Semiconductor particle detectors

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Detectors in high-energy physic (1)

- **particle tracking**: identify that a particle crosses a given surface at a given time

- **energy spectroscopy**: identify the energy of a particle

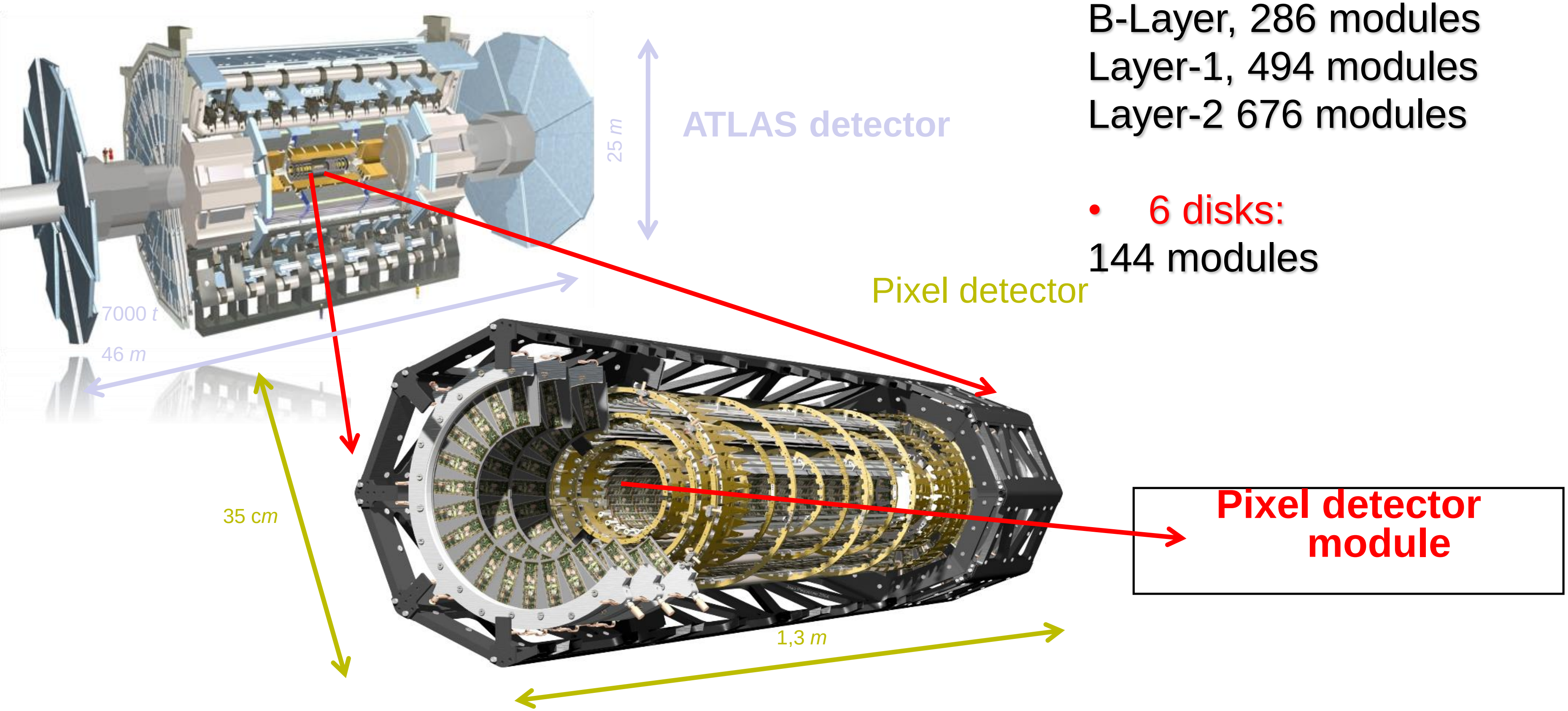
Detectors in high-energy physic (2)

- 3 Layers:

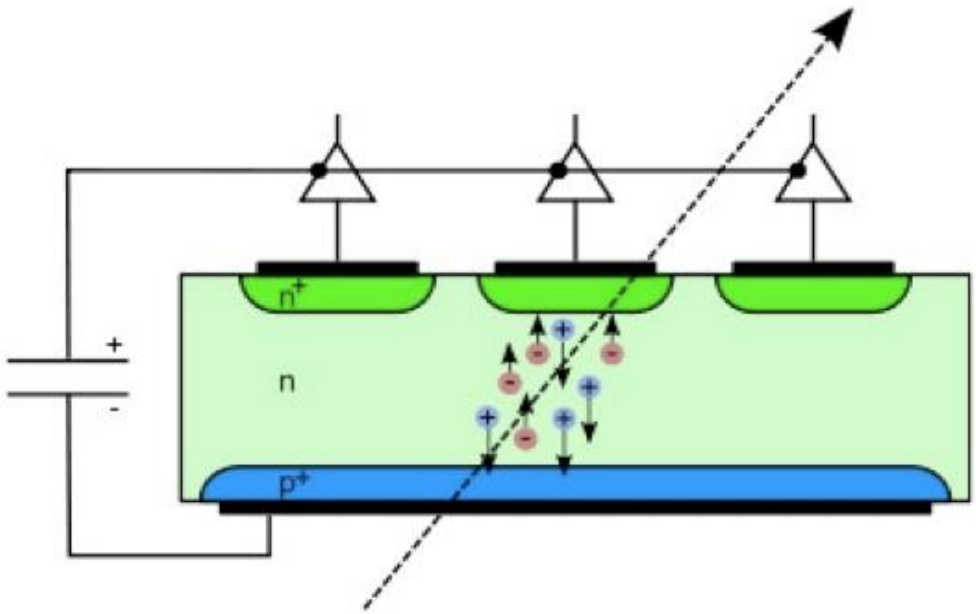
B-Layer, 286 modules
Layer-1, 494 modules
Layer-2 676 modules

- 6 disks:

144 modules



What a detector does

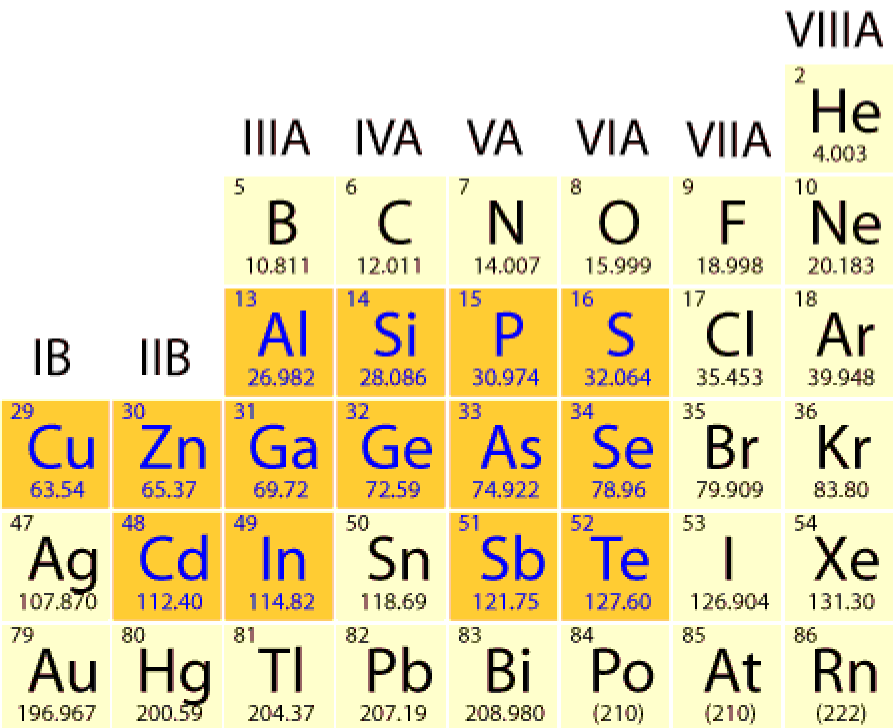


- the incoming particle generates free carriers inside a semiconductor
- the electric field inside the device separates the charges and creates a current at the terminals
- the electrical signal is amplified by an electronic read-out

Outline

- **Semiconductors**
- p-n junction
- Main figures of merits for detectors

Semiconductors (1)

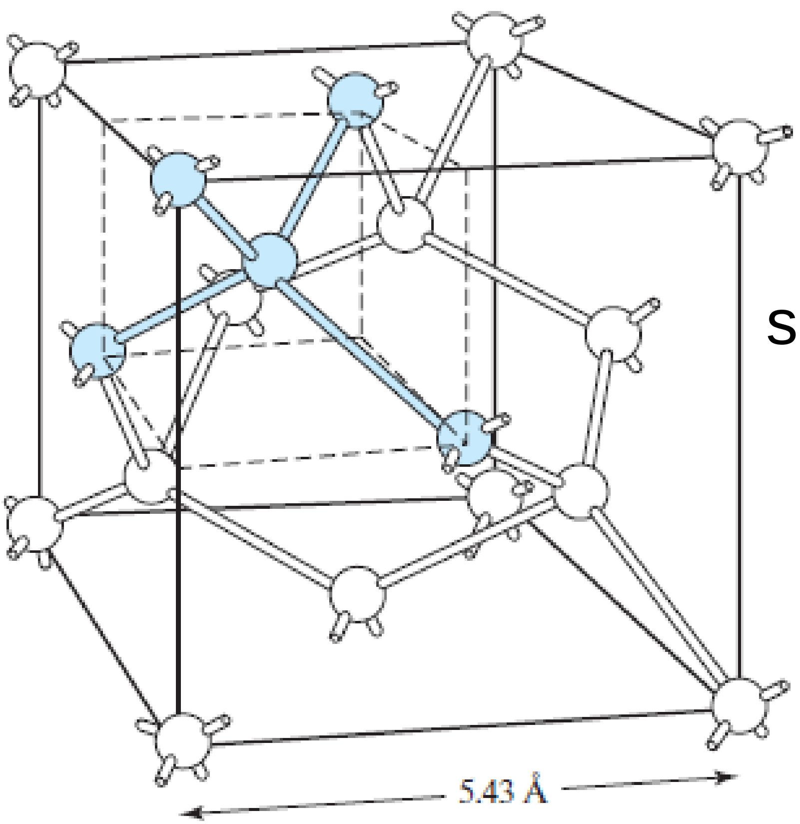


- group IV: Si, Ge
- III-V compounds (GaAs, InP, InAs, GaN…)
- Alloys ($Si_{1-x}Ge_x$, $In_{1-x}Ga_xAs$)
- CdTeSe, ZnTeSe, CdZnTe

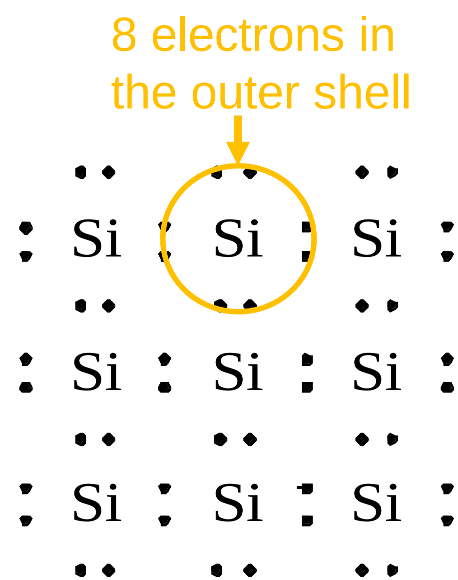
- behave as conductive or insulating materials by adding impurities a/o changing the device bias

Semiconductors (2)

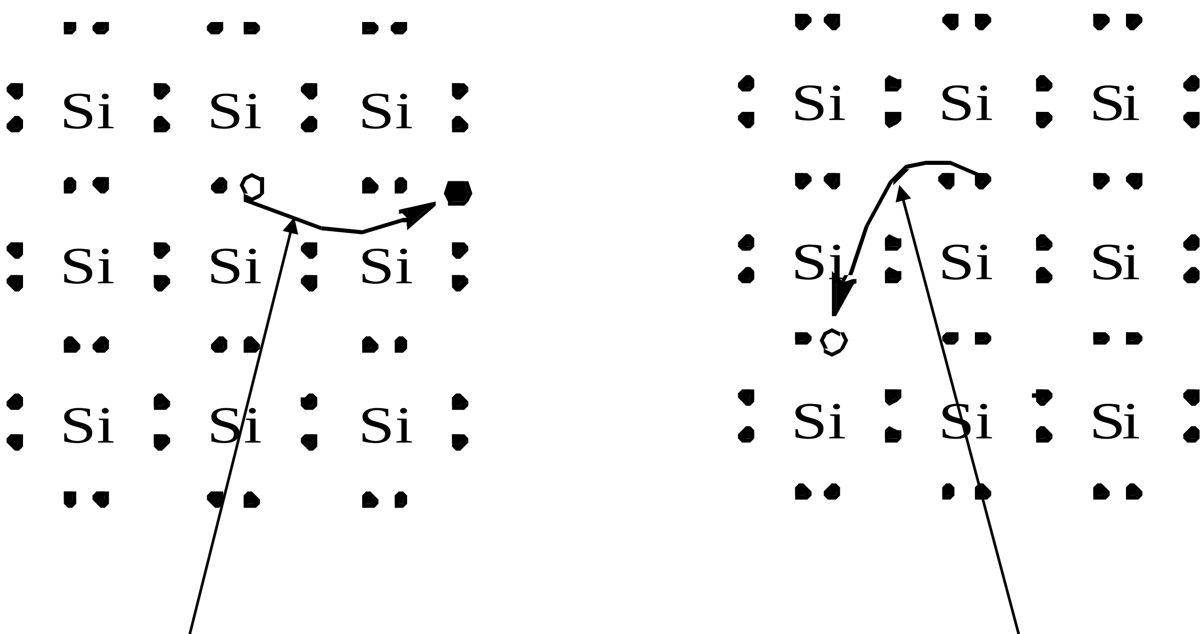
- crystal structure of silicon



simplified 2D view



Free carriers: electrons and holes



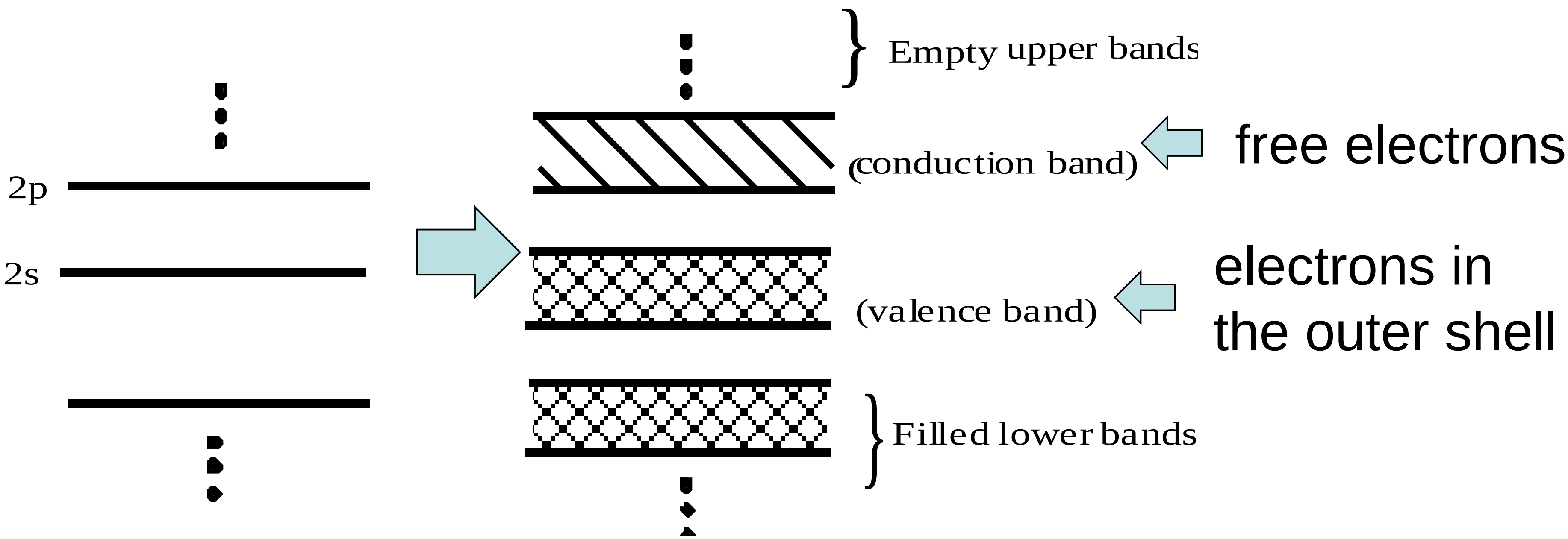
one **electron** can break the bond and become a **free carrier** (negative charge)

the **hole** that is left can move too: free carrier with positive charge

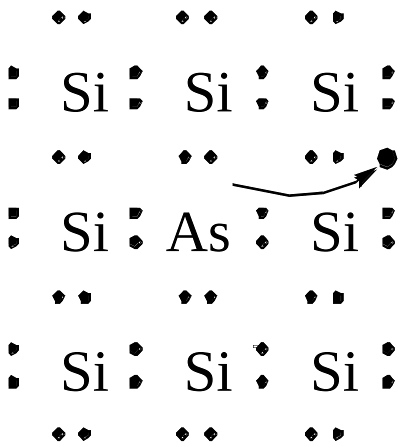
Energy bands

single atom:
energy levels

crystal:
energy bands

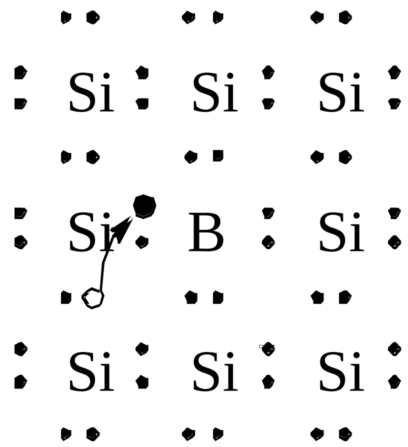


Doping (1)



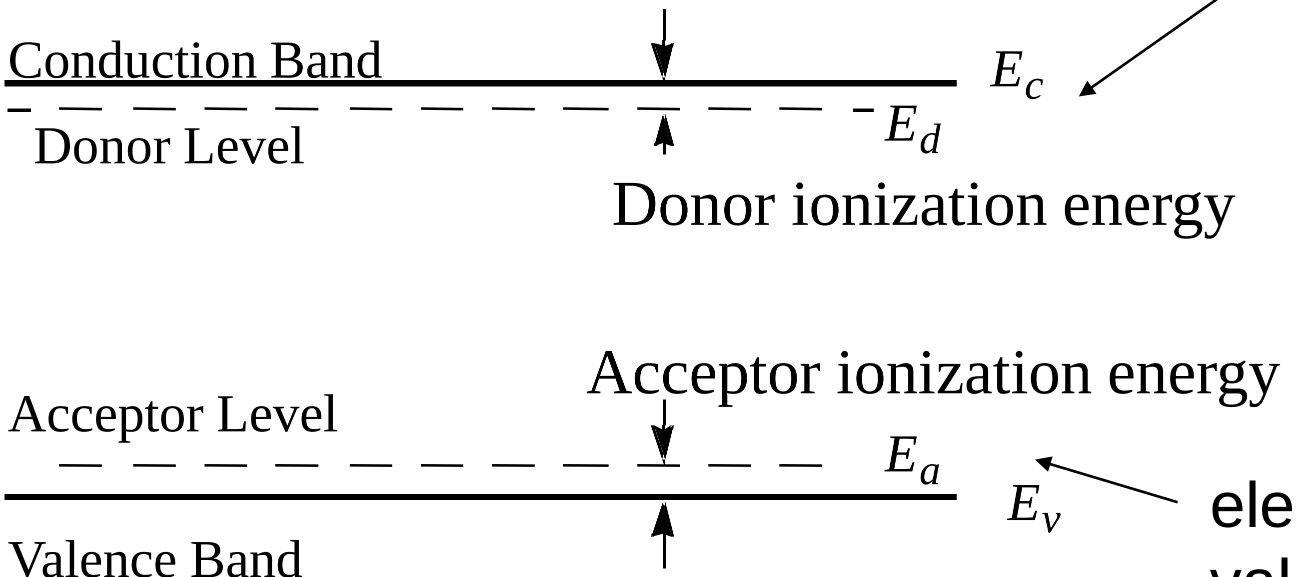
doping with donors: As has 5 electrons in the outer shell→ one is not needed for bonding and becomes a **free electron**

Doping (2)



doping with acceptors: B has 3 electrons in the outer shell and this results in a **hole** that can move in the crystal

Doping (3)



electron from the donor easily jumps to the conduction band

electron in the valence band easily captured by the acceptor→ a hole is left in the valence band

Doping (4)

It can be shown that $np = n_i^2$ with $n_i = \sqrt{N_c N_v} e^{-E_g/2kT}$

free electron concentration

hole concentration

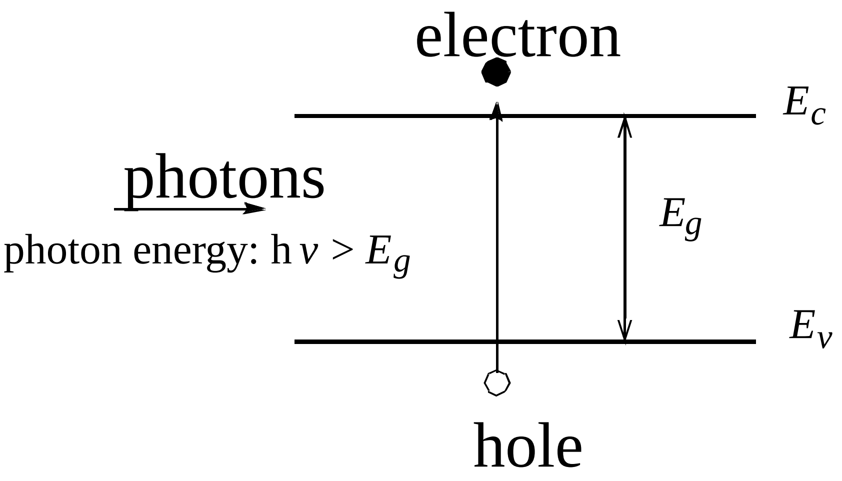
intrinsic density (~10^{10}cm^{-3} in Si@room temperature)

Charge neutrality: $n + N_a = p + N_d$

Example: $N_a = 10^{16} cm^{-3}$, $N_d = 0$ → $p = 10^{16} cm^{-3}$, $n = 10^4 cm^{-3}$

Note: density of atoms in Si is $5 \cdot 10^{22}$cm^{-3}

e-h generation by radiation



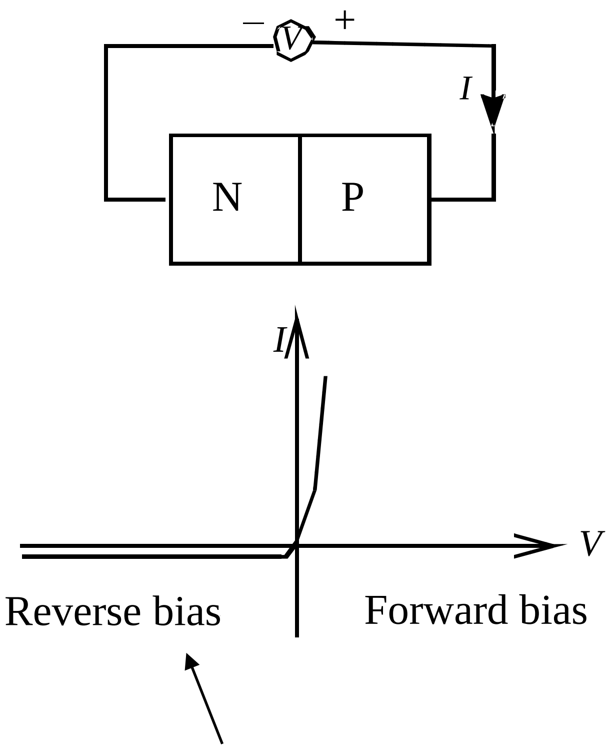
- the photon promotes an electron in the conduction band
- a hole is left in the valence band

- if $h\nu >> E_g$: number of pairs ~ $h\nu / E_g$
- The same happens with many types of particles, not only photons
- To measure the generated e-h pairs we need to separate electrons and holes → **p-n junction**

Outline

- Semiconductors
- **p-n junction**
- Main figures of merits for detectors

Structure



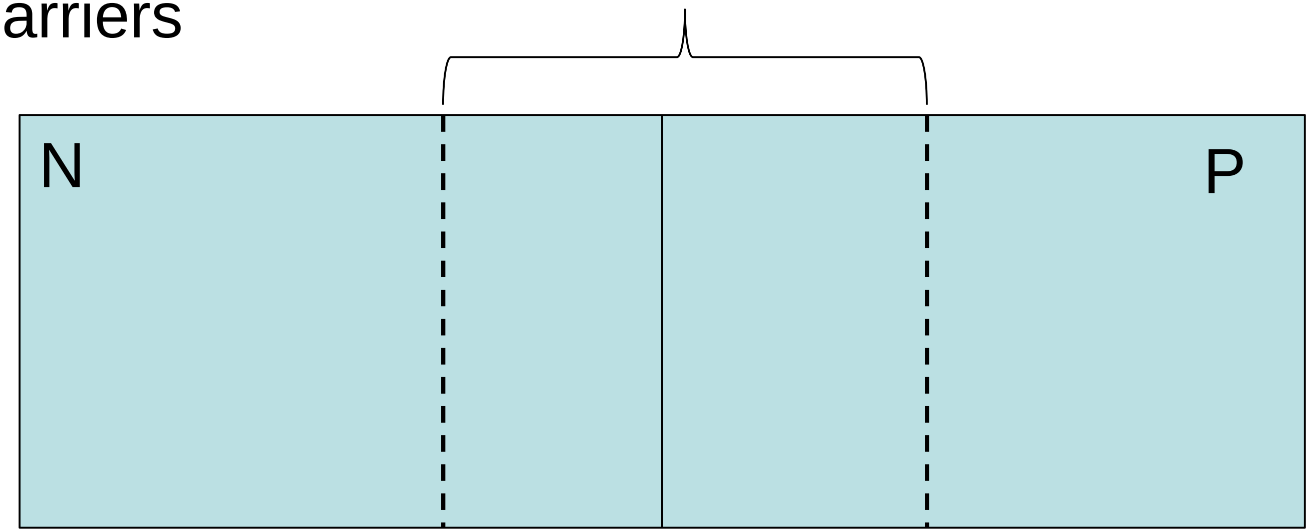
region where the detectors operate

N-region:
- donor doping;
- plenty of free electrons
- balanced by fixed positive charge

P-region:
- acceptor doping;
- plenty of free holes
- balanced by fixed negative charge

Charge profile (1)

at the border between the N and P region we have very few free carriers



neutral N-region:
- donor doping;
- plenty of free electrons
- balanced by fixed positive charge

depletion region:
only fixed charges

neutral P-region:
- acceptor doping;
- plenty of free holes
- balanced by fixed negative charge

Charge profile (2)

net charge concentration:

$$\rho = q(p - n + N_D - N_A)$$

N			P
$n=N_D$	$n \sim 0$	$n \sim 0$	$p=N_A$
$p \sim 0$	$p \sim 0$	$p \sim 0$	$n \sim 0$
$\rho=0$	$\rho=qN_D$	$\rho=-qN_A$	$\rho=0$

neutral N-region:

- donor doping;
- plenty of free electrons
- balanced by fixed positive charge

depletion region:
only fixed charges

neutral P-region:

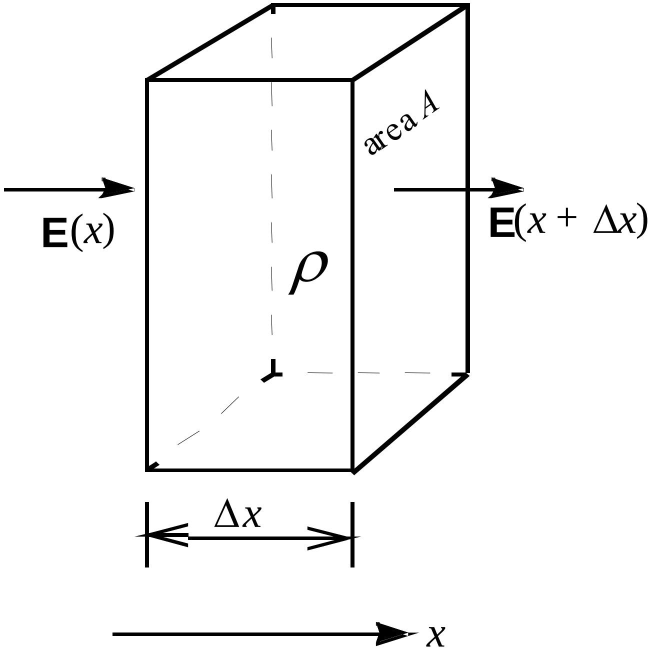
- acceptor doping;
- plenty of free holes
- balanced by fixed negative charge

Poisson equation

Gauss's Law:

$$\varepsilon_S \boldsymbol{E}(x+\Delta x)A - \varepsilon_S \boldsymbol{E}(x)A = \rho \Delta x A$$

ε_s: permittivity (~12ε_o for Si)
ρ: charge density (C/cm^3)



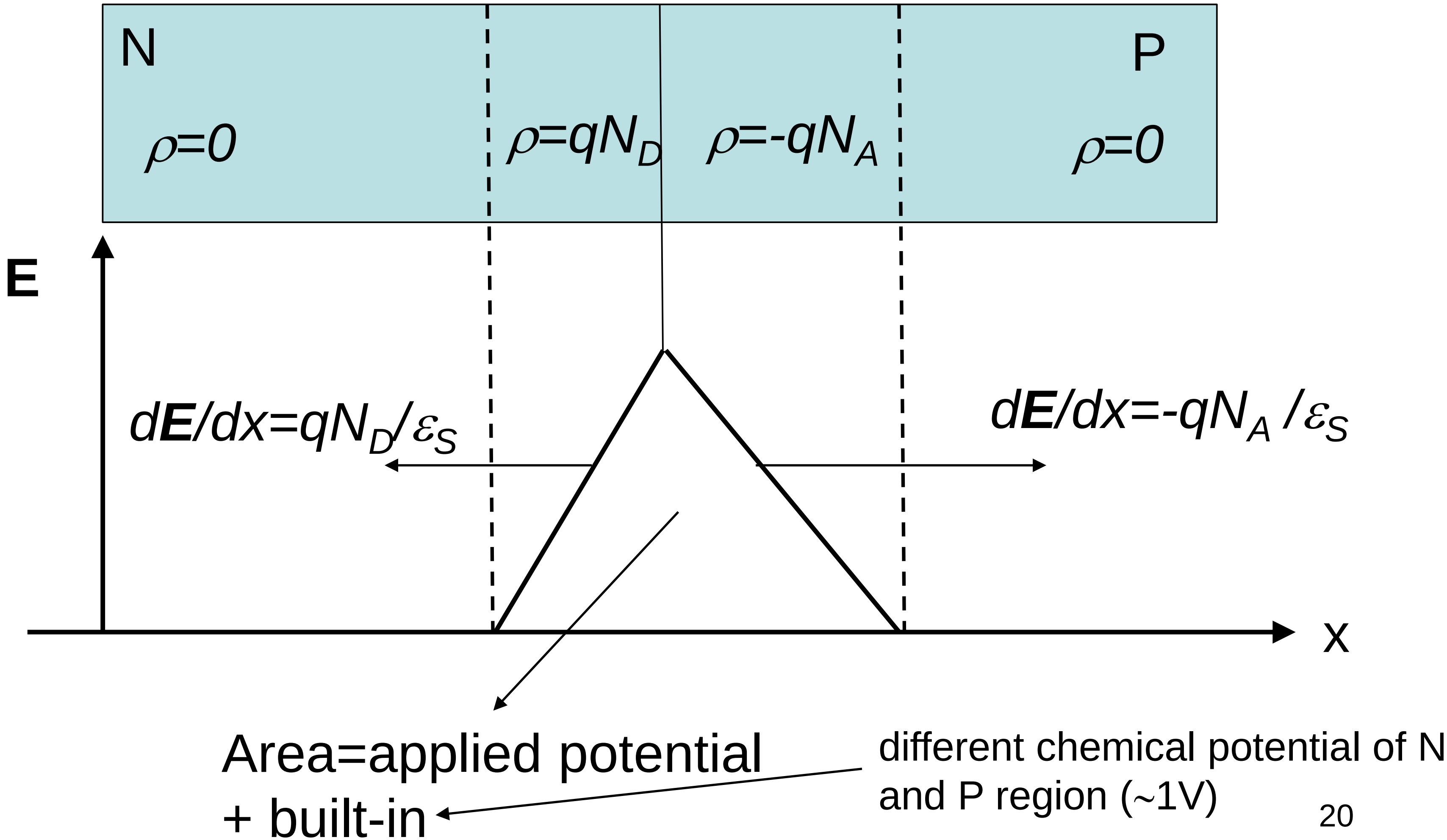
$$\frac{\varepsilon_S \boldsymbol{E}(x+\Delta x) - \varepsilon_S \boldsymbol{E}(x)}{\Delta x} = \rho$$

$$\frac{d\boldsymbol{E}}{dx} = \frac{\rho}{\varepsilon_S}$$

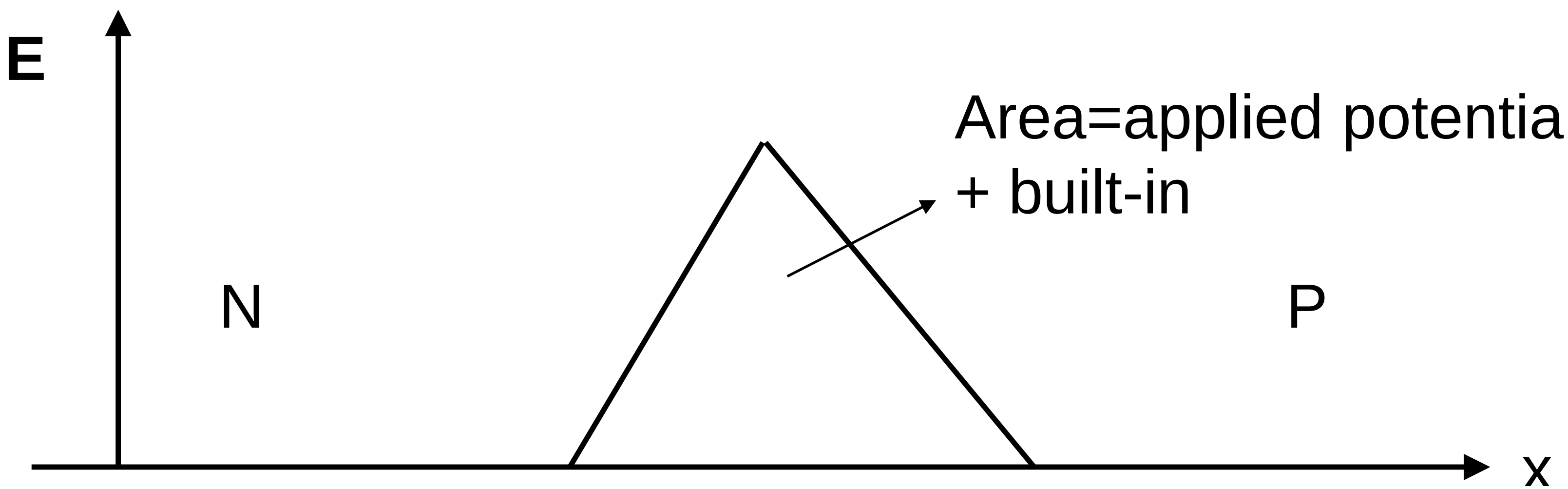
$$\frac{d^2V}{dx^2} = -\frac{d\boldsymbol{E}}{dx} = -\frac{\rho}{\varepsilon_S}$$

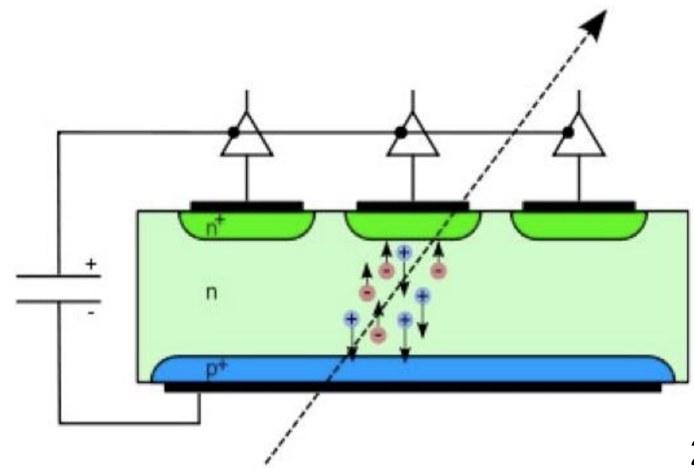
Poisson's equation

Electric field profile (1)



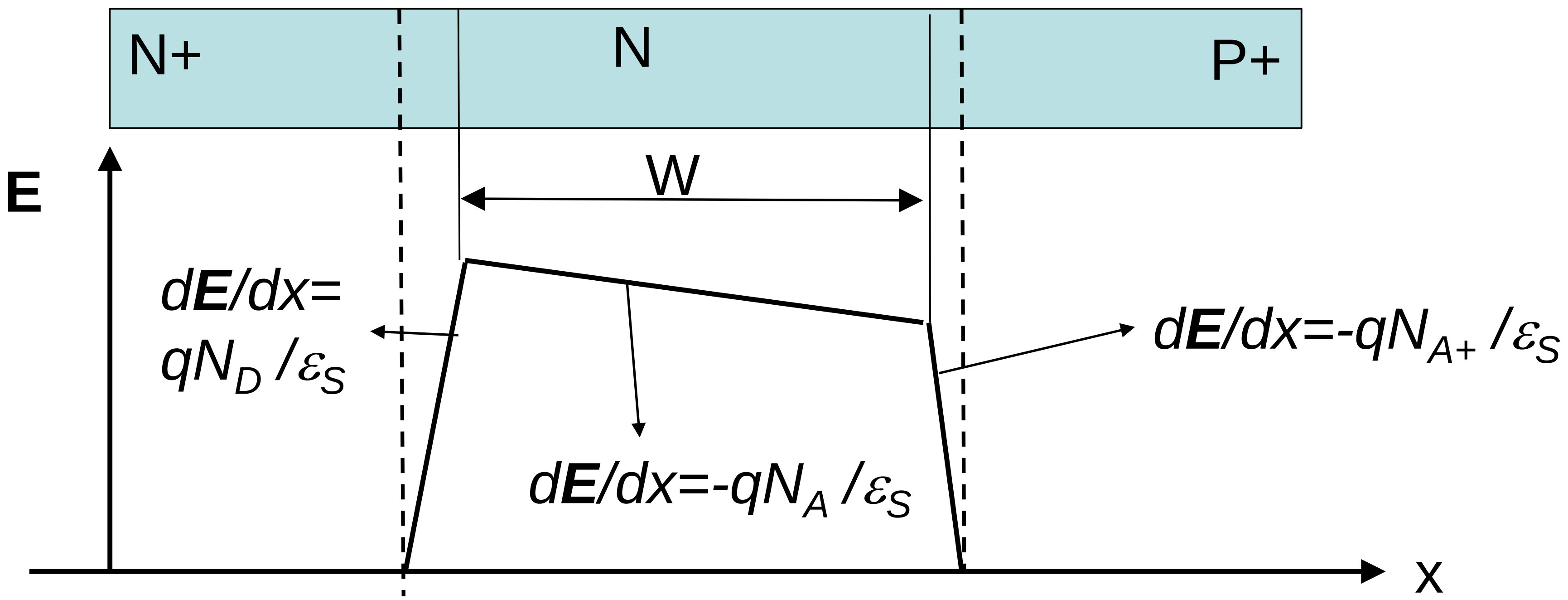
Electric field profile (2)





- positive electric field → electrons (holes) generated by radiation go to the N (P) region

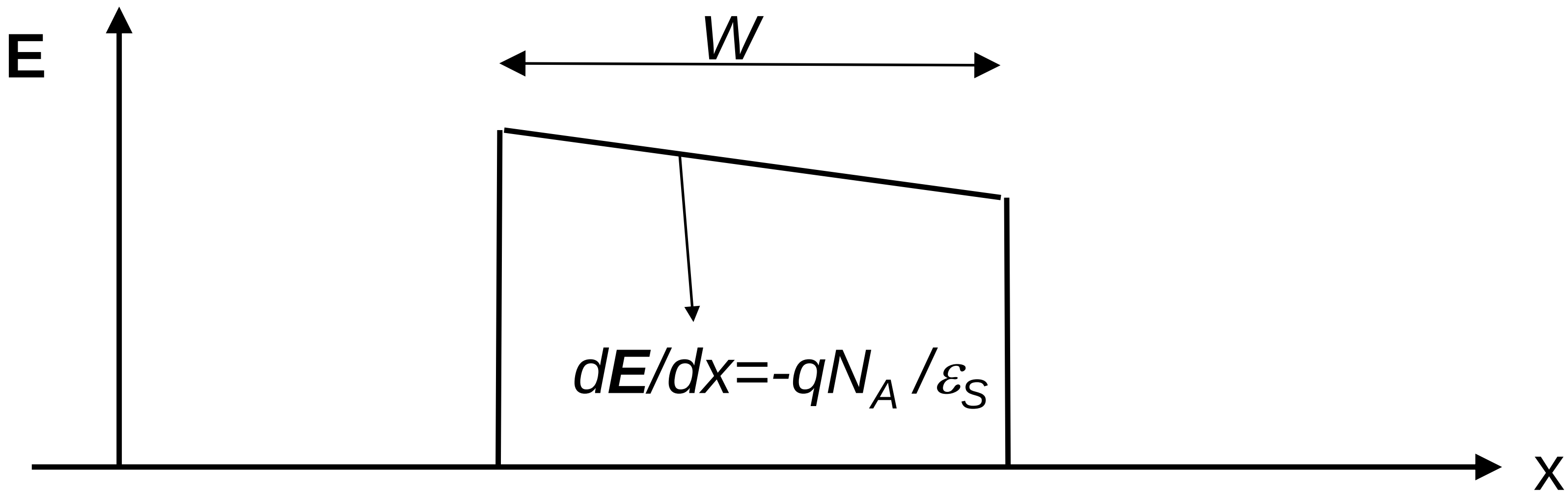
Electric field profile (3)



- insertion of a low-doped region: trapezoidal electric field profile → same "area" with lower peak electric field

Electric field profile (4)

- doping in the P+ and N+ regions is large so that:



- this however requires: $V + V_{BI} > \frac{qN_A}{\varepsilon_S} W^2$ to fully deplete the low doping region

Outline

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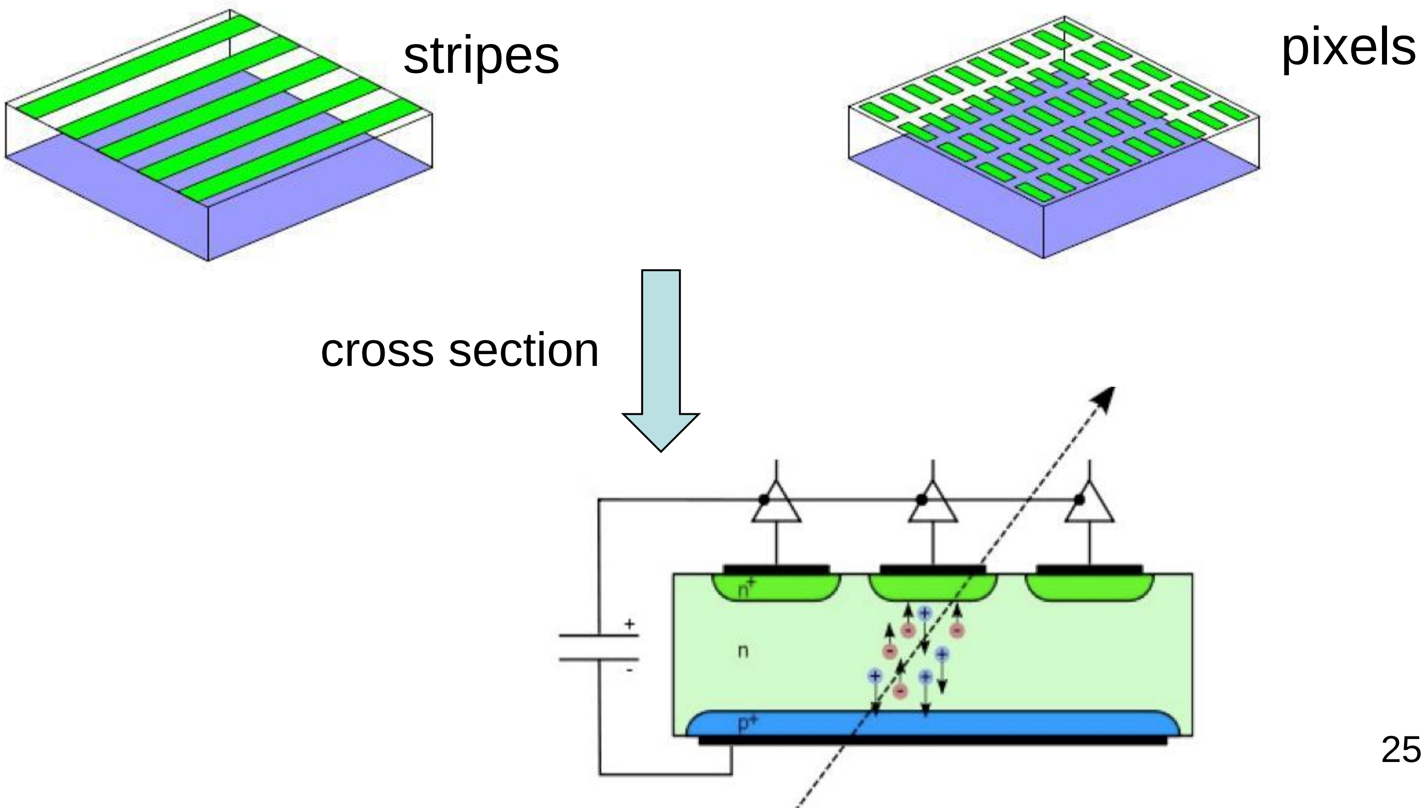
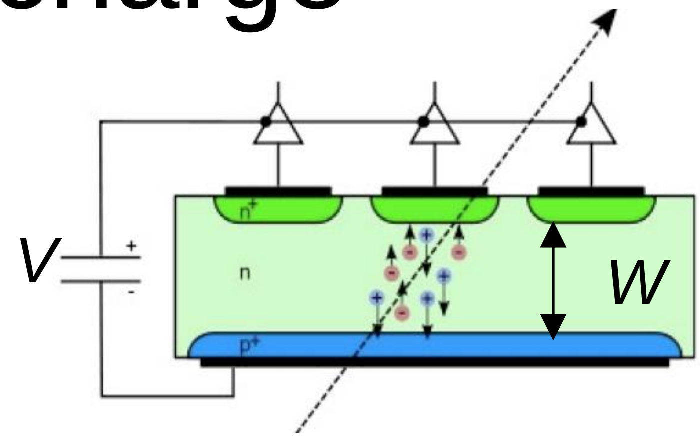
- p-n junction
- **Main figures of merits for detectors**

Spatial resolution

- the structure needs to be split in stripes or pixels



Collected charge



- the longer the particle travels in the detector the larger the induced charge
- **collected charge proportional to** $W{\cdot}A$ where A is the pixel area.
- large W is required,
- but the condition for depletion

$$V + V_{BI} > \frac{qN_A}{\varepsilon_S} W^2$$

implies using **high bias** and **very low doping** levels (high purity crystals)

Dark current

- there are other mechanisms creating e-h pairs;
- e-h creation is assisted by defects;
- simple model:

$$I_{dark} \sim \frac{qWAn_i}{\tau}$$

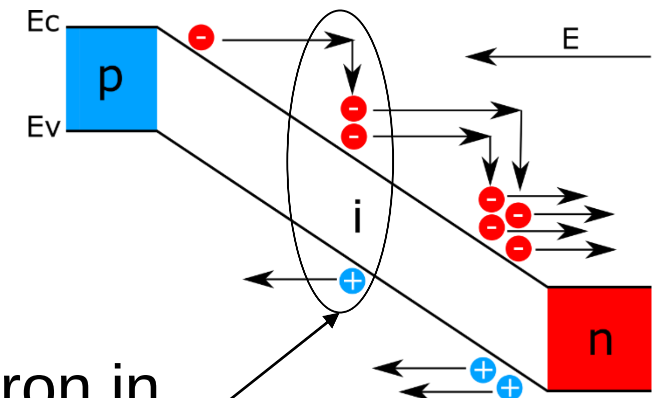
depletion width (W), area (A), generation time (τ)

$$n_i = \sqrt{N_c N_v}\, e^{-E_g/2kT}$$

- a particle can be detected only if the induced current is larger than the dark current;
- this requires **high purity** material and **low temperature**

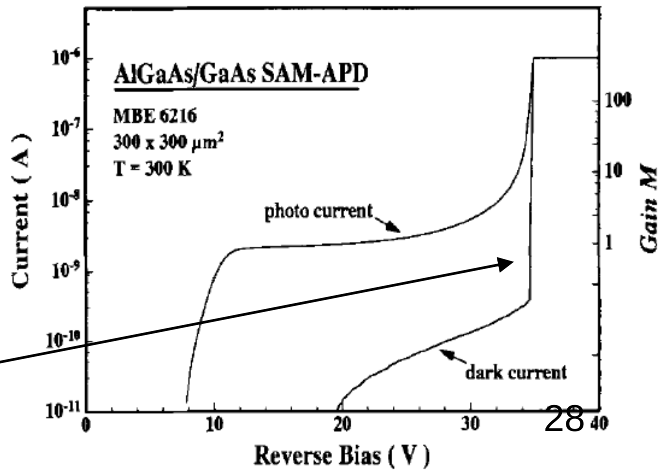
Breakdown voltage (1)

high electric field results in unwanted e-h pair generation by **impact ionization**



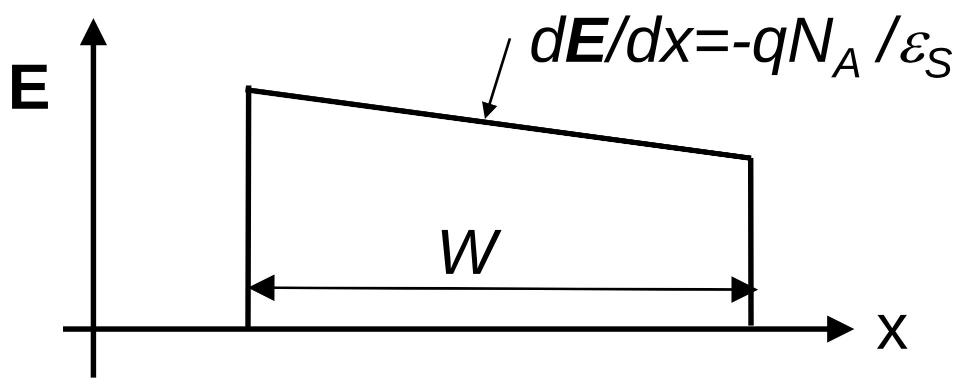
a free electron hits an electron in the valence band obtaining an additional free electron + a hole

the same process can be initiated by a hole → the dark current increases significantly



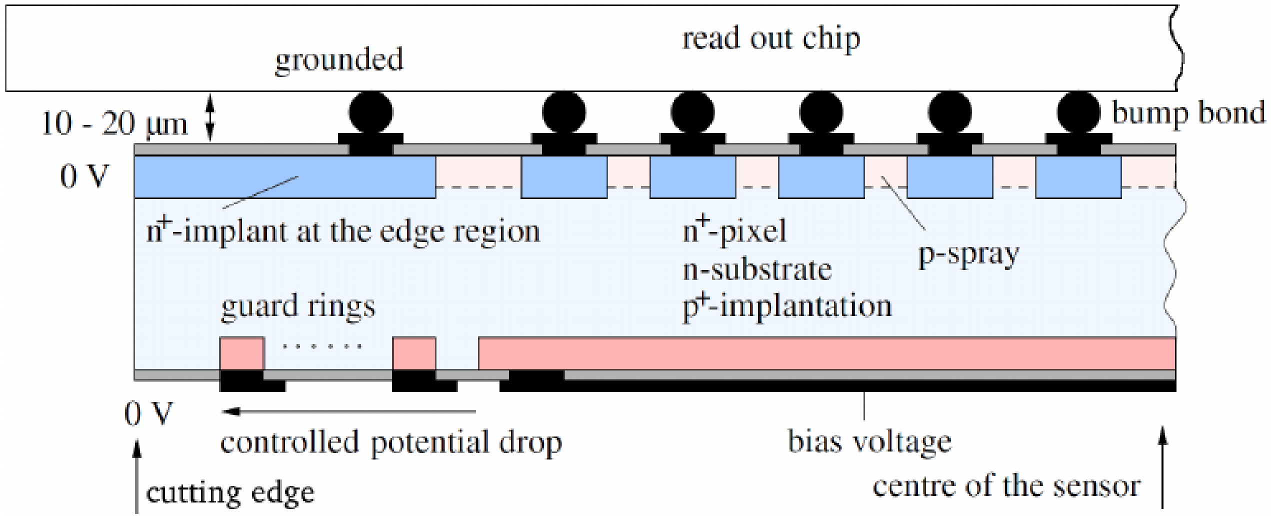
Breakdown voltage (2)

- reduce peak electric field as much as possible → **low doping**

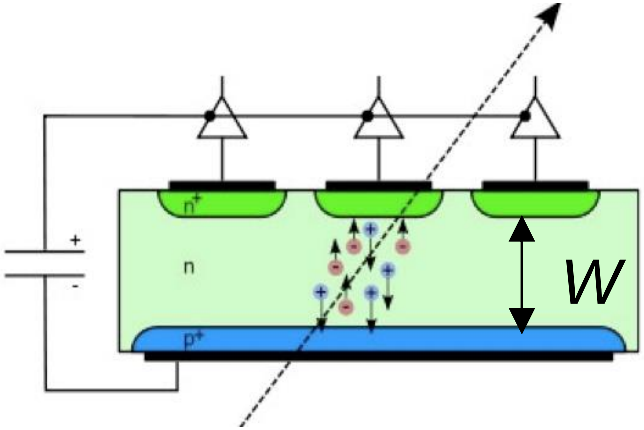


Breakdown voltage (3)

- avoid breakdown at the borders → **guard rings**



Speed



- generated e-h pairs need to reach the high-doping regions

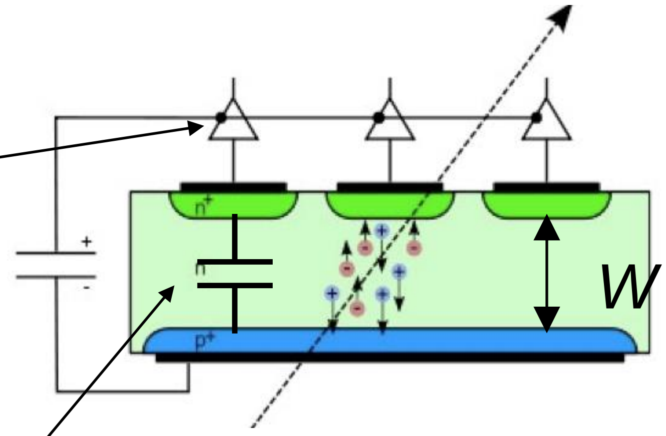
- the duration of the current pulse induced by a particle is in the order of

$$T_{pulse} = \frac{W}{\min(v_e, v_h)}$$

carrier velocity ~10^7cm/s

Capacitance

- The electronic read-out converts the generated charge into a signal
- it adds noise (unwanted random signal) during the process
- this noise is amplified by the detector capacitance
- *C* should be as small as possible



$$C \sim \varepsilon_S \frac{A}{W}$$

area of the pixel