

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

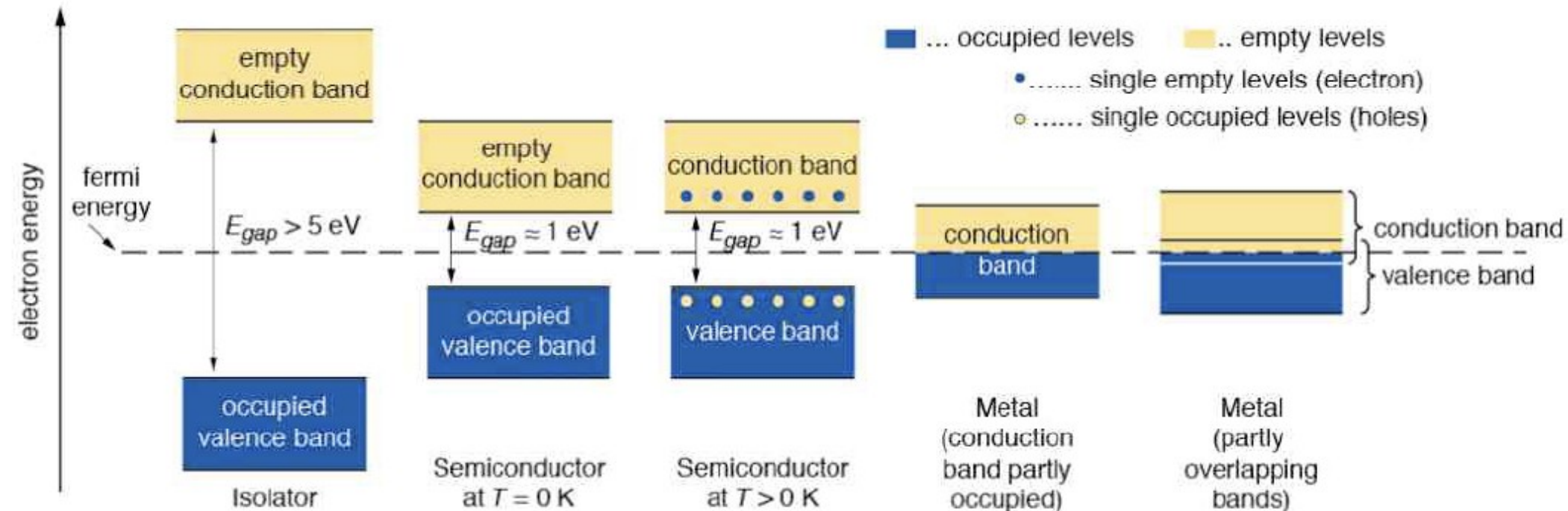
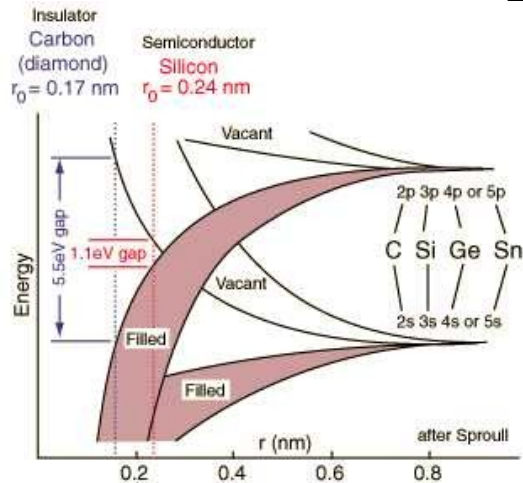
- Glen F. Knoll, Radiation Detection and Measurements, chapters 11,13,19
- Semiconductor Radiation Detectors, Gerhard Lutz, Springer-Verlag, 1999
- Nanohub tutorials

Elements used in semiconductor sensors

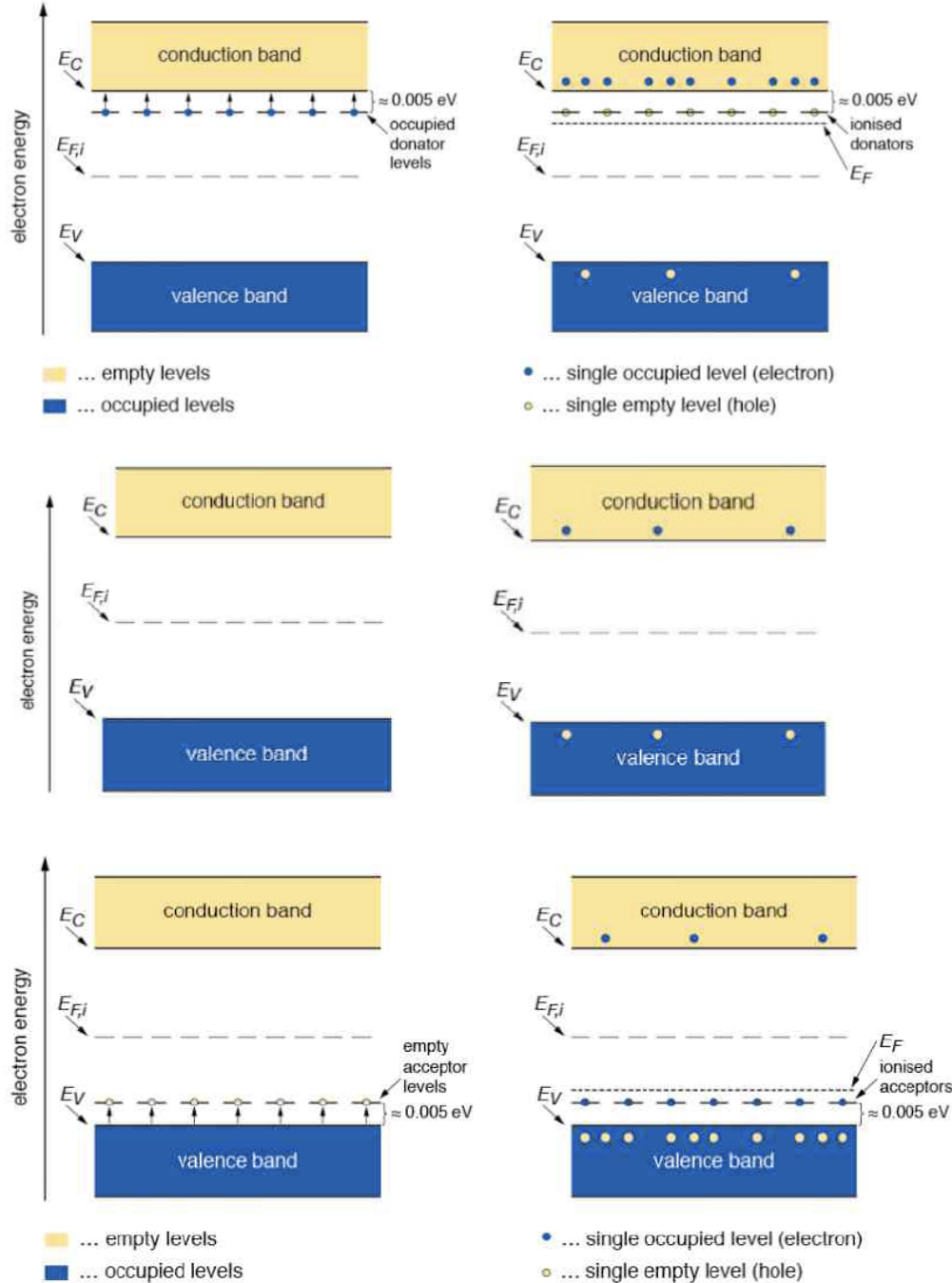
Semiconductor Compound semiconductor

1 IA																	18 VIIIA																				
1 H Hydrogen 1.00794		2 He Helium 4.002602																																			
3 Li Lithium 6.941		4 Be Beryllium 9.012182																																			
PERIODIC TABLE OF THE ELEMENTS																																					
11 Na Sodium 22.989770		12 Mg Magnesium 24.3050		13 Al Aluminum 26.981538		14 Si Silicon 28.0855		15 P Phosphorus 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 Germanium 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 Molybdenum 95.94		43 Tc Technetium (97.907215)		44 Ru Ruthenium 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 Lanthanide series		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 (209)		85 At Astatine (210)		86 Rn Radon (222)			
87 Fr Francium (223)		88 Ra Radium (226)		89-103 Actinide series		104 Rf Rutherfordium (261)		105 Db Dubnium (262)		106 Sg Seaborgium (263)		107 Bh Bohrium (264)		108 Hs Hassium (265)		109 Mt Meitnerium (266)		110 Ds Darmstadtium (269)		111 Nh Nihonium (271)		112 Fl Flerovium (277)															
Lanthanide series				57 La Lanthanum 138.9055		58 Ce Cerium 140.116		59 Pr Praseodymium 140.90765		60 Nd Neodymium 144.24		61 Pm Promethium (144.912745)		62 Sm Samarium 150.36		63 Eu Europium 151.964		64 Gd Gadolinium 157.25		65 Tb Terbium 158.92534		66 Dy Dysprosium 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)		90 Th Thorium 232.0381		91 Pa Protactinium 231.03588		92 U Uranium 238.0289		93 Np Neptunium (237)		94 Pu Plutonium (244)		95 Am Americium (243)		96 Cm Curium (247)		97 Bk Berkelium (247)		98 Cf Californium (251)		99 Es Einsteinium (252)		100 Fm Fermium (257)		101 Md Mendelevium (258)		102 No Nobelium (259)		103 Lr Lawrencium (262)					

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)

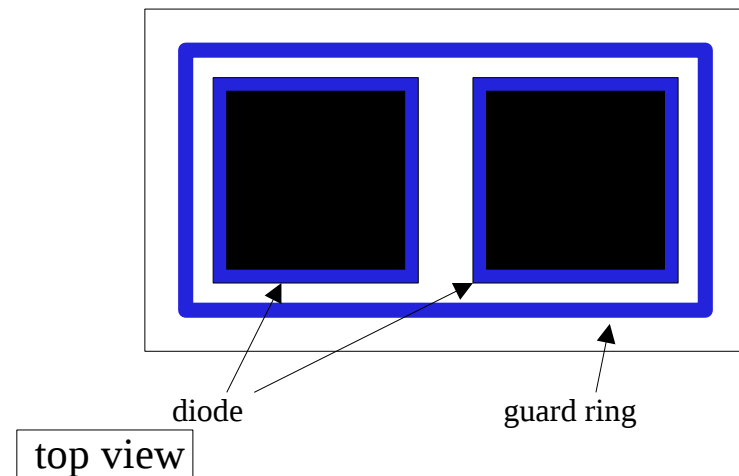
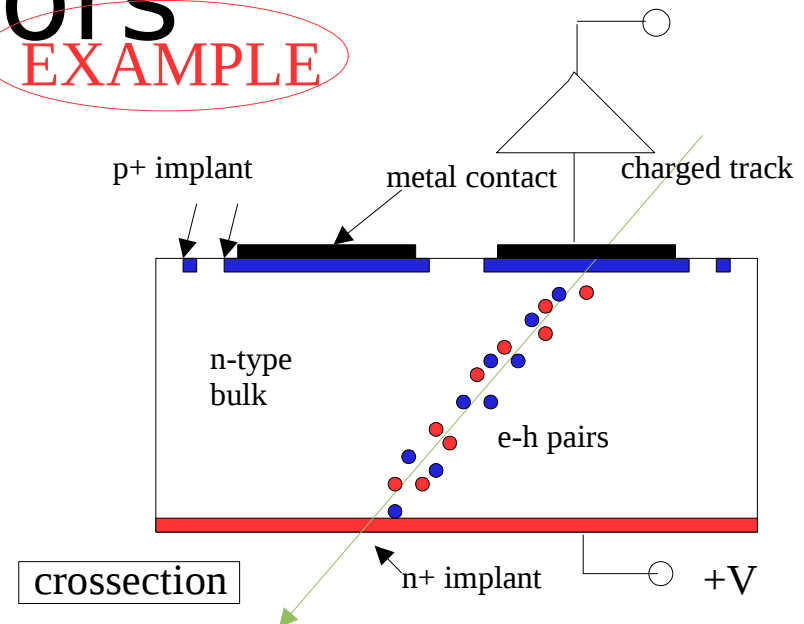
Properties of common semiconductors

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	$1,5 \times 10^{10}$	$2,4 \times 10^{12}$	$2,1 \times 10^{10}$		
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}	$2,30 \times 10^5$	47			

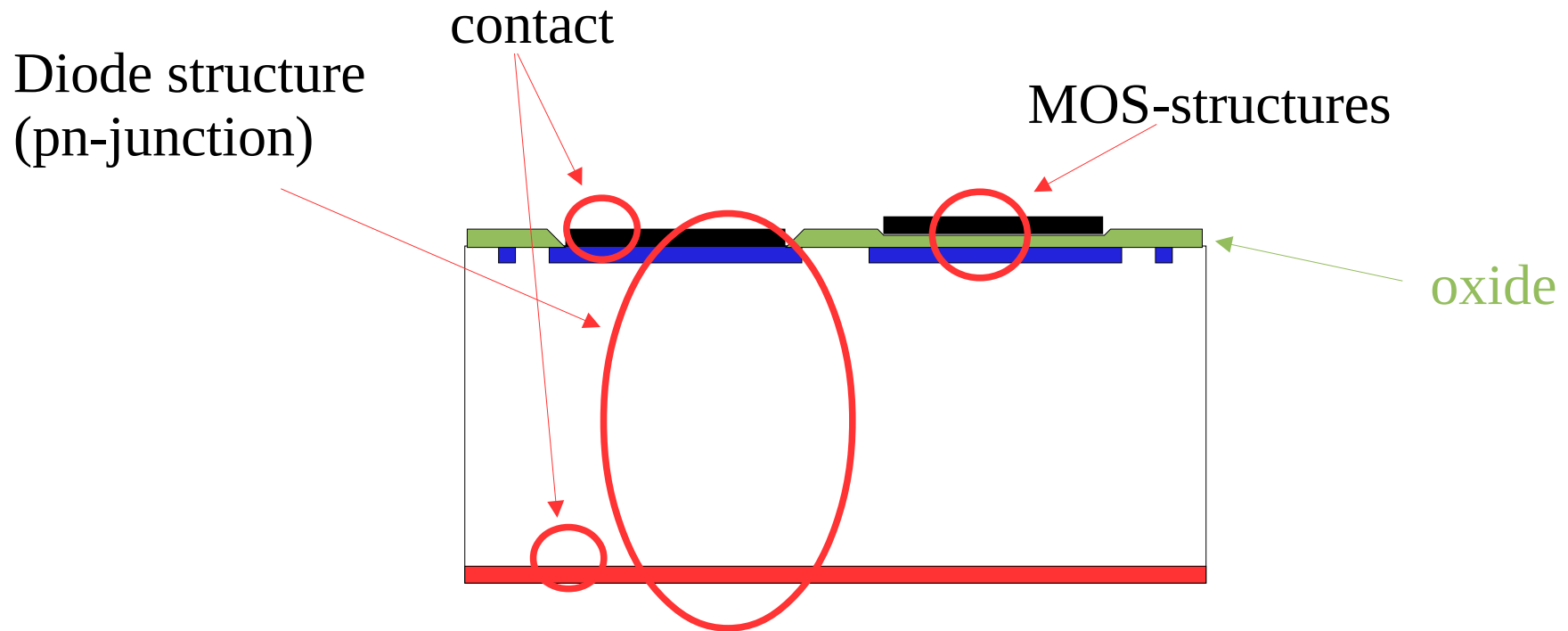
Properties of semiconductor sensors

EXAMPLE

- ✓ 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



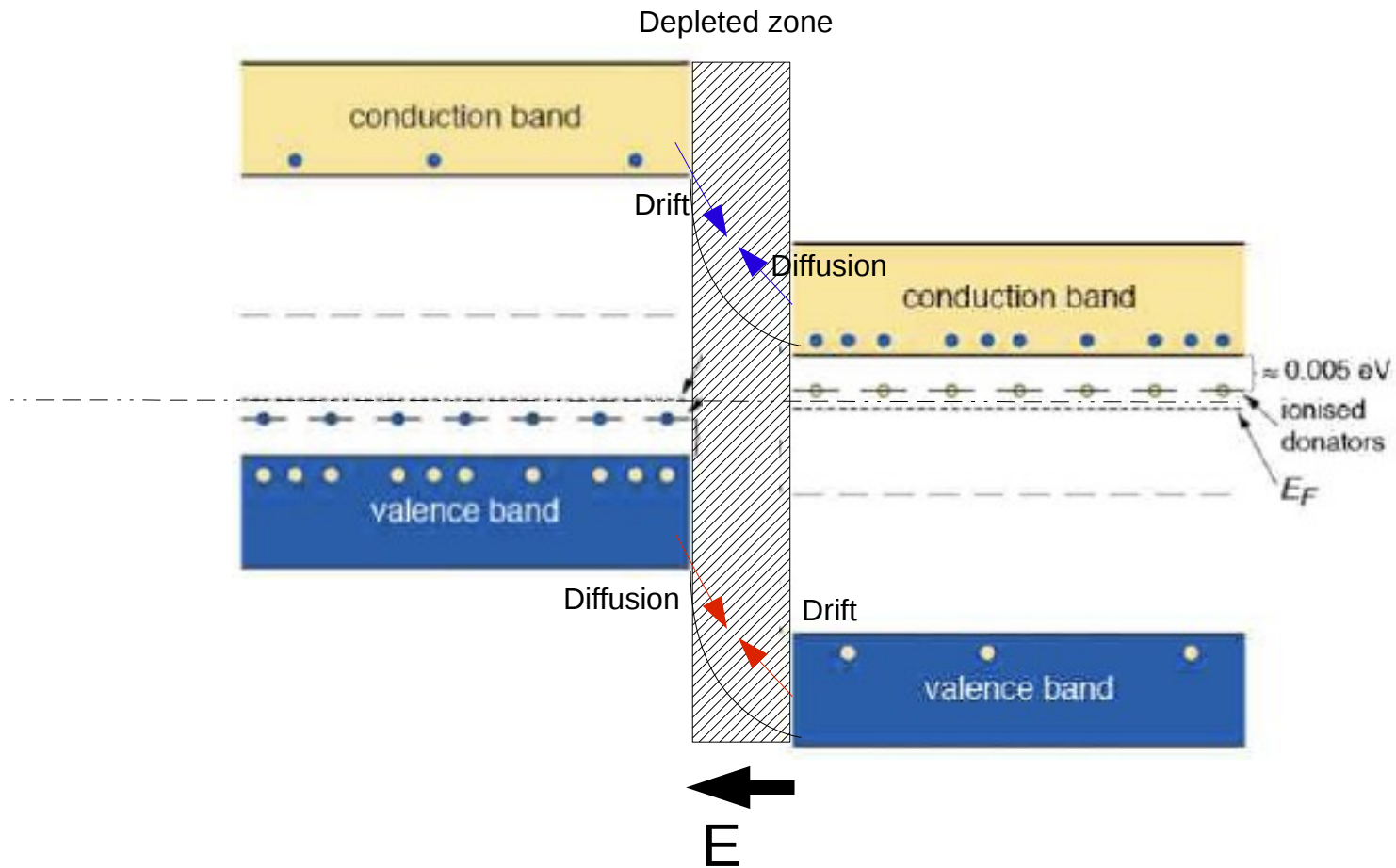
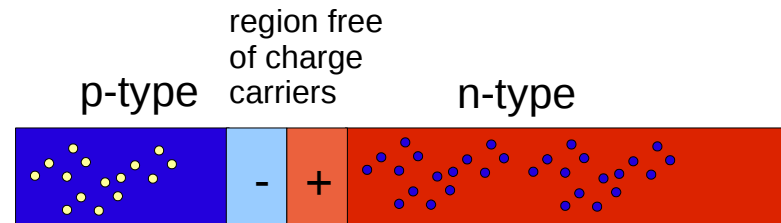
Structures in semiconductor sensors



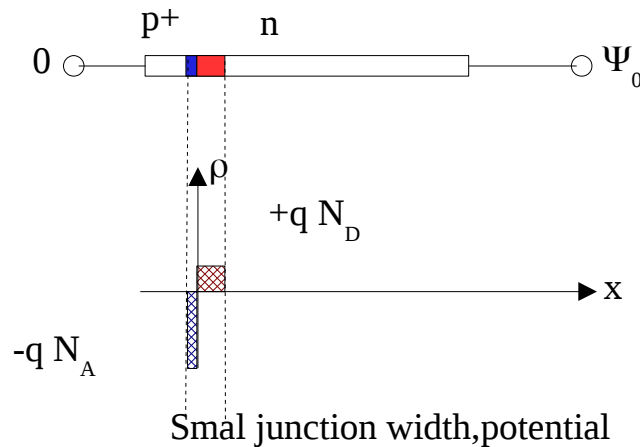
Most important and commonly used structures in semiconductor sensors are

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

pn-junction



Diode structure (*1 dimension*)



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)

$$N_A \gg N_D$$

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

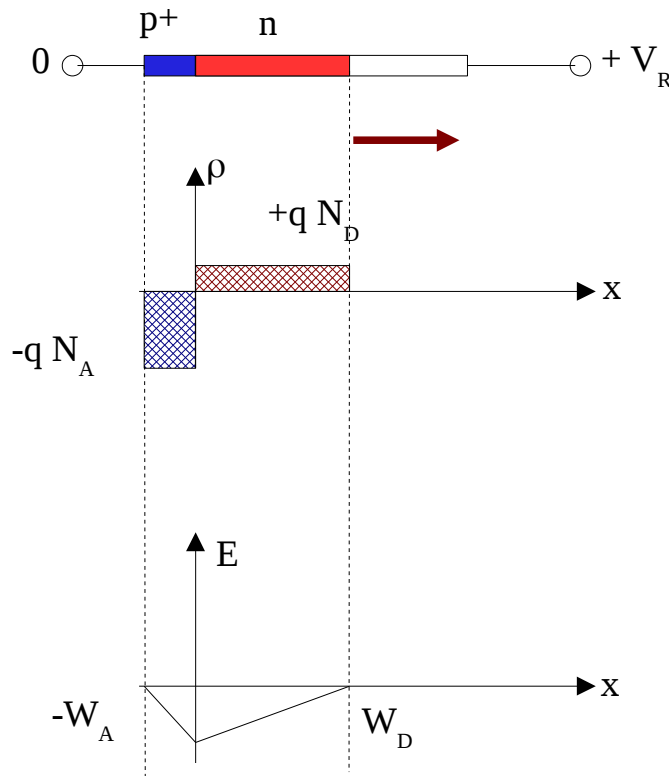
$$V_T = \frac{k_B T}{q} \approx 26 \text{ mV}$$

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 ($1.5 \text{E}10 \text{ cm}^{-3}$ 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

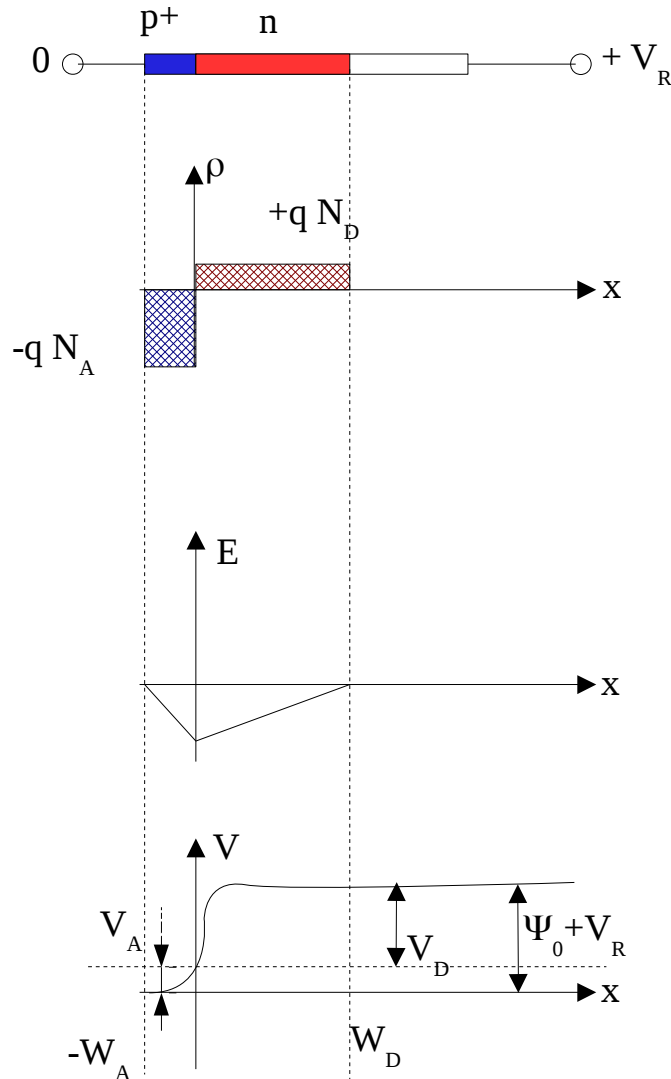
$$\frac{d^2 V}{dx^2} = -\frac{\rho}{\epsilon_R \epsilon_0} = \frac{q N_A}{\epsilon_R \epsilon_0}$$

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 =>

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

Diode structure (cont. 2)



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

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

$$-W_A < x < 0$$

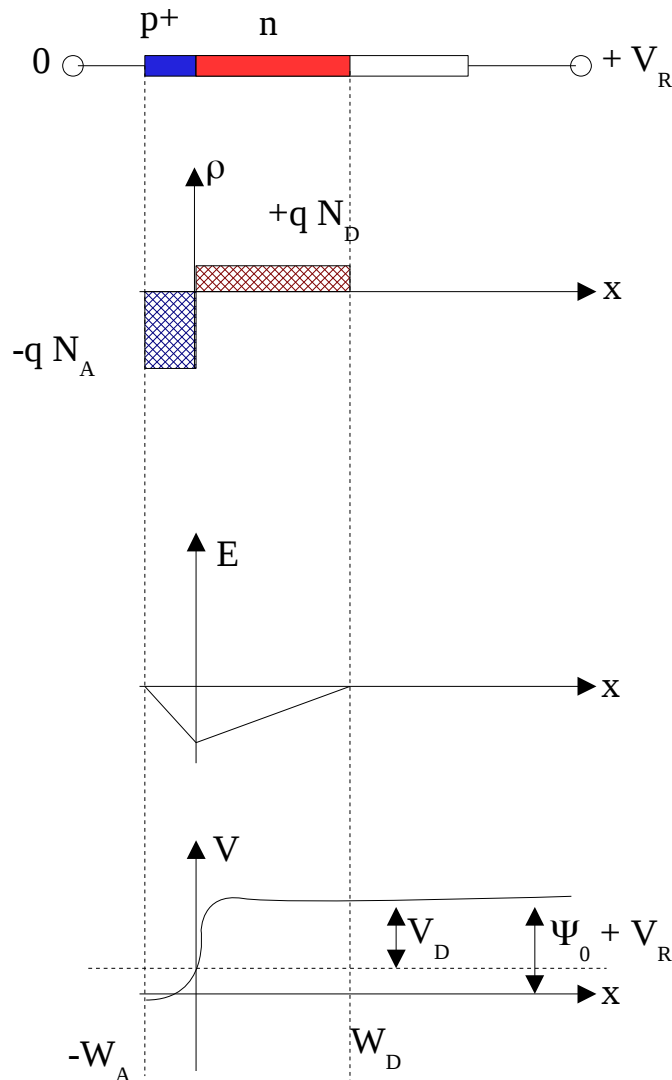
Use this expression to define the potentials V_A at $x=0$

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

We can with similar considerations determine V_D at $x=0$

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

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

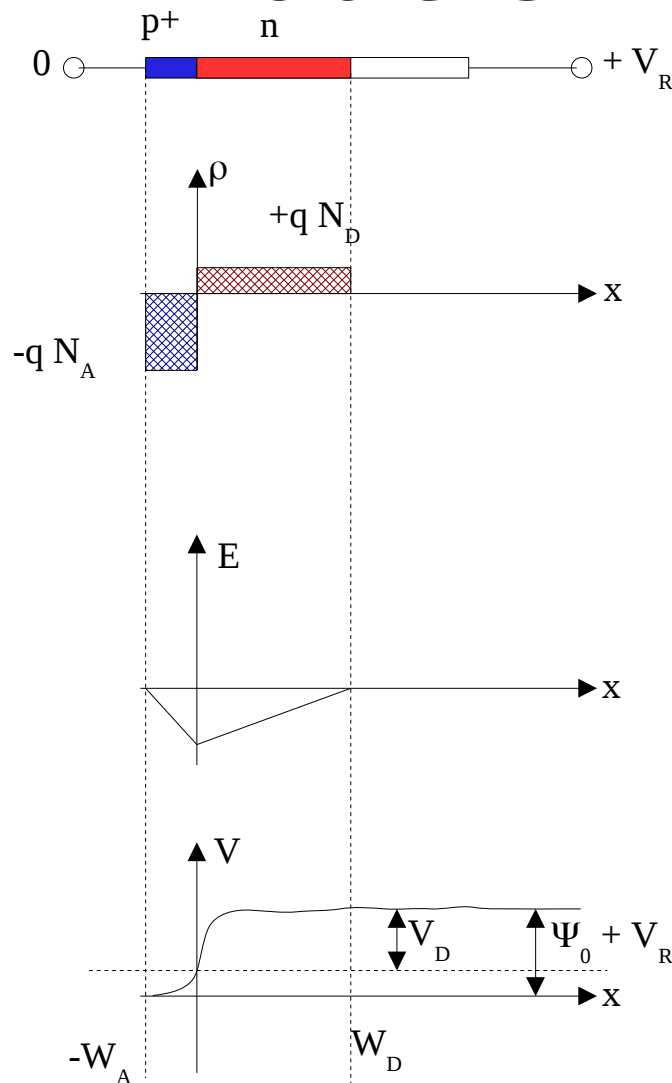
$$W_A N_A = W_D N_D$$

the expression can be written for the n-region

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

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

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 \rightarrow 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 fully depleted.

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

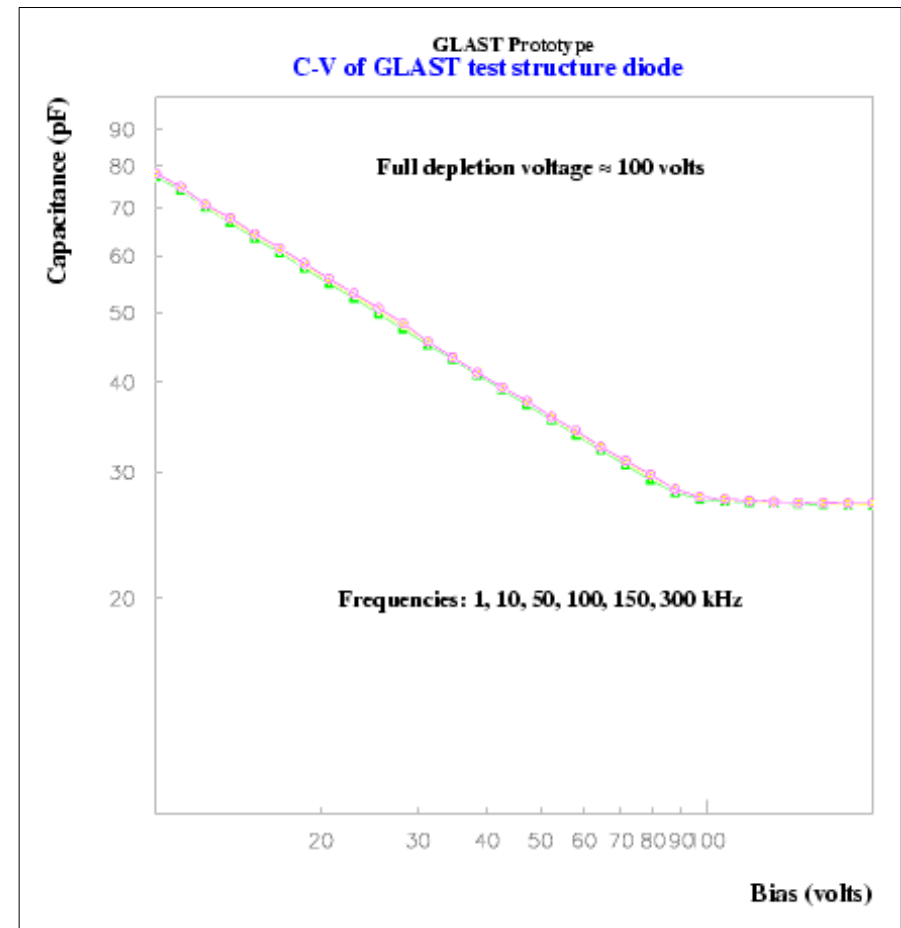
- **Capacitance (C-V)**

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)**

- ✓ diffusion current

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

- ✓ generating current

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

$$J_g = q g W$$

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

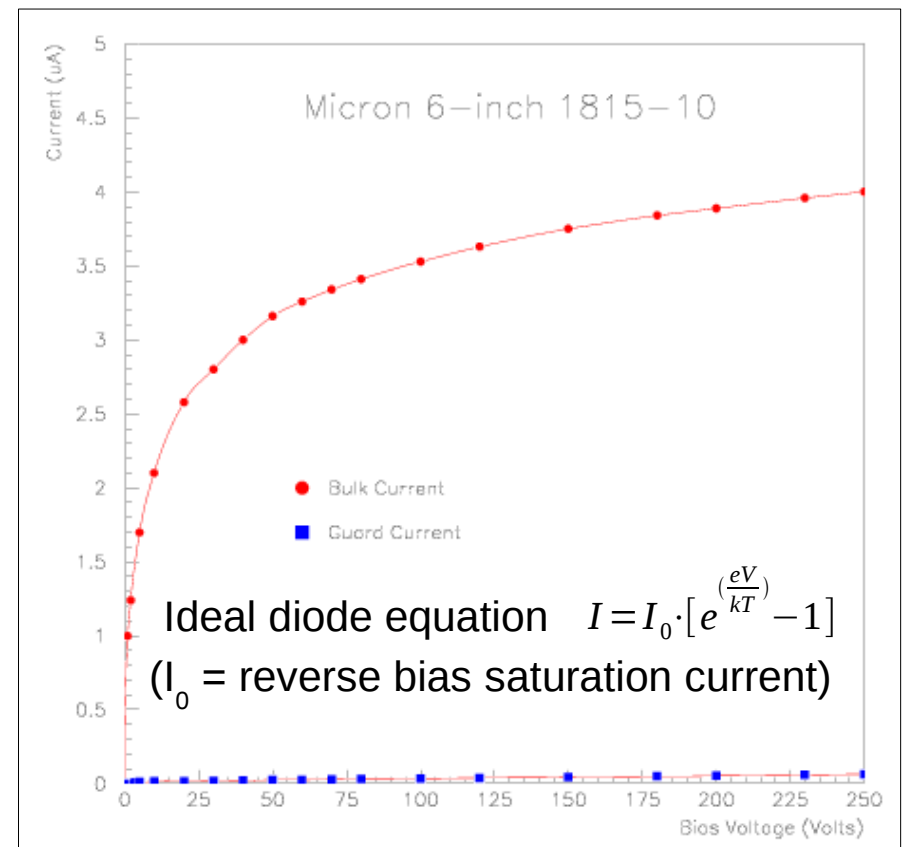
- **Leakage current (I-V)**

- ✓ generating current(cont.)

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

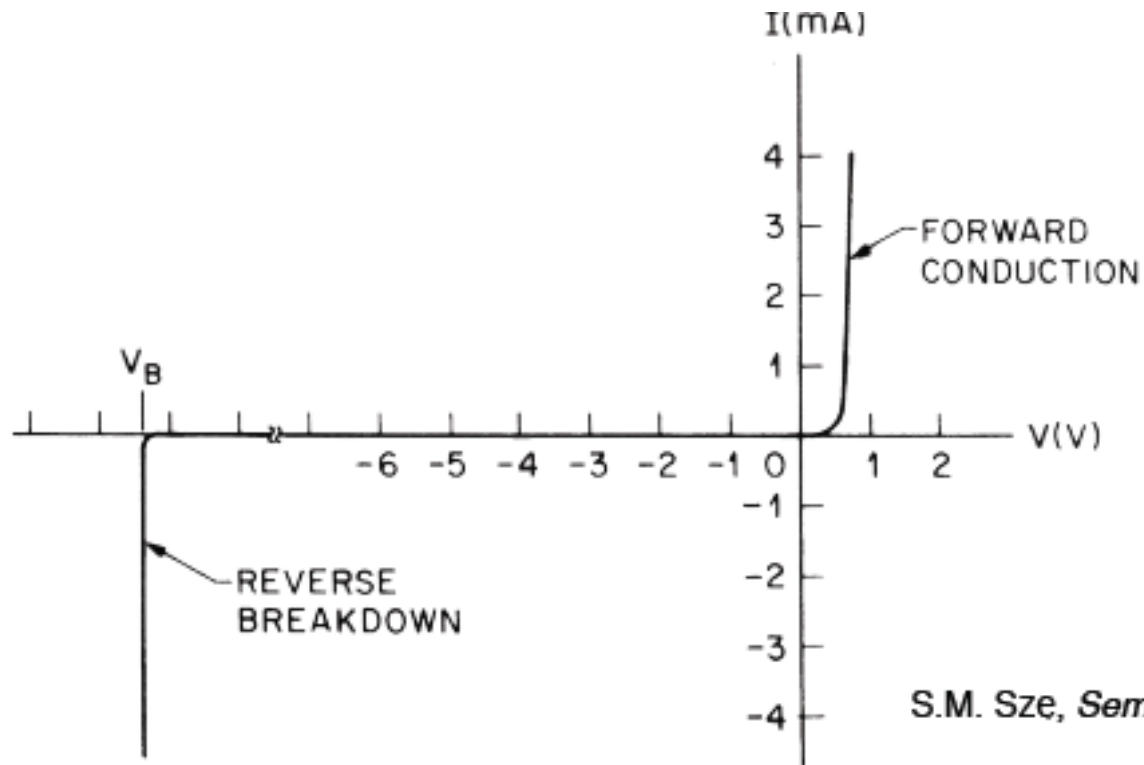
- ✓ surface current

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.

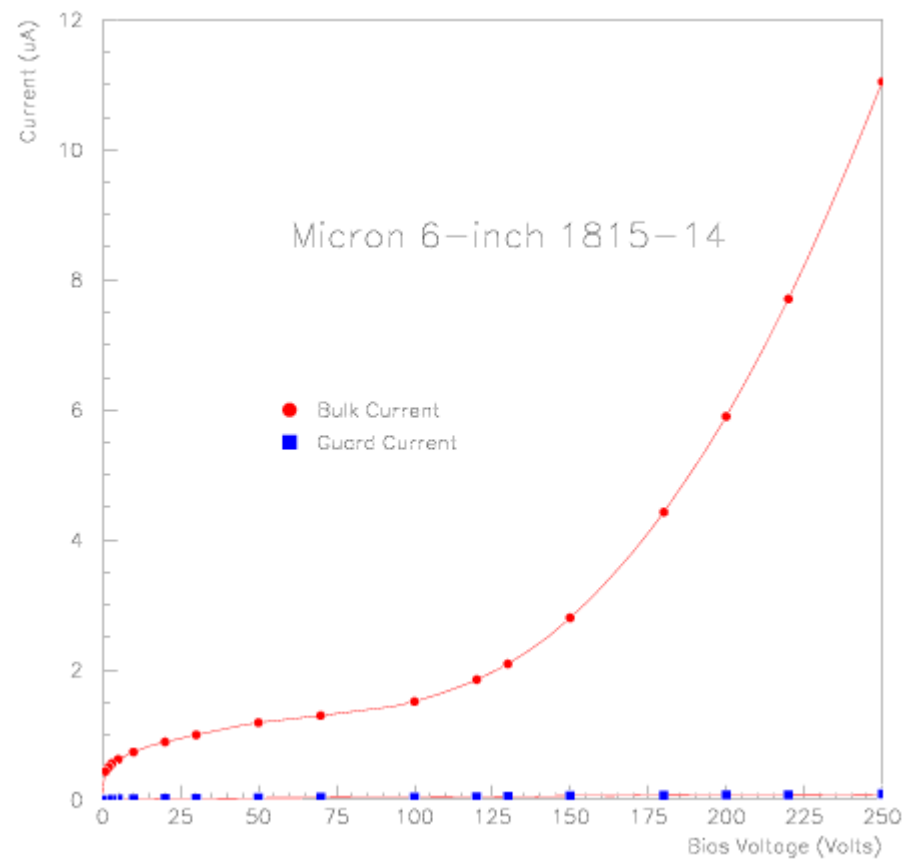


GOOD I-V curve

More on IV-characteristics

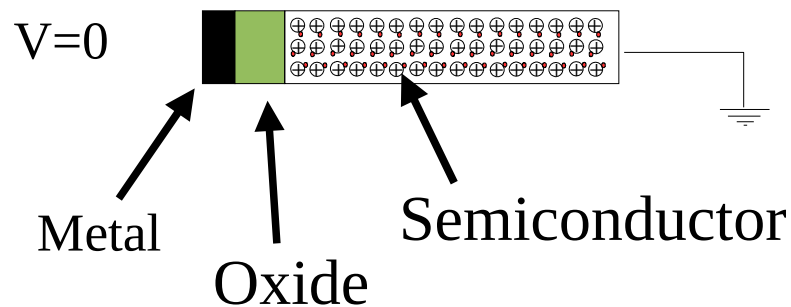


S.M. Sze, *Semiconductor Devices*, J. Wiley & Sons, 1985



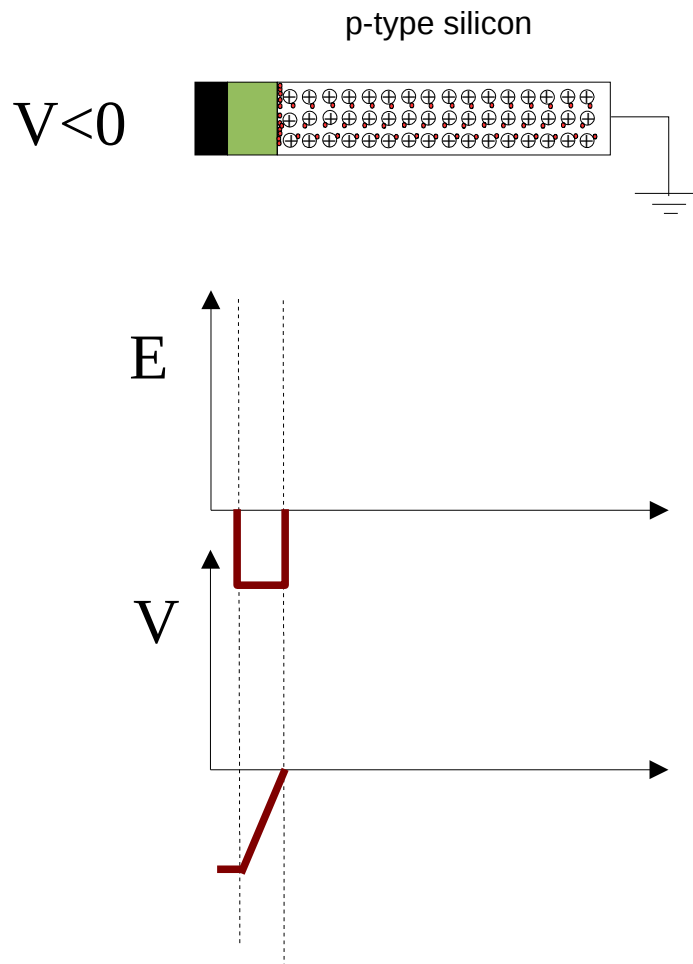
BAD I-V curve !

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 an 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

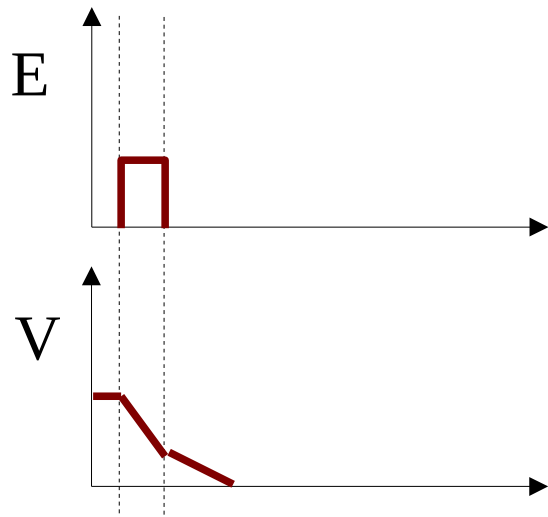
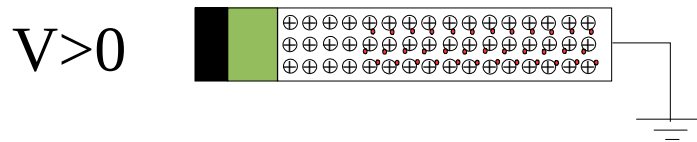


- If the potential on the metal is set below the voltage of the semiconductor the holes are attracted to the semiconductor-oxide interface where they accumulate to a very thin layer. This is called Accumulation condition.
- A field is created across the oxide.

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

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

MOS in depletion

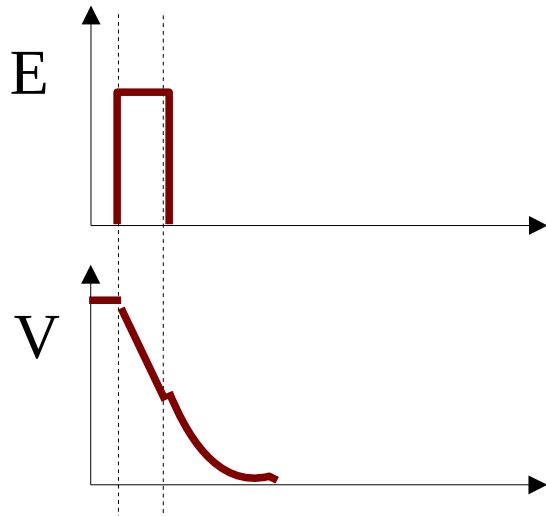
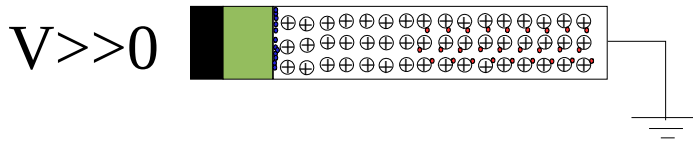


- If the potential on the metal is increased slightly above the voltage of the semiconductor the holes are repelled from the semiconductor-oxide interface and a negative space charge region is formed. This is called Depletion condition (*used by CCD detectors*)
- A field is created across the oxide and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

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

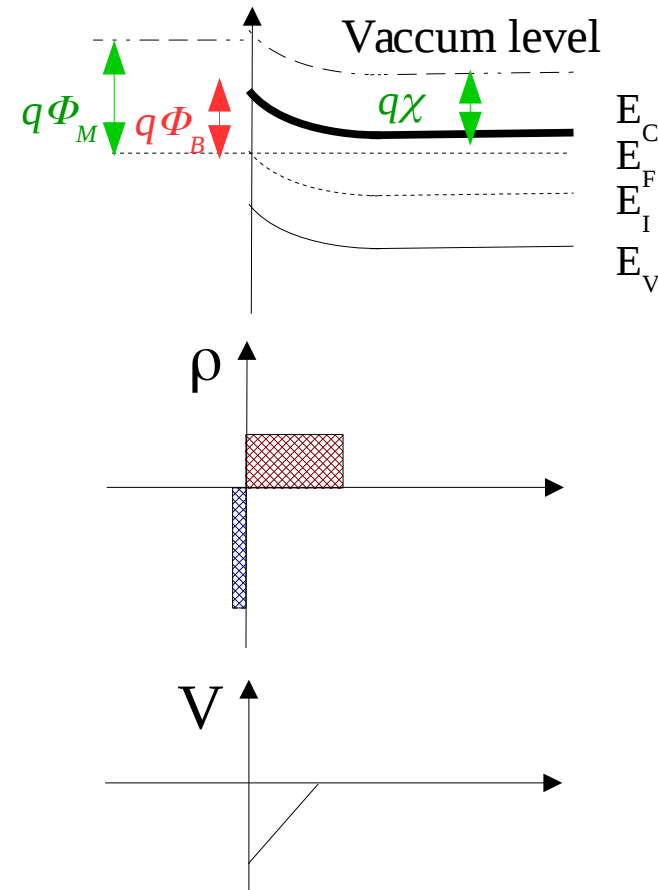
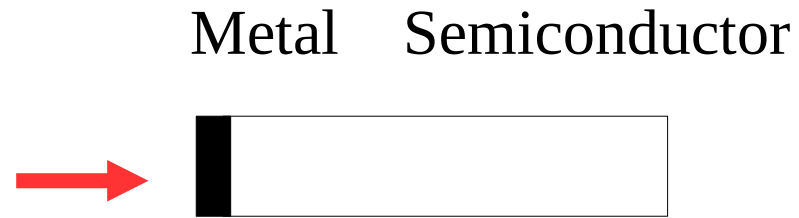
$$E_s = -\frac{q N_D}{\epsilon_s \epsilon_0} d_s$$

Schottky contact

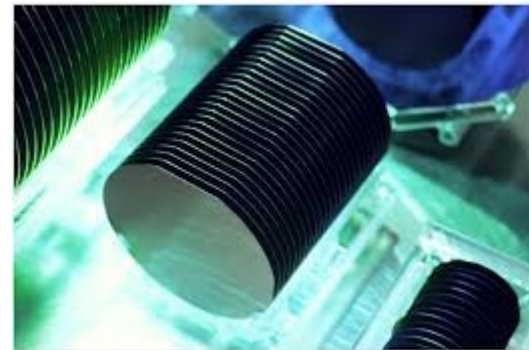
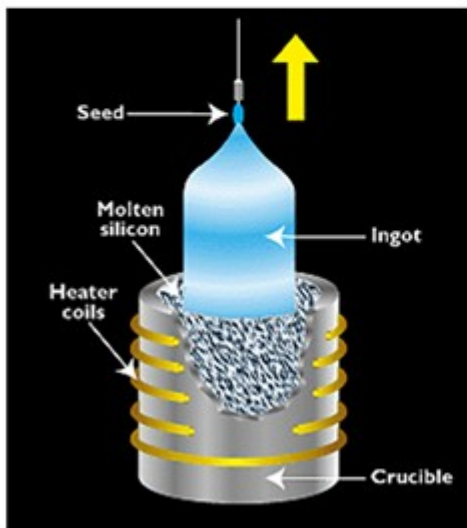
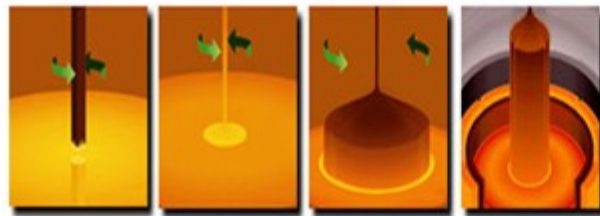
- A contact to the semiconductor can be made by deposition of a metal layer directly onto the silicon. This metal-semiconductor contact was one of the first practical semiconductor showing rectifying properties, the Schottky contact (used in surface barrier detectors).
- If the doping concentration under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

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

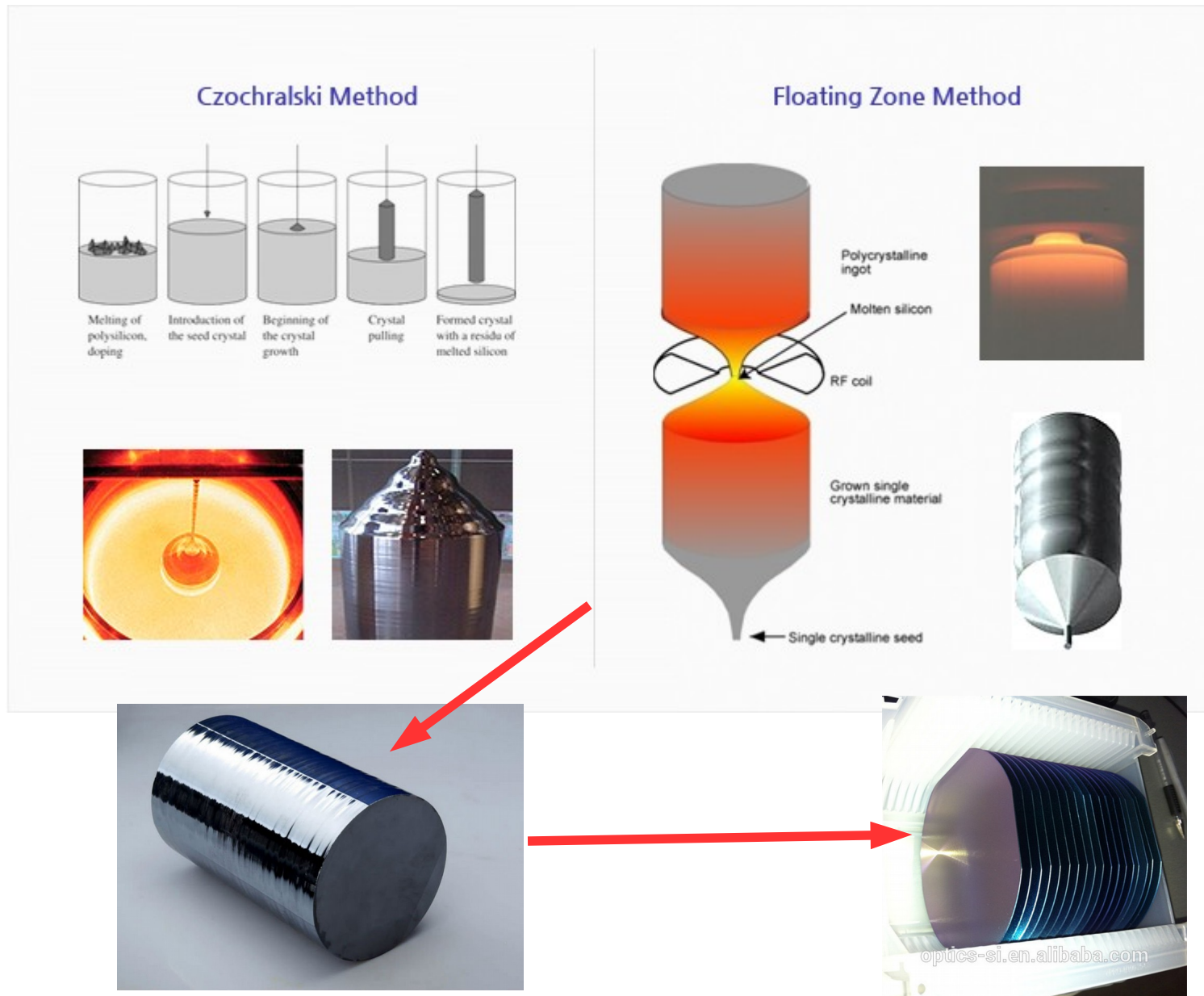
where Φ_m = work function and χ = electron affinity for a electron to reach vacuum from metal and conduction band respectively.



Fabrication of semiconductor sensors



Material

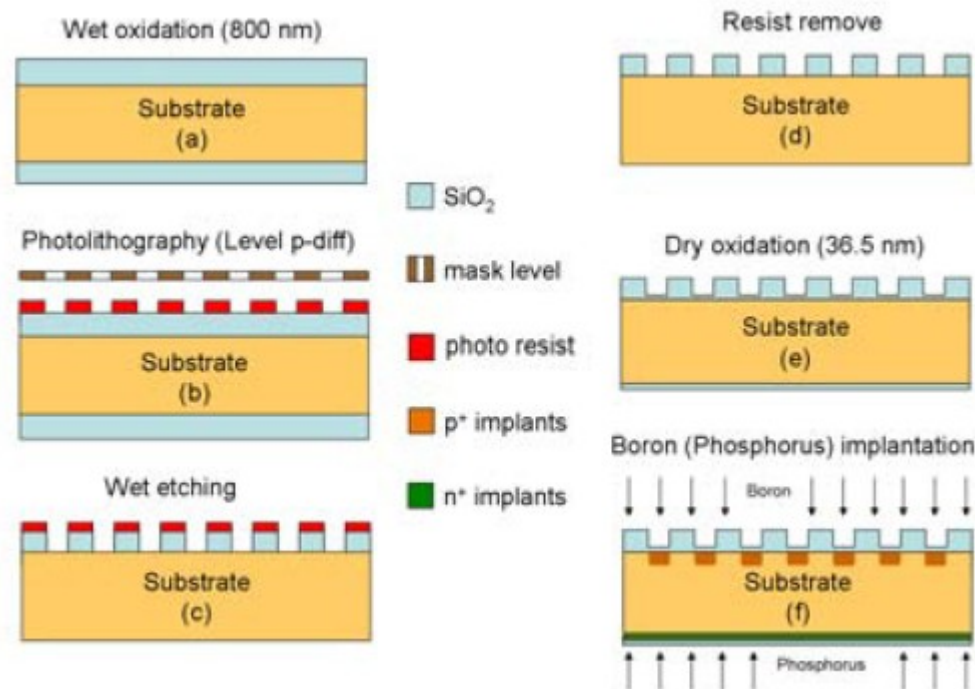


You will probably visit the silicon producer Okmetic Oy during your lab-week in Helsinki

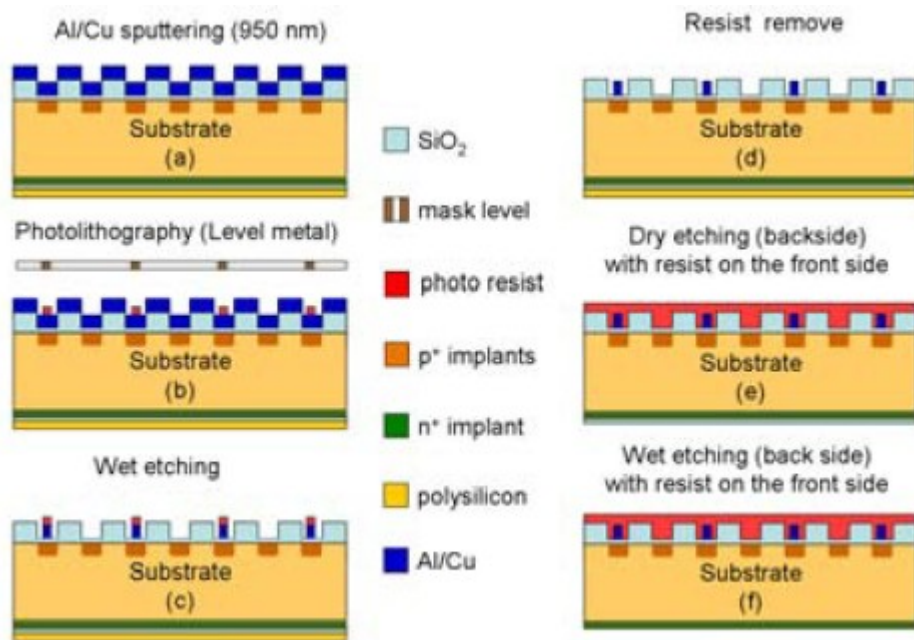
Processing steps

(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).



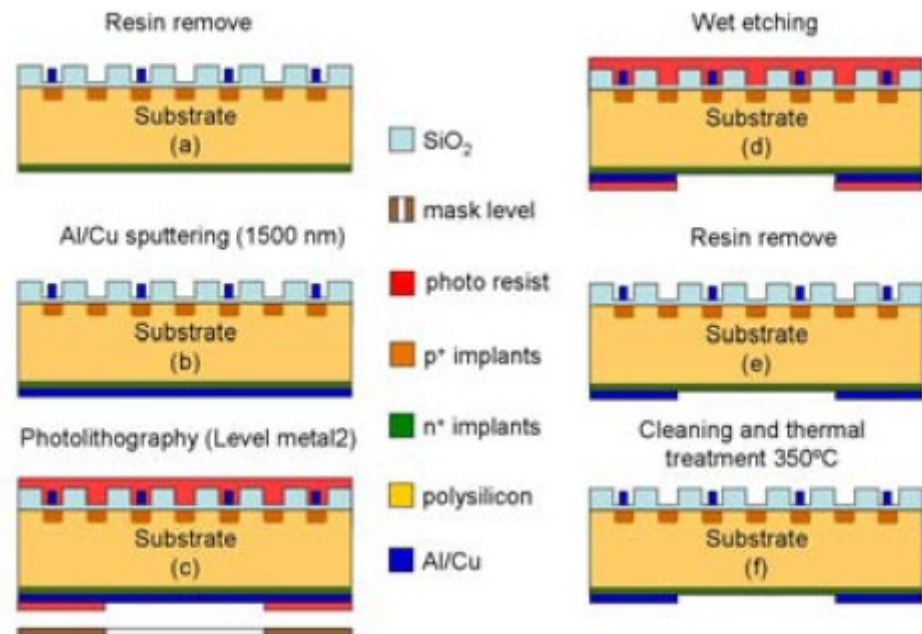
Dopant	Dose [at/cm ²]	Energy [keV]	Final conc. [at/cm ²]	Junction depth [μm]
Boron	$1.5 \cdot 10^{14}$	100	10^{20}	1
Phosphorus	$1 \cdot 10^{13}$	50	10^{19}	1



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