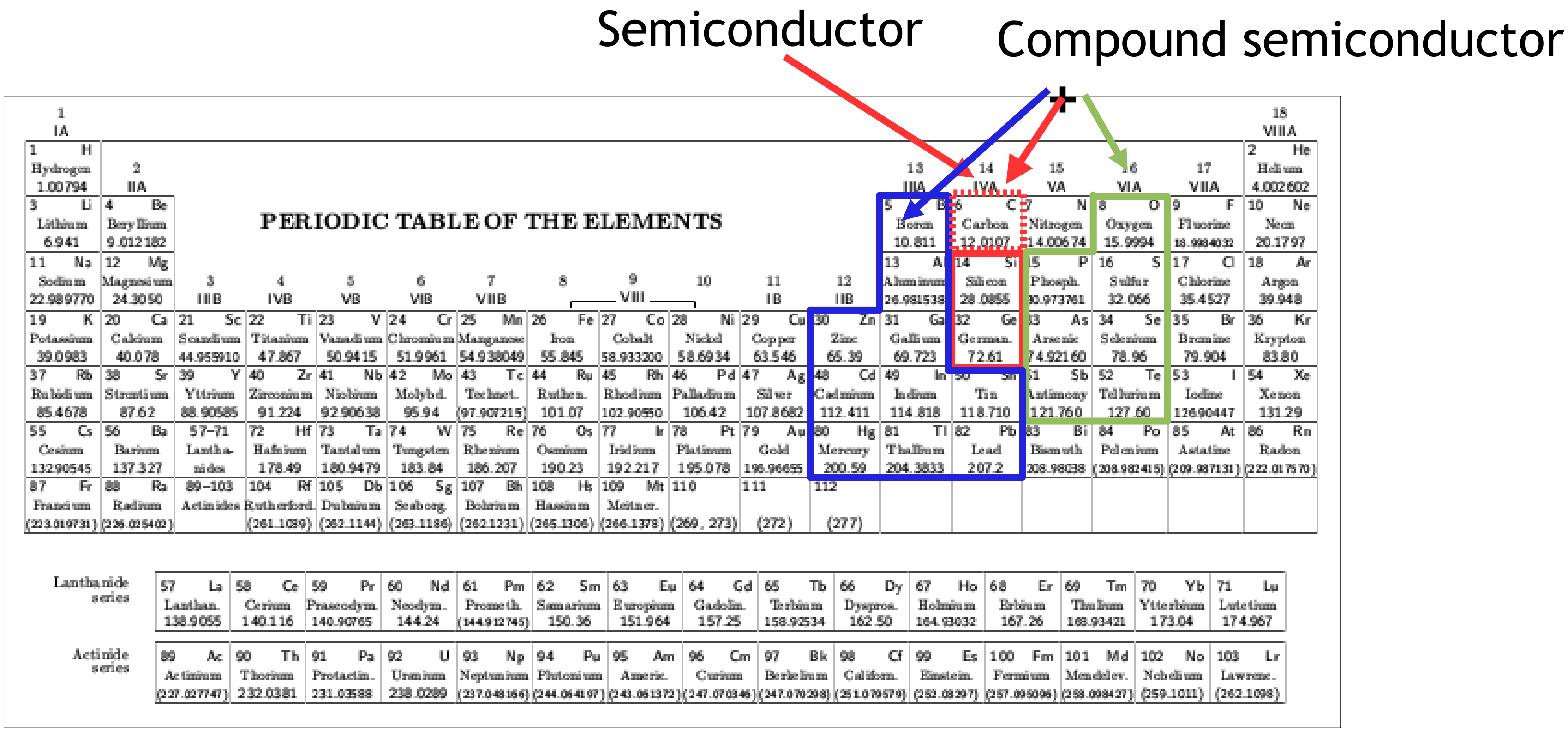
Lecture 2

- 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



Semiconductor

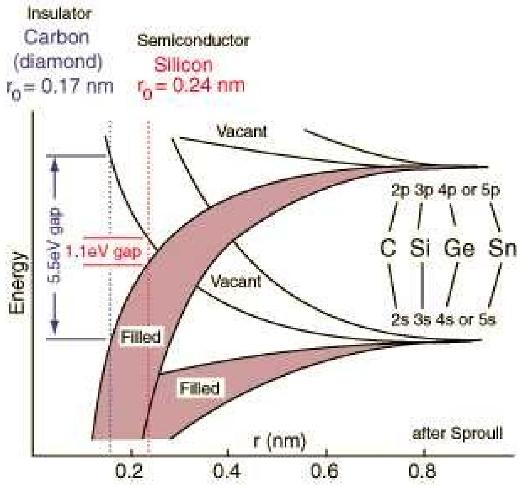
Compound semiconductor

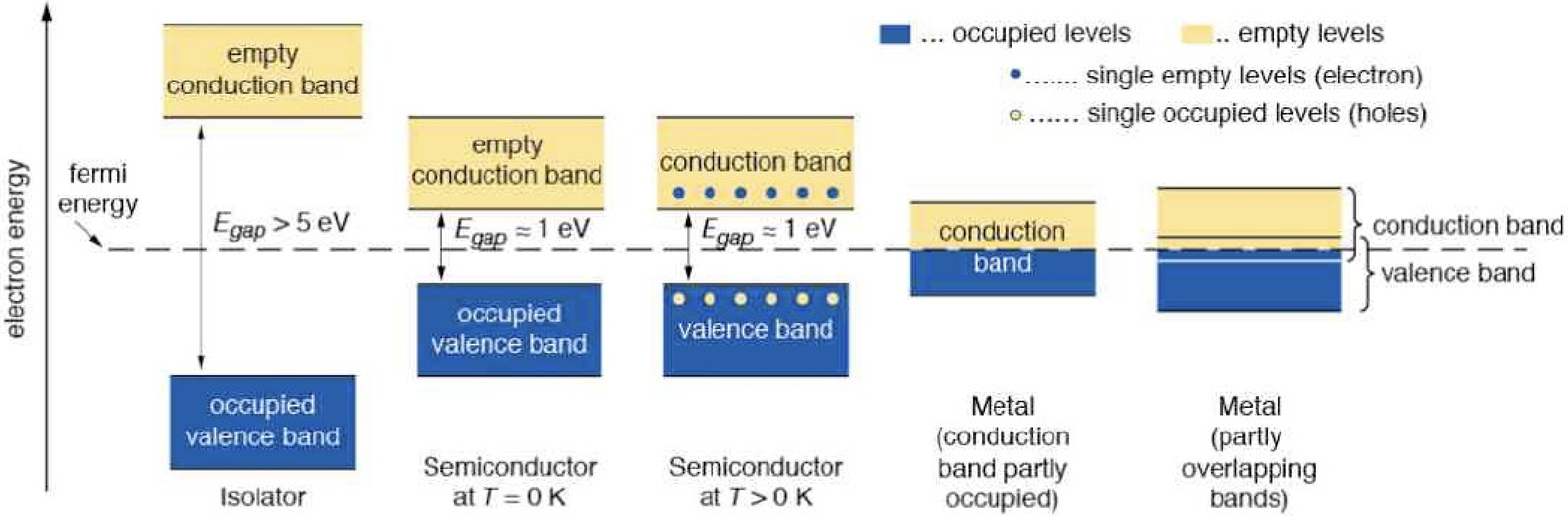
PERIODIC TABLE OF THE ELEMENTS

1 IA	2 IIA	3 IIIB	4 IVB	5 VB	6 VIB	7 VIIB	8	9 VIII	10	11 IB	12 IIB	13 IIIA	14 IVA	15 VA	16 VIA	17 VIIA	18 VIIIA
1 H Hydrogen 1.00794																	2 He Helium 4.002602
3 Li Lithium 6.941	4 Be Beryllium 9.012182											5 B Boron 10.811	6 C Carbon 12.0107	7 N Nitrogen 14.00674	8 O Oxygen 15.9994	9 F Fluorine 18.9984032	10 Ne Neon 20.1797
11 Na Sodium 22.989770	12 Mg Magnesium 24.3050											13 Al Aluminum 26.981538	14 Si Silicon 28.0855	15 P Phosph. 30.973761	16 S Sulfur 32.066	17 Cl Chlorine 35.4527	18 Ar Argon 39.948
19 K Potassium 39.0983	20 Ca Calcium 40.078	21 Sc Scandium 44.955910	22 Ti Titanium 47.867	23 V Vanadium 50.9415	24 Cr Chromium 51.9961	25 Mn Manganese 54.938049	26 Fe Iron 55.845	27 Co Cobalt 58.933200	28 Ni Nickel 58.6934	29 Cu Copper 63.546	30 Zn Zinc 65.39	31 Ga Gallium 69.723	32 Ge German. 72.61	33 As Arsenic 74.92160	34 Se Selenium 78.96	35 Br Bromine 79.904	36 Kr Krypton 83.80
37 Rb Rubidium 85.4678	38 Sr Strontium 87.62	39 Y Yttrium 88.90585	40 Zr Zirconium 91.224	41 Nb Niobium 92.90638	42 Mo Molybd. 95.94	43 Tc Technet. (97.907215)	44 Ru Ruthen. 101.07	45 Rh Rhodium 102.90550	46 Pd Palladium 106.42	47 Ag Silver 107.8682	48 Cd Cadmium 112.411	49 In Indium 114.818	50 Sn Tin 118.710	51 Sb Antimony 121.760	52 Te Tellurium 127.60	53 I Iodine 126.90447	54 Xe Xenon 131.29
55 Cs Cesium 132.90545	56 Ba Barium 137.327	57–71 Lanthanides	72 Hf Hafnium 178.49	73 Ta Tantalum 180.9479	74 W Tungsten 183.84	75 Re Rhenium 186.207	76 Os Osmium 190.23	77 Ir Iridium 192.217	78 Pt Platinum 195.078	79 Au Gold 196.96655	80 Hg Mercury 200.59	81 Tl Thallium 204.3833	82 Pb Lead 207.2	83 Bi Bismuth 208.98038	84 Po Polonium (208.982415)	85 At Astatine (209.987131)	86 Rn Radon (222.017570)
87 Fr Francium (223.019731)	88 Ra Radium (226.025402)	89–103 Actinides	104 Rf Rutherford. (261.1089)	105 Db Dubnium (262.1144)	106 Sg Seaborg. (263.1186)	107 Bh Bohrium (262.1231)	108 Hs Hassium (265.1306)	109 Mt Meitner. (266.1378)	110 (269, 273)	111 (272)	112 (277)						

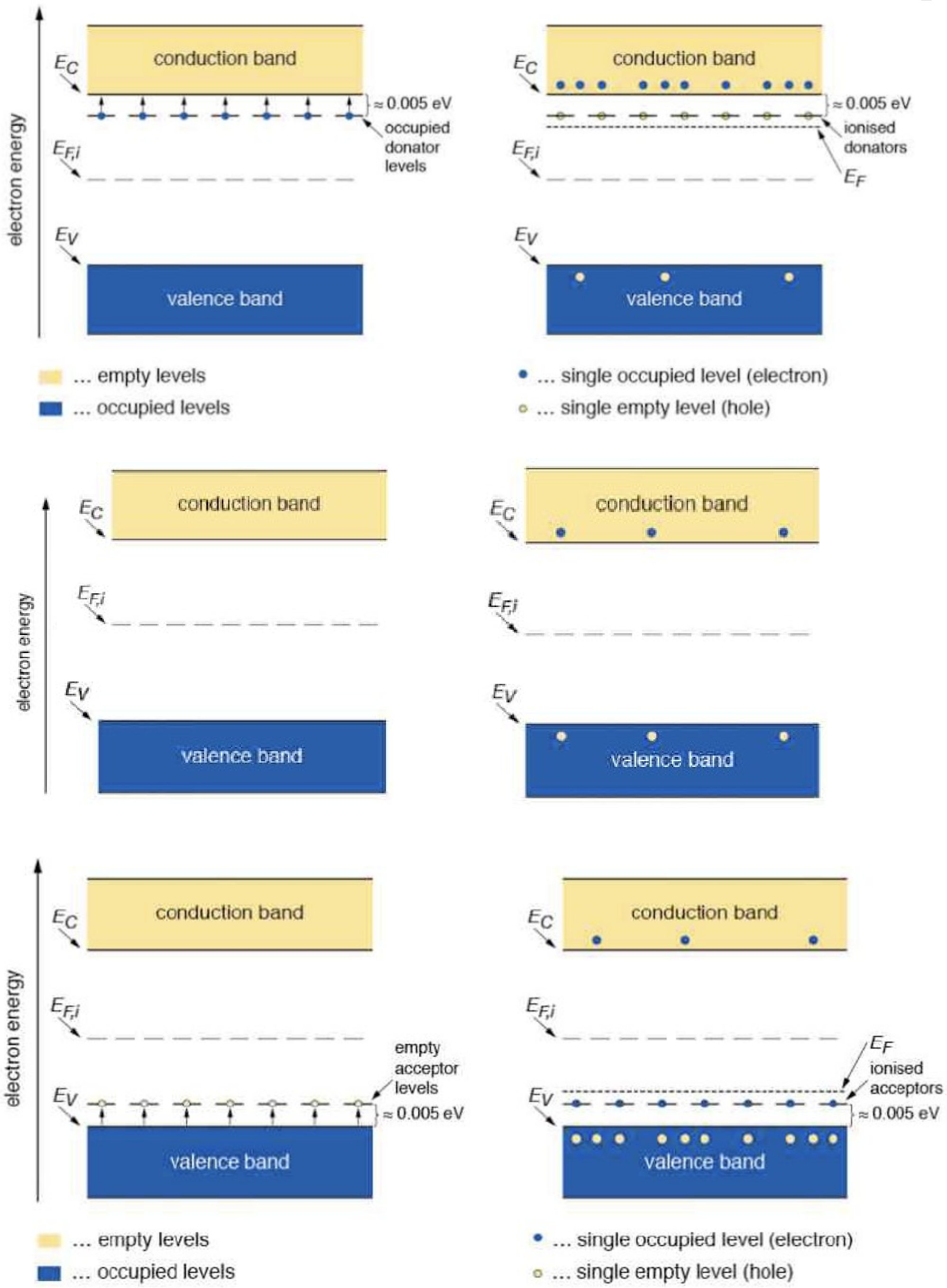
Lanthanide series	57 La Lanthan. 138.9055	58 Ce Cerium 140.116	59 Pr Praseodym. 140.90765	60 Nd Neodym. 144.24	61 Pm Prometh. (144.912745)	62 Sm Samarium 150.36	63 Eu Europium 151.964	64 Gd Gadolin. 157.25	65 Tb Terbium 158.92534	66 Dy Dyspros. 162.50	67 Ho Holmium 164.93032	68 Er Erbium 167.26	69 Tm Thulium 168.93421	70 Yb Ytterbium 173.04	71 Lu Lutetium 174.967
Actinide series	89 Ac Actinium (227.027747)	90 Th Thorium 232.0381	91 Pa Protactin. 231.03588	92 U Uranium 238.0289	93 Np Neptunium (237.048166)	94 Pu Plutonium (244.064197)	95 Am Americ. (243.061372)	96 Cm Curium (247.070346)	97 Bk Berkelium (247.070298)	98 Cf Californ. (251.079579)	99 Es Einstein. (252.08297)	100 Fm Fermium (257.095096)	101 Md Mendelev. (258.098427)	102 No Nobelium (259.1011)	103 Lr Lawrenc. (262.1098)

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)

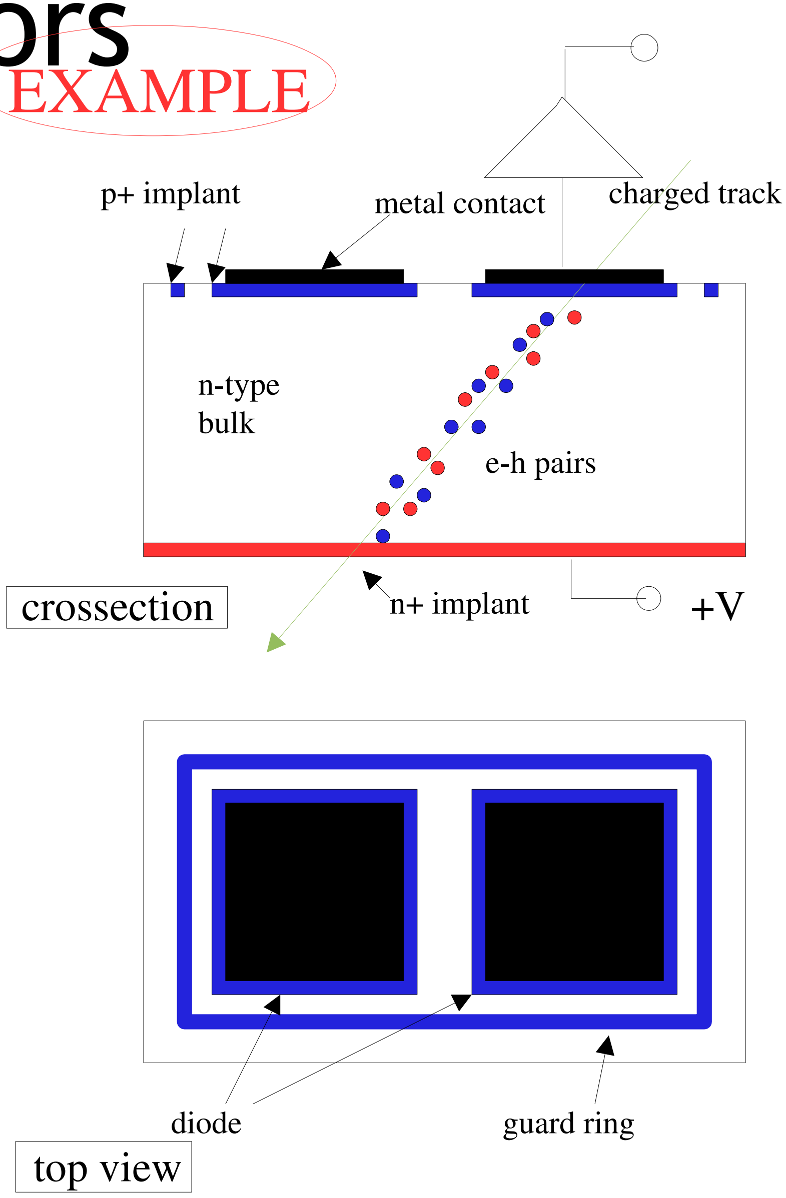
Properties of common semiconductors

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			

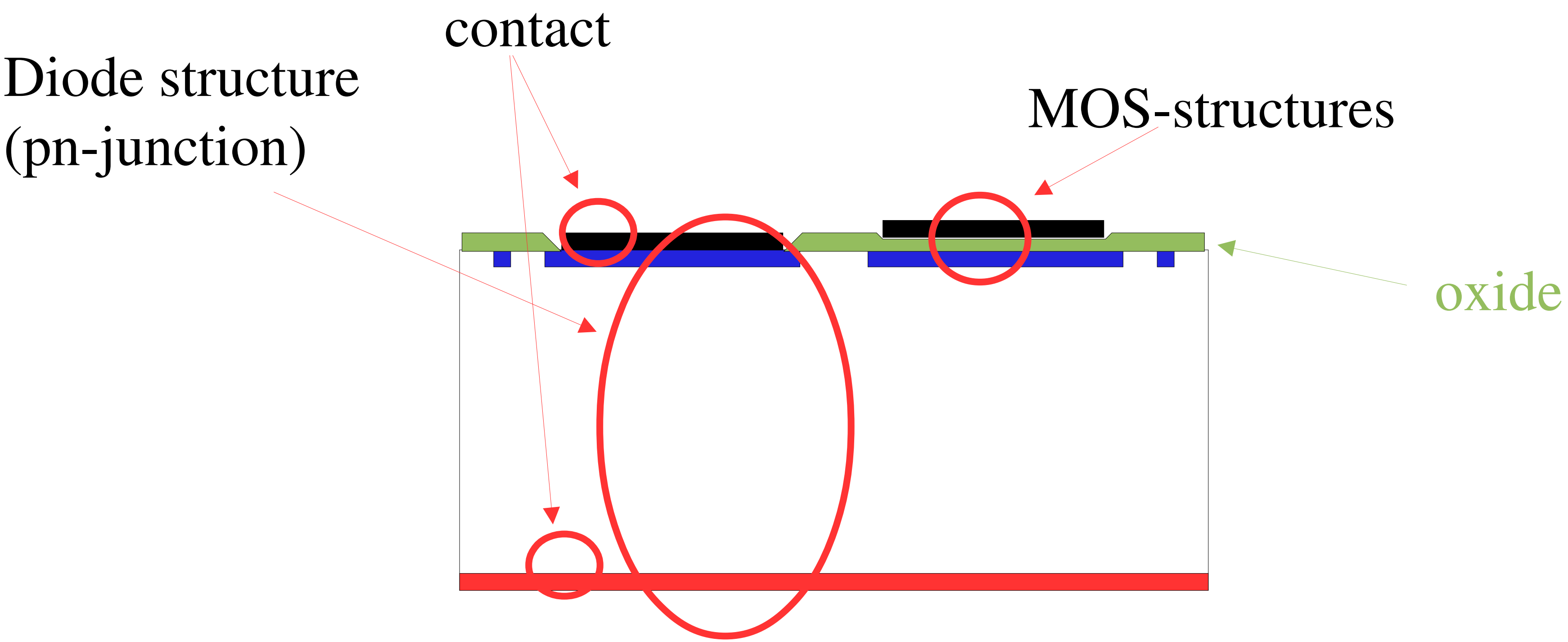
Properties of semiconductor sensors

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

EXAMPLE



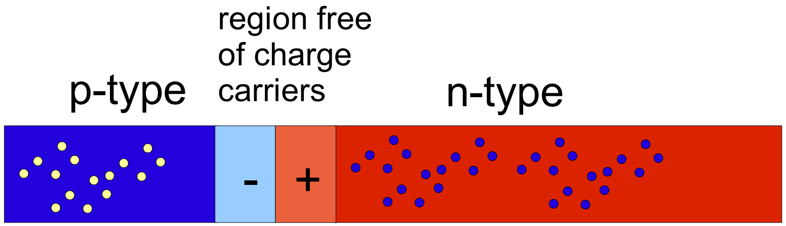
Structures in semiconductor sensors

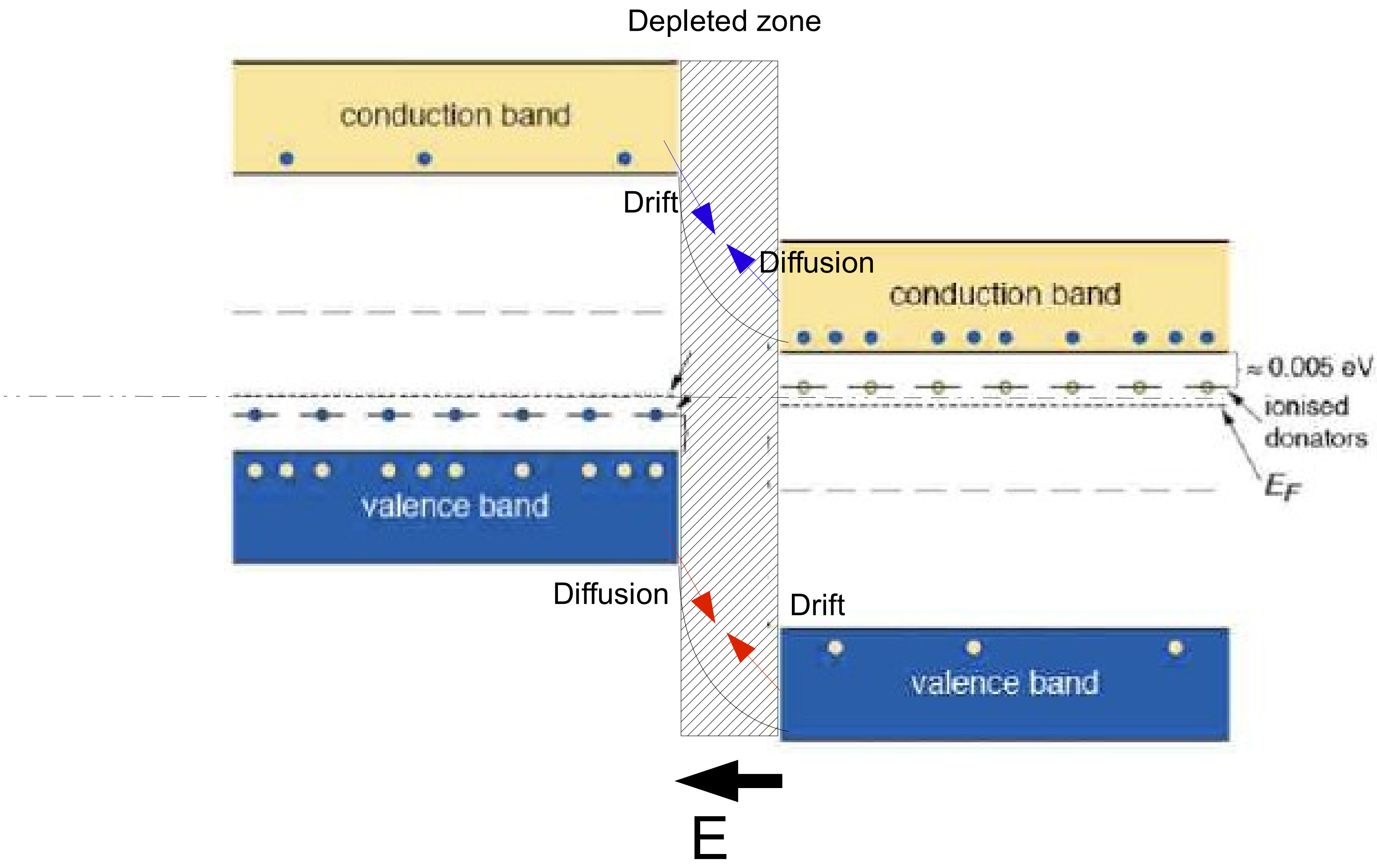


Most important and commonly used structures in semiconductor sensors are

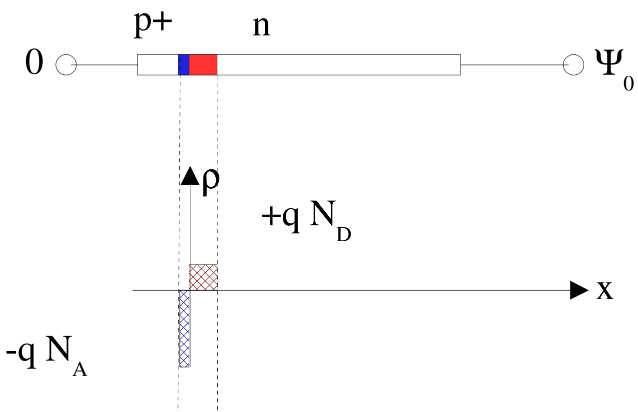
- ✔ Diode structure, pn-junction and np-junction
- ✔ MOS structure (Metal-Oxide-Semiconductor)
- ✔ Contact (OHMIC,SCHOTTKY)

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)*



Smal junction width,potential

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

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

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)

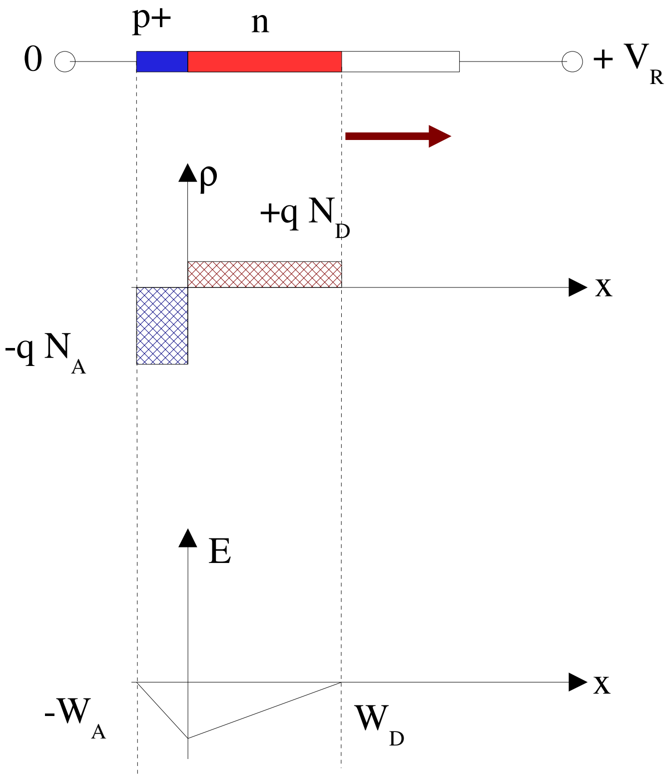
$$N_A >> N_D$$

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)



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

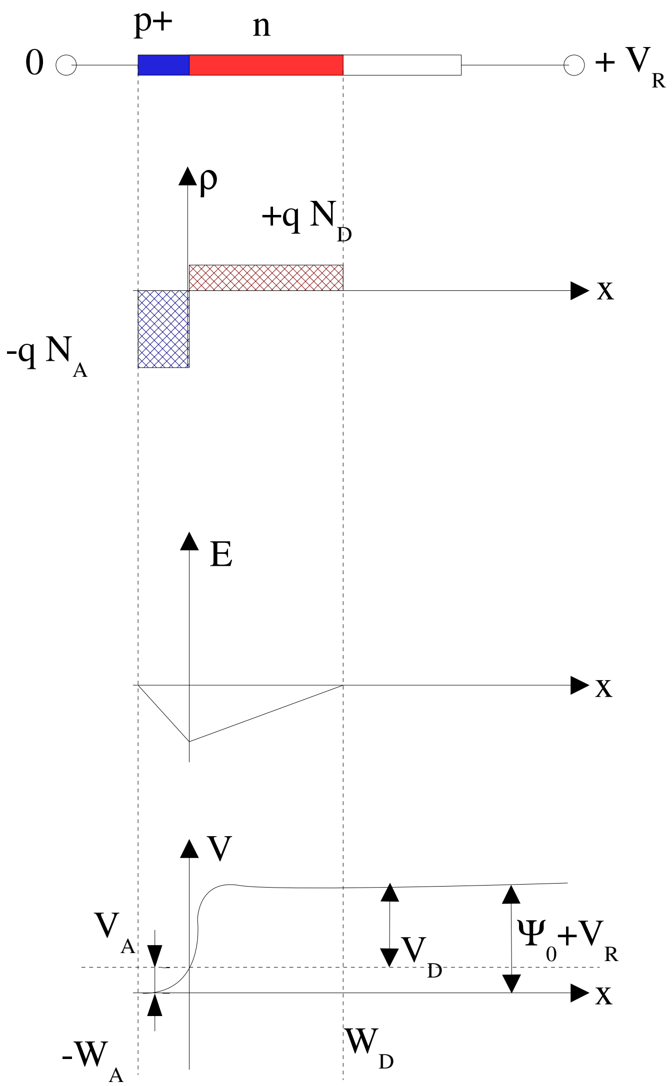
$$\frac{d^2 V}{d x^2} = -\frac{\rho}{\epsilon_R \epsilon_0} = \frac{q N_A}{\epsilon_R \epsilon_0}$$

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

$$\boxed{E = -\frac{d V}{d x} = \; = -\frac{q N_A}{\epsilon_R \epsilon_0}(x + W_A)}$$

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

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

$-W_A < x < 0$

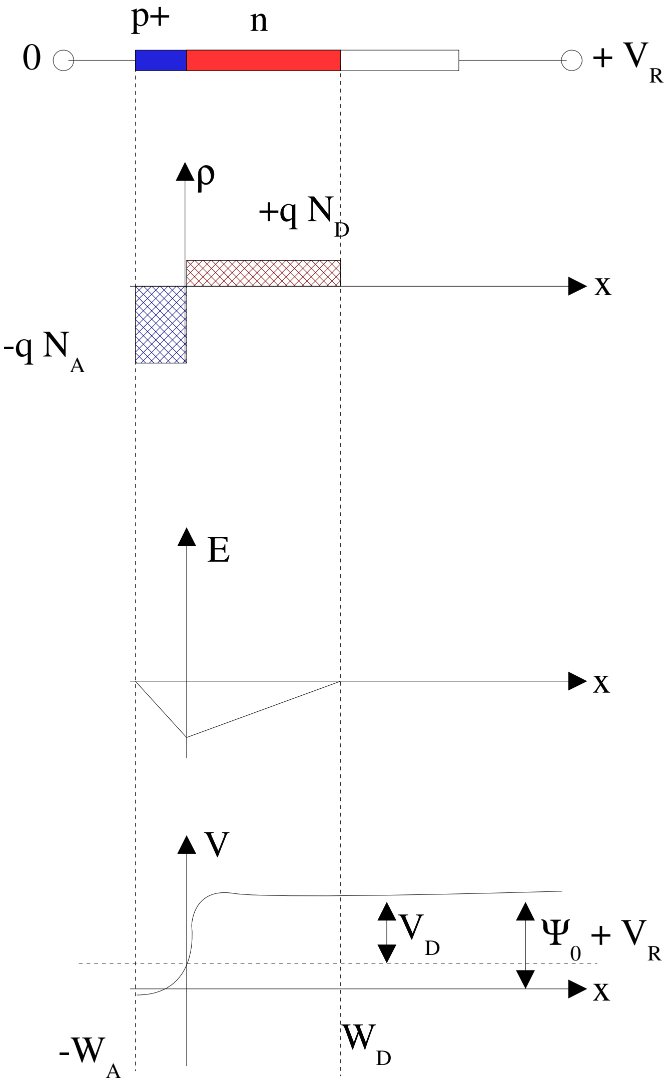
Use this expression to define the potentials V_A at x=0

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

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

$$W_A N_A = W_D N_D$$

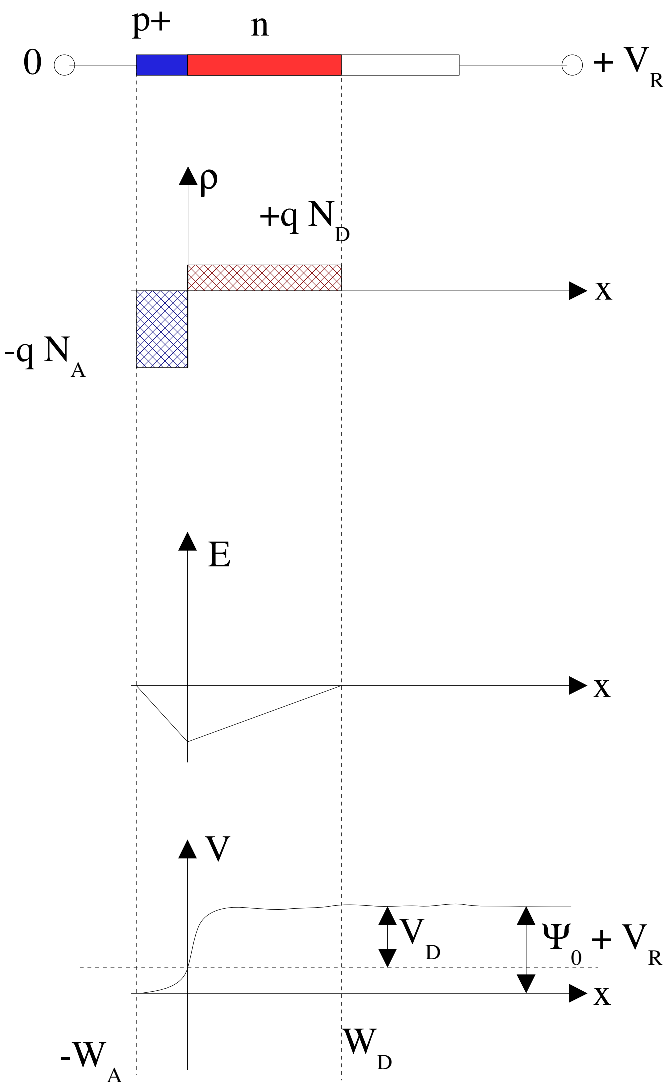
the expression can be written for the n-region

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

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

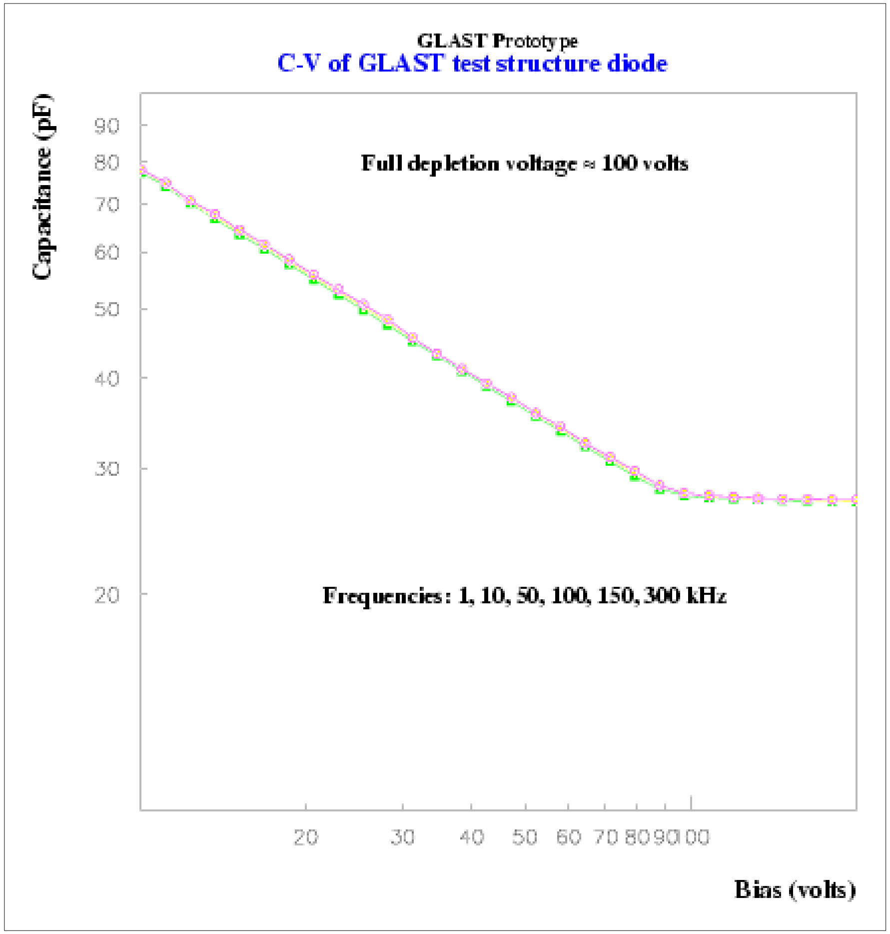
- Macroscopic features of a good semiconductor sensor are
  - ✔ Low capacitive load Ấ low noise in readout electronics
  - ✔ Low leakage current Ấ low noise in readout electronics
  - ✔ Good charge collection
  - ✔ High speed

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)

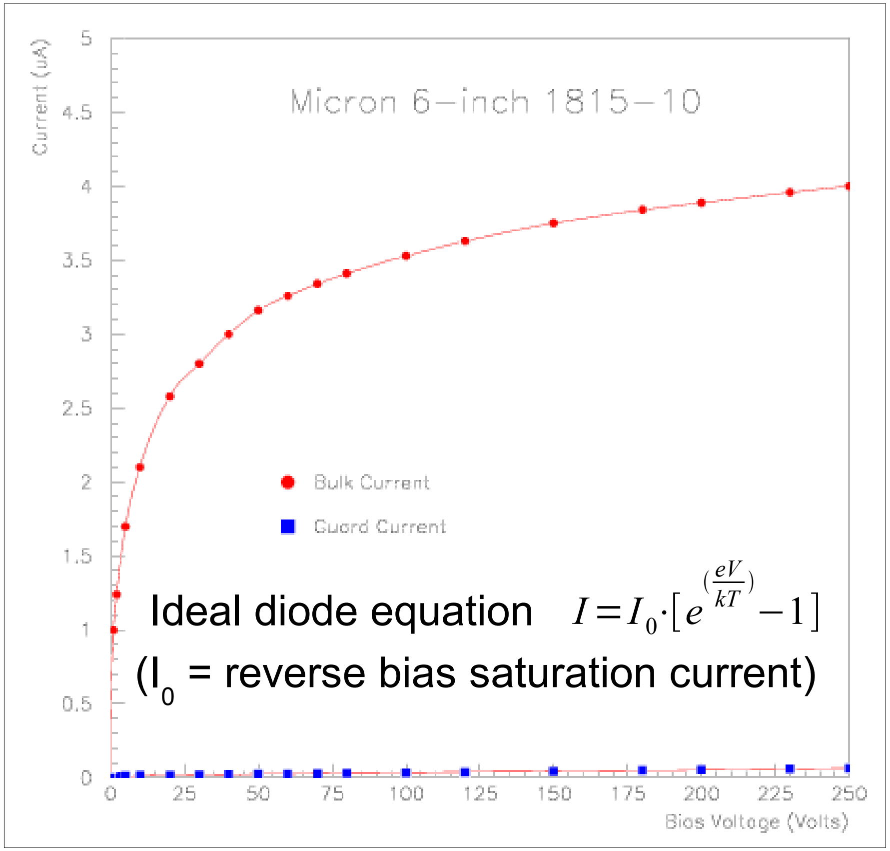
Characteristics of the diode structure

- **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.

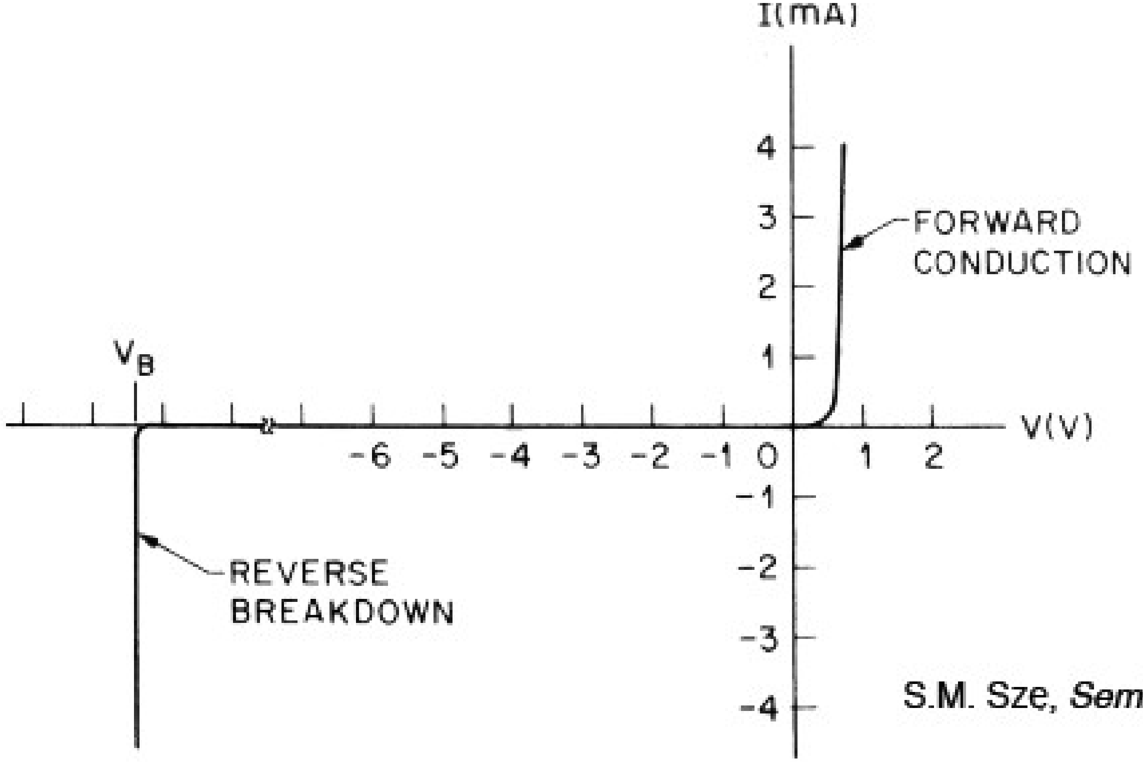


Ideal diode equation $I = I_0 \cdot [e^{(\frac{eV}{kT})} - 1]$

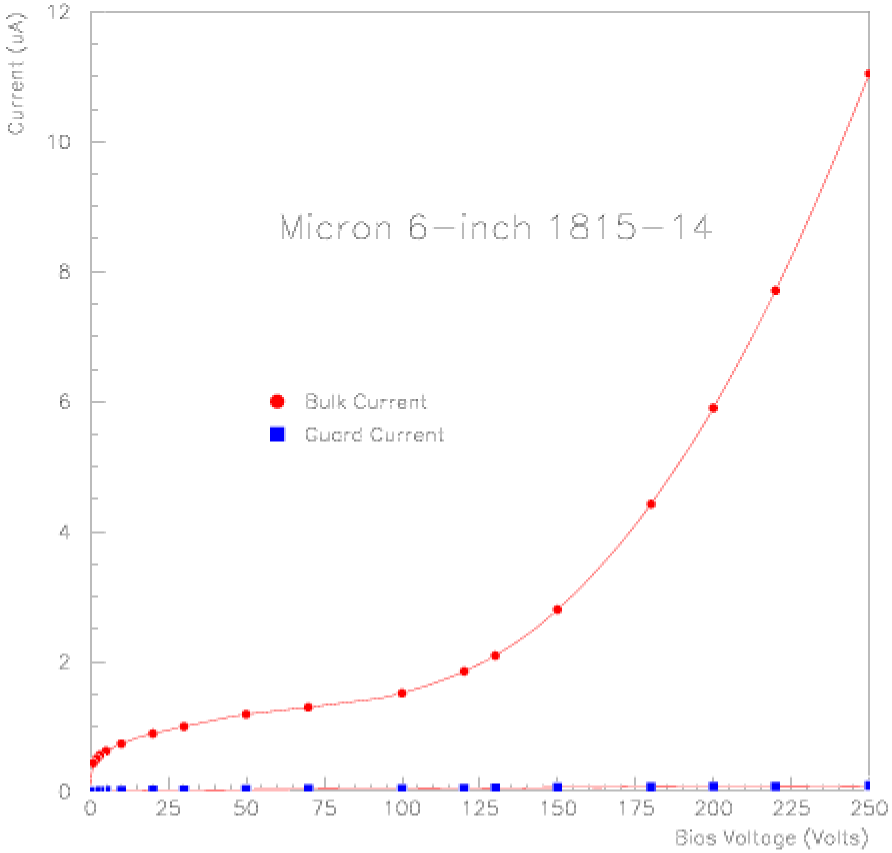
(I_0 = reverse bias saturation current)

GOOD I-V curve

More on IV-characteristics

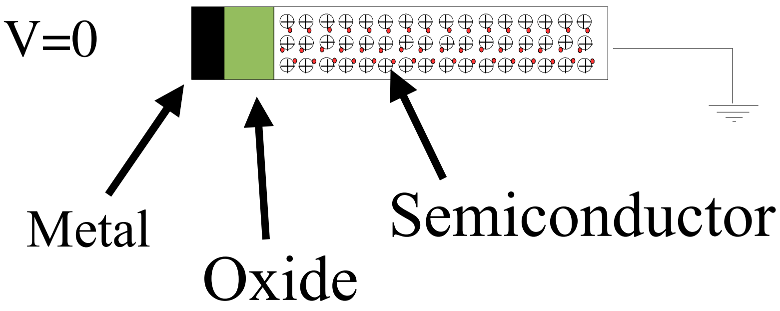


S.M. Sze, *Semiconductor Devices* , J. Wiley & Sons, 1985


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

BAD I-V curve !

Metal-Oxide-Semiconductor structure

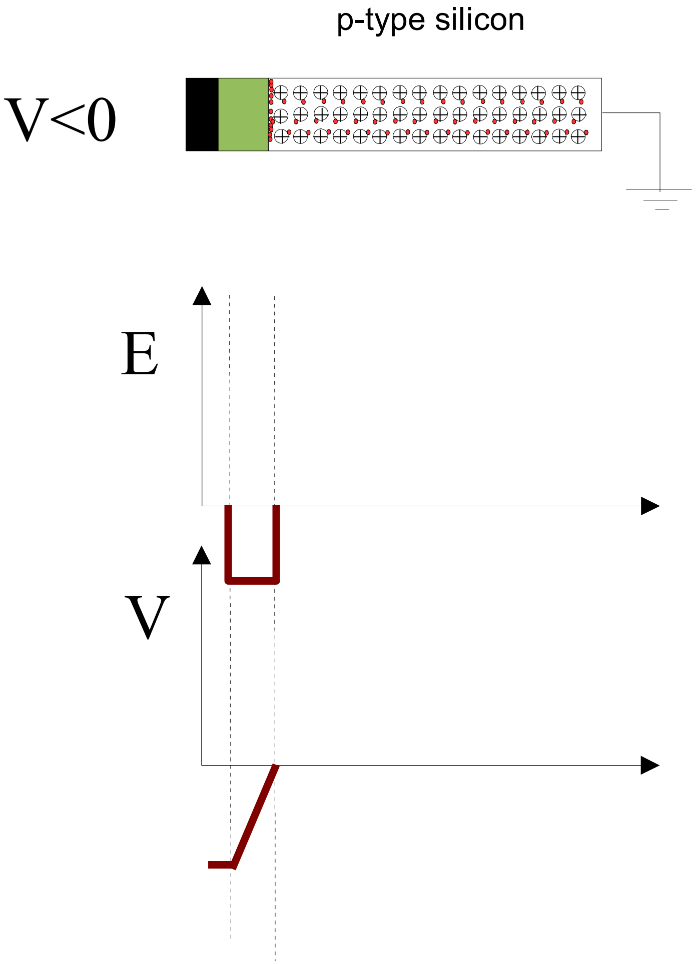


- MOS structure (or more general Metal-Insulator-Semiconductor, MIS) is widely used in electronics industry to make gates and in sensor industry to make AC-coupled sensors

- 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 Flat Band condition.

MOS in accumulation

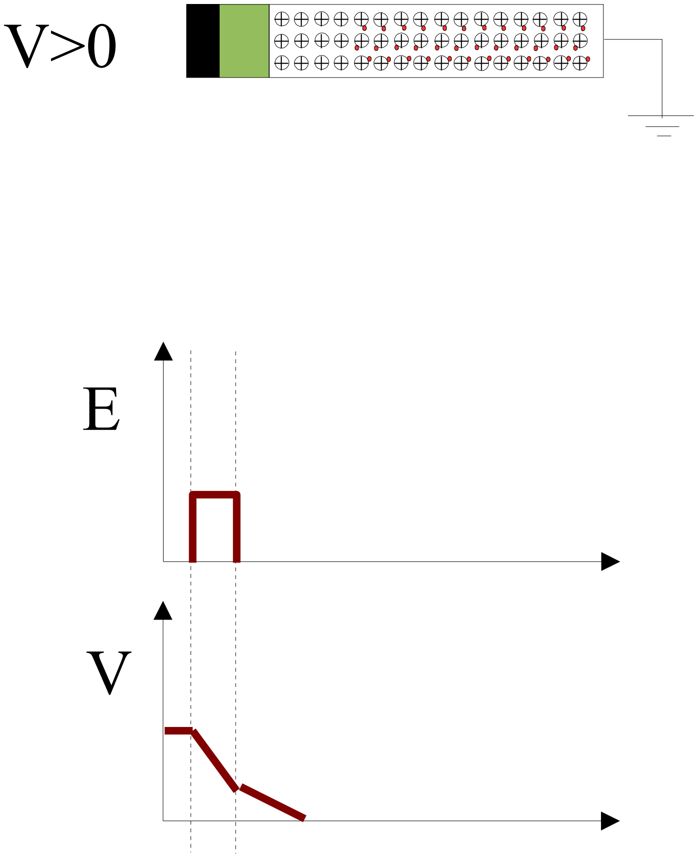


- If the potential on the metal is set below the voltage of the semiconductor the holes are attracted to the semiconductor-oxide interface where they accumulate to a very thin layer. This is called Accumulation condition.
- A field is created across the oxide.

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

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

MOS in depletion

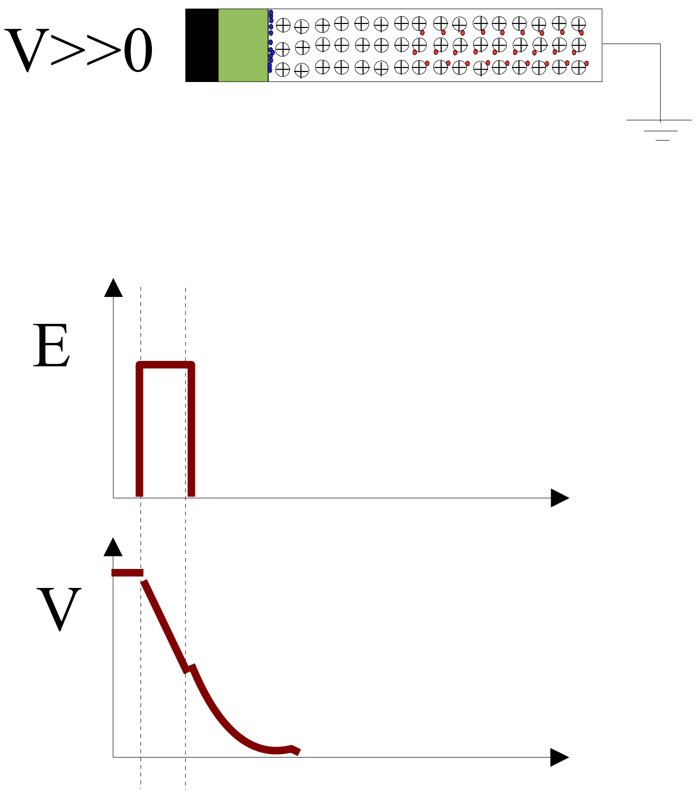


- If the potential on the metal is increased slightly above the voltage of the semiconductor the holes are repelled from the semiconductor-oxide interface and a negative space charge region is formed. This is called Depletion condition *(used by CCD detectors)*
- A field is created across the oxide and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

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

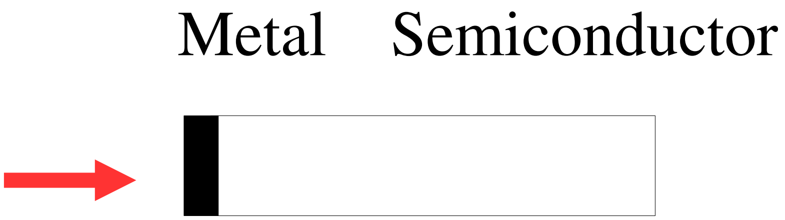
$$E_s = -\frac{q N_D}{\epsilon_s \epsilon_0} d_s$$

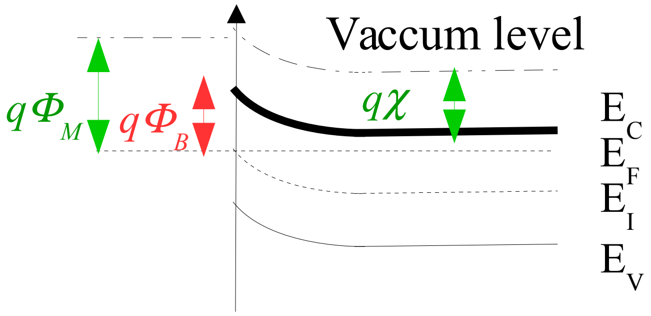
Schottky contact

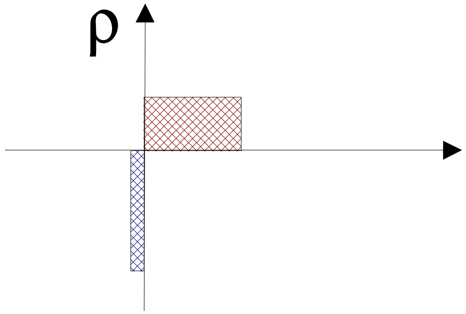
- A contact to the semiconductor can be made by deposition of a metal layer directly onto the silicon. This metal-semiconductor contact was one of the first practical semiconductor showing rectifying properties, the Schottky contact (used in surface barrier detectors).
- If the doping concentration under 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.

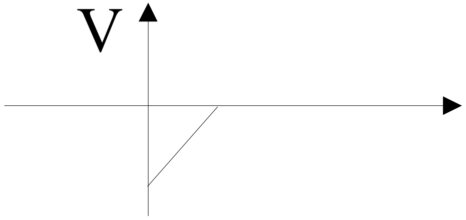
$$q\Phi_B = q(\Phi_m - \chi)$$

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

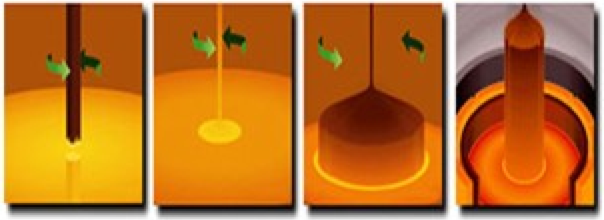


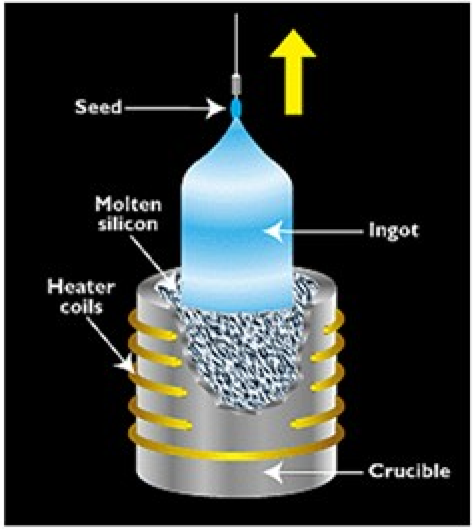


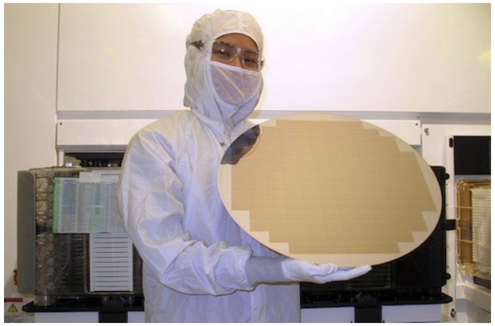




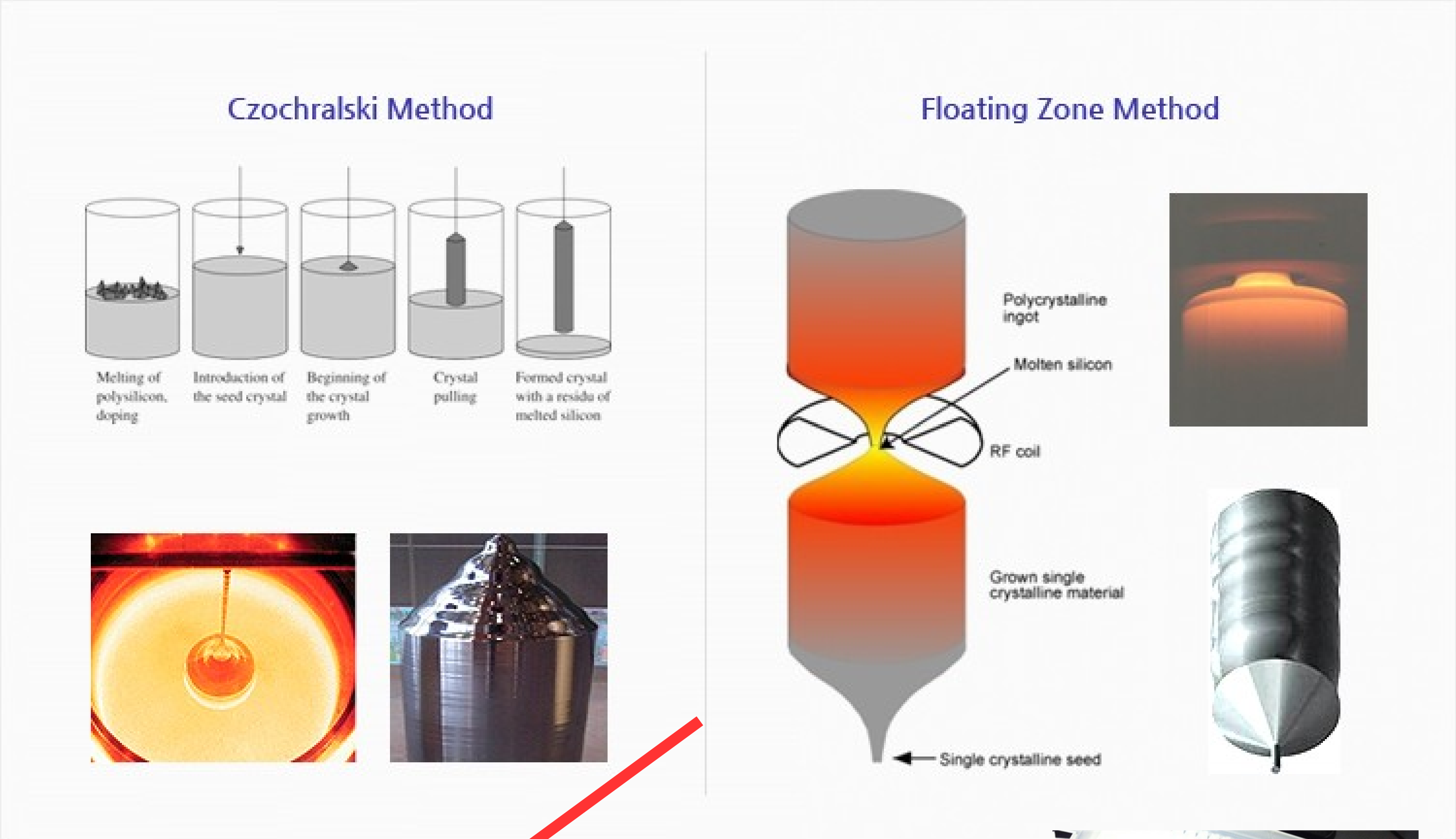
Fabrication of semiconductor sensors

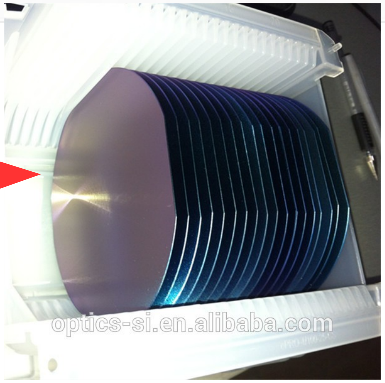






Material



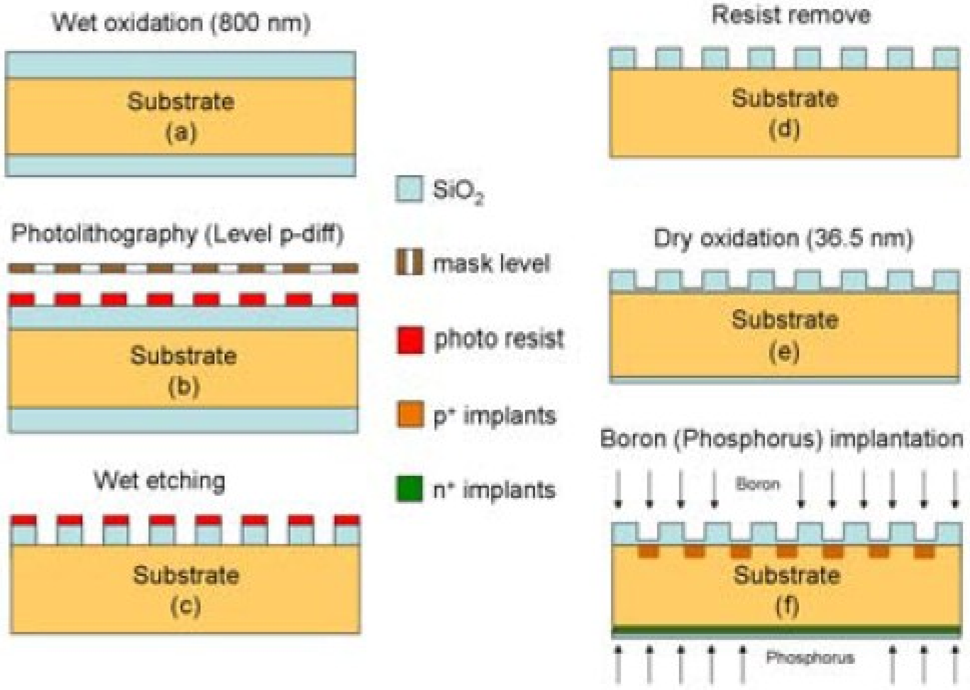


You will probably visit the silicon producer Okmetic Oy during your lab-week in Helsinki

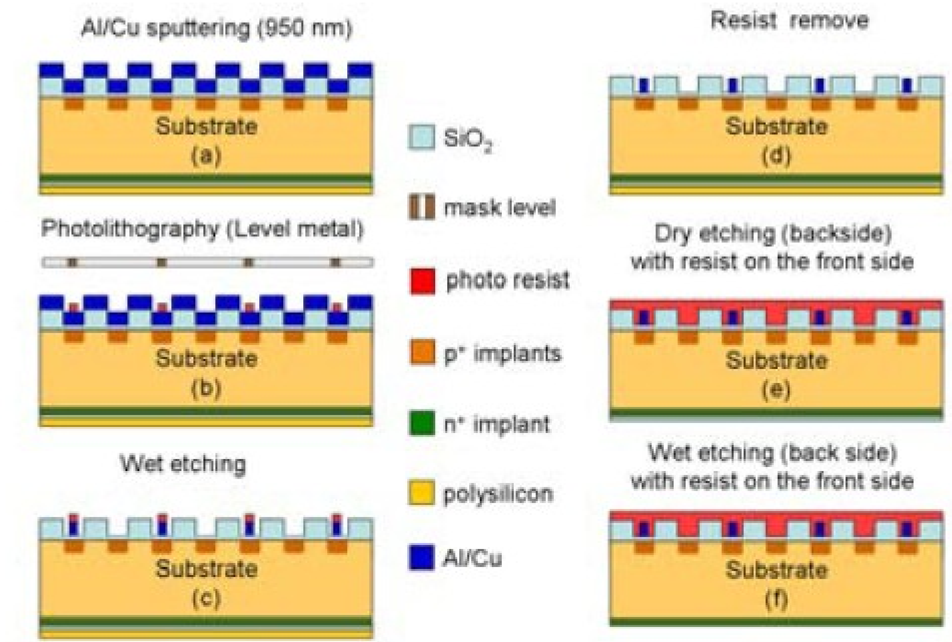
Processing steps

(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).

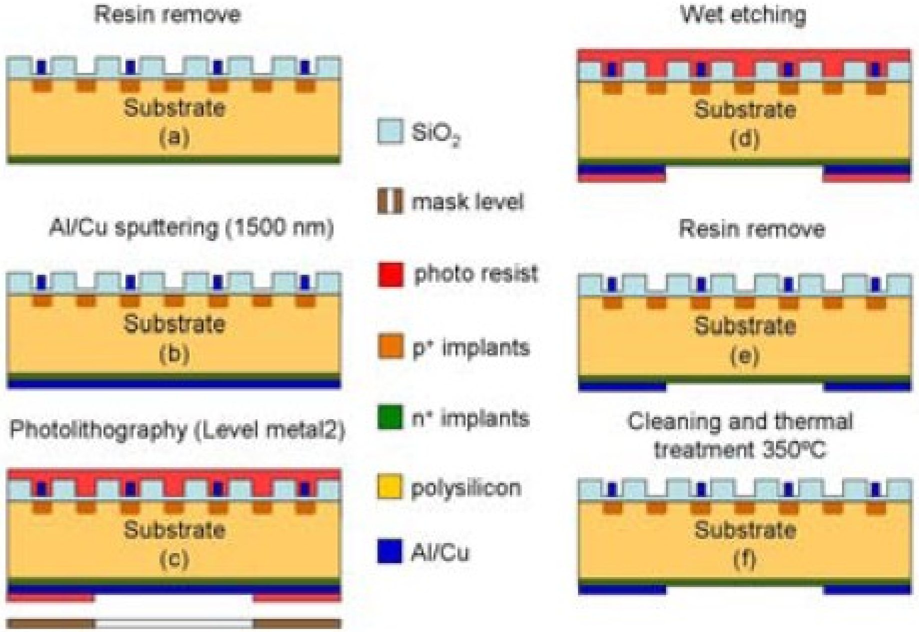


Dopant	Dose [at/cm^2]	Energy [keV]	Final conc. [at/cm^2]	Junction depth [μm]
Boron	$1.5 \quad 10^{14}$	100	10^{20}	1
Phosphorus	$1 \quad 10^{13}$	50	10^{19}	1



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