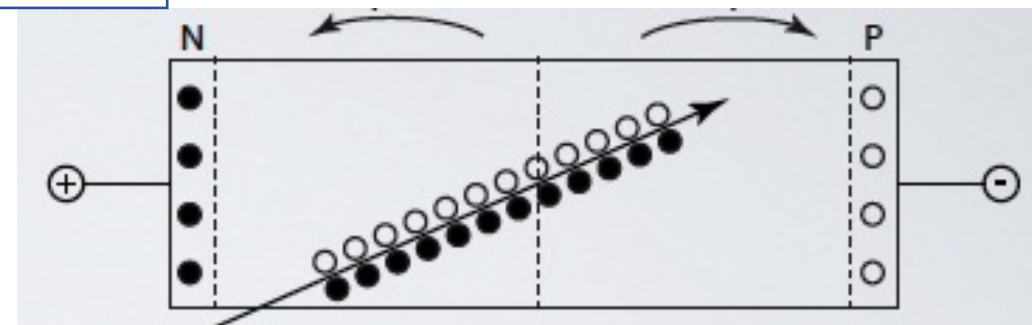
The voltage  $V$  needed to fully deplete a device of thickness  $d$  is called the depletion voltage  $V_d$

- The depleted region is the useful volume for detection

ionizing particles produce e<sup>-</sup>-hole pairs

e<sup>-</sup> (holes) drift to the n (p) side → current pulses

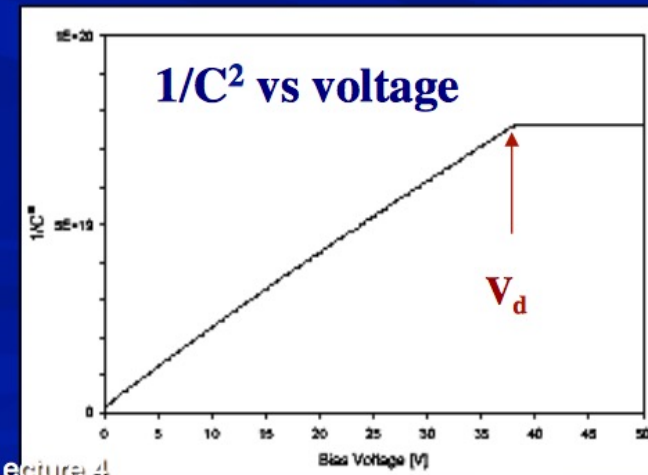
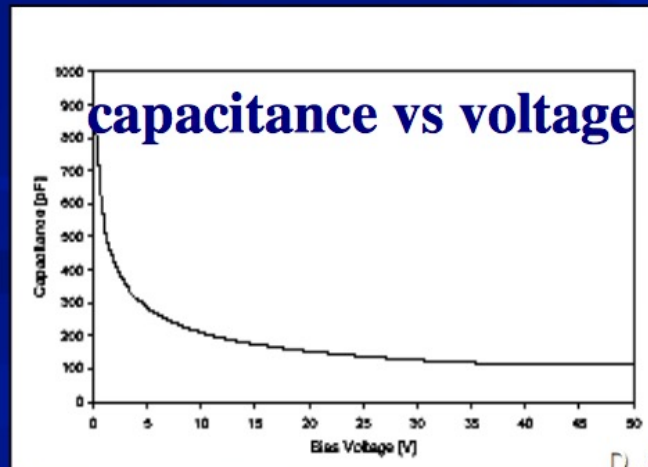
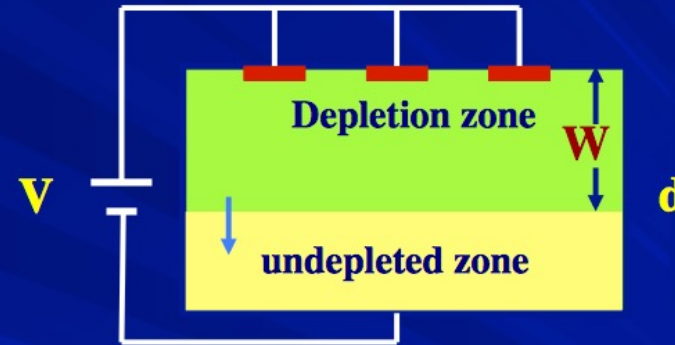
proportional to the energy deposit



# Depletion region and capacitance

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

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



D. Bortoletto Lecture 4

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# 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  $\mu$  depends on T and E. (Attention! Here E is the electric field)

Charge collections times  $O(10\text{ns}) \rightarrow$  fast!

- Linearity

the depleted region has a capacitance  $C = \epsilon A/d$

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

$\rightarrow$  linear with the deposited energy

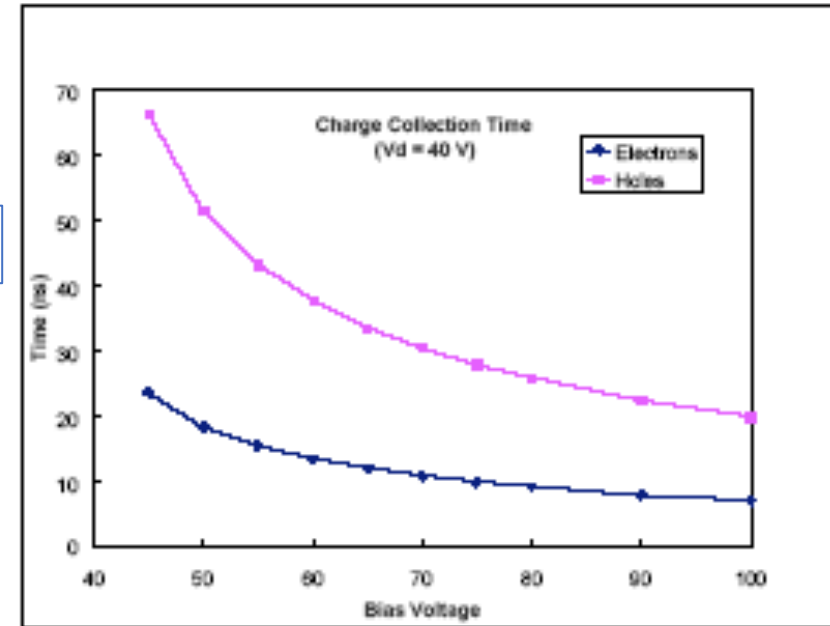
$A, d$  : detector area and thickness  
 $n$  : collection efficiency  
 $E$  : deposited energy  
 $w$  : average energy for e-h pair creation

- Energy resolution

the intrinsic energy resolution depends on the number of carriers  $E/w$  and the Fano Factor  $F \sim 0.12$

$$R = 2.35 \sqrt{\frac{Fw}{E}} \quad (\text{Attention! Here E is the deposited energy})$$

(+ 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**

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

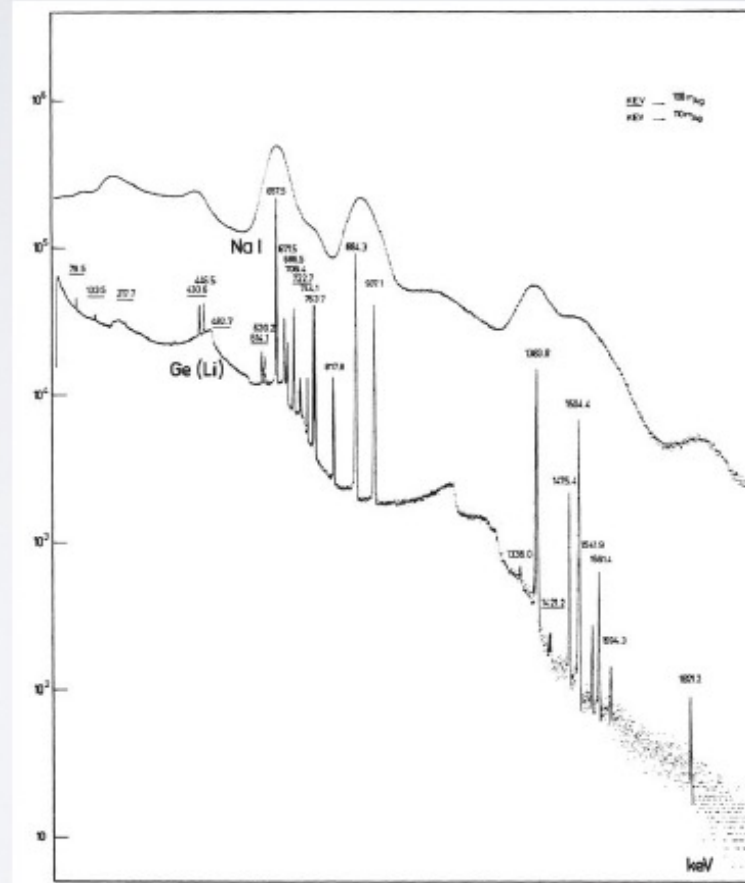
- so the resolution is  $R = \frac{2.35 k\sqrt{N}\sqrt{F}}{kN} = 2.35 \sqrt{\frac{F}{N}} = 2.35 \sqrt{\frac{F W}{E}}$

in scintillators  $F \sim 1$   
in Si/Ge  $F \sim 0.1$

# Semiconductor detector characteristics

## RESOLUTION

- For a 1 MeV photon
- NaI(Tl):
  - 40000 photons/MeV
  - Light collection efficiency  $\sim 0,2$
  - QE  $\sim 0,25$
  - Np.e.  $\sim 2000$
  - $\sigma(E)/E = 1/\sqrt{2000} \sim 2\%$
- Si:
  - 300000 e-/holes pairs per MeV
  - Essentially all carriers collected
  - For  $F = 0,1$ ,  
 $\sigma(E)/E = \sqrt{0,1/300000} \sim 0,06\%$



# Semiconductor detector characteristics

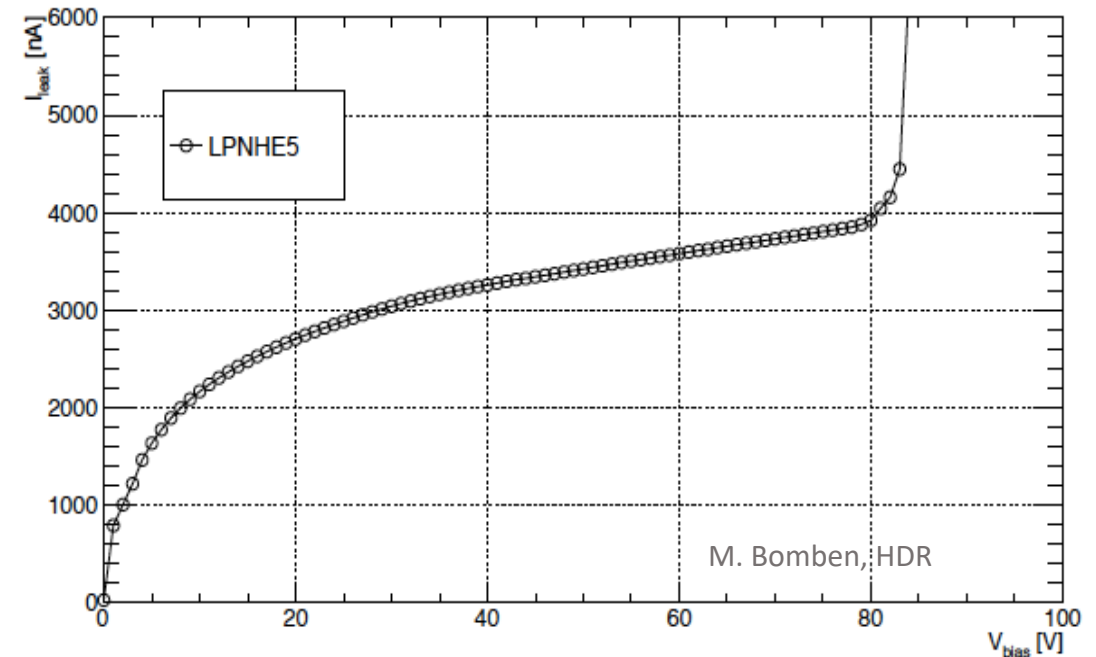
- Leakage current

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

It limits the smallest signal pulse height that can be observed.

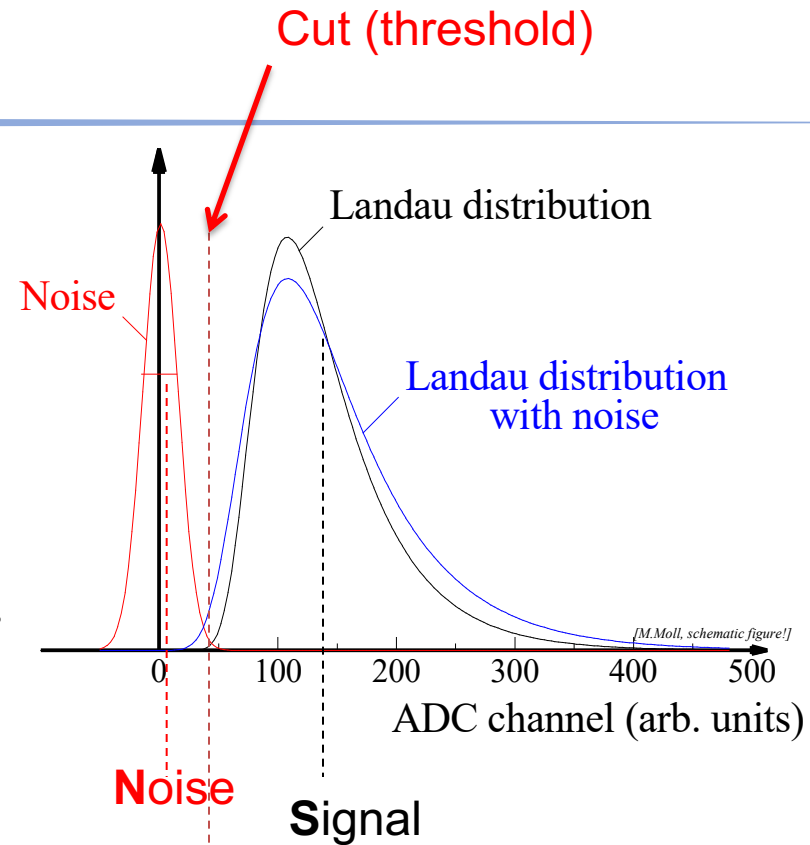
Several sources:

- 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

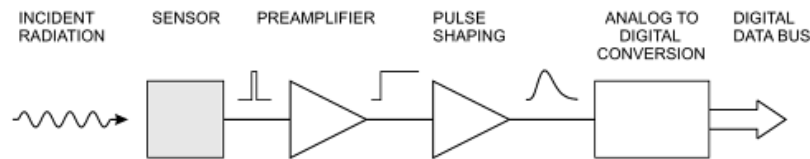


# A quick word about noise

- 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)	Germanium (Ge)
<b>Z, A</b>	14, 28.1	32, 72.6
<b><math>\rho</math> [g/cm<sup>3</sup>]</b>	2.33	5.32
<b><math>E_g</math> (T=300K) [eV]</b>	1.1	0.7
<b><math>E_g</math> (T=0K) [eV]</b>	1.21	0.785
<b>w (T=300K) [eV]</b>	3.62	-
<b>w (T=77K) [eV]</b>	3.81	2.96
<b><math>\mu_e</math> (T=300K) [cm<sup>2</sup>/Vs]</b>	1350	3900
<b><math>\mu_h</math> (T=300K) [cm<sup>2</sup>/Vs]</b>	480	1900

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

- Low  $\rho$ : good for charged particles

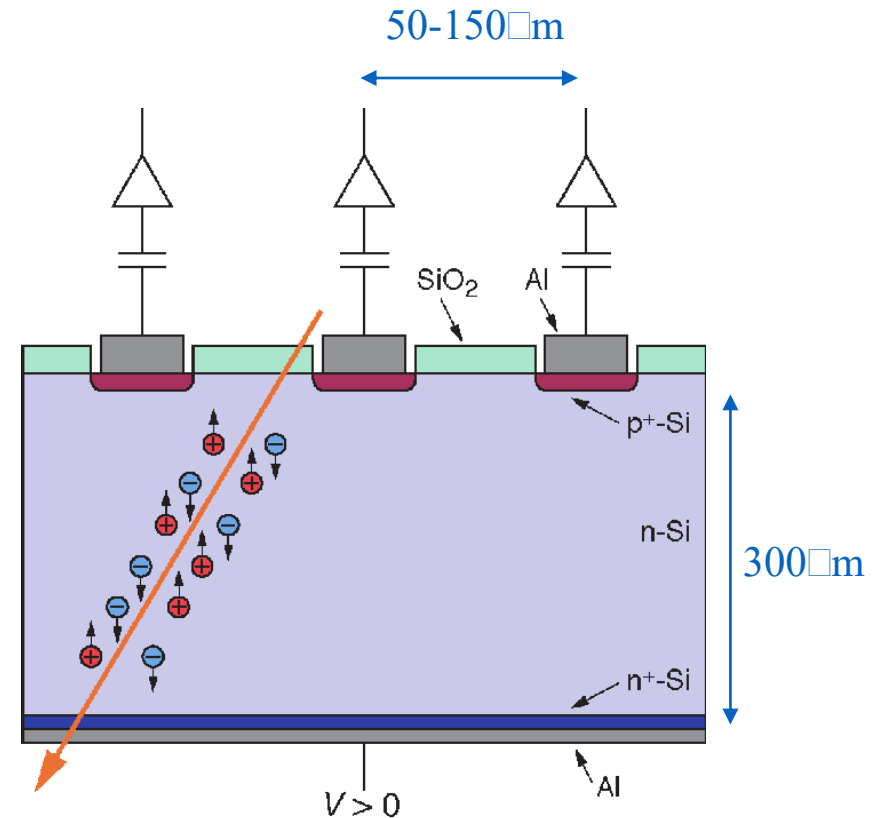
- High Z: good for  $\gamma$  detection ( $\sigma$  for photoelectric effect x60 Si)
- Needs cooling

# 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:  
 $N_a \approx 10^{15} \text{ cm}^{-3}$ ,  $N_d \approx 1-5 \cdot 10^{12} \text{ cm}^{-3}$
  - ★ n-type bulk:  $\rho > 2 \text{ k}\Omega\text{cm}$   
→ thickness  $300 \mu\text{m}$
  - ★ Operating voltage  $< 200 \text{ V}$ .
  - ★ 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



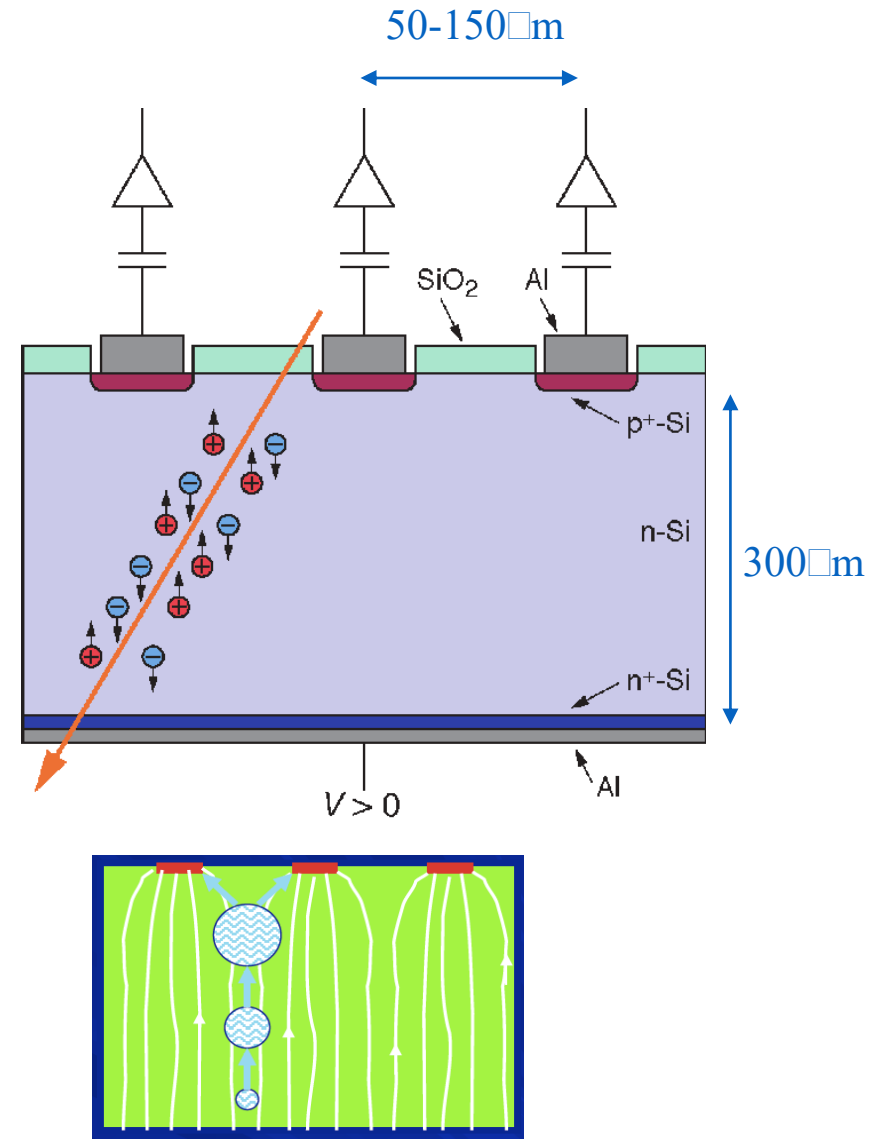
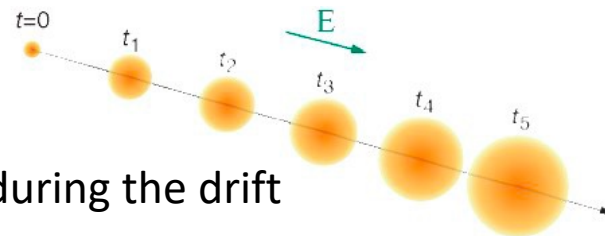
# Position measurement: Microstrip detectors

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

→ position resolution = pitch/sqrt(12)  
 ~ O(10-50 $\mu$ m)

Diffusion:

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



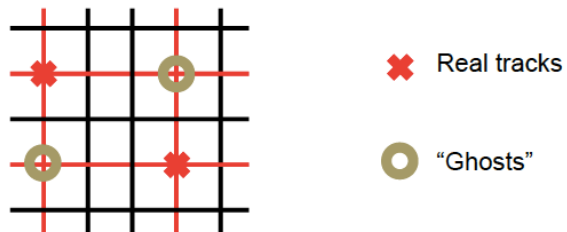


# Double-Sided Silicon Detectors

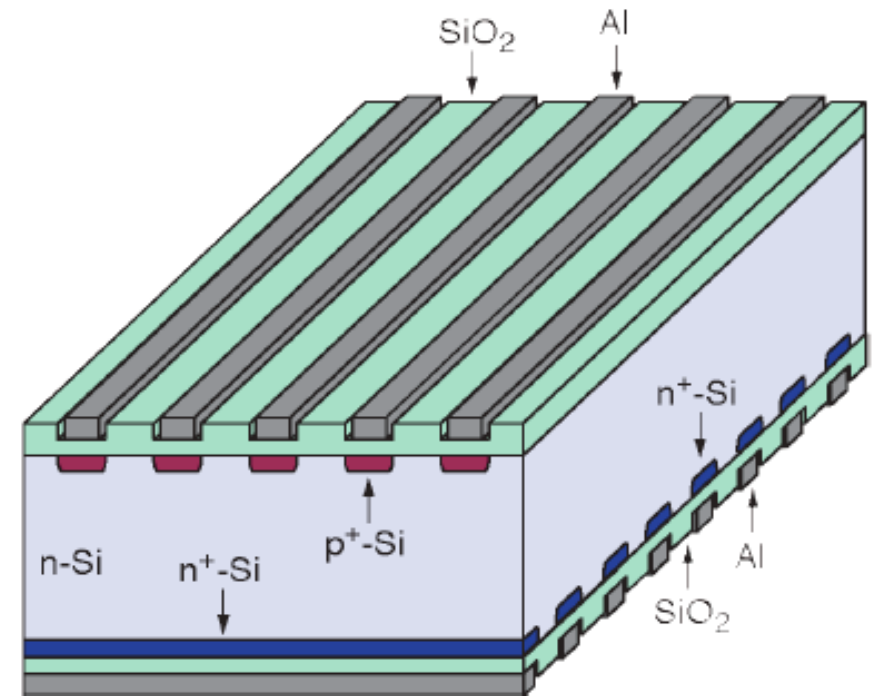
- Reconstruction of two coordinates with one detector layer

+ Advantage: minimize multiple scattering

- Disadvantage: "ghost hits" at high particle multiplicity



The solution: Pixel detectors...



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

# Pixel Detectors

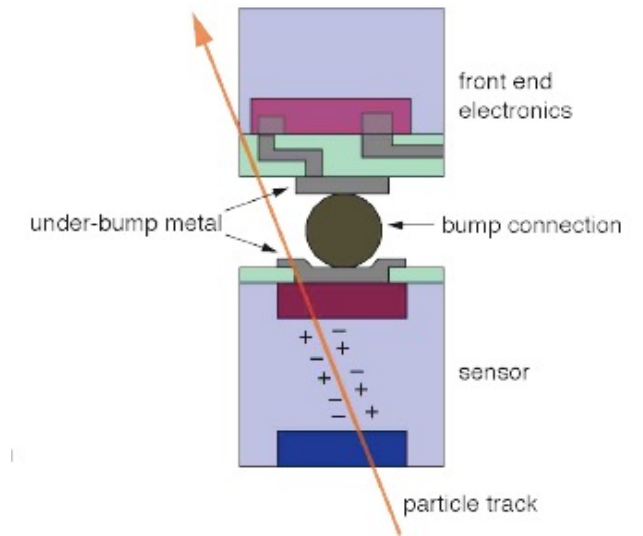
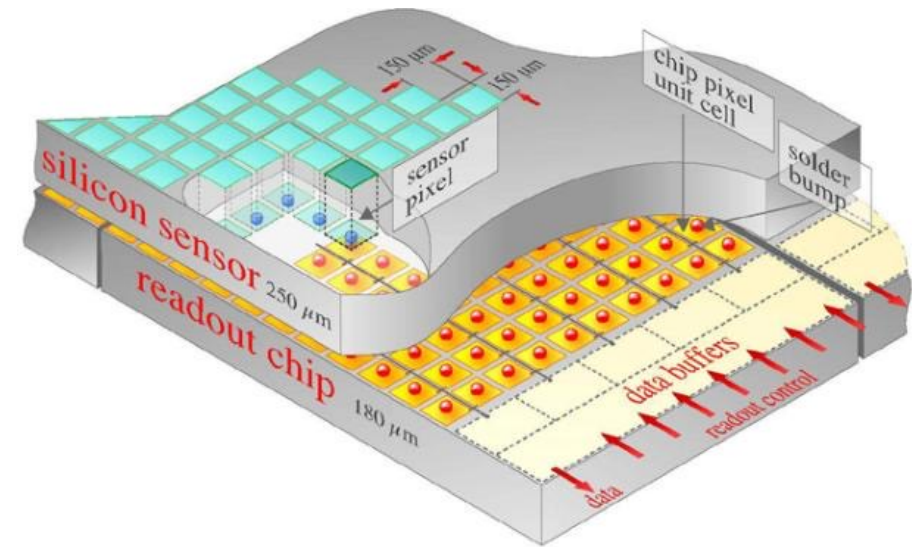
- Two-dimensional arrays of p-n diodes organised in a matrix
- Each p-n junction is readout by a dedicated readout integrated circuit
- Sensor and readout electronics are physically separated and linked by a bump bonding

→ Hybrid Pixel Detectors (HPDs)

+ Unambiguous 2D position measurement, pitch  $\sim 50\mu\text{m}$

+ Smaller leakage currents than DSSD

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

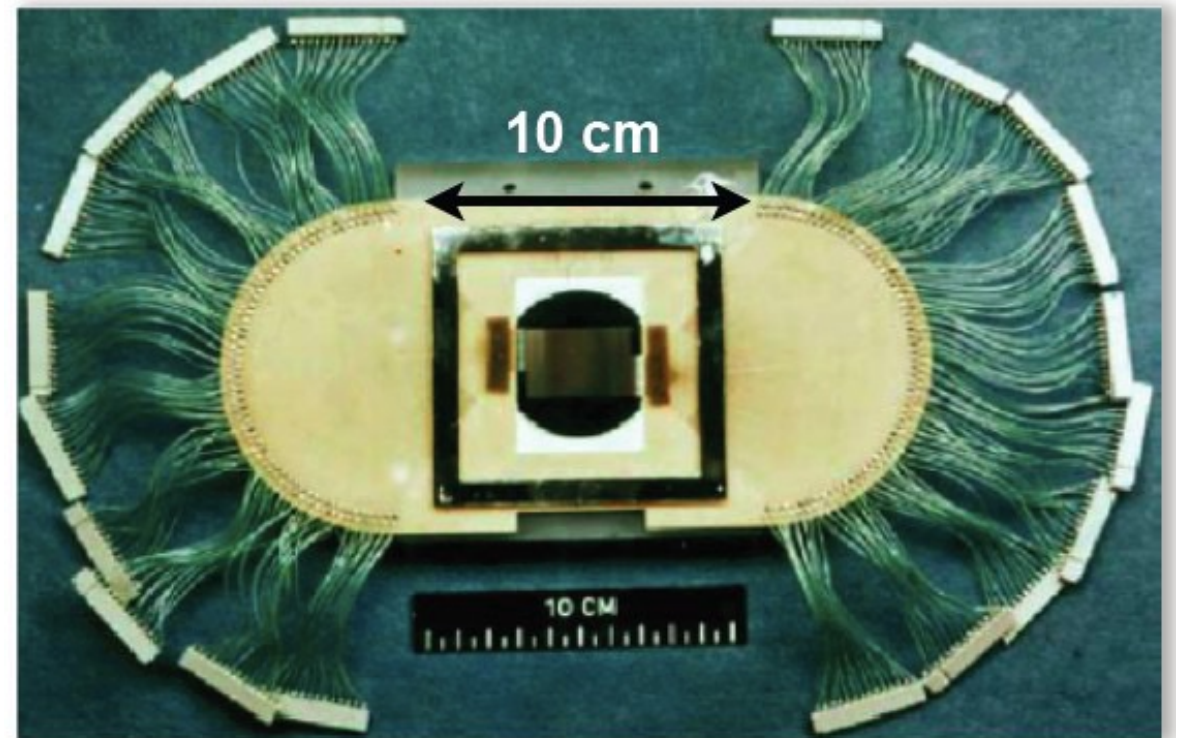


# Examples

## NA11 at CERN, 1983

First use of a position-sensitive Si detector in HEP

- To measure lifetimes of charmed mesons
- Surface: 24 cm<sup>2</sup> (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

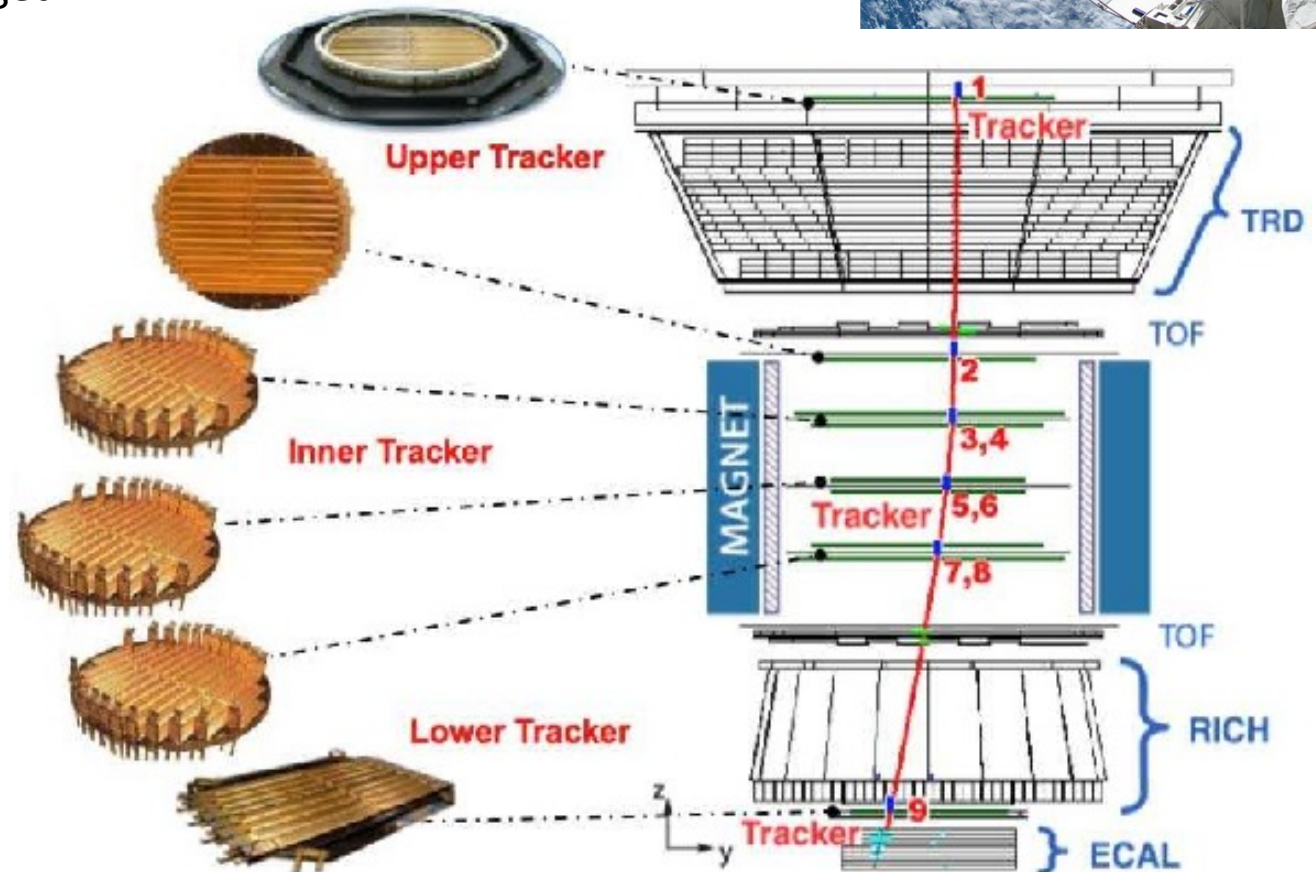
## AMS-02

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<sup>2</sup> with 196 k readout channels
- Position resolution: 8.5  $\mu\text{m}$  (30  $\mu\text{m}$ ) 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<sup>2</sup> of pixel sensors,  
60x106 channels,  
hit resolution 10x17 μm<sup>2</sup>

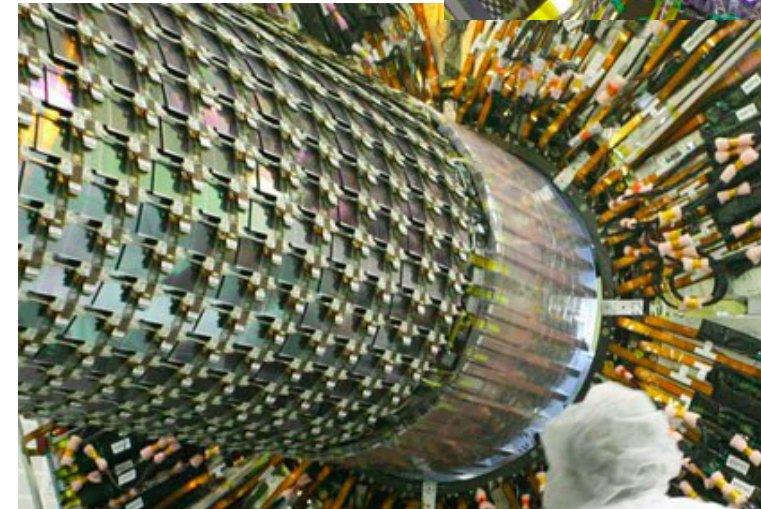
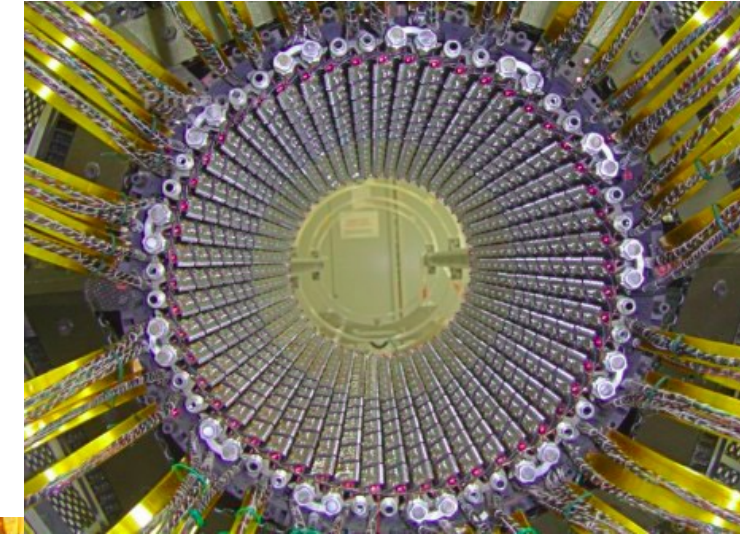
200 m<sup>2</sup> of strip sensors (single sided)  
11 x 106 readout channels, hit  
resolution 40-60 μm



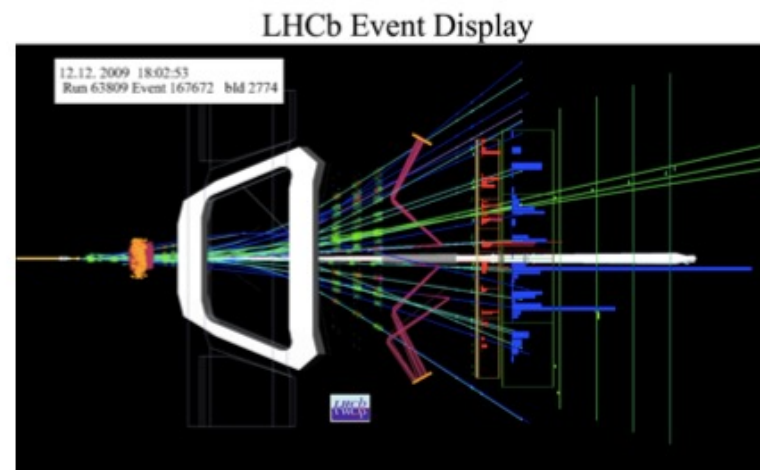
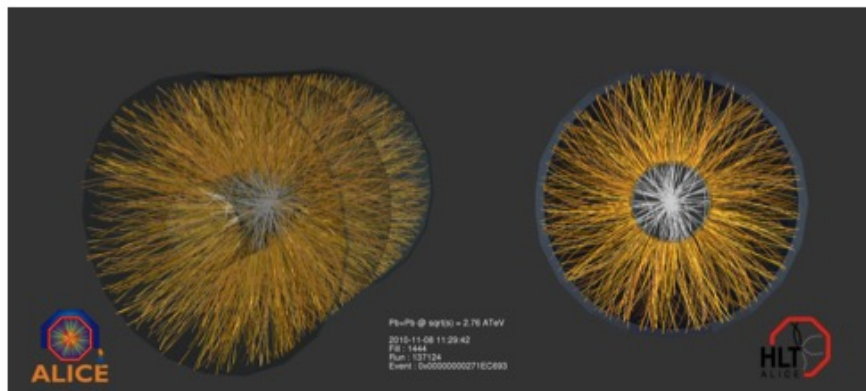
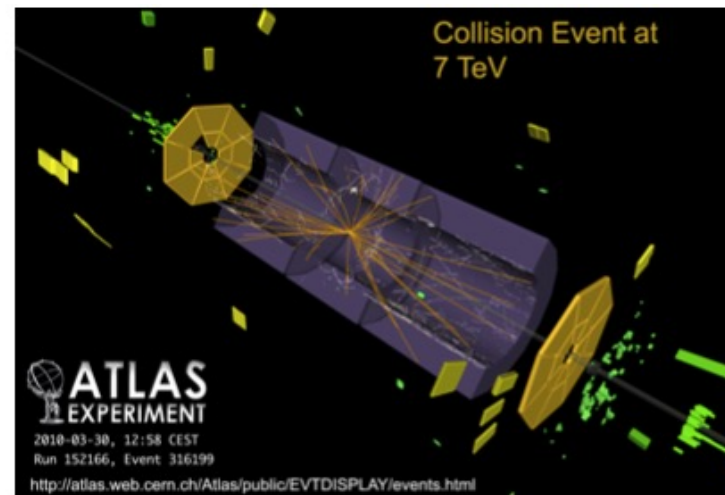
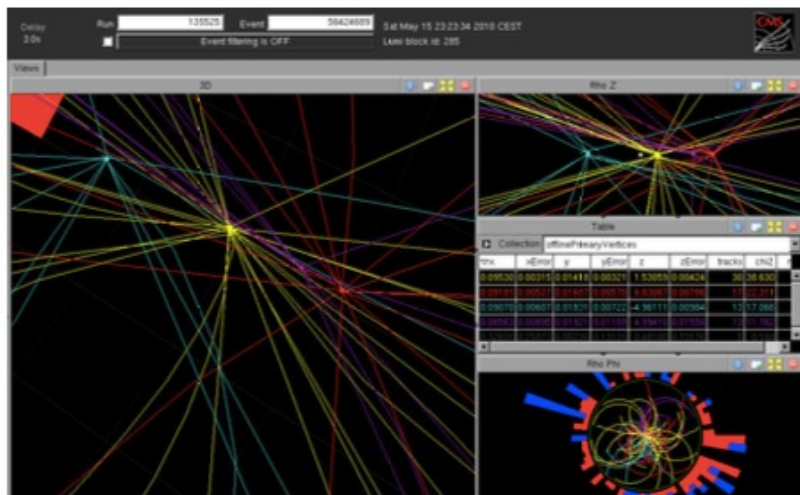
## ATLAS

Pixels: 1744 modules,  
80 x 106 channels.  
Pixel size 50 x 400μm<sup>2</sup> .  
Resolution 14 x 115μm<sup>2</sup>

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



# Examples

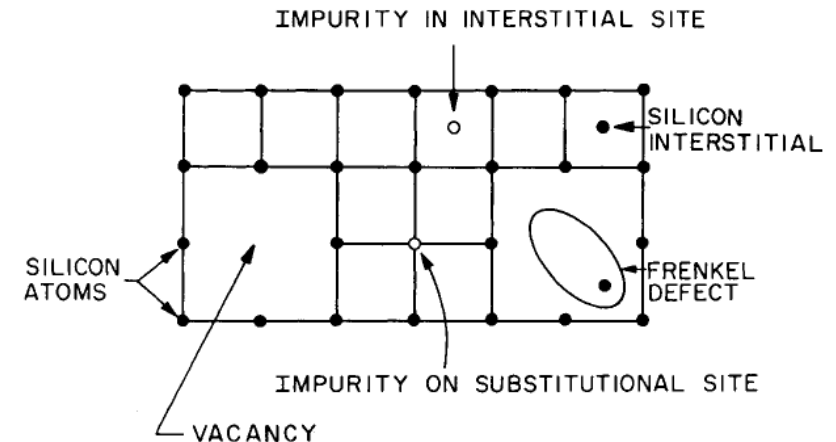


# Radiation damage

- 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 ( $\sim 10^{16}/\text{cm}^2$  for pixels,  $10^{15}/\text{cm}^2$  for strips;  $\sim 20$  x current)
- High hit rate (up to  $1.5 \text{ GHz}/\text{cm}^2$  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  $\sim 3$  microns)

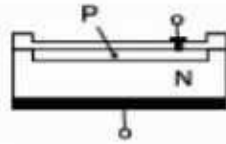


# Some other Si detectors

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.

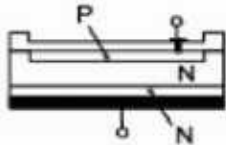
## Planar Diffusion Type

An SiO<sub>2</sub> coating is applied to the P-N junction surface, yielding a photodiode with a low level dark current.



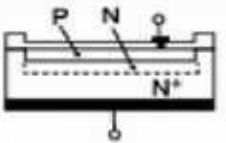
## Low-Capacitance Planar Diffusion Type

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.



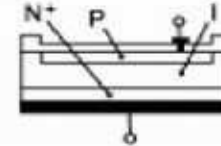
## PNN+ Type

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.



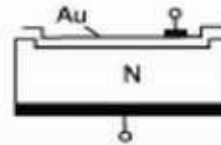
## PIN Type

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.



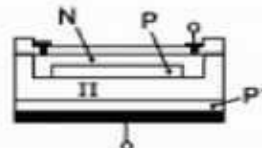
## Schottky Type

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



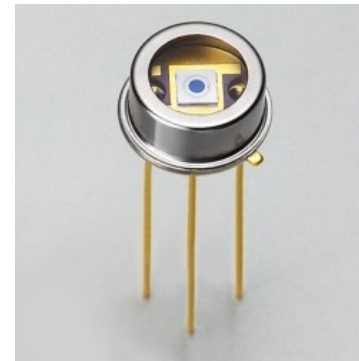
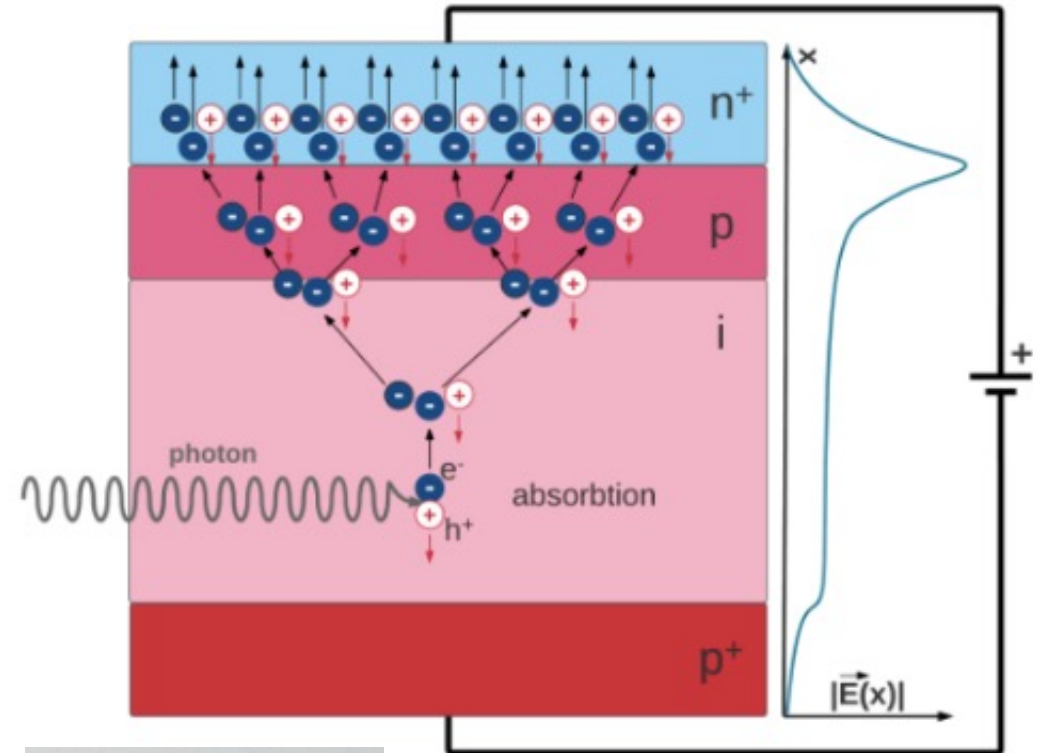
# Photodetectors: Avalanche PhotoDiodes (APD)

Conversion of photons into a charge current :  
e-h pair creation + avalanche multiplication

+ Gain  $O(100)$

+ Fast response times  
(formation of avalanche  $< ns$ )

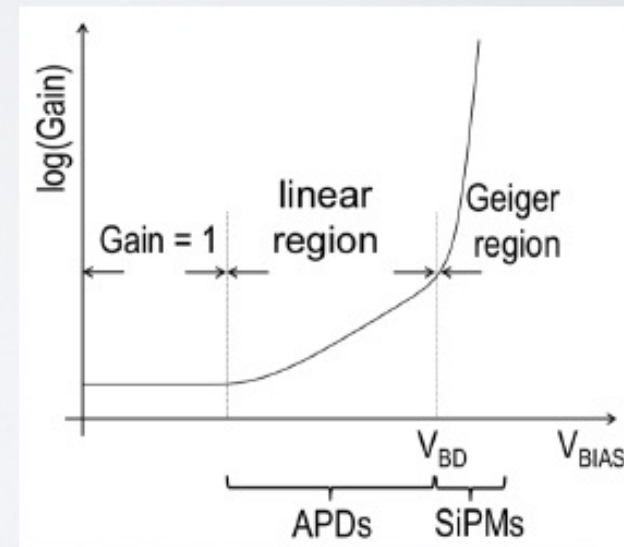
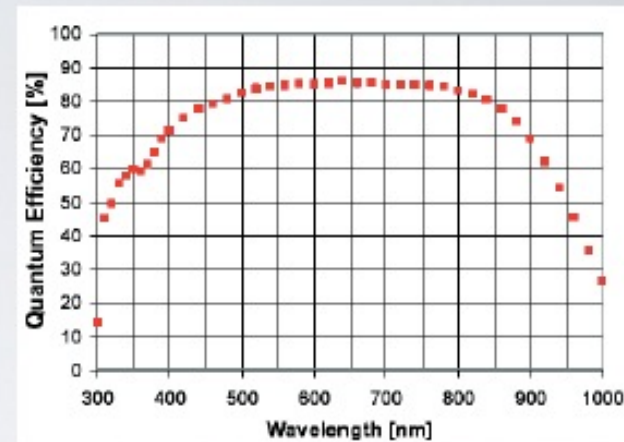
- Large operation voltage ( $E > 10^5$  V/cm)
- Poor energy resolution (fluctuations in the avalanche), extremely sensitive to voltage changes



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 bias voltage between 150 et 350 V
  - ▶ Exponential increase
- Above, Geiger region



# 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  $\rightarrow$  measure the photon flux

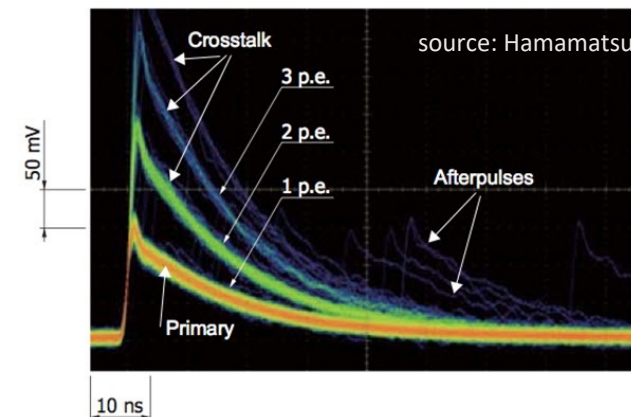
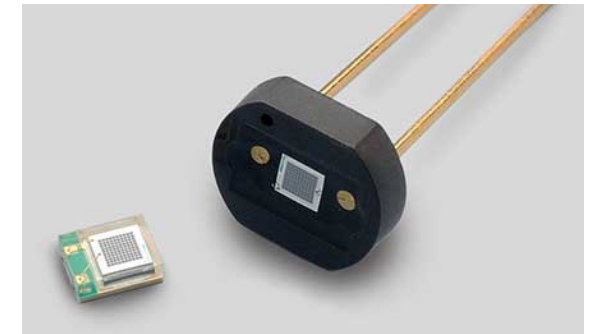
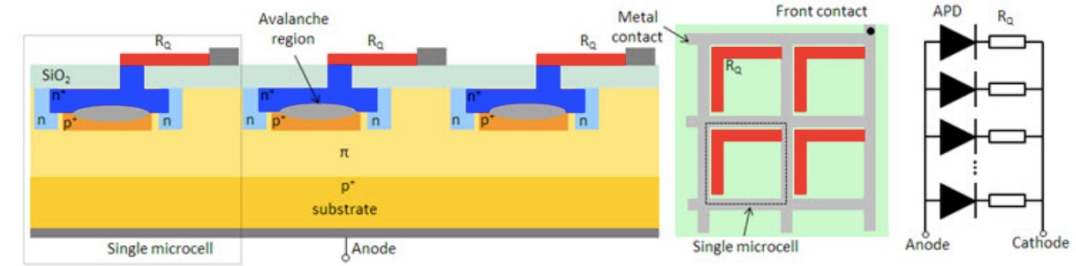
+ Gain  $\sim 10^5$ - $10^7$  (cfr PMTs)

+ Good charge resolution

+ No need for HV

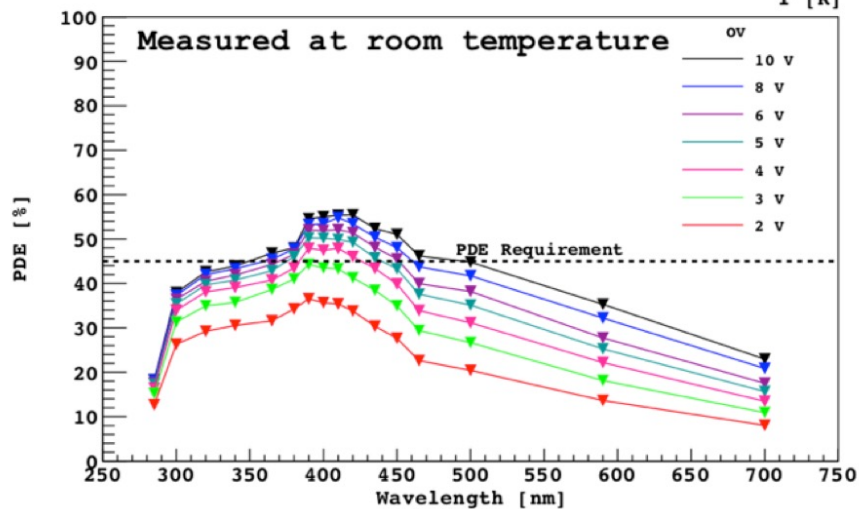
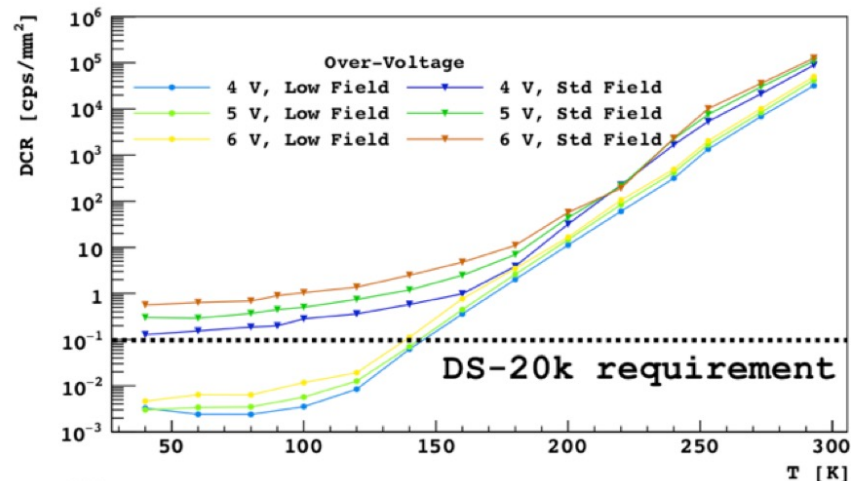
+ Not sensitive to magnetic field

- Dark noise, crosstalk, afterpulses, ...



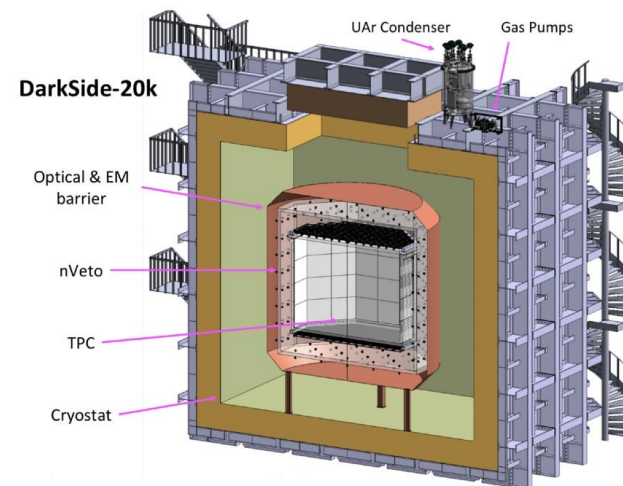
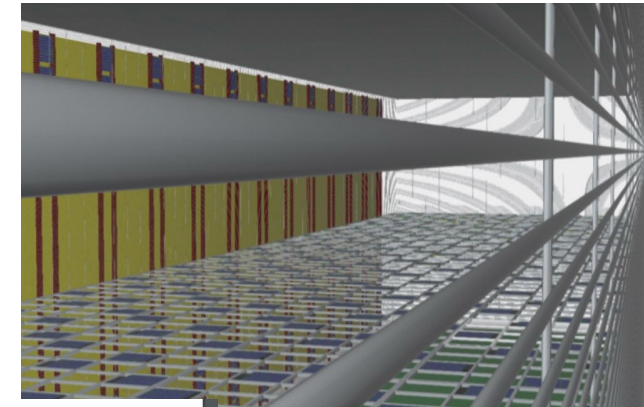
# SiPM at cryogenic temperatures

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

# Semiconductor detectors: key notions

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

# Exercises

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## 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  $1 \text{ cm}^2$  while that of detector B is  $4 \text{ cm}^2$ .

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 ?

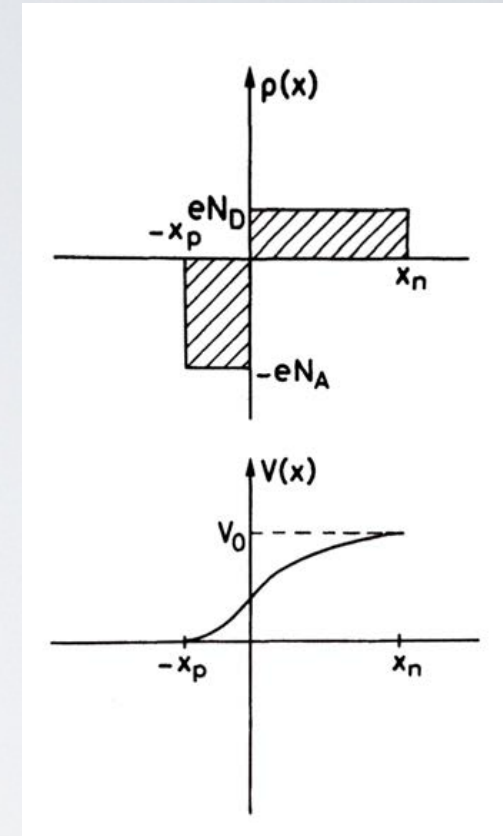
# DEPLETION REGION

- It is possible to compute the width of the depletion region starting from simple hypotheses on the geometry of the charge distribution:

$$\rho(x) = \begin{cases} +eN_D & 0 < x < x_n \\ -eN_A & -x_p < x < 0 \end{cases}$$

$N_A$  : acceptor concentration (= 0 for N type)  
 $N_D$  : donor concentration (= 0 for P type)

- The net charge must be zero:  $N_A x_p = N_D x_n$
- ID Poisson equation to be solved:  $\frac{d^2 V}{dx^2} = -\frac{\rho(x)}{\epsilon}$



Dielectric constant

- Using boundary conditions (the electric field should vanish at both edges of the distribution), we get the potential at contact

(in Volts):  $V_0 = \frac{e}{2\epsilon} (N_D x_n^2 + N_A x_p^2)$

- And the width of the depletion region:  $d = x_n + x_p = \left( \frac{2\epsilon V_0}{E} \frac{N_A + N_D}{N_A N_D} \right)^{1/2}$