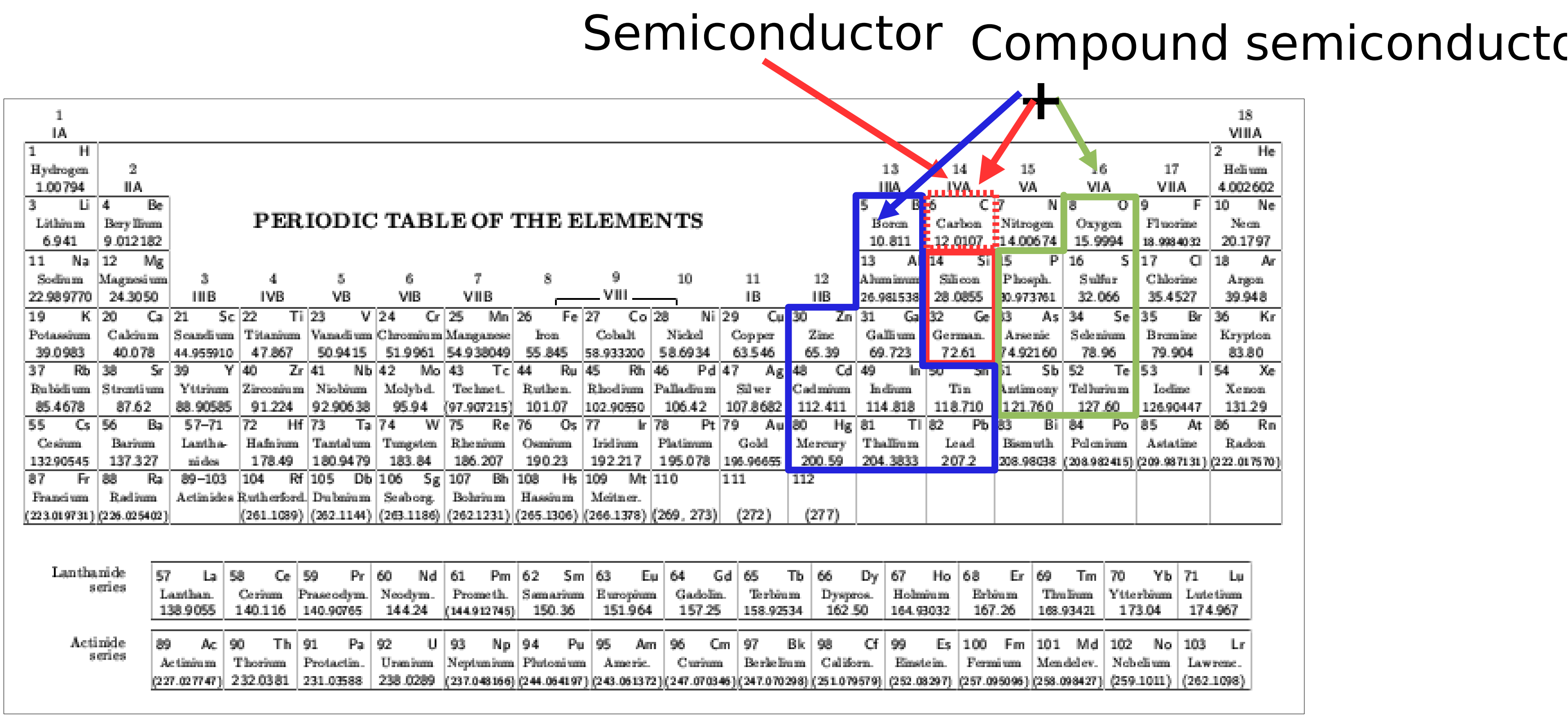
Lecture 1

- Introduction to semiconductors
- Structures and characteristics in semiconductors
    - Semiconductor p-n junction
    - Metal Oxide Silicon structure
    - Semiconductor contact
- Fabrication of semiconductor sensor

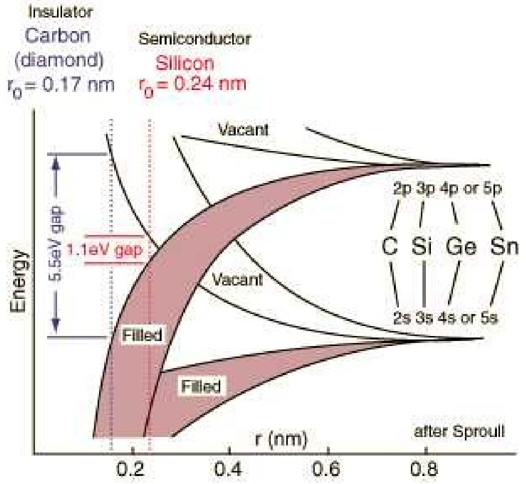
Literature

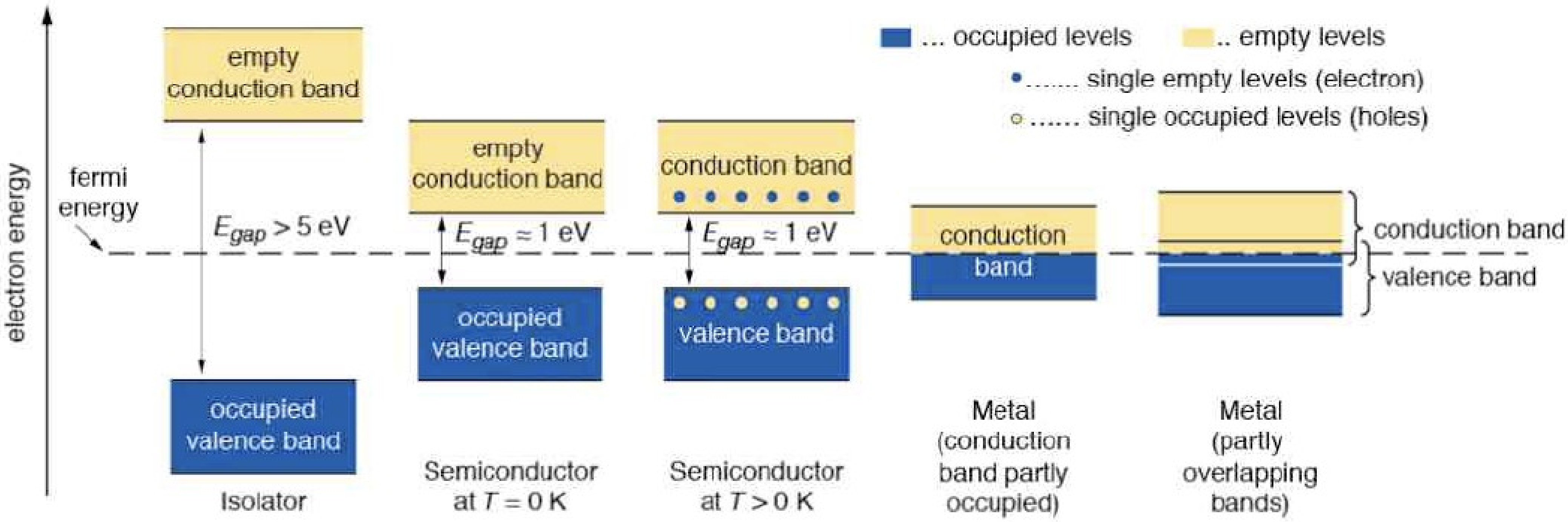
- Glen F. Knoll, Radiation Detection and Measurements, chapters 11,13,19
- Semiconductor Radiation Detectors, Gerhard Lutz, Springer-Verlag, 1999
- Nanohub tutorials

Elements used in semiconductor sensors

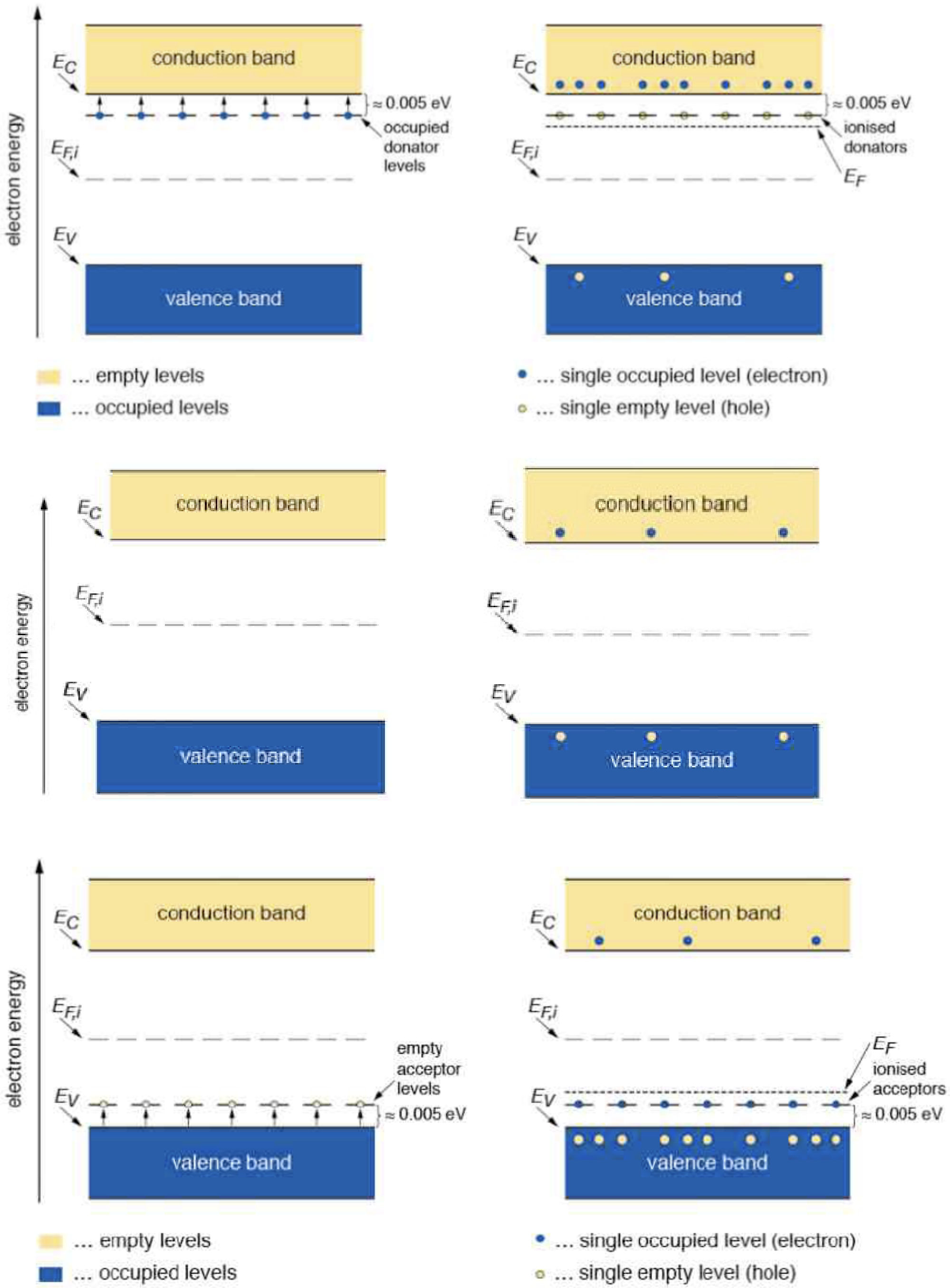


Basics on semiconductors





Semiconductor types



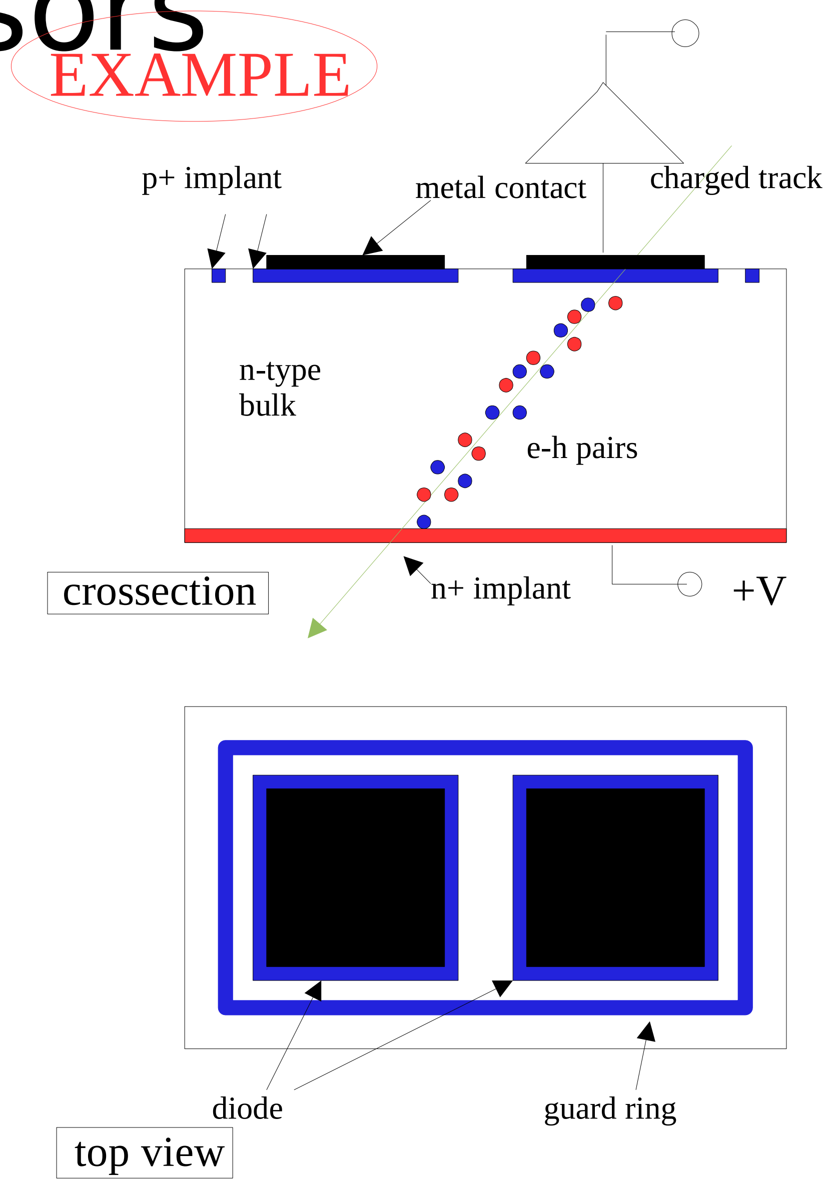
- n-type
  - ✔ Negative donor ions-> excess of electrons in conduction band
  - ✔ Doping with elements from VA,VIA (eg Arsenid)
- Intrinsic
  - ✔ Equal amount of electrons in conduction band and holes in valence band
  - ✔ Pure silicon.
- p-type
  - ✔ Positive acceptor ions-> excess of holes in valence band
  - ✔ Doping with elements from IIA, IIIA (eg Boron)

Properties of common semiconductors

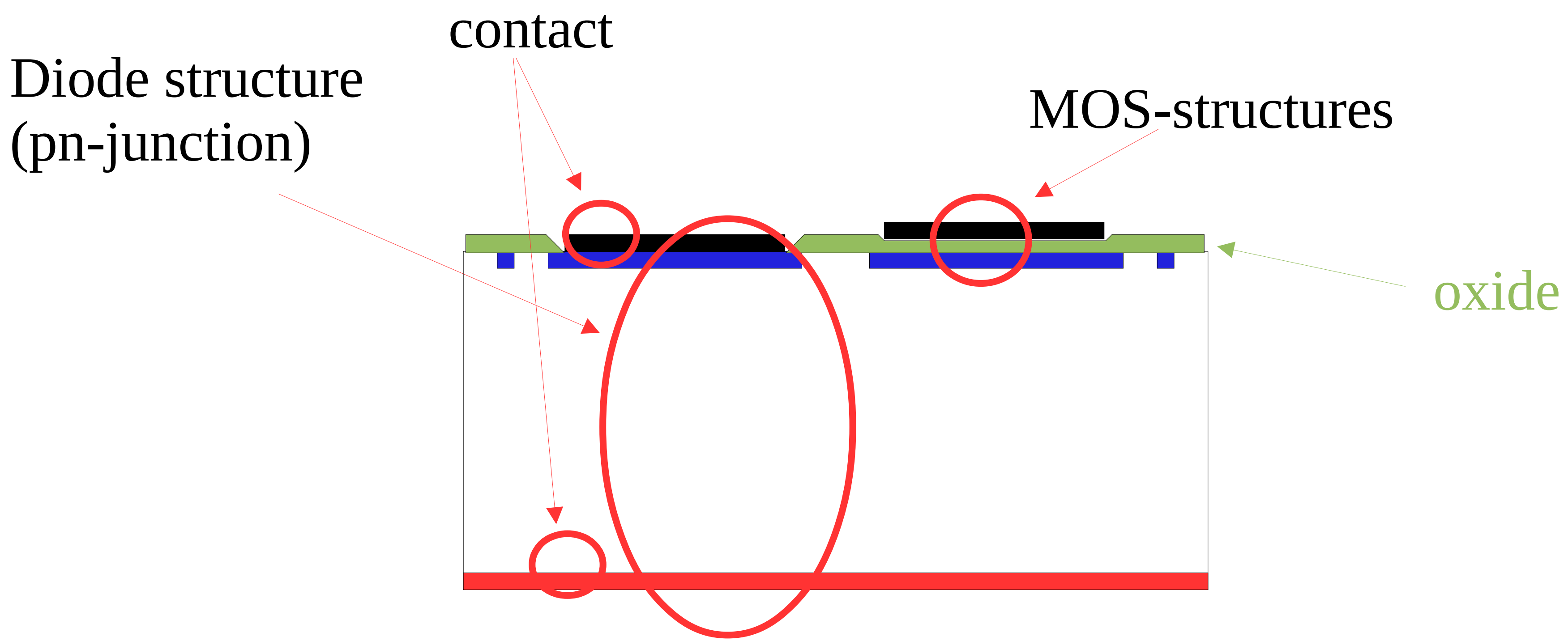
Substance	Si	Ge	GaAs	C	CdTe
Optical transition	Indirect	Indirect	Direct	Indirect	Direct
Energy gap [eV]	1.12	0.67	1.52	5.48	1.56
Intrinsic carrier concentration [cm^{-3}], n_i	1,5 x 10^{10}	2,4 x 10^{12}	2,1 x 10^{10}		
Mean energy for electron-hole pair creation [eV]	3.63	2.96	4.35	13.1	3.9
Drift mobility for electrons, μ_e [cm^2/Vs}	1350	3900	8800	1800	10500
Drift mobility for holes, μ_h[cm^2/Vs}	480	1900	320	1200	100
Intrinsic resistivity [Ω cm}	2,30 x 10^5	47			

Properties of semiconductor sensors

- Small band gap → large number of charge carriers per unit energy loss → excellent energy resolution
- High density compared with gaseous detectors
- High mobility → high speed
- Excellent material properties → rigidity, thermal
- Flexible to design
- Linearity and gain stability
- Tolerant to radiation
- High spatial resolution



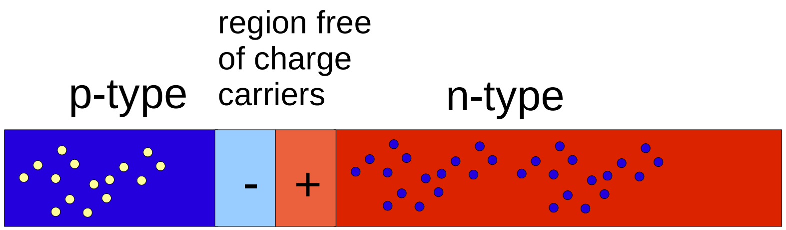
Structures in semiconductor sensors

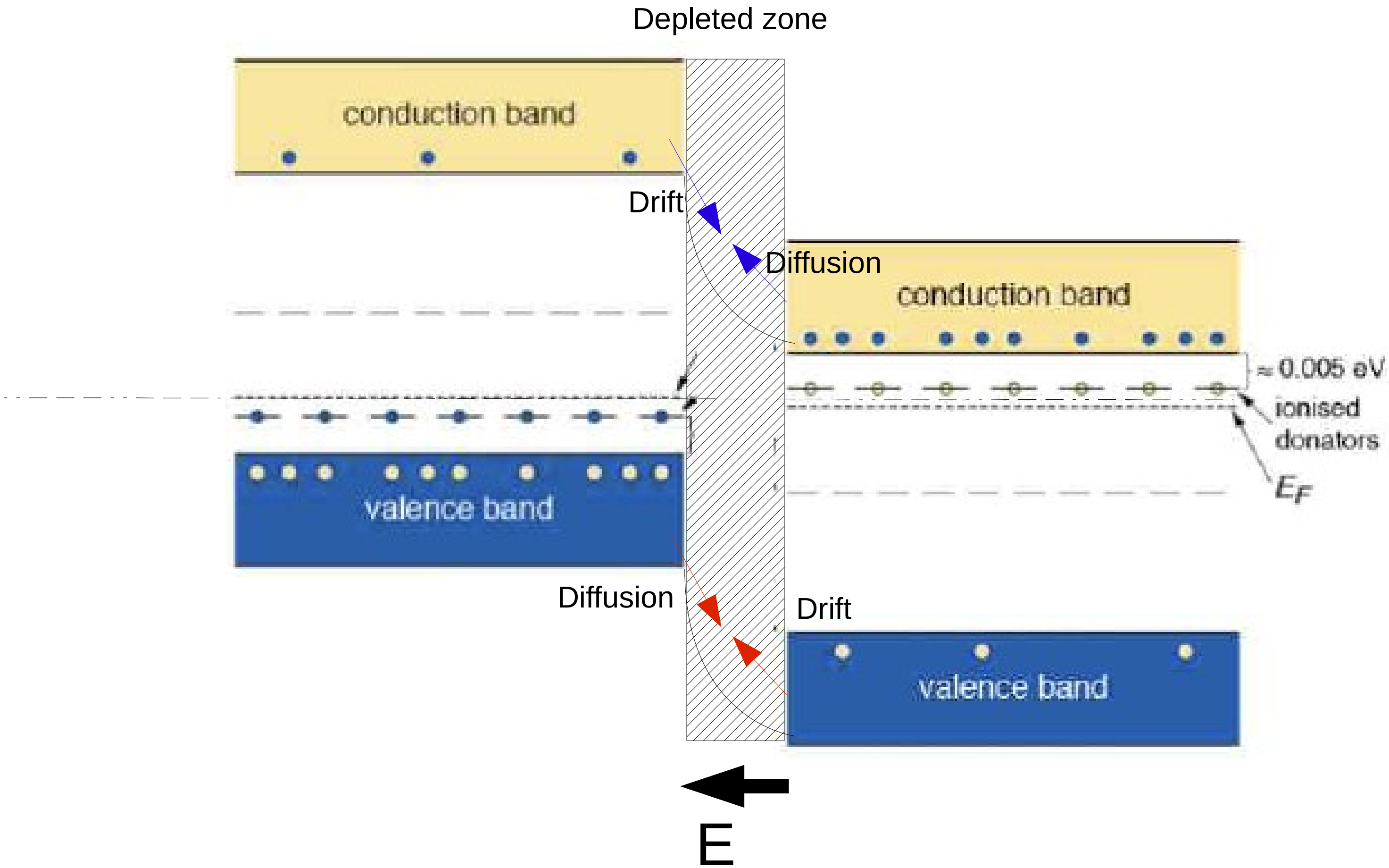


Most important and commonly used structures in semiconductor sensors are

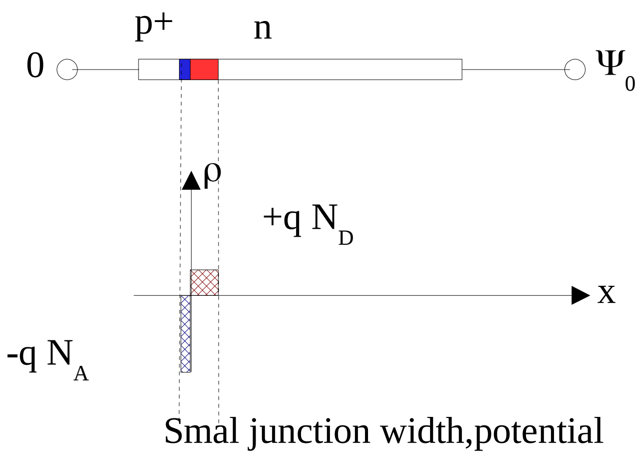
- ✔ Diode structure, pn-junction and np-junction
- ✔ MOS structure (Metal-Oxide-Semiconductor)
- ✔ Contact (OHMIC,SCHOTTKY)

pn-junction


p-type
region free
of charge
carriers
n-type
-
+


Depleted zone
conduction band
Drift
Diffusion
conduction band
≈ 0.005 eV
ionised
donators
E_F
valence band
Diffusion
Drift
valence band
E

Diode structure *(1 dimension)*



$$\Psi_0 = V_T \ln\left(\frac{N_A N_D}{n_i^2}\right)$$

$$V_T = \frac{k_B T}{q} \approx 26\,mV$$

Study a typical n-bulk sensor structure:

Doping concentration in n-region (bulk) is low while the p-region has been implanted with high doping concentration. (Asymmetric junction)

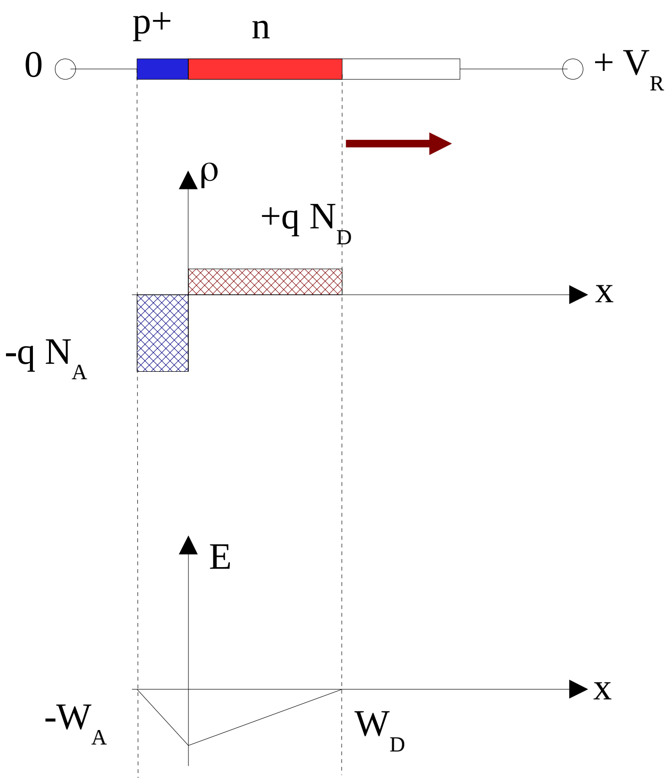
$$N_A >> N_D$$

The built in potential (Ψ_0) in the junction is created by thermal diffusions of electrons into p-region and holes into n-region.

N_A,N_D = concentration of acceptor and donor ions.

n_i = concentration of charge carriers in the bulk (1.5E10 cm^{-3} for Silicon at 300K)

Diode structure (cont. 1)



$$E = -\frac{dV}{dx} = \; = -\frac{q N_A}{\epsilon_R \epsilon_0}(x + W_A)$$

If an external reverse bias voltage V_R is applied the junction will grow. The charge balance in the structure is maintained which results in:

$$W_A N_A = W_D N_D$$

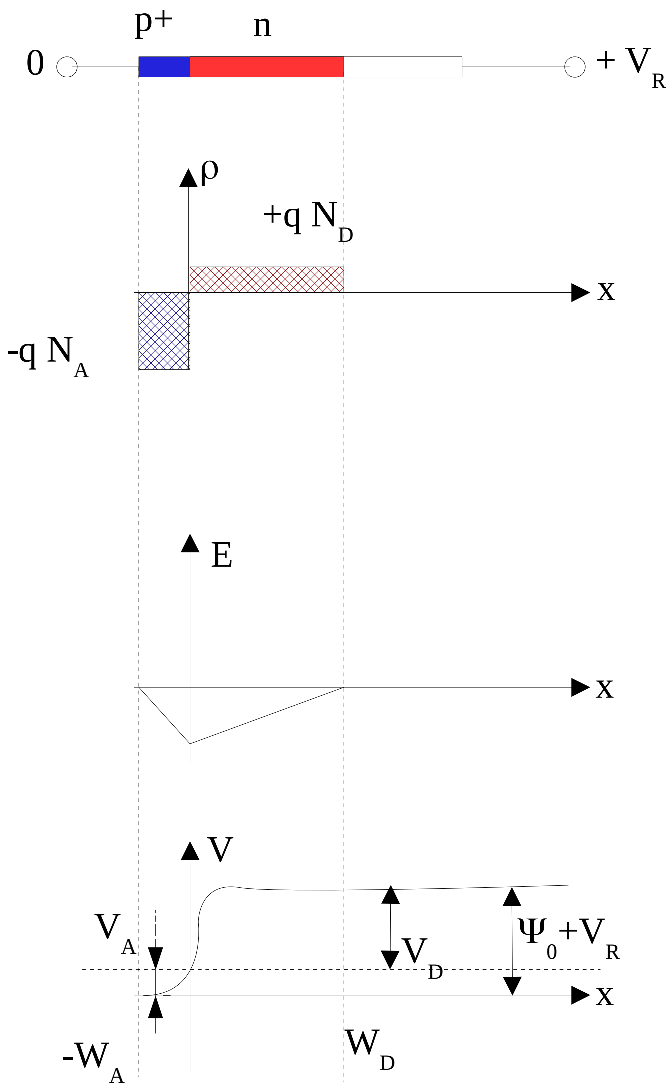
For the region $-W_A$ to x=0 the potential across the region is described by the Poisson equation

$$\frac{d^2 V}{d x^2} = -\frac{\rho}{\epsilon_R \epsilon_0} = \frac{q N_A}{\epsilon_R \epsilon_0}$$

Integration over the p+ region and setting boundary condition $E(-W_A)=0$ results in the field in that region

Integration once more gives the potential in the region =>

Diode structure (cont. 2)



The potential in the region with boundary condition $V(-W_A) = 0$ becomes

$$V = \frac{q N_A}{\epsilon_R \epsilon_0}\left(\frac{x^2}{2} + W_A x + \frac{W_A^2}{2}\right)$$

$-W_A < x < 0$

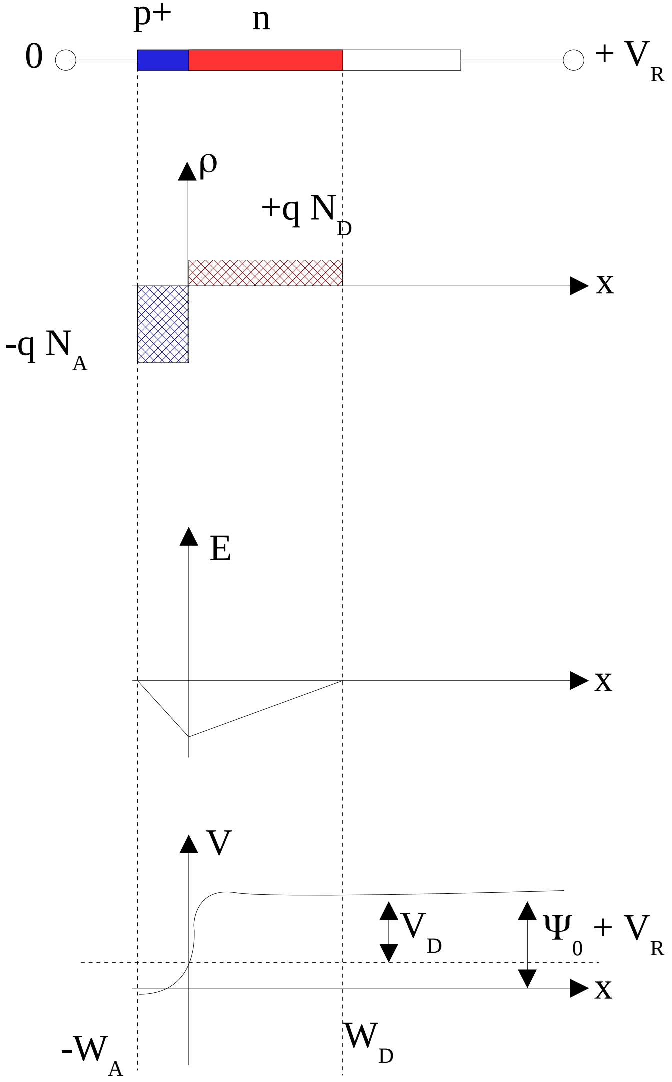
Use this expression to define the potentials V_A at x=0

$$V_A = \frac{q N_A}{\epsilon_R \epsilon_0}\frac{W_A^2}{2}$$

We can with similar considerations determine V_D at x=0

$$V_D = \frac{q N_D}{\epsilon_R \epsilon_0}\frac{W_D^2}{2}$$

Diode structure (cont. 3)



The total potential over the junction (with or without extra reverse bias) is

$$\Psi_0 + V_R = V_A + V_D$$

Because the junction is in equilibrium

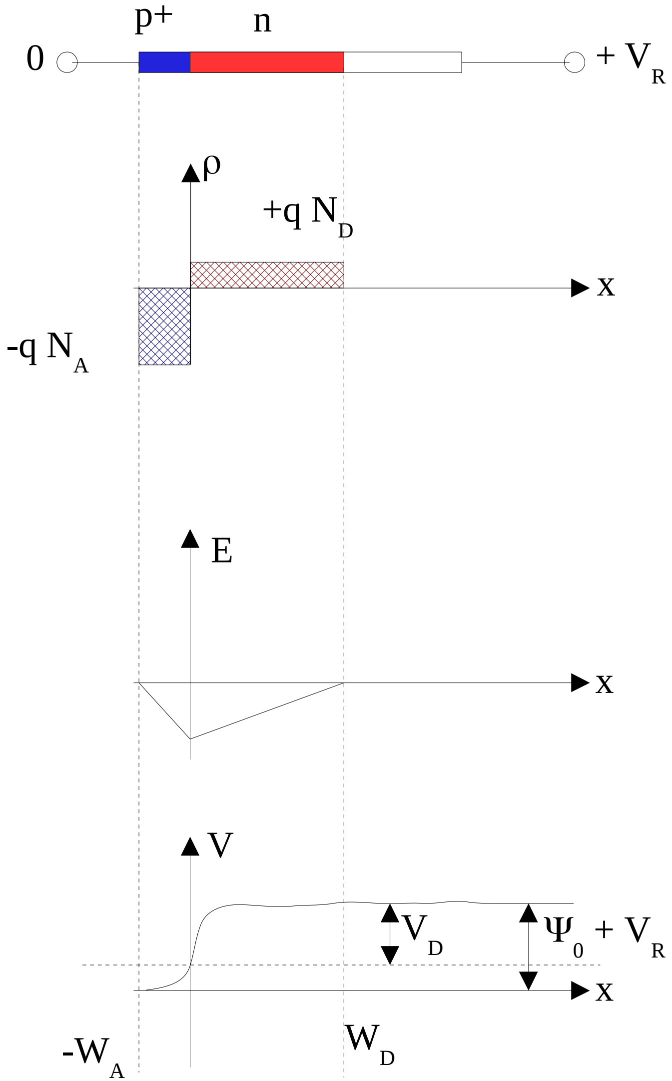
$$W_A N_A = W_D N_D$$

the expression can be written for the n-region

$$\Psi_0 + V_R = \frac{q W^2_D N_D}{\epsilon_R \epsilon_0}\left(1 + \frac{N_D}{N_A}\right)$$

because of our geometry (n-bulk with shallow p+ implant) the only direction the depleted region can grow is in the n-region → $W_D >> W_A = W$

Diode structure (cont. 4)



$$W \approx W_D = \sqrt{\frac{\epsilon_R \epsilon_0 (\Psi_0 + V_R)}{q N_D \left(1 + \frac{N_D}{N_A}\right)}}$$

SUMMARY:

•Depletion width is proportional to the square root of the reverse bias voltage.

•More doping in bulk gives less depletion layer → more voltage will be needed to give same *W*.

•When W_D reaches the physical end of the n-bulk (back plane) the sensor is <u>fully depleted</u>.

Important features

- Macroscopic features of a good semiconductor sensor are
    - ✔ Low capacitive load → low noise in readout electronics
    - ✔ Low leakage current → low noise in readout electronics
    - ✔ Good charge collection
    - ✔ High speed

Characteristics of the diode structure

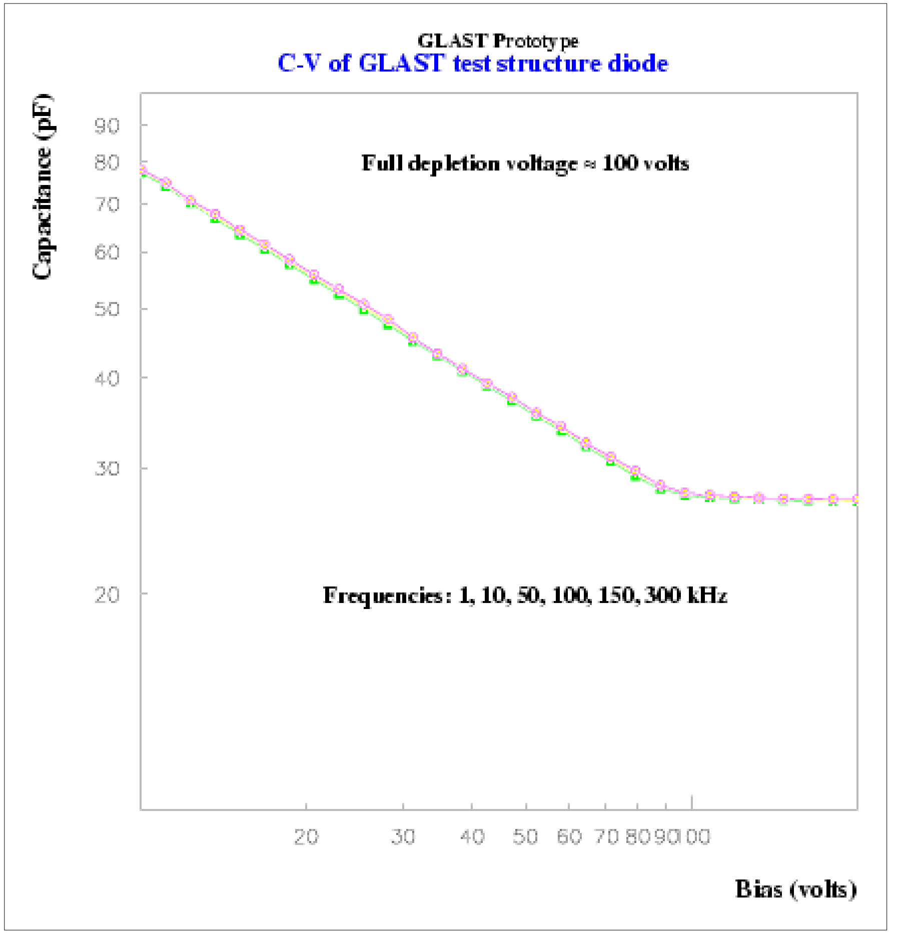
- **Capacitance (C-V)**

The capacitance of the diode influences the noise of the readout electronics by loading the amplifier *(will be discussed later in this series)*. The capacitance of the pn-junction is given by

$$C_j = \frac{\epsilon_R \epsilon_0}{W_D}$$

The capacitance of the junction will decrease when reverse bias voltage is applied until full depletion is reached.

WE WANT LOW CAPACITANCE!



Characteristics of the diode structure

- **Leakage current (I-V)**
  - ✔ <u>diffusion current</u>

Electrons generated in the p+ region and holes generated in the n+ region diffuse to the junction and are collected by electrodes. Small effect for Si but large for Ge at room temperature.

$$J_s = q\sqrt{\frac{D_P}{\tau_P}}\frac{n_i^2}{N_D}$$

where D_P is the diffusion constant for electrons in the p+ region and τ_P is the lifetime of the electron

✔ <u>generating current</u>

This is the dominated current in a good sensor. The current is due to generation-recombination in the depleted region.

$$J_g = q\,gW$$

g is the generation rate dependent of the intrinsic carrier concentration, n_i.

$$g = \frac{n_i}{\tau_g}$$

τ_g is the generation lifetime ($\sim 10^{-3}$ s)

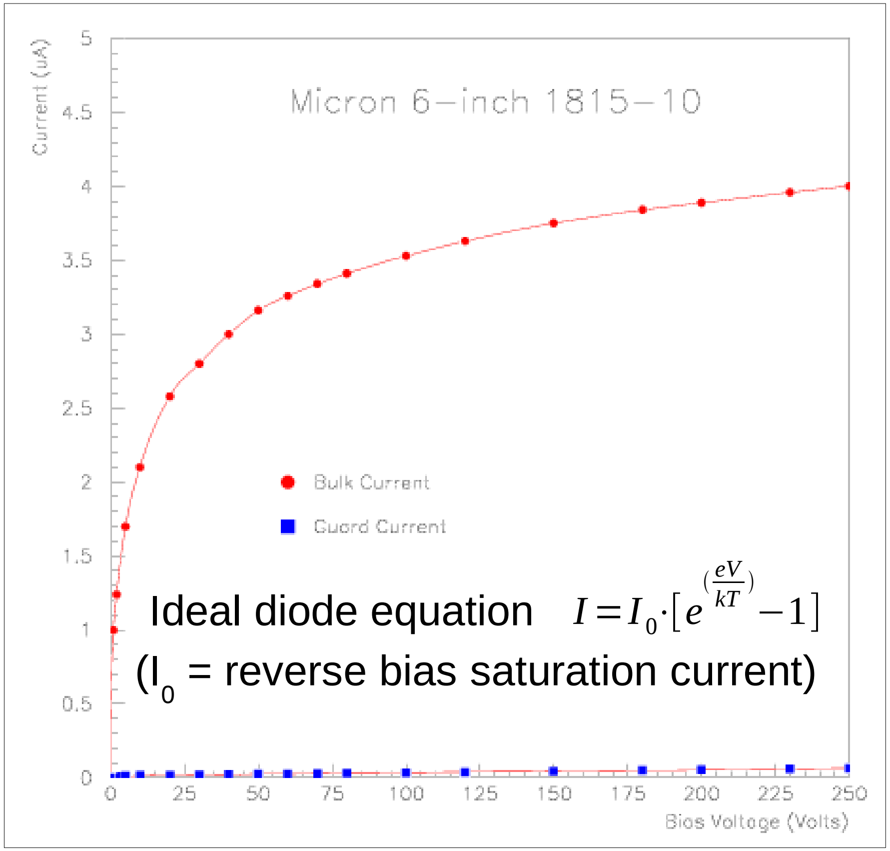
Characteristics of the diode structure

- **Leakage current (I-V)**
  - ✔ generating current(cont.)

The current is also sensitive to temperature. 8K increase in temperature doubles the current!!

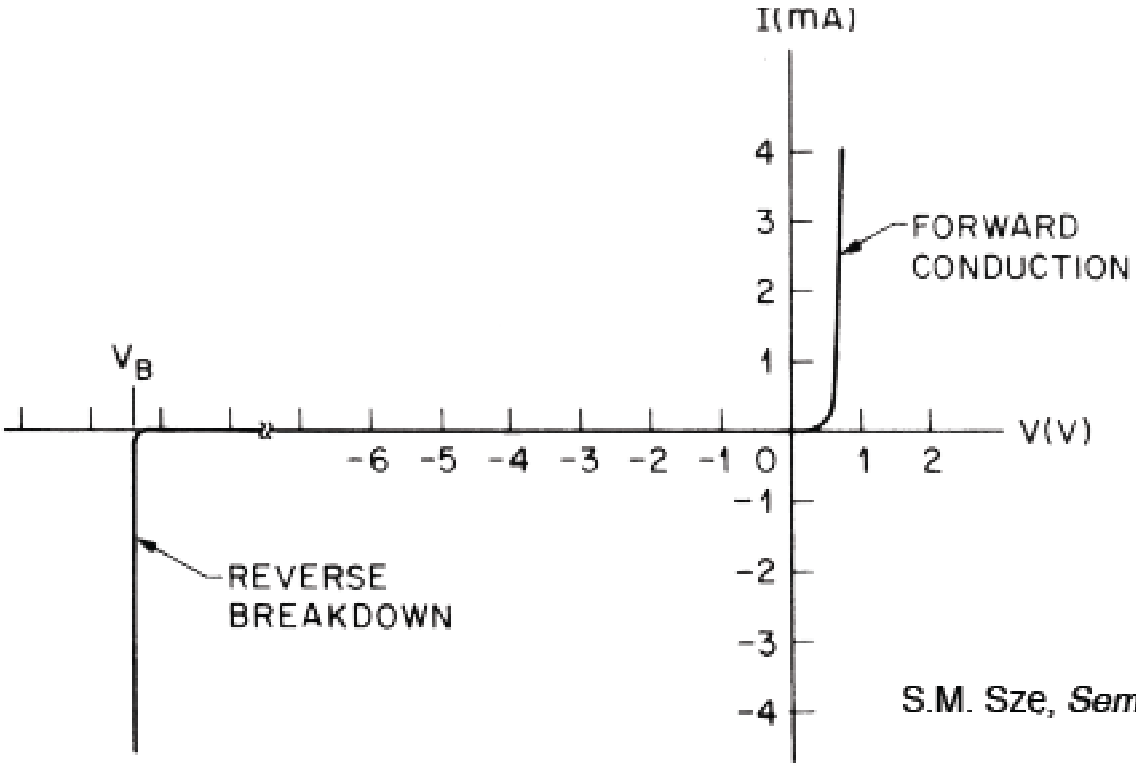
  - ✔ surface current

Surface current is a contribution on complex effects happening in the boarder between the semiconductor and surface oxide. The current level is very dependent on processing quality and handling.

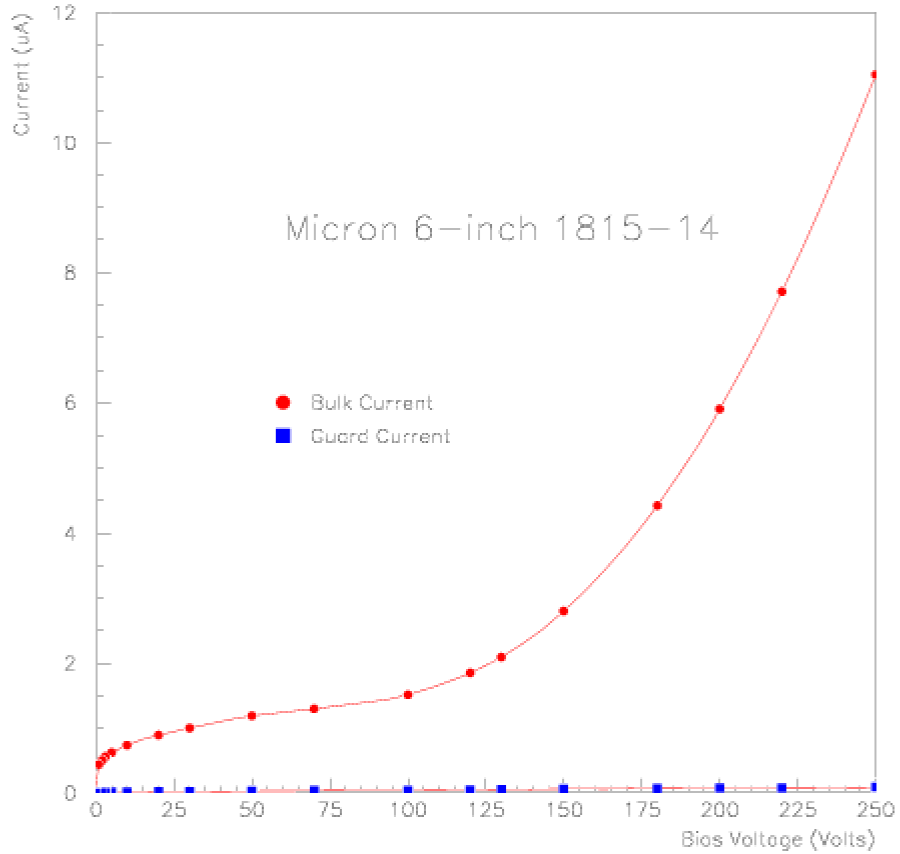


GOOD I-V curve

More on IV-characteristics

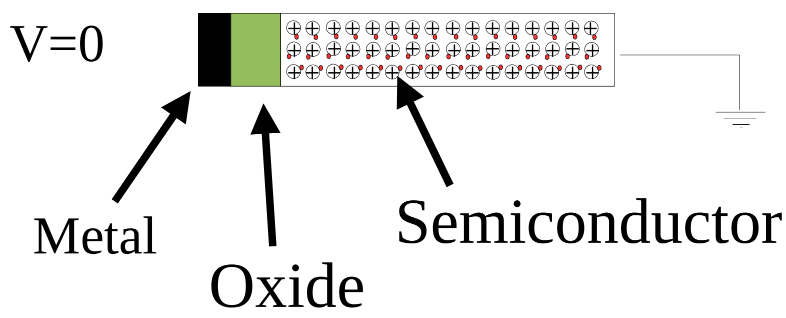


S.M. Sze, *Semiconductor Devices* , J. Wiley & Sons, 1985


Current (uA)
Micron 6–inch 1815–14
Bulk Current
Guard Current
Bias Voltage (Volts)
0
2
4
6
8
10
12
0
25
50
75
100
125
150
175
200
225
250

BAD I-V curve !

Metal-Oxide-Semiconductor structure

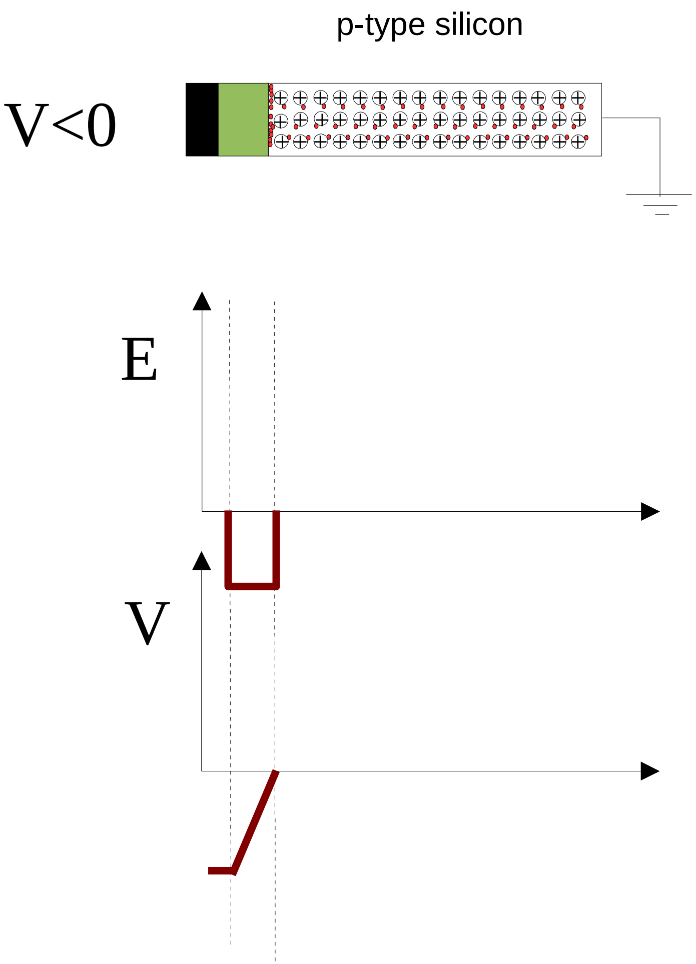


- MOS structure (or more general Metal-Insulator-Semiconductor, MIS) is widely used in electronics industry to make gates and in sensor industry to make AC-coupled sensors

- The figure shows a 1-dimensional picture of a MOS structure with a n-doped semiconductor insulated from a metal layer with a oxide.

- If the potential at the metal is at the same potential as the semiconductor and the charge carrier electrons in the n-type semiconductor will be homogeneously distributed → no field across the oxide. This is called the <u>Flat Band condition</u>.

MOS in accumulation

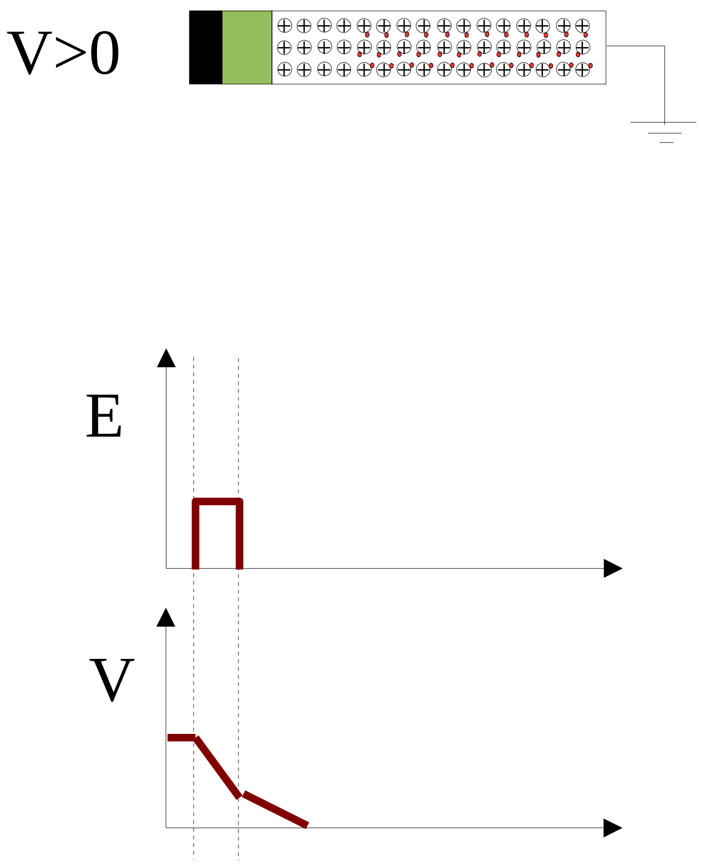


- If the potential on the metal is set below the voltage of the semiconductor the holes are attracted to the semiconductor-oxide interface where they accumulate to a very thin layer. This is called <u>Accumulation condition.</u>
- A field is created across the oxide.

$$E_{ox} = \frac{Q_{acc}}{\epsilon_{ox}\epsilon_0}$$

$$V = E_{ox} d_{ox} = -\frac{Q_{acc}}{C_{ox}}$$

MOS in depletion

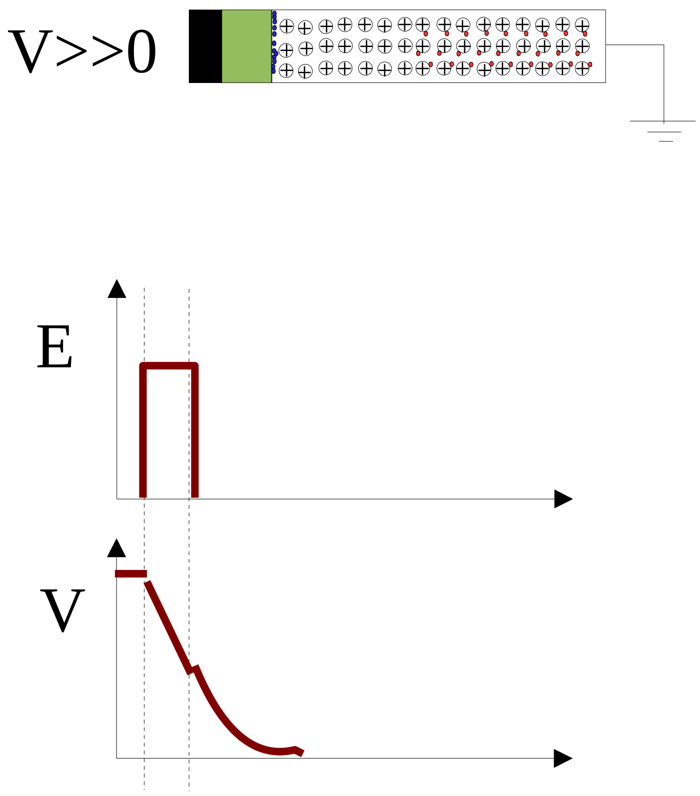


- If the potential on the metal is increased slightly above the voltage of the semiconductor the holes are repelled from the semiconductor-oxide interface and a negative space charge region is formed. This is called <u>Depletion condition</u> *(used by CCD detectors)*
- A field is created across the oxide and the space charge regions.

$$E_{ox} = -\frac{q N_D}{\epsilon_{ox}\epsilon_0} d_s$$

$$E_s = -\frac{q N_D}{\epsilon_s \epsilon_0} d_s$$

MOS in inversion



- If the potential on the metal is very much above the voltage of the semiconductor the holes are pushed even further away from the semiconductor-oxide interface. Thermally generated electron-holes pairs are separated from each other thus an inversion layer of electrons is built up at the interface. This is called <u>Inversion condition.</u>

$$E_{ox} = -\frac{q N_D}{\epsilon_{ox}\epsilon_0} d_{max} - \frac{Q_{inv}}{\epsilon_{ox}\epsilon_0}$$

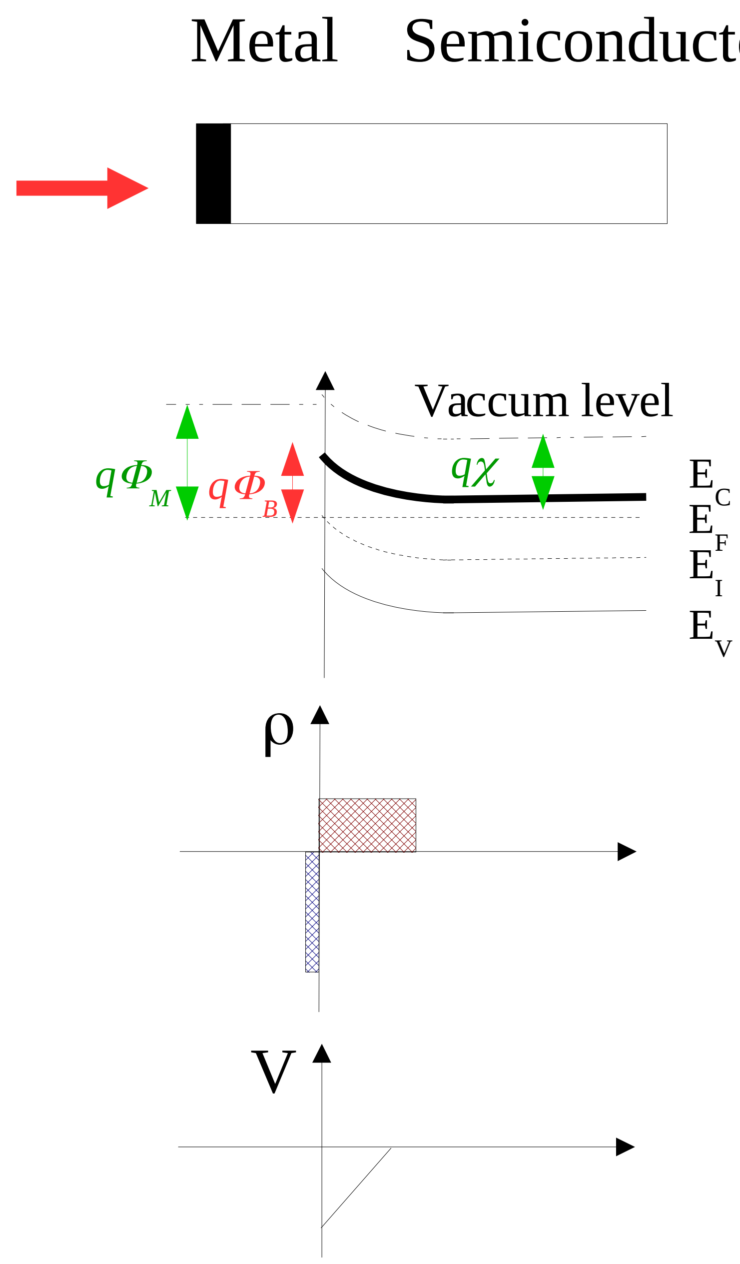
$$E_s = -\frac{q N_D}{\epsilon_s \epsilon_0} d_s$$

Schottky contact

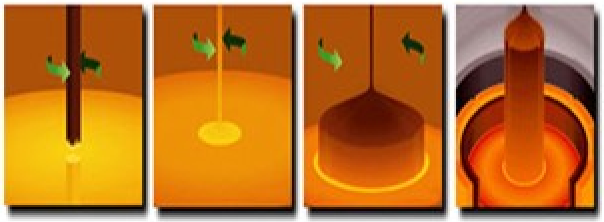
- A contact to the semiconductor can be made by deposition of a metal layer directly onto the silicon. This metal-semiconductor contact was one of the first practical semiconductor showing rectifying properties, the Schottky contact (used in surface barrier detectors).
- If the doping concentration under the metal is high the characteristic resistance of the junctions becomes small, the rectifying feature turns into an Ohmic contact.
- It is not trivial to model the metal-silicon junction. To the first order the barrier an electron has to overcome to get from the metal to the silicon region is related to the work function of the metal (Schottky-Mott model) but in reality it is much more complex.

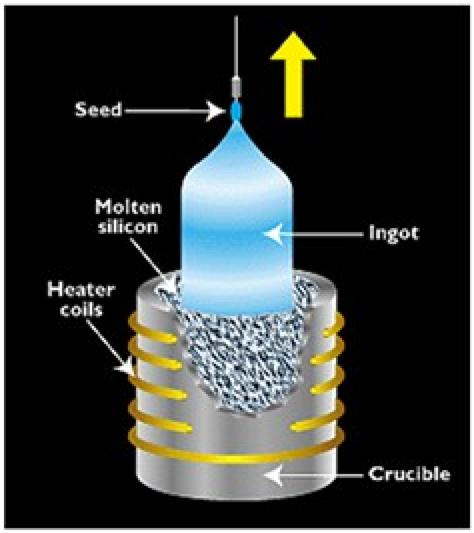
$$q\Phi_B = q(\Phi_m - \chi)$$

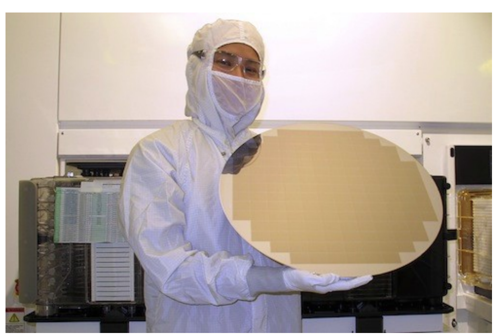
where Φ_m = work function and χ = electron affinity for a electron to reach vacuum from metal and conduction band respectively.



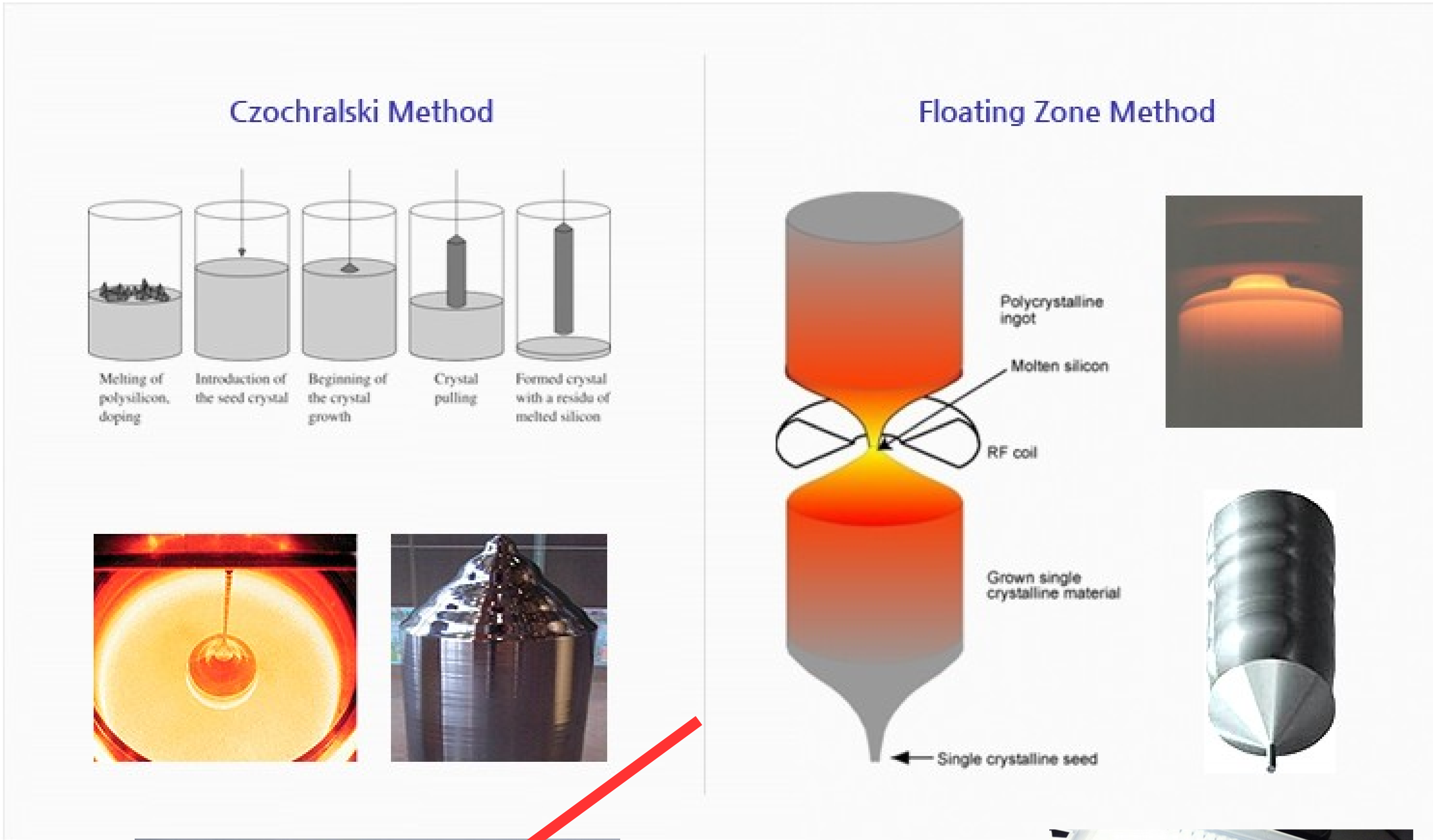
Fabrication of semiconductor sensors

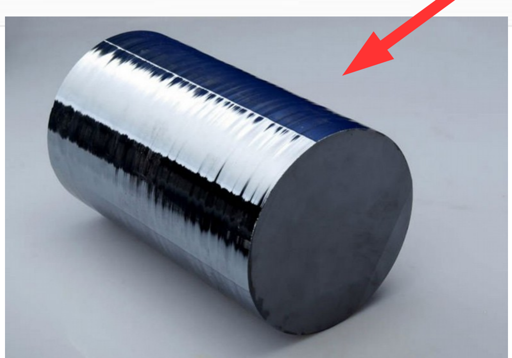


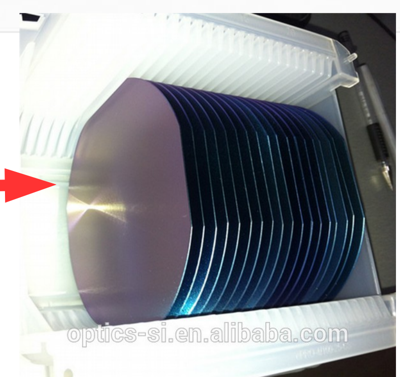




Material





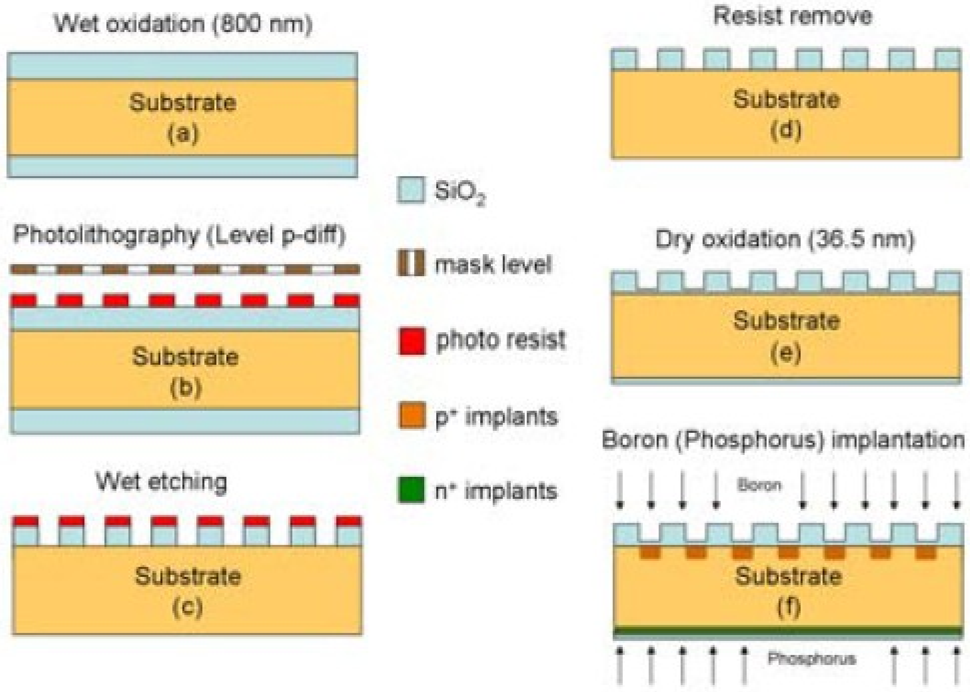


You will probably visit the silicon producer Okmetic Oy during your lab-week in Helsinki

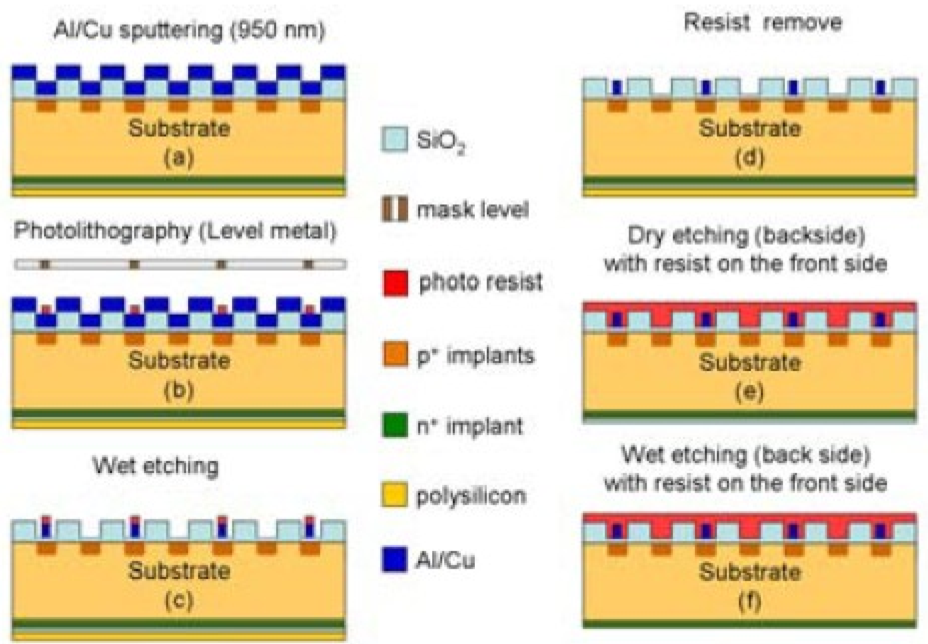
Processing steps

(example taken from PhD thesis of Daniela Bassignama-INB-CNM, Barcelona)

The processing of silicon sensors for tracking is done in a planar process (opposite to sensors for eg. Gamma spectroscopy that are coaxial).

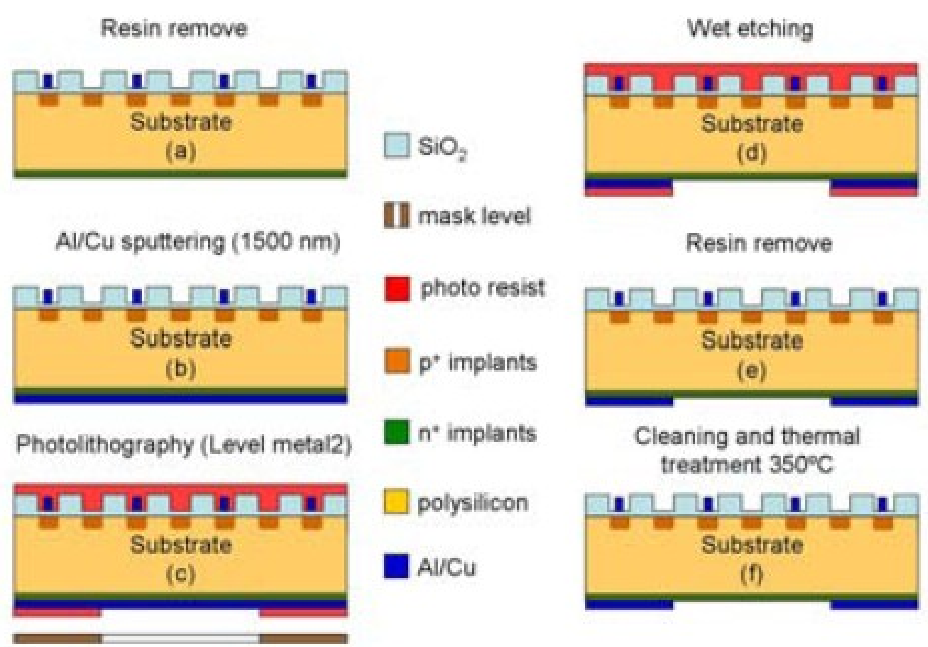


Dopant	Dose [at/cm^2]	Energy [keV]	Final conc. [at/cm^2]	Junction depth [μm]
Boron	1.5 10^{14}	100	10^{20}	1
Phosphorus	1 10^{13}	50	10^{19}	1



It is important to design the sensor to prevent high field regions. Care has to be taken in the design of metallisation and implants

We will look at a number of different sensors/detectors used
In particle physics in next lecture



END LECTURE