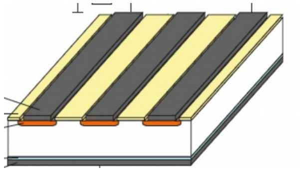

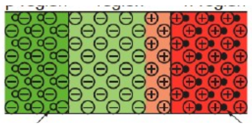

Tracking – 4
Semiconductor Detectors

Jochen Kaminski
University of Bonn

BND – summer school
Callantsoog, Netherlands
4.-6.9.2017

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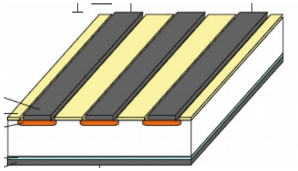
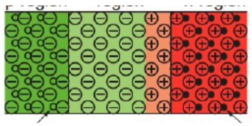


Overview Course



Lecture 1: Tracking - Basics and Reconstruction

Lecture 2: Basic Principle of Detectors

Lecture 3: Gaseous Detectors

Lecture 4: Semiconductor Detectors
- Principle of Si-Detectors
- Silicon Strips
- Silicon Pixel Detectors
- Radiation Damage
- Comparison Gaseous and Semiconductor Detectors

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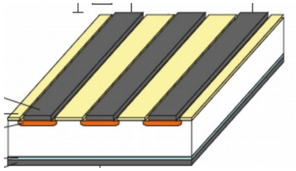
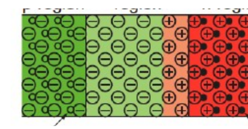




What are Semiconductors?

Conductors: specific resistivity = $10^{-6} - 10^{-4}\ \Omega$cm

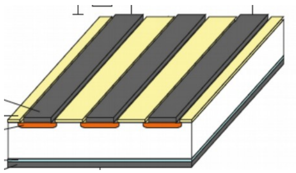
Semiconductors: specific resistivity = $10^{-3} - 10^{8}\ \Omega$cm

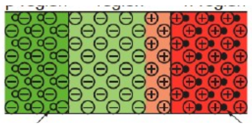
Insulators: specific resistivity > $10^{10}\ \Omega$cm

There are elementary semiconductors: silicon and germanium
there are also III-V compounds: e.g. GaAs (AlP, AlAs,BN, GaP, InSb,..)
and of the II-VI compounds: CdTe (CdS, CdSe, ZnS, HgS, HgTe,…)

Germanium has been used for a long time in calorimeters.
CdTe is interesting for high energetic X-rays.

For tracking detectors in HEP – only silicon plays a role.
(Diamonds are studied as radiation hard alternatives.)





Crystal Structures

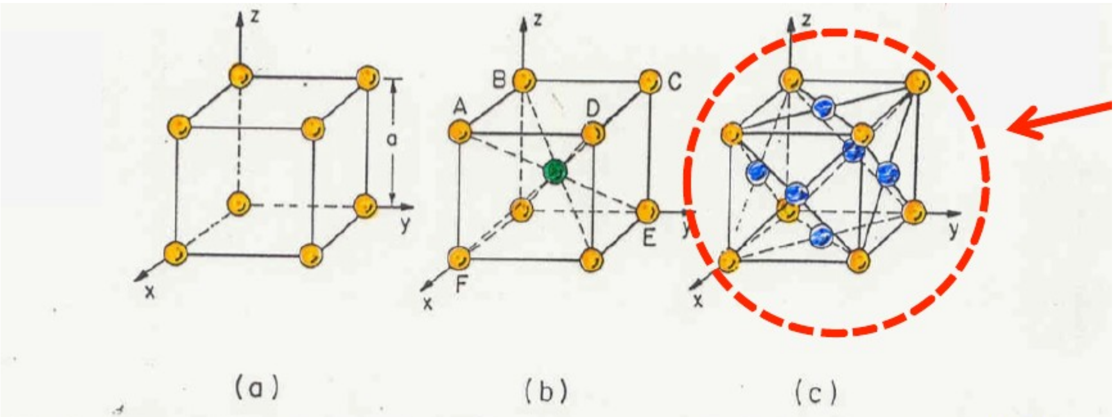
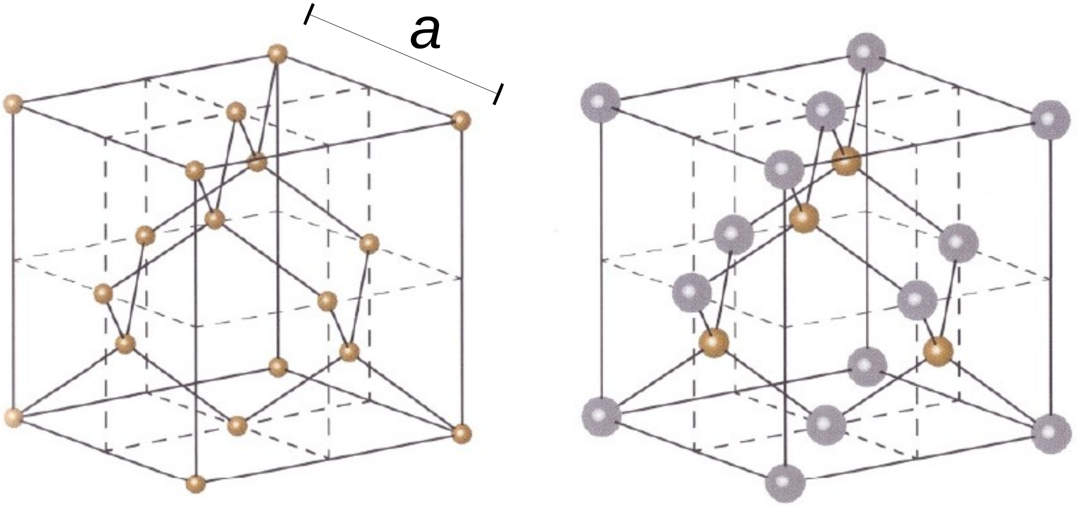


Fig. 2 Three cubic-crystal unit cells. (*a*) Simple cubic. (*b*) Body-centered cubic. (*c*) Face-centered cubic.

Face centered cubic (fcc)
→ Diamond lattice:
2 fcc with same atoms nested

<u>Properties of the Si-crystal</u>
Atomic number: Z = 14
Atomic mass: M_{si} = 28.09 u
Density: ρ = 2.328 g/cm3
Lattice constant: a = 5.431 A



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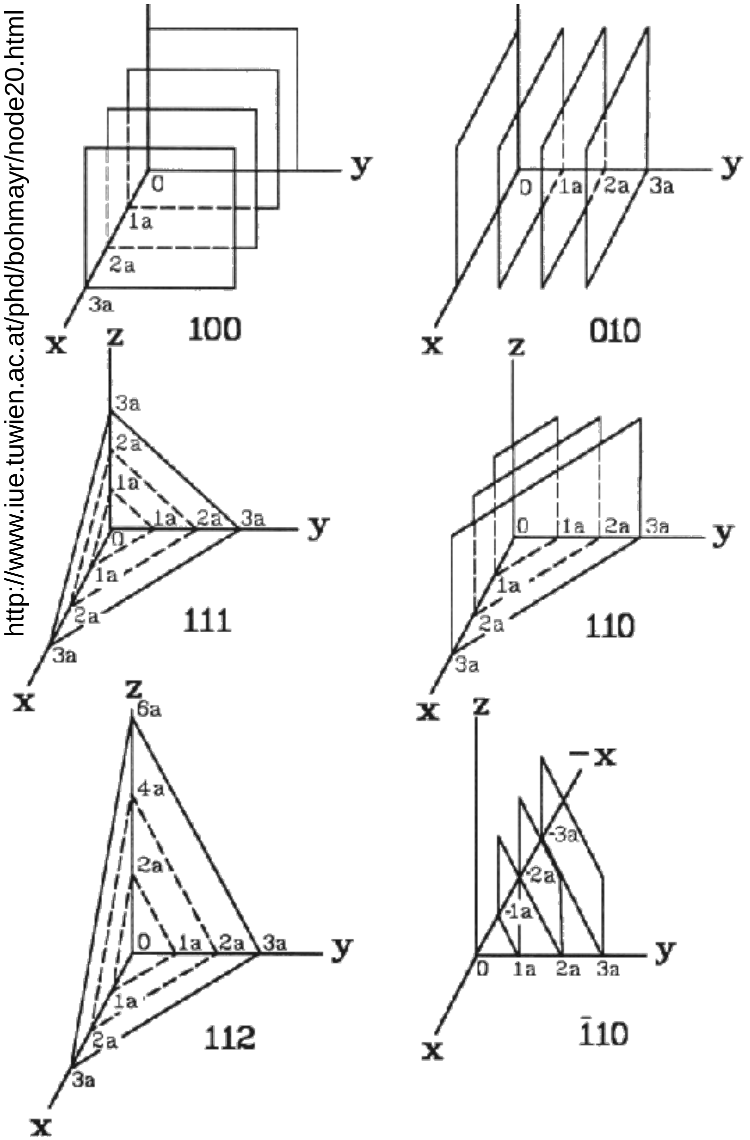
Directions of cutting (Miller's indices)

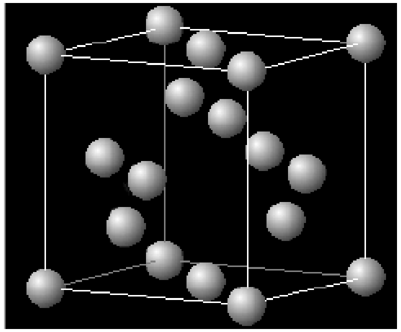
http://www.iue.tuwien.ac.at/phd/bohmayr/node20.html



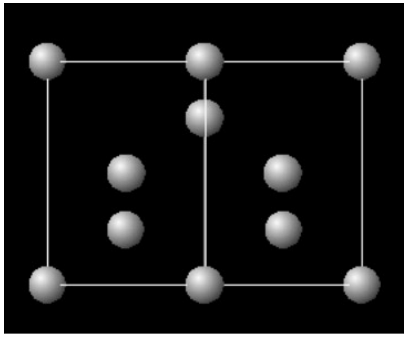
reminder Miller index

$$h = \frac{kgV_1}{x_1}, \quad k = \frac{kgV_1}{y_1}, \quad l = \frac{kgV_1}{z_1}$$

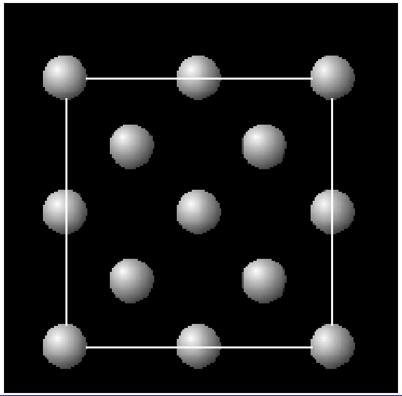
unit cell



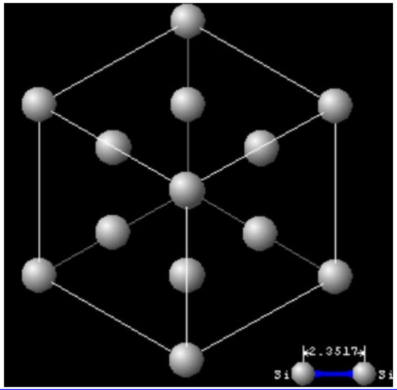
View in <110> direction



View in <100> direction



View in <111> direction



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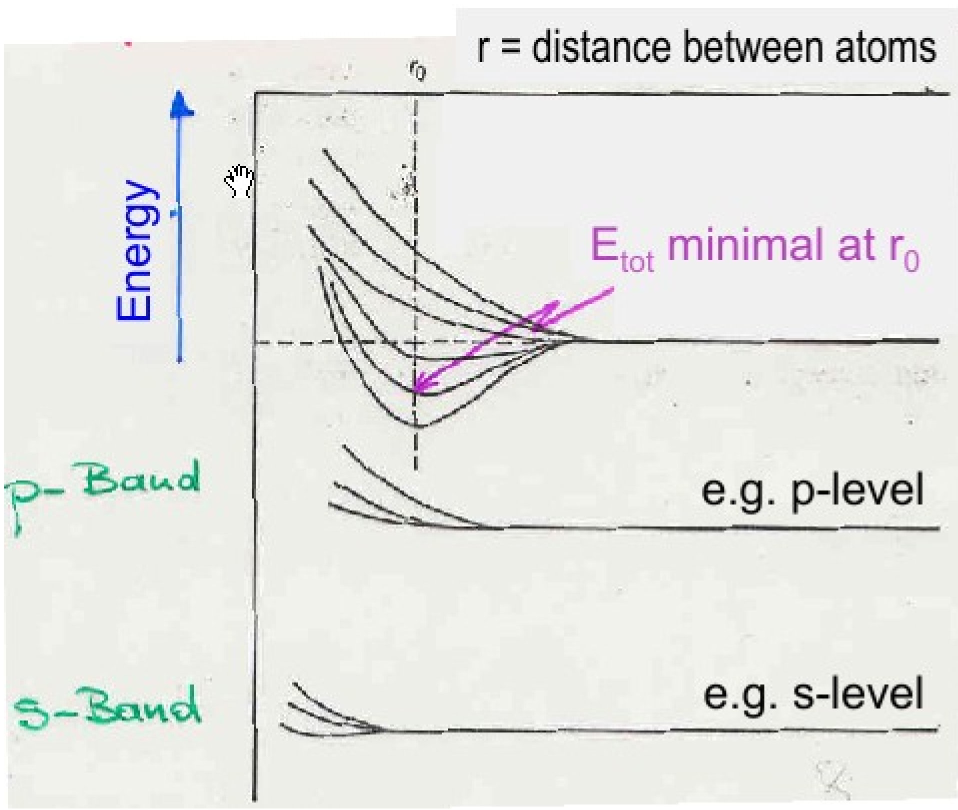
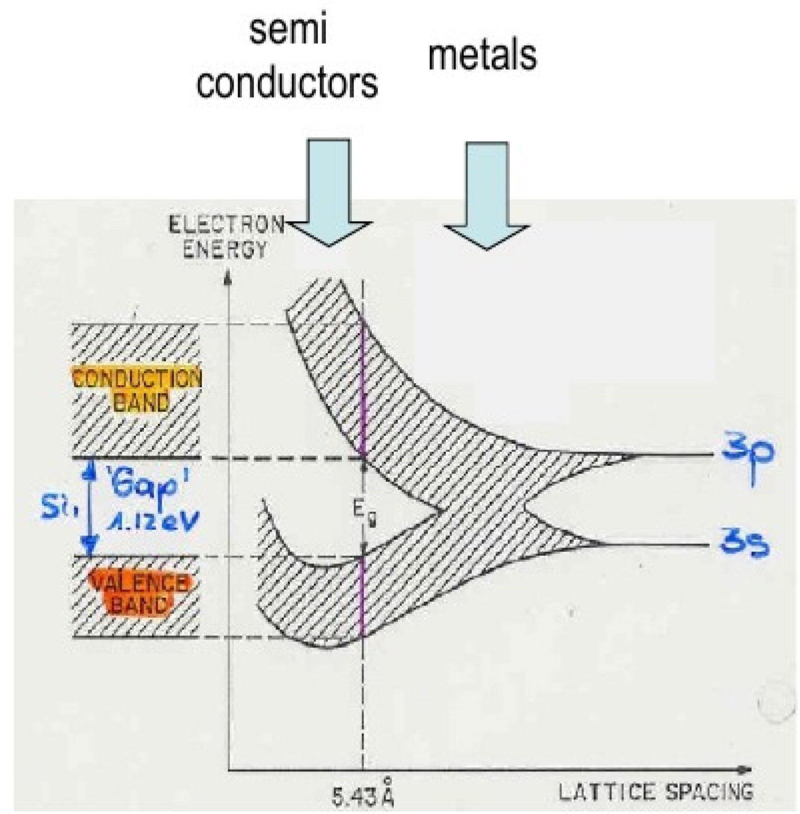
Band Structure (I)

Because of the close distance between the atoms, the energy levels are degenerated and form energy bands.





Temperature and pressure influence the lattice constant, which influences the energy band and gaps between them.

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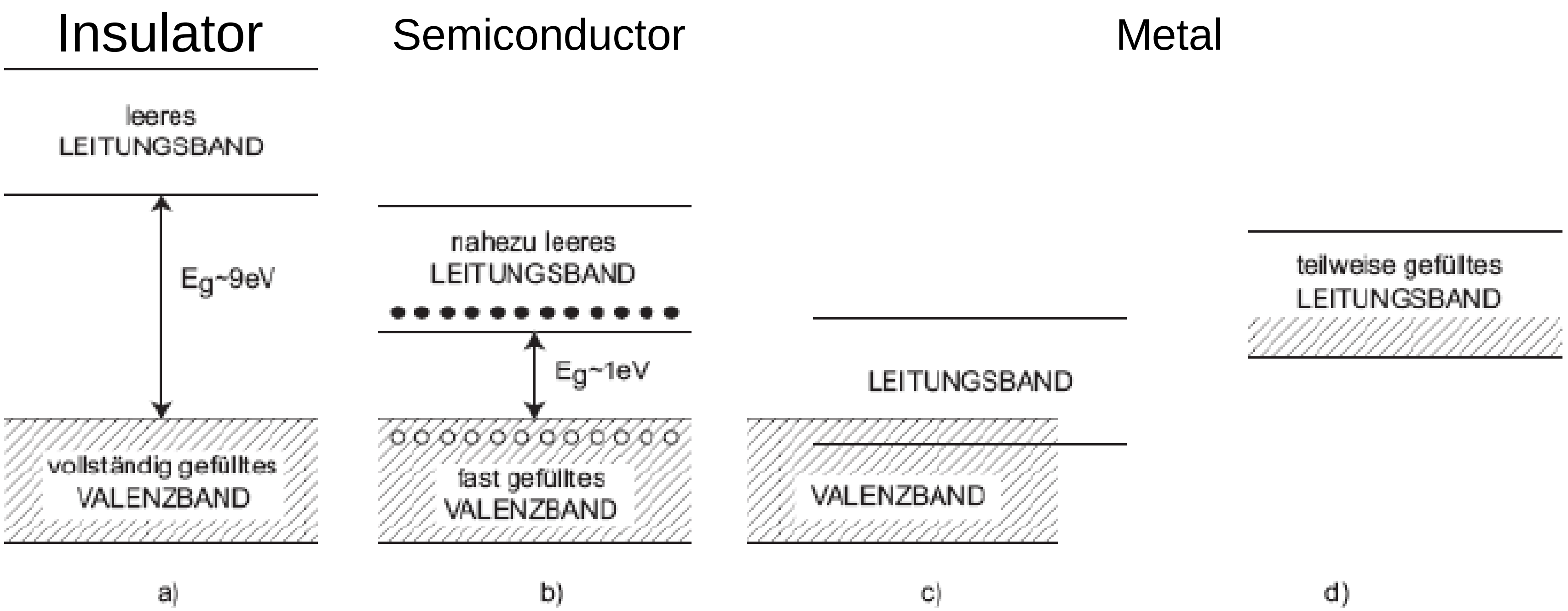
Band Structure (II)



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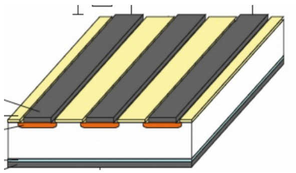
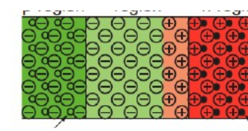
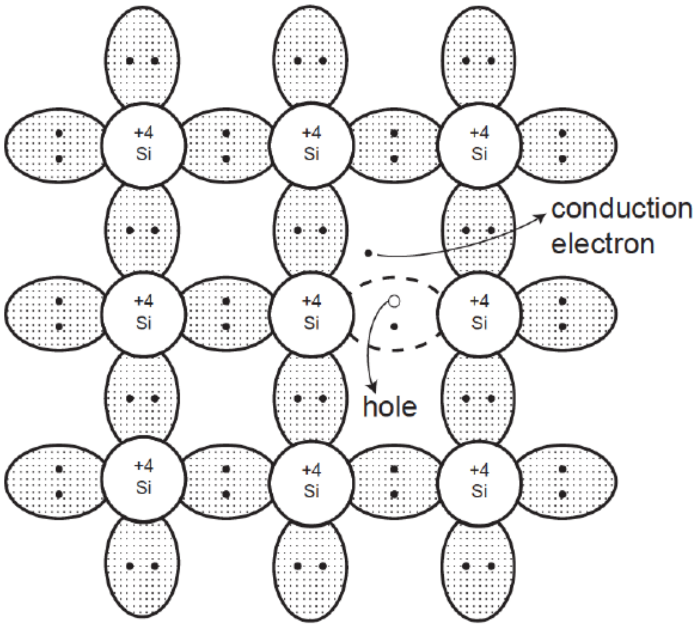


Conductor Mechanism





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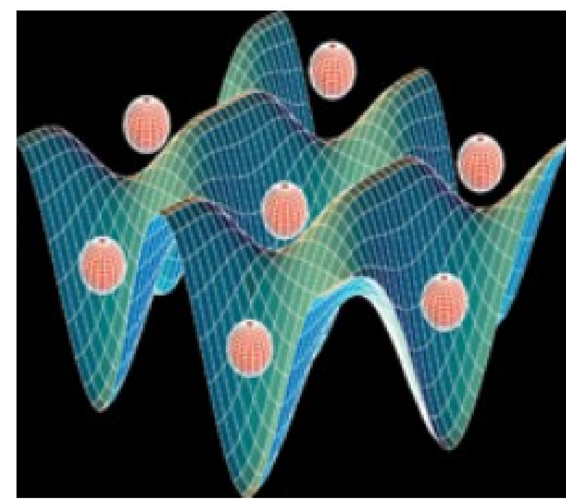
Either by thermal processes or by a charged particle passing by, the bonds of an electron with lattice atoms break and a free electron and a hole appear.
In an electric field both drift in opposite directions.
Holes move slower than electrons, because more particles are involved.

Electrons and holes move from potential well to potential well → classical description of motion is not valid
=> described by waves with wave vector $\bar{k}$

Because of periodic structure of lattice it is not a free movement, but they follow the curvature of the band structures.



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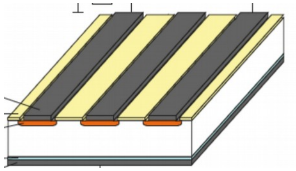
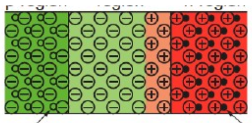


Effective Mass



We need : $E = \hbar\omega \quad p = \hbar k$ and the dispersion relation $E(k) = \dfrac{\hbar^2 k^2}{2m}$

1.) The electron drift velocity corresponds to the group velocity of the wave:

$$\frac{dx}{dt} = \mathrm{v} = \frac{d\omega}{dk} = \frac{dE}{dp}$$

2.) The accelerating force depends on the gradient of the electric field:

$$F = \frac{dE}{dx} \overset{dx=\frac{dE}{dp}dt}{=} \frac{1}{\mathrm{v}}\frac{dE}{dt} \overset{\mathrm{v}=\frac{dE}{dp}}{=} \frac{dp}{dE}\frac{dE}{dt} = \frac{dp}{dt}$$

3.) The effective mass of the electron is finally obtained by:

$$F = m^{\star}a = m^{\star}\frac{d\mathrm{v}}{dt} \overset{\mathrm{v}=\frac{dE}{dp}}{=} m^{\star}\frac{d\frac{dE}{dp}}{dt} = m^{\star}\frac{d^2E}{dp^2}\frac{dp}{dt}$$

$$\Rightarrow \frac{1}{m^{\star}} = \frac{d^2E}{dp^2}\frac{dp}{dt} \overset{p=\hbar k}{=} \frac{1}{\hbar^2}\frac{d^2E}{dk^2}$$

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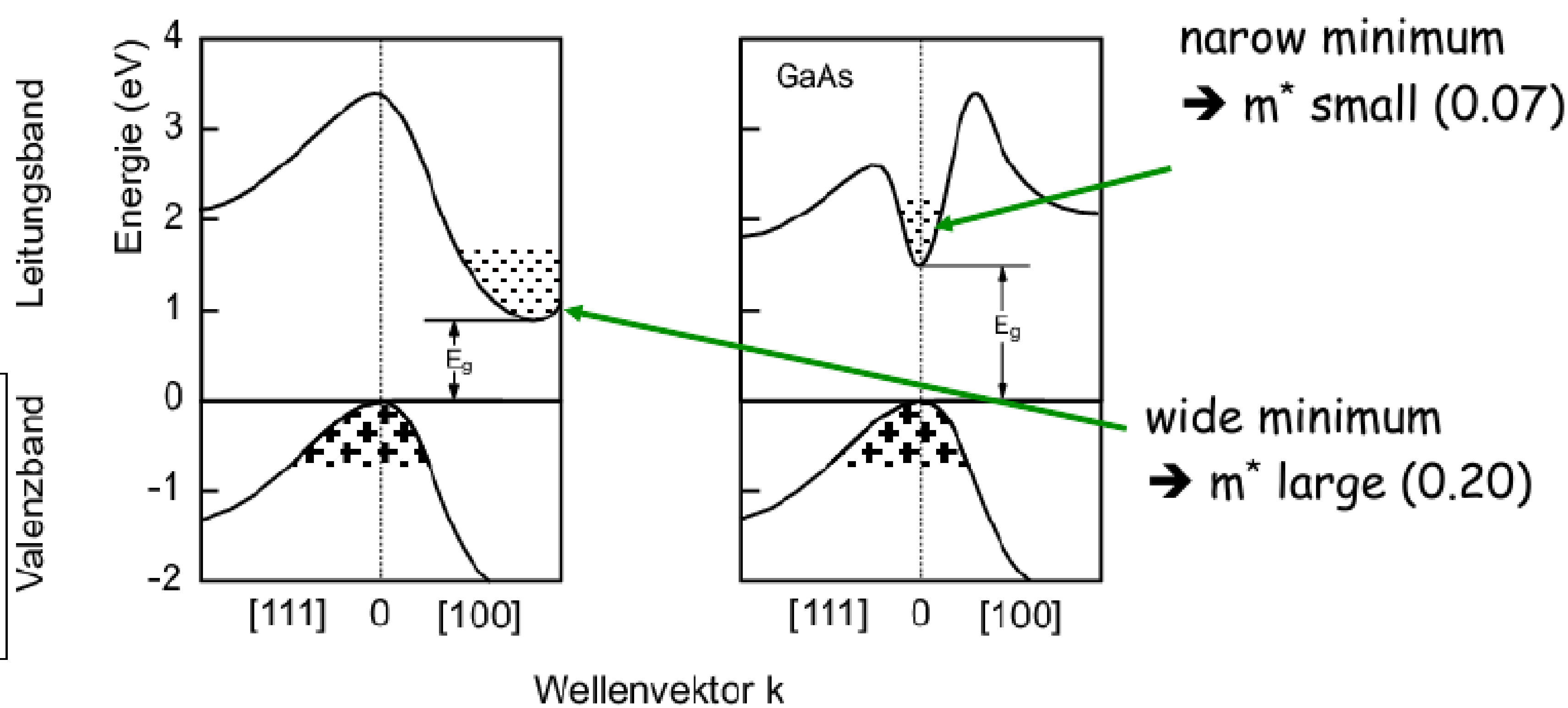
Direct and Indirect Semiconductors

indirect e.g. Si, Ge

to produce e/h must change E AND k

direct e.g. GaAs



several k-values for the same energy value possible
→ bands overlap in k-space

Direct semiconductors are good for photon detection, because e^-/h pairs can be generated without interaction of the lattice.

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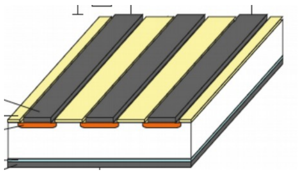
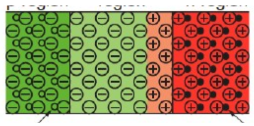


Charge Carrier Density in a Thermal Equilibrium (I)

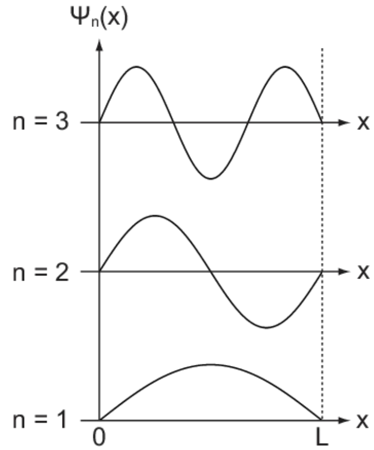


To calculate the charge carrier density $n(E)$, one has to calculate the number of momentum state $Z(E)$ and the probability $f(E)$ to occupy them:

$$n(E)dE = Z(E) \cdot f(E)dE$$

The number of momentum state $Z(E)$ can be easily calculated in the k space, Therefore we make the transformation

$$Z(E)dE = Z(k(E))\frac{dk(E)}{dE}dE$$



The lattice corresponds to an infinite potential well of length L_i and the movement of the electrons is described by a standing wave with wave length λ and the energy of the electrons is $E=\hbar^2k^2/2m$. This can be use to get:

$$E = \frac{\hbar \vec{k}^2}{2m} \quad \rightarrow \quad k = \sqrt{\frac{2m}{\hbar}}E^{\frac{1}{2}} \quad \rightarrow \quad dk = \frac{1}{2}\sqrt{\frac{2m}{\hbar E}}dE \quad \rightarrow \quad \frac{dk}{dE} = \frac{1}{2}\sqrt{\frac{2m}{\hbar E}}$$

The states are discrete with levels $k_x=2\pi n_x/L_x$ (standing waves) and form a lattice in the k-space, where each k states occupies a volume of $V=8\pi^3/L_xL_yL_z=8\pi^3/V$.

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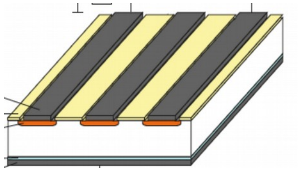
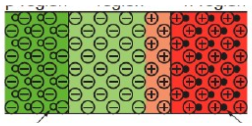


Charge Carrier Density in a Thermal Equilibrium (II)



This results in a k-state density of $\rho_k = V/8\pi^3$.

Free electrons with constant energy form spherical shells in the k-space, which have a volume of $dV_k = 4\pi k^2\, dk$.

The density of k-states is thus given by $Z(k) = 2\, \rho_k\, dV_k$

$$Z(k)dk = 2\rho_k dV_k = 2\frac{V}{8\pi^3}4\pi k^2 dk = \frac{k^2 V}{\pi^2}dk$$

Now we make the transformation from k to E

$$Z(E)dE = Z(k(E))\frac{dk(E)}{dE}dE = \frac{k^2 V}{\pi^2}\cdot\frac{1}{2}\sqrt{\frac{2m}{\hbar E}}\cdot dE =$$

$$= \frac{V}{2\pi^2}\cdot\left(\sqrt{\frac{2m}{\hbar}}E^{\frac{1}{2}}\right)^2\sqrt{\frac{2m}{\hbar E}}\cdot dE = \frac{V}{2\pi^2}\cdot\left(\frac{2m}{\hbar}\right)^{\frac{3}{2}}\sqrt{E}\cdot dE$$

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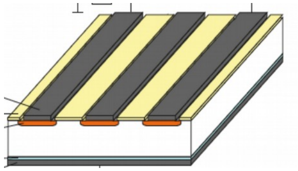
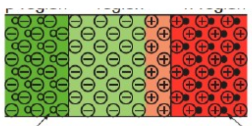


Charge Carrier Density in a Thermal Equilibrium (III)



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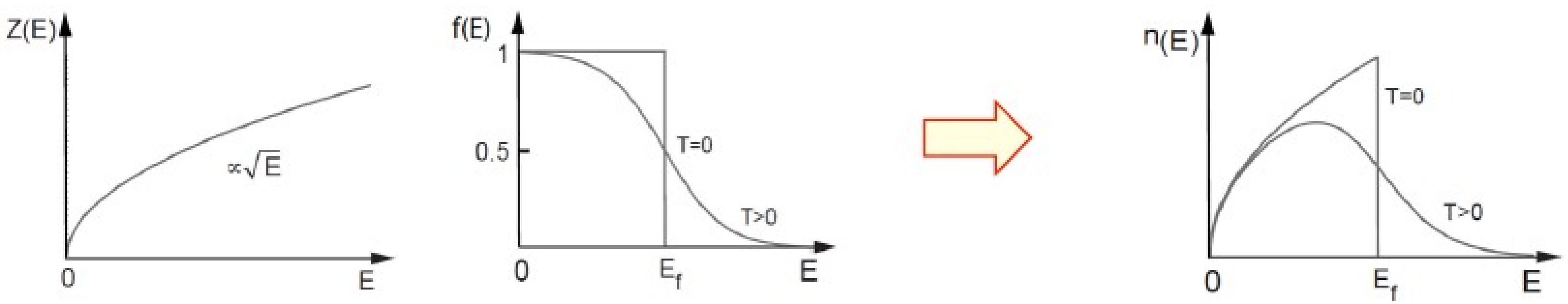
The probability to occupy levels is given by the Fermi-Dirac statistics

$$f_n(E) = \frac{1}{e^{\left(\frac{E-E_f}{kT}\right)}+1} \qquad \text{and} \qquad f_p(E) = \frac{1}{e^{\left(\frac{E_f-E}{kt}\right)}+1}$$

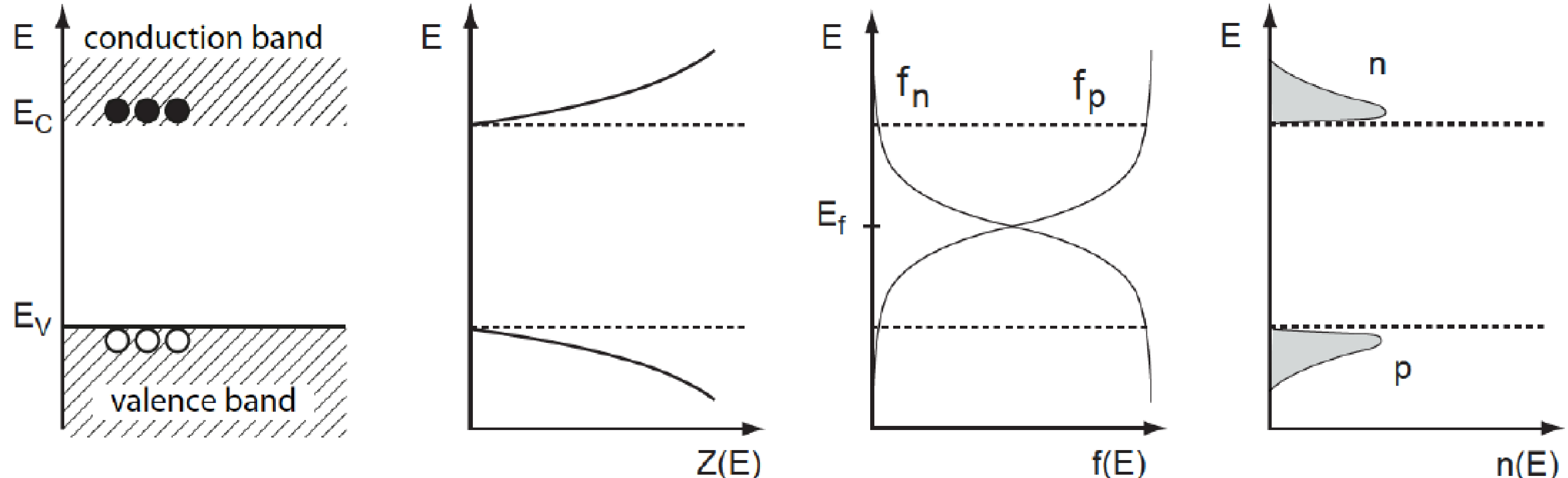


If the band gap should be taken into account, a Θ-function is used:

$$n(E)dE = 4\pi \left(\frac{2m_{eff,n}}{h^2}\right)^{\frac{3}{2}} \sqrt{E-E_L}\,\Theta(E-E_L)\frac{1}{e^{\left(\frac{E-E_f}{kT}\right)}+1}dE$$

$$p(E)dE = 4\pi \left(\frac{2m_{eff,p}}{h^2}\right)^{\frac{3}{2}} \sqrt{E_V-E}\,\Theta(E_V-E)\frac{1}{e^{\left(\frac{E_f-E}{kT}\right)}+1}dE$$

Charge Carrier Density in a Thermal Equilibrium (IV)



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Integrating over all energies gives

$$n = 2\left(\frac{m_{eff,n}kT}{2\pi\hbar^2}\right)^{\frac{3}{2}} e^{\left(-\frac{E_L-E_f}{kT}\right)} = N_L \cdot e^{\left(-\frac{E_L-E_f}{kT}\right)}$$

$$p = 2\left(\frac{m_{eff,p}kT}{2\pi\hbar^2}\right)^{\frac{3}{2}} e^{\left(-\frac{E_f-E_V}{kT}\right)} = N_V \cdot e^{\left(-\frac{E_f-E_V}{kT}\right)}$$

The charges always have to be in equilibrium

$$n \cdot p = n_i^2 = N_L N_V \cdot e^{\left(-\frac{E_L-E_V}{kT}\right)} = N_L N_V \cdot e^{\left(-\frac{E_G}{kT}\right)}$$

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Put in some Numbers

Let's concentrate on Si at T = 300 K.

Effective mass: m_{eff} for electrons is transverse to the 100-axis: 0.19 m_e
and longitudinal to the 100-axis: 0.92 m_e

m_{eff} for holes there are also several: $m_{eff,h}^{light}$ = 0.16 m_e
$m_{eff,h}^{heavy}$ = 0.53 m_e

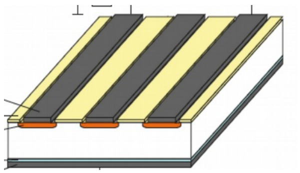
For all applications these values are averaged and one uses
$m_{eff,e}$ = 1.14 m_e and $m_{eff,h}$ = 1.01 m_e.

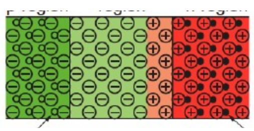
Thus we get
$$N_L = 2\left(\frac{m_{eff,n}kT}{2\pi\hbar^2}\right)^{\frac{3}{2}} \approx 3.05\cdot 10^{19}\ \mathrm{cm}^{-3}$$

$$N_V = 2\left(\frac{m_{eff,p}kT}{2\pi\hbar^2}\right)^{\frac{3}{2}} \approx 2.55\cdot 10^{19}\ \mathrm{cm}^{-3}$$

$$n_i \approx 1.01\cdot 10^{10}\ \mathrm{cm}^{-3}$$

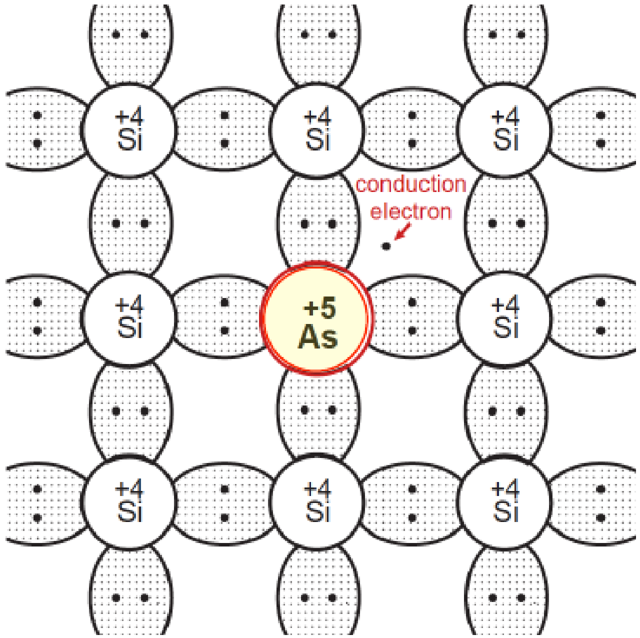
conductivity $\sigma_i = n_i e(\mu_e+\mu_h) \simeq 2.8\ 10^{-4}\ (\Omega\mathrm{m})^{-1}$ $\sigma_{Cu} = 10^8\ (\Omega\mathrm{m})^{-1}$



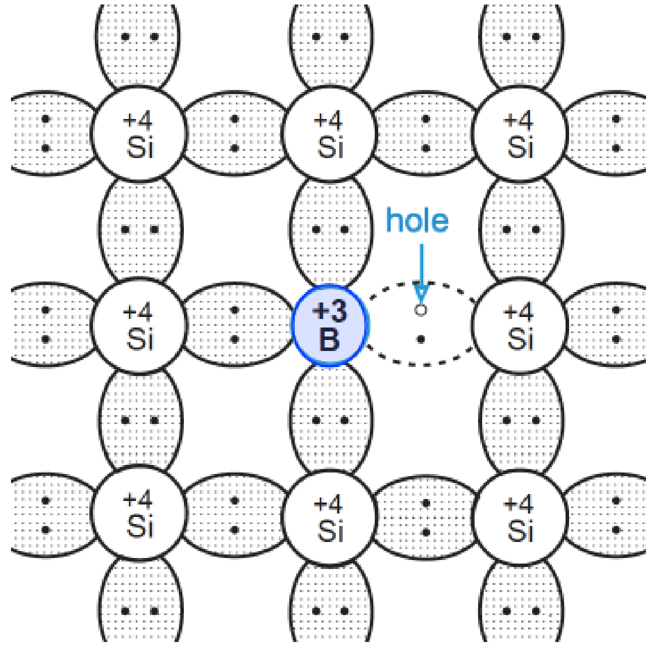


Doping (I)

Donor (As, P, Sb, ..)



Acceptor (B, Al, ..)



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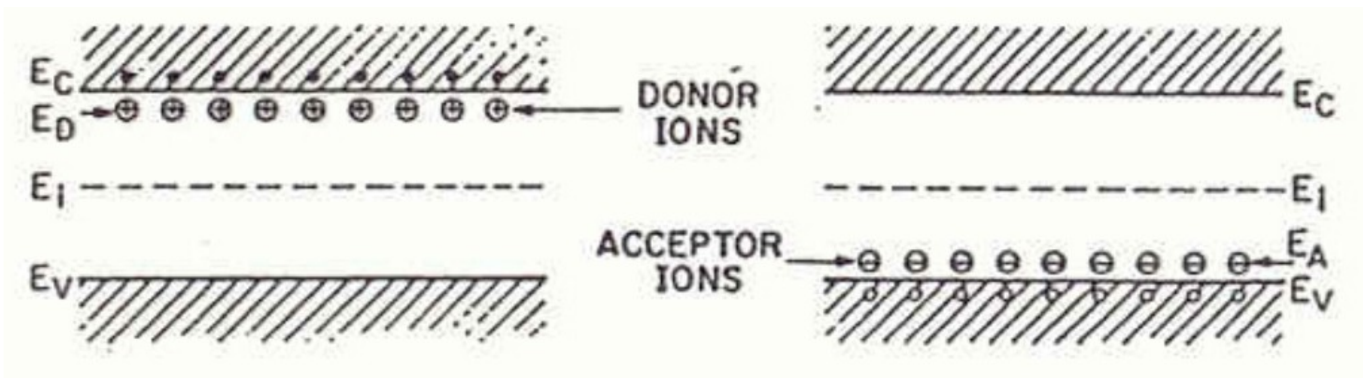

Doping with donors
  n-type semiconduc.
  (additional electrons)
Doping with acceptors
  p-type semiconduc.
  (additional holes)

Typical doping
  concentrations are
  N_D=10^{16} cm^{-3}

=> $n=N_D+n_i \approx 10^{16}$ cm^{-3}

$p = n_i^2/n \approx 10^4$ cm^{-3}

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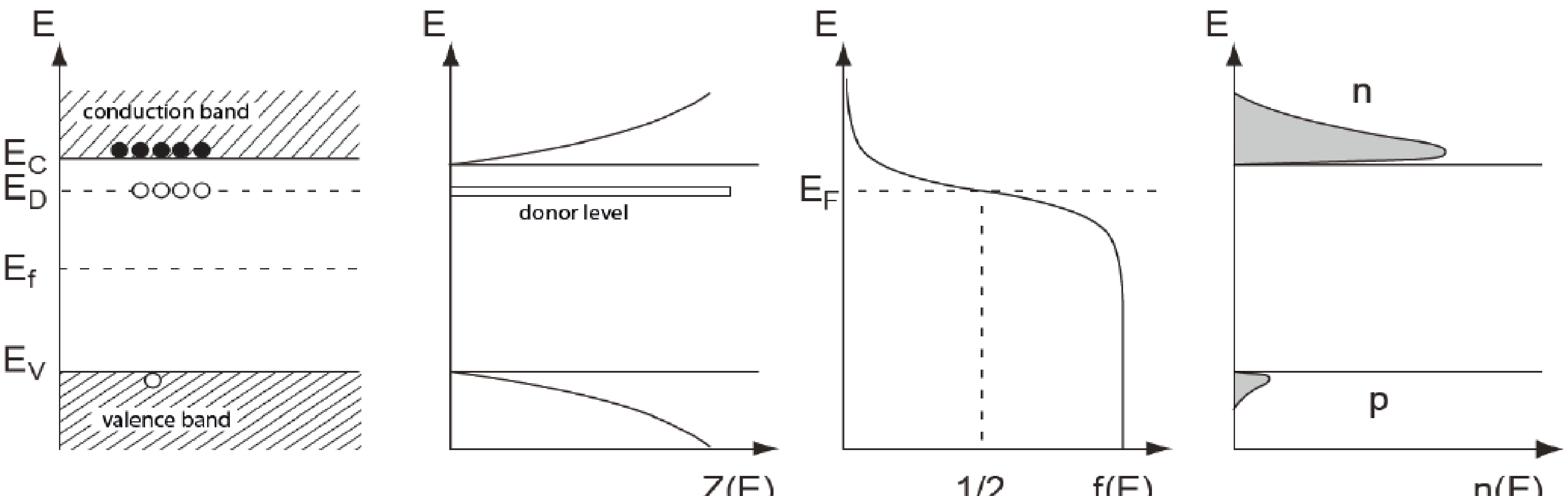
Doping (II)



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Calculating the number of carriers in the conductor and valence band gives:

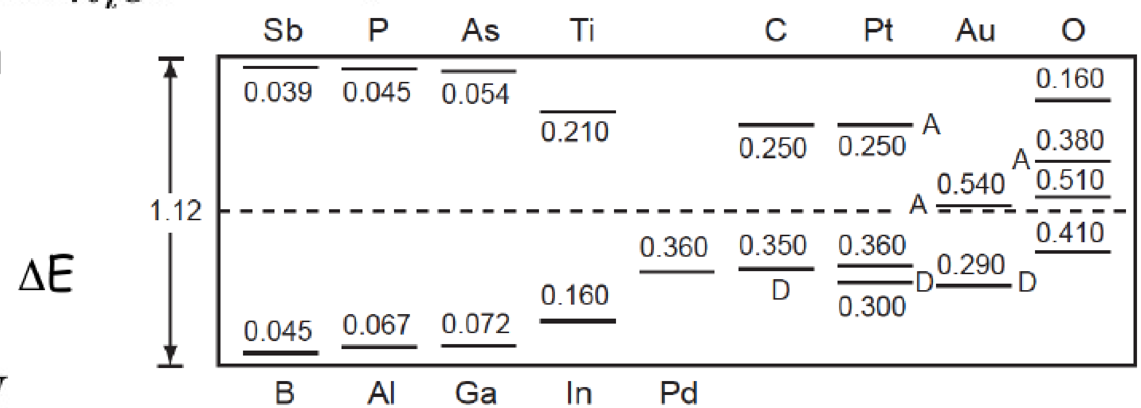
$$n \approx N_D = N_L e^{\left(-\frac{E_L - E_F}{kT}\right)} = N_L e^{\left(-\frac{E_L - E_f}{kT}\right)} e^{\left(-\frac{E_f - E_F}{kT}\right)} = n_i e^{\left(\frac{E_F - E_f}{kT}\right)}$$

$$p \approx n_i e^{\left(-\frac{E_f - E_F}{kT}\right)}$$

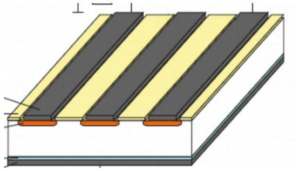
Where the energy levels are given

$$E_F - E_f = kT \ln \frac{N_D}{n_i} = 0.348 \text{ eV}$$

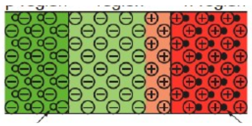
$$E_L - E_F = kT \ln \frac{N_L}{n_D} = 0.209 \text{ eV}$$



ul $E_F - E_V = 1.12 \text{ eV} - 0.209 \text{ eV} = 0.911 \text{ eV}$



Junctions



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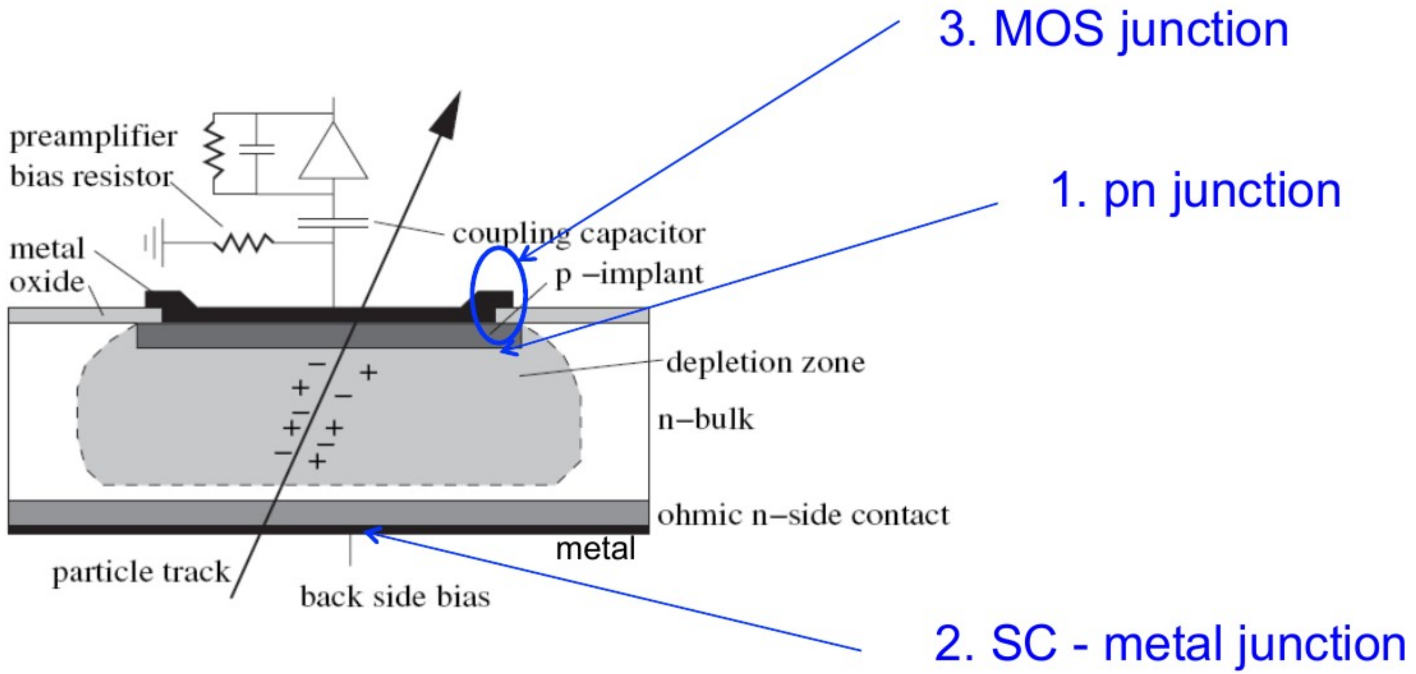

The chemical potential $\mu = (\partial F / \partial N)_{U,T}$, where F = free energy, U = inner energy, T = temperature, N = particle number, is a measure of the particle concentration in an ensemble. When μ = const. everywhere in the device, there is no net diffusion, i.e. thermal equilibrium is established. → Rules for junctions:

1.) Temperature and Chemical Potential ($\mu = E_F$) are uniform over the device after equilibrium is established

2.) Far away from the junction the bulk properties must be recovered (i.e bands bend in junction regions only)

3.) For junctions of the same type (e.g. *pn*) only: In the junction region the bands are simply connected without discontinuities

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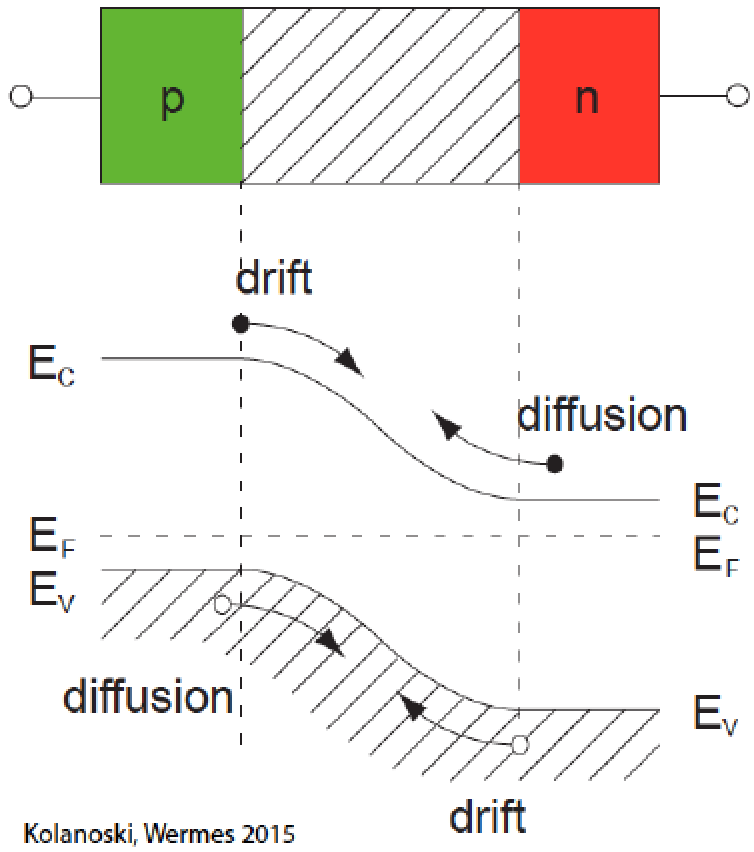
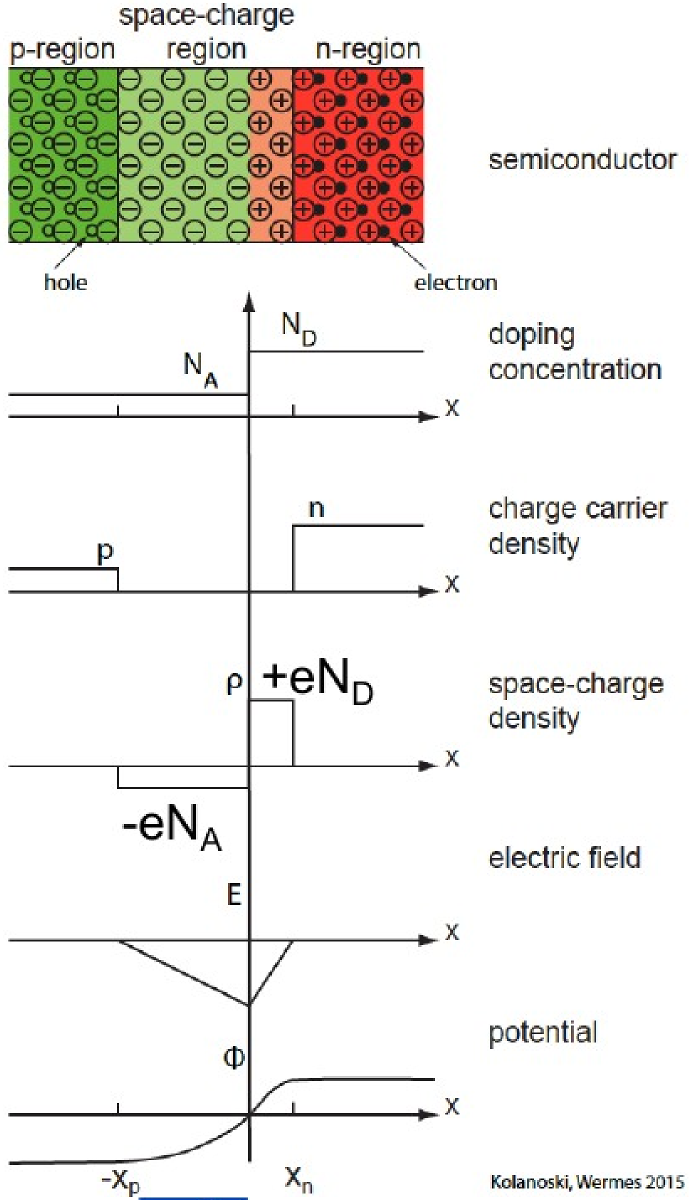
PN Junction (I)



Joining a *p* and a *n* doped semiconductor, the majority charges of each side will diffuse into the other region where they will recombine with the other majority charge
→ stops when E_F is same on both sides
→ In the region between there is a space without free charges
depletion zone
a space charge develops.
Alternative explanation: diffusion current because of concentration gradient is the same as the drift because of *E*-field of space charge.

PN Junction (II)



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Considering an abrupt junction:

- Concentrations of donors and acceptors are given by doping.
- In the depletion zone free charges recombine leaving the immovable ionized atoms as space charges
- Density is $\rho(x) = -eN_A$ for $x_p<x<0$ and

  $\rho(x) = eN_D$ for $0<x<x_n$
- The electric field is $$\frac{dE}{dx} = \frac{1}{\epsilon\epsilon_0}\rho(x)$$

$$E(x) = \begin{cases} \frac{-eN_A}{\epsilon\epsilon_0}(x+x_p) & -x_p < x < 0 \\ \frac{+eN_D}{\epsilon\epsilon_0}(x-x_n) & 0 < x < n_n \end{cases}$$

$$E_{max} = -\frac{eN_A}{\epsilon\epsilon_0}x_p = \frac{eN_D}{\epsilon\epsilon_0}(-x_n)$$

- The potential is then given by

$$\phi(x) = \begin{cases} \phi_p + \frac{eN_A}{2\epsilon\epsilon_0}(x+x_p)^2 & -x_p < x < 0 \\ \phi_n - \frac{eN_D}{2\epsilon\epsilon_0}(x-x_n)^2 & 0 < x < n_n \end{cases}$$

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PN Junction (III)

From the previous considerations, one can deduce the diffusion voltage, which is connected to the differences between the extrinsic and intrinsic Fermi-levels E_f-E_f^p and E_f^n-E_f.

$$U_{bi} = -\frac{kT}{e}\ln\frac{N_A N_D}{ni^2} \approx 0.6 - 0.8\ \mathrm{V}$$

This can be also expressed in dependence on the depletion zone widths

$$U_{bi} = -\int_{-x_p}^{n_n} E(x)dx = \frac{e}{2\epsilon\epsilon_0}\left(N_A x_p^2 + N_D x_n^2\right) = \frac{e}{2\epsilon\epsilon_0} x_p^2 \frac{N_A}{N_D}\left(N_A + N_D\right)$$

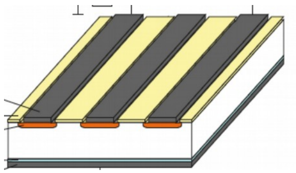
and with the neutrality requirement, one can specify the thickness of the depletion zone

$$x_p = \sqrt{\frac{2\epsilon\epsilon_0}{e} U_{bin} \frac{N_D}{N_A\left(N_A + N_D\right)}}$$

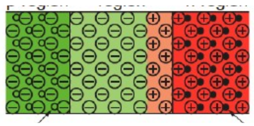
$$x_n = \sqrt{\frac{2\epsilon\epsilon_0}{e} U_{bin} \frac{N_A}{N_D\left(N_A + N_D\right)}}$$

Putting in typical numbers: $N_A = 10^{19}$ cm^{-3} and $N_D = 2.3 \cdot 10^{12}$ cm^{-3} we get:

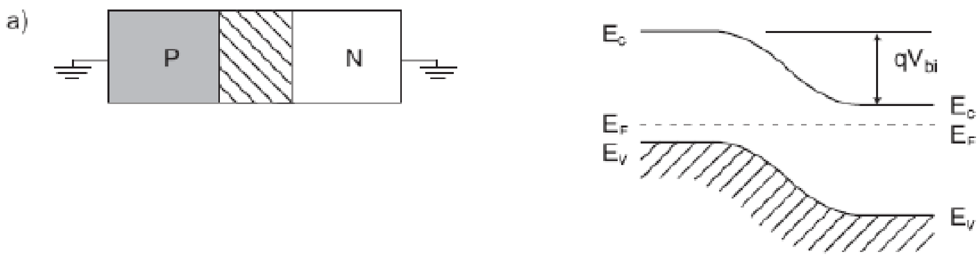
$x_p \approx 4 \cdot 10^{-6}$ µm and $x_n \approx x_p\ N_A/N_D = 20$ µm



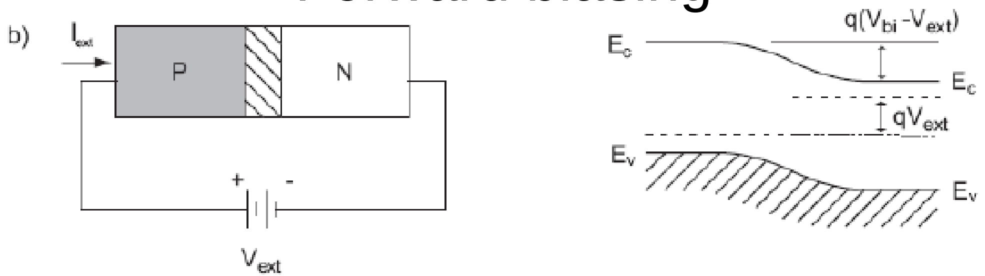
PN-Junction with External Field



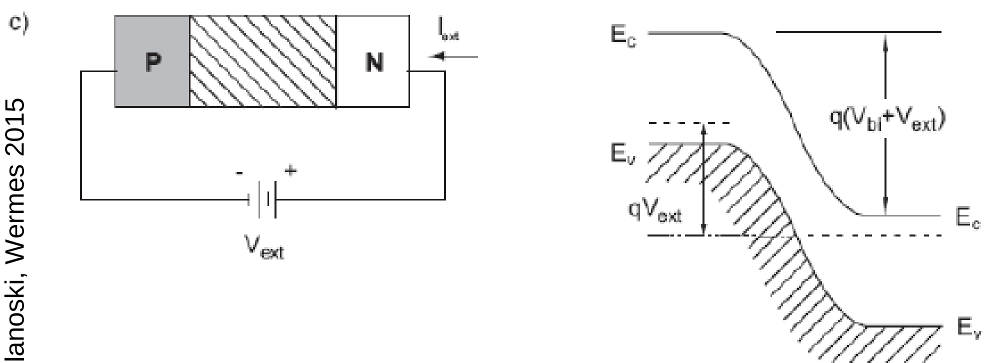
No biasing



Forward biasing



Reverse biasing



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With an external field applied, system is not in thermal equilibrium anymore.

Forward biasing: $np > n_i^2$

The drift is suppressed, depletion zone is shorter

Reverse Biasing: $np < n_i^2$

E-field is higher, the depletion zone increases → used in detectors

The thickness is now

$$d \approx x_n \approx \sqrt{\frac{2\epsilon\epsilon_0}{e}\frac{1}{N_D}(U_{bin} + U_{ext})}$$

$$\approx 3.6 \cdot 10^3 \sqrt{\frac{U_{ext}}{N_D(\mathrm{V\ cm})}}$$

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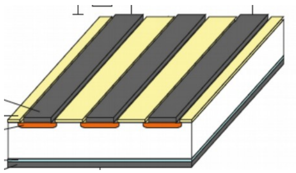
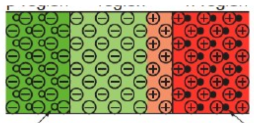
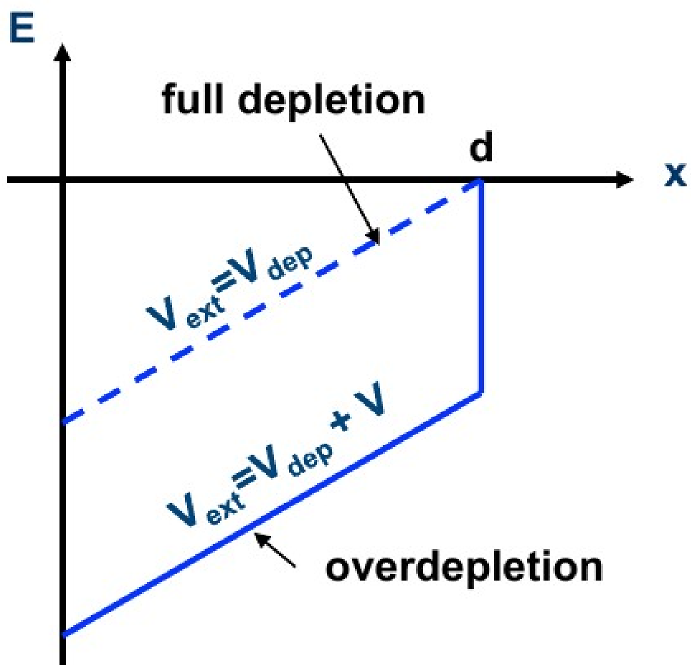


PN-Junction with External Field as a Particle Detector





$E_{max} = 2V_{ext}/d$

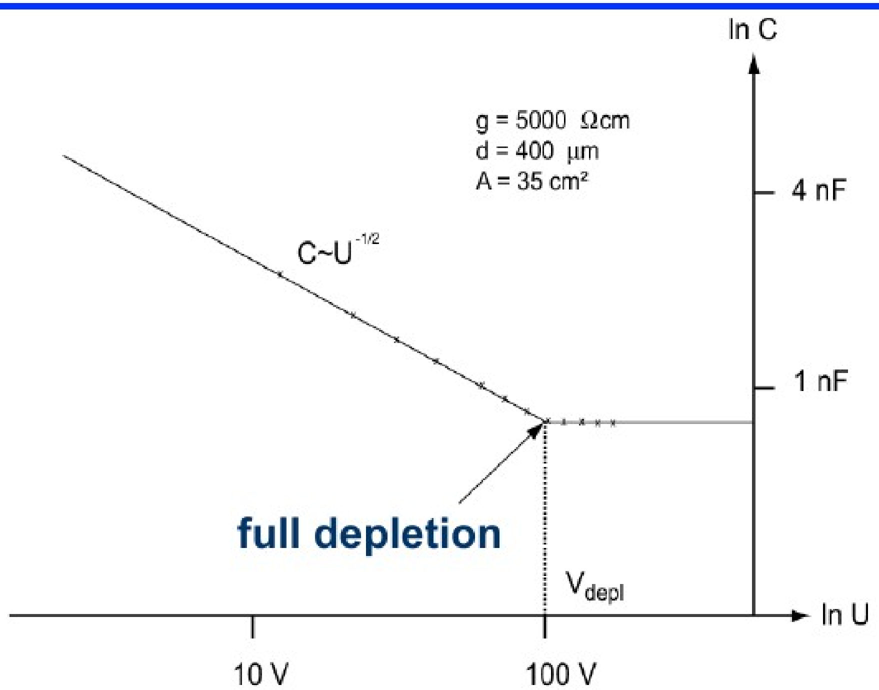
with applied external bias voltage

$$E(x) = -\frac{V+V_{dep}}{d} + \frac{2V_{dep}\,x}{d^2}$$

$$d = x_n = \sqrt{\frac{2\epsilon}{e}\frac{1}{N_D}\left(V_{bi}+V_{ext}\right)} \propto \sqrt{V_{ext}}$$

capacitance

$$\frac{\mathrm{C}}{\mathrm{A}} = \frac{1}{\epsilon\epsilon_0}\frac{1}{d} \propto \frac{1}{\sqrt{V_{ext}}}$$



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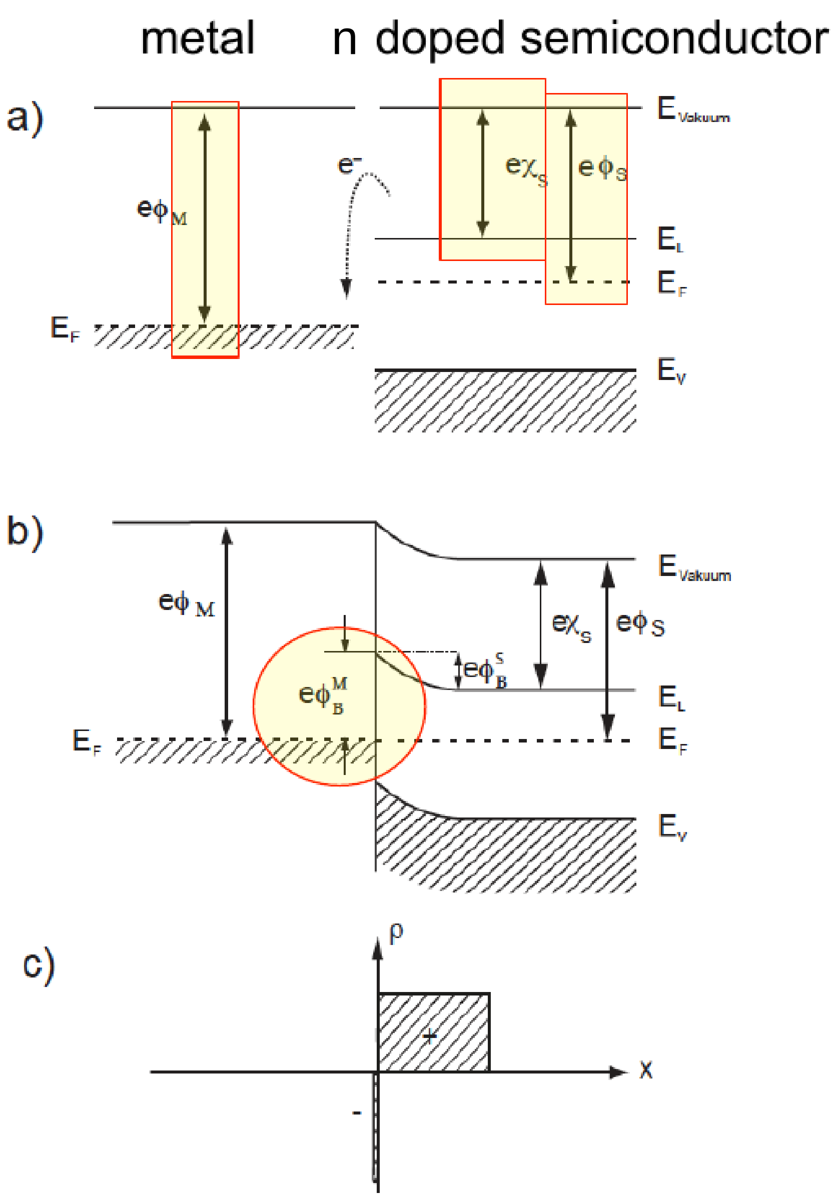
Semiconductor-Conductor Junction



In metal we have to take into account:

- Fermi level is in the conductor band
- Number of free e_- is very high 10^{23} cm^{-3}

Two types of contacts exist

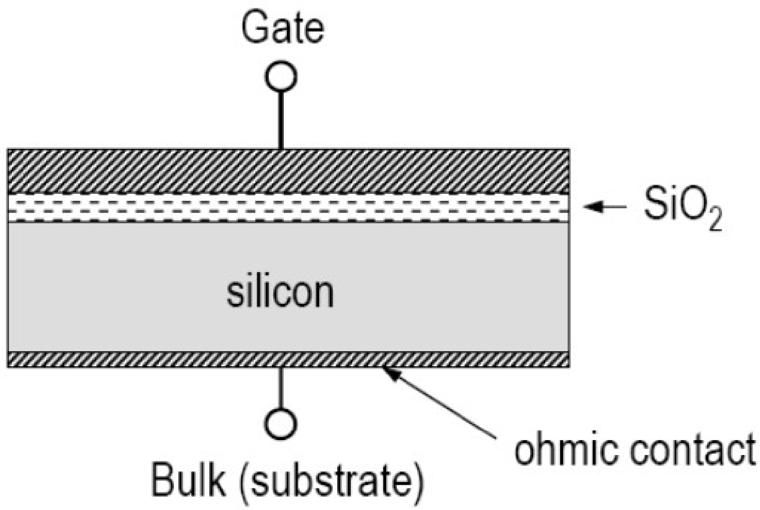
1) Schottky contact ($\Phi_M > \Phi_S$):

e- flow into metal → bands bend down
=> like a *pn* junction.
The voltage step is $U_{bi} = e\Phi_B^S = e(\Phi_M - \Phi_S)$
independent of an external voltage.

2) Ohmic contact ($\Phi_M < \Phi_S$):

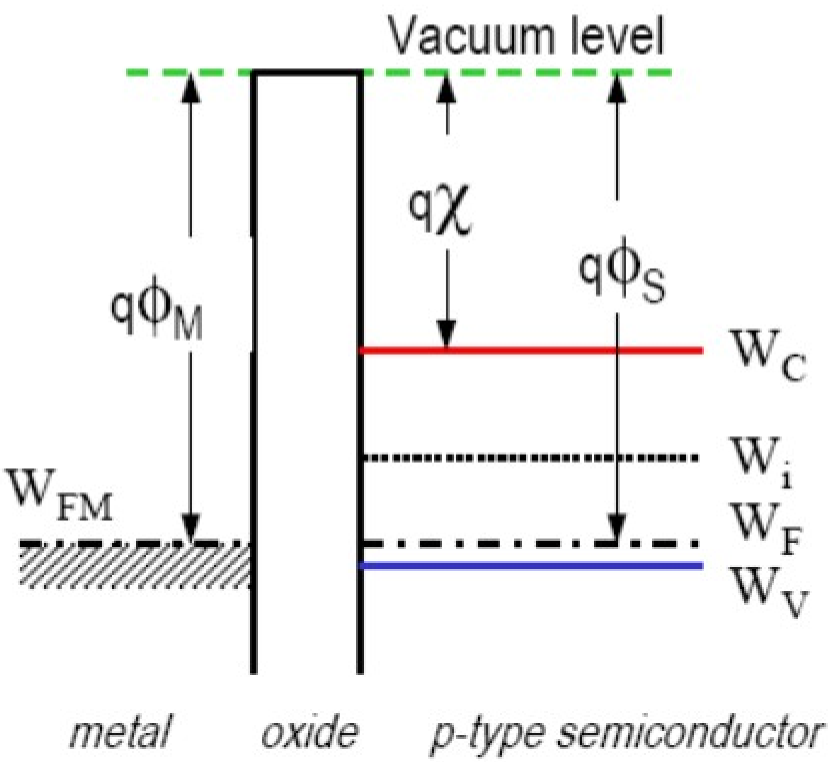
Mostly preferred contact, but difficult to find appropriate metal.
=> high n^+ doping (10^{19} cm^{-3}) for 10 nm
=> E_F almost at E_L and electrons can tunnel through junction.

MOS Junction (I)



Assumptions for the ideal MOS structure:

1. No workfunction difference between metal and semiconductor
2. charges at any bias exist only in the semiconductor and on the metal surface
3. no carrier transport through the oxide under dc-biasing conditions



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Energy band diagram of an ideal MOS structure
$q\phi_M$ = metal workfunction (Al: 4.1 eV)
$q\chi$ = semiconductor electron affinity (~ 4.05 eV)
$q\phi_S$ = semiconductor work function

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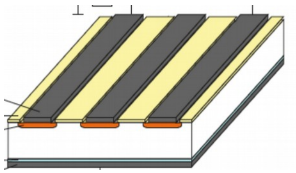

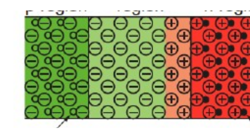

MOS-Junction (II)

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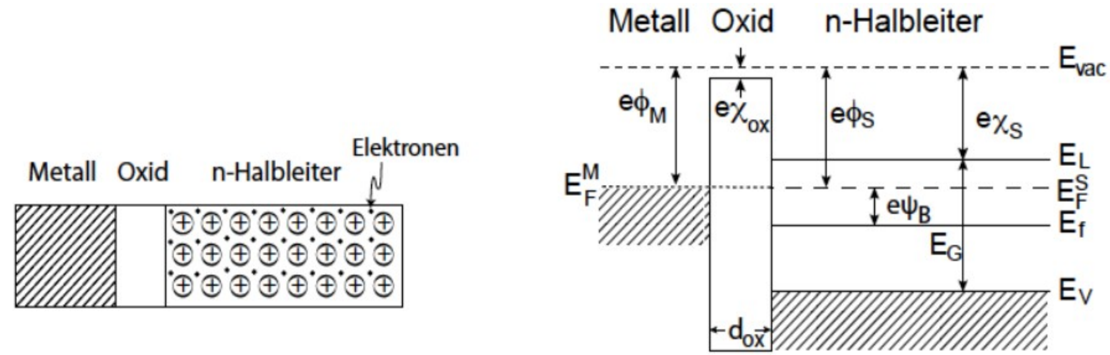
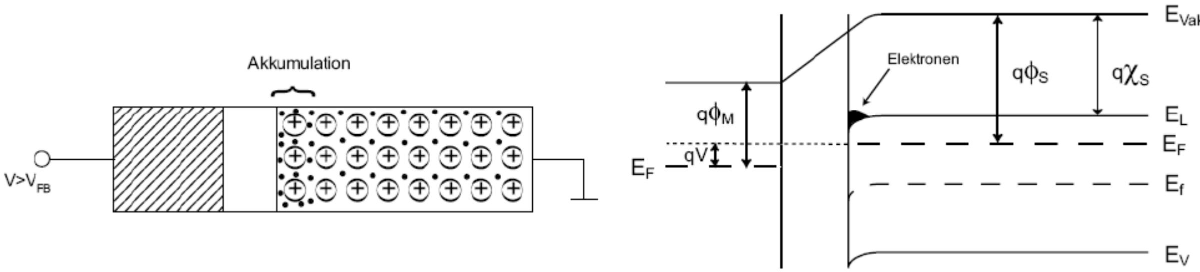
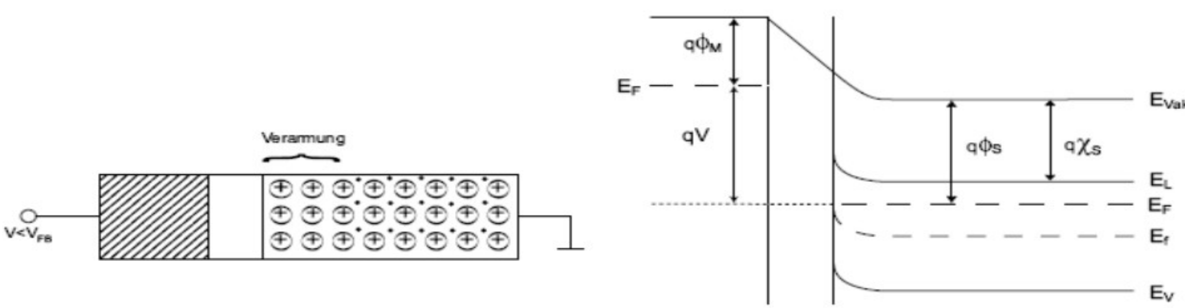


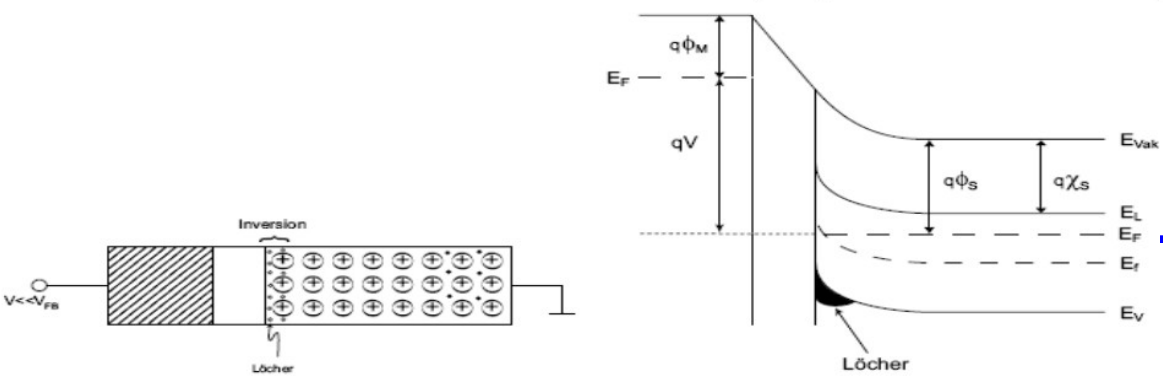
Ideal MOS structure



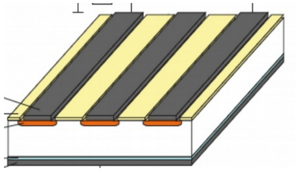
real MOS structure with $U > U_{flat}$ applied

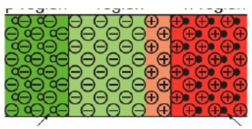


real MOS structure with $U < U_{flat}$ applied



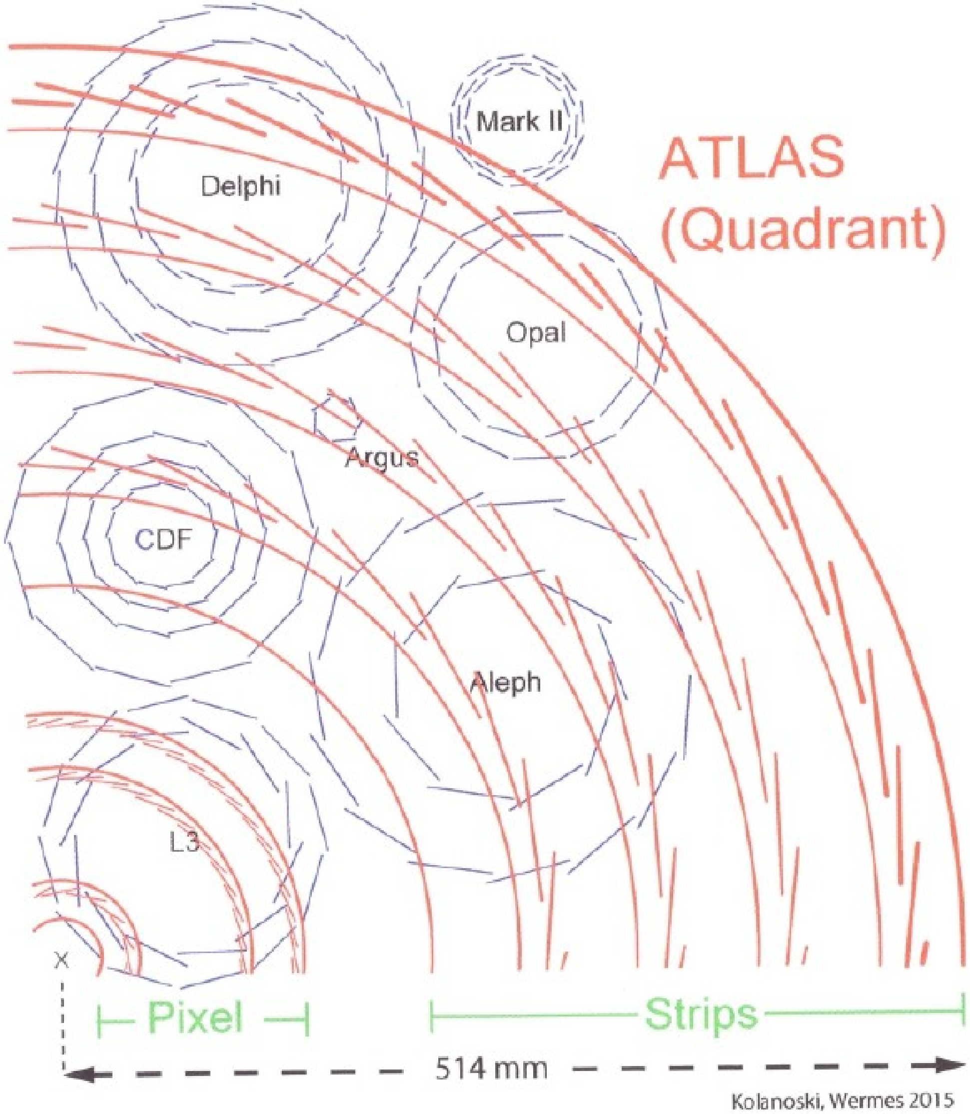
real MOS structure with $U << U_{flat}$ applied





Silicon Strip Detectors

Particle Detection with Semiconductor Detectors



Use of semiconductors as tracking detectors started in the 1980s with very small sizes. Today's largest experiment has a total area the size of a tennis court (~200 m²).

- Material is ionized in the depletion zone by the track
- Charges drift in the electric field towards the electrodes
- During the drift, they influence a signal

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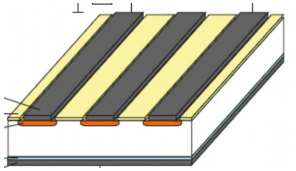
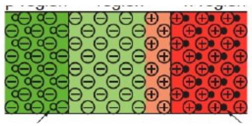


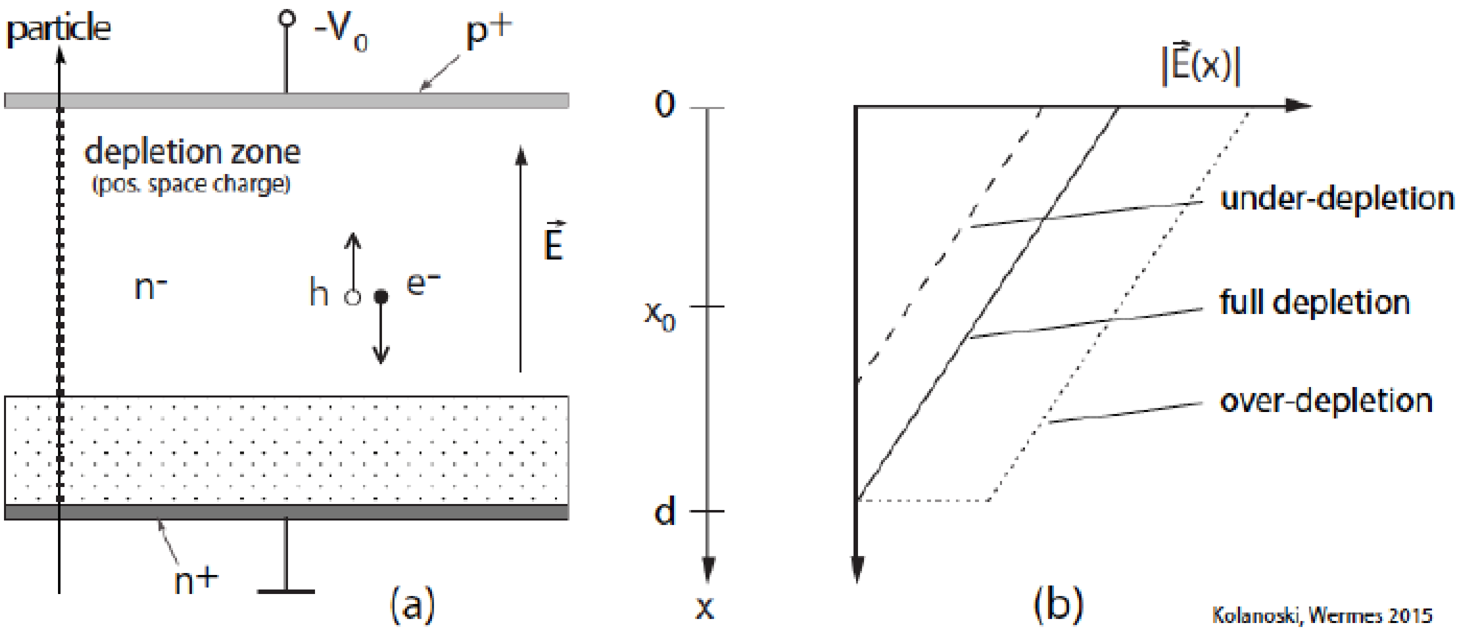
Particle Detection with Semiconductor Detectors (I)



Typical silicon detectors have a thickness of 300 µm. The average energy loss given by the BBF is dE/dx = 3870 keV/cm
→ Energy deposited in detector is 116 keV/cm.
On average 3.65 eV are need to create an e^-/h pair
→ approximately 32,000 e^-/h are created by a track.

The mobility of electrons and holes in Si is 1500 cm^2/Vs and 500 cm^2/Vs.
For typical electric fields of 1 V/µm one gets a $v_{d,h} \approx$ 50 µm/ns.

The total signal length is then $t = d/v_{d,h}$ = 300 µm/ 50 µm/ns = 6 ns



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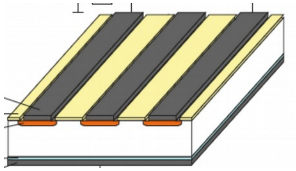
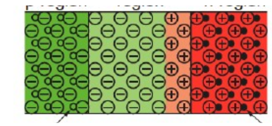
Electric field in detector is not homogenous, but changes because of space charges



Particle Detection with Semiconductor Detectors (II)



The electric field is $\vec{E}(x) = -\left[\frac{2U_{dep}}{d^2}(d-x) + \frac{U_{ext}-U_{dep}}{d}\right]\vec{e}_x = -\left[\frac{U_{ext}+U_{dep}}{d} - \frac{2U_{dep}}{d^2}x\right]\vec{e}_x$

Where U_{dep} is the voltage necessary for a full depletion of the detector:

$$U_{dep} \approx \frac{eN_D}{\epsilon\epsilon_0}\frac{d^2}{2}$$

With the drift velocities we can make a differential equation:

$$v_e = -\mu_e E_x(x) = +\mu_e(a-bx) = +\frac{1}{\tau_e}\left(\frac{a}{b}-x\right)\dot{x}_e$$

$$v_h = +\mu_h E_x(x) = -\mu_h(a-bx) = -\frac{1}{\tau_h}\left(\frac{a}{b}-x\right)\dot{x}_h$$

Where τ is the characteristic time
Solving the differential equation gives

$$\tau_{e,h} = \frac{1}{\mu_{e,h}b} = \frac{d^2}{2\mu_{e,h}U_{dep}}$$

$$x_e(t) = \frac{a}{b} - \left(\frac{a}{b}-x_0\right)e^{-\frac{t}{\tau_e}}, \qquad v_e = \left(\frac{a}{b}-x_0\right)\frac{1}{\tau_e}e^{-\frac{t}{\tau_e}}$$

$$x_h(t) = \frac{a}{b} - \left(\frac{a}{b}-x_0\right)e^{+\frac{t}{\tau_h}}, \qquad v_h = -\left(\frac{a}{b}-x_0\right)\frac{1}{\tau_h}e^{\frac{t}{\tau_h}}$$

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Particle Detection with Semiconductor Detectors (III)

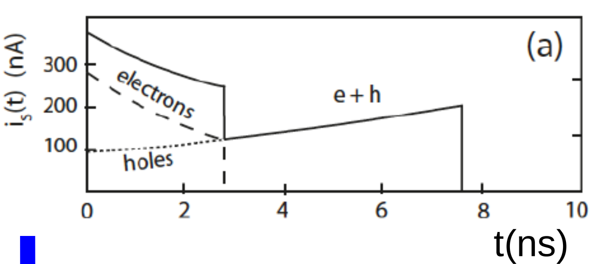
The drift times from the position of creation (x_0) to the electrodes is

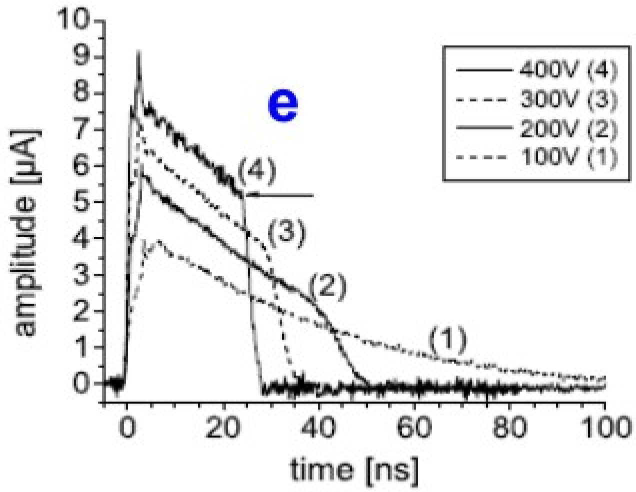
$$T^- = \tau_e \ln \frac{a - bx_0}{a - bd} \qquad T^+ = \tau_h \ln \frac{a}{a - bx_0}$$

This gives with the Shockley-Ramo-Theorem the signal currents:

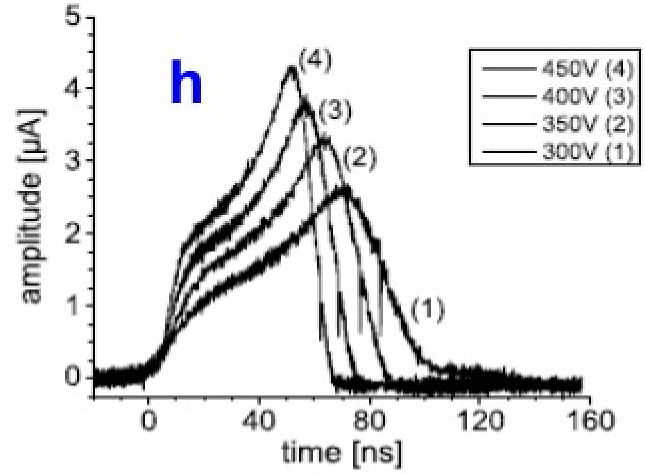
$$\vec{i}_S^{\pm} = q \cdot \vec{E}_w \cdot \vec{v}_{e,h} = e \cdot \frac{-1}{d}\vec{e}_x \cdot \left(\frac{a}{b} - x_0\right) \frac{1}{\tau_{e,h}} e^{\pm\frac{t}{\tau_{e,h}}} \qquad \text{for}:\ \ t < T^{\pm}$$

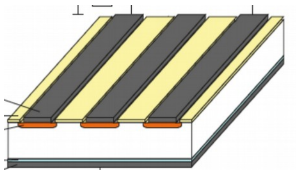
$$\vec{i}_S = \frac{e}{d}\left(\frac{a}{b} - x_0\right)\left(\frac{1}{\tau_e} e^{-\frac{t}{\tau_e}} \Theta(T^- - t) + \frac{1}{\tau_h} e^{-\frac{t}{\tau_h}} \Theta(T^+ - t)\right)$$

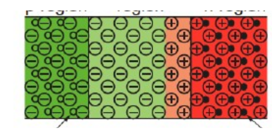




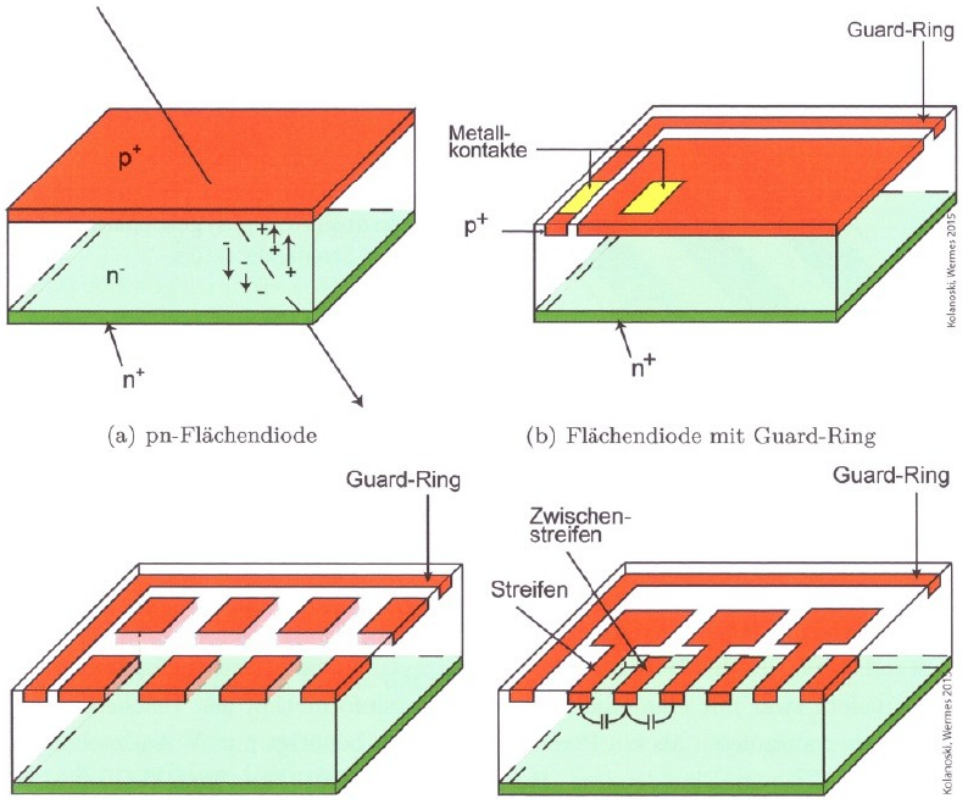
Si







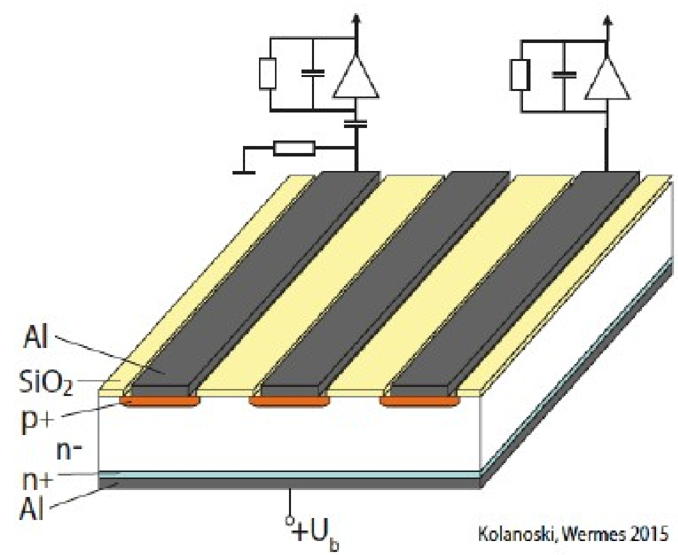
Single sided Semiconductor Detectors



(a) pn-Flächendiode (b) Flächendiode mit Guard-Ring

(c) Pad bzw. Pixeldetektor (d) Streifendetektor

Structuring of the detector is quite diverse:
a) *pn* diode (complete area)
b) diode with guard ring to absorb leakage current at the edges
c) pixels with guard ring
d) microstrips with guard ring



For reading out the signal to modes are used:
1.) AC-coupled → SiO_2 layer is used as insulator
2.) DC coupled → leakage current goes into preamp

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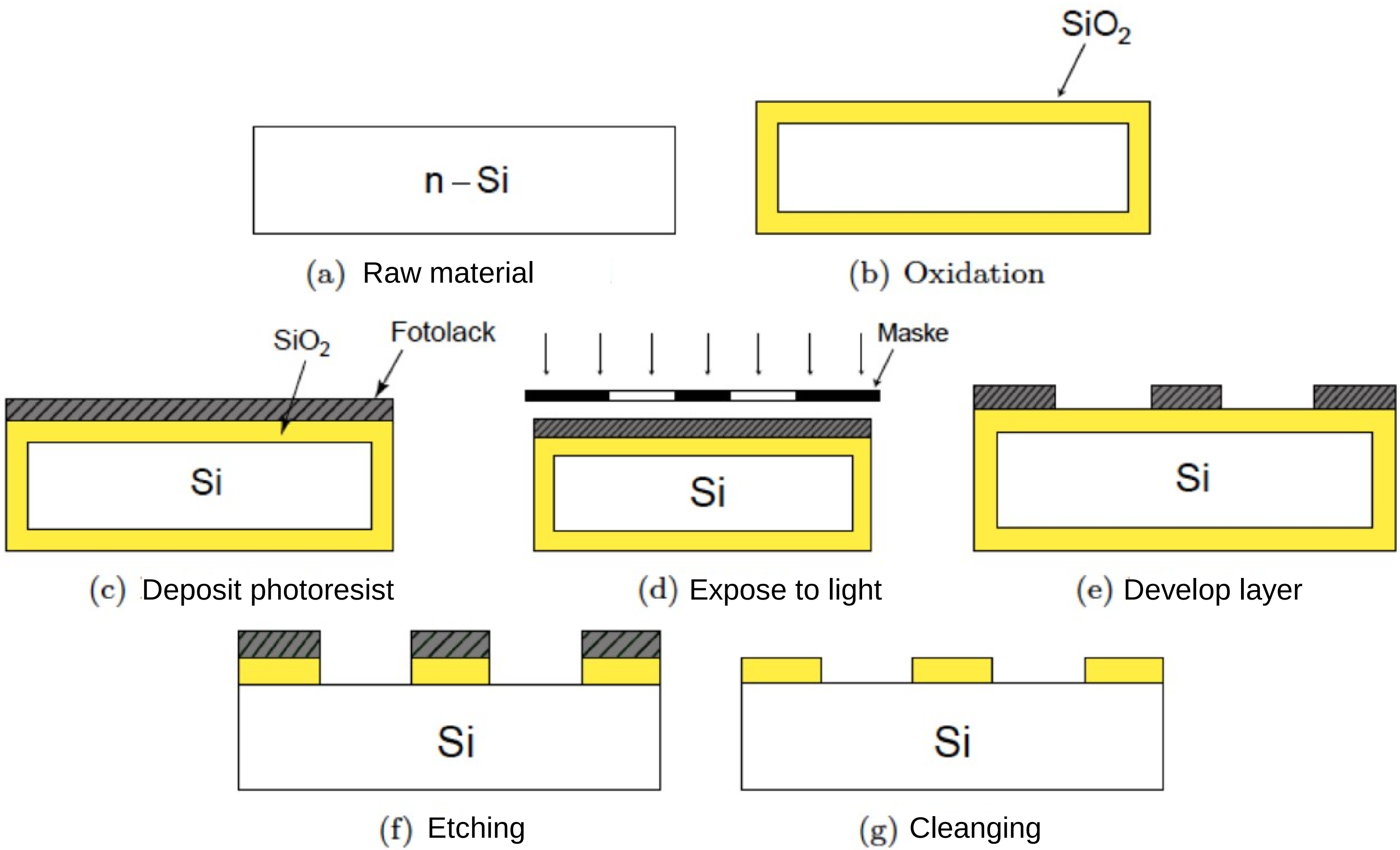
Production of Semiconductor Sensors (I)



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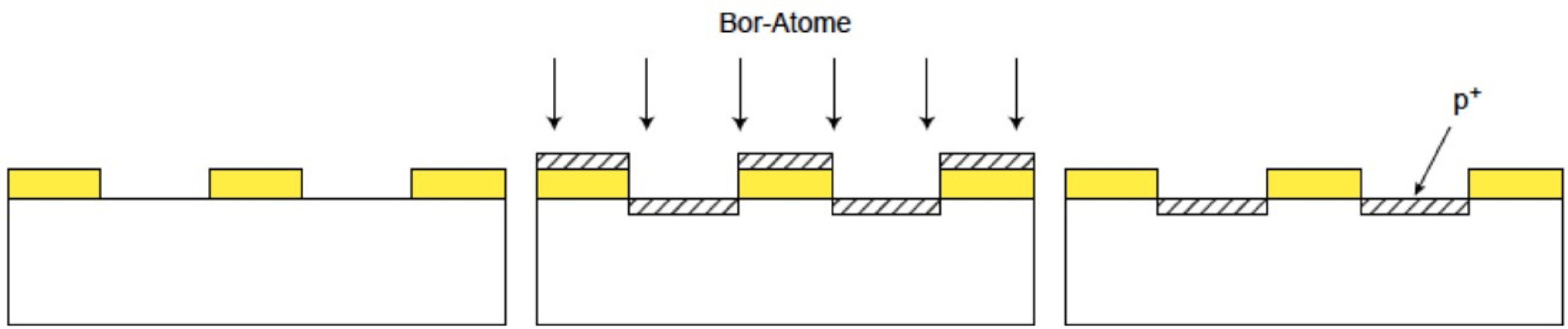
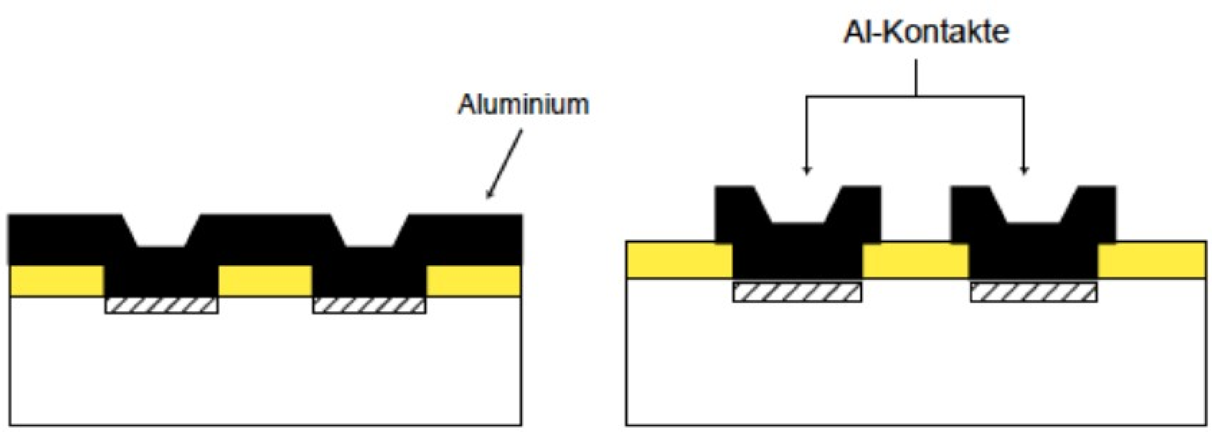
Production of Semiconductor Sensors (II)



(a) Continue from previous slide (b) Implanting boron (c) Heating



(d) Deposit metal layer (e) Further photo lithography steps to pattern metal layer

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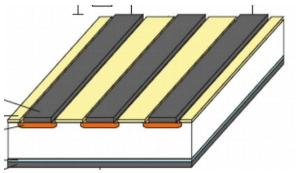
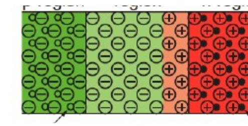
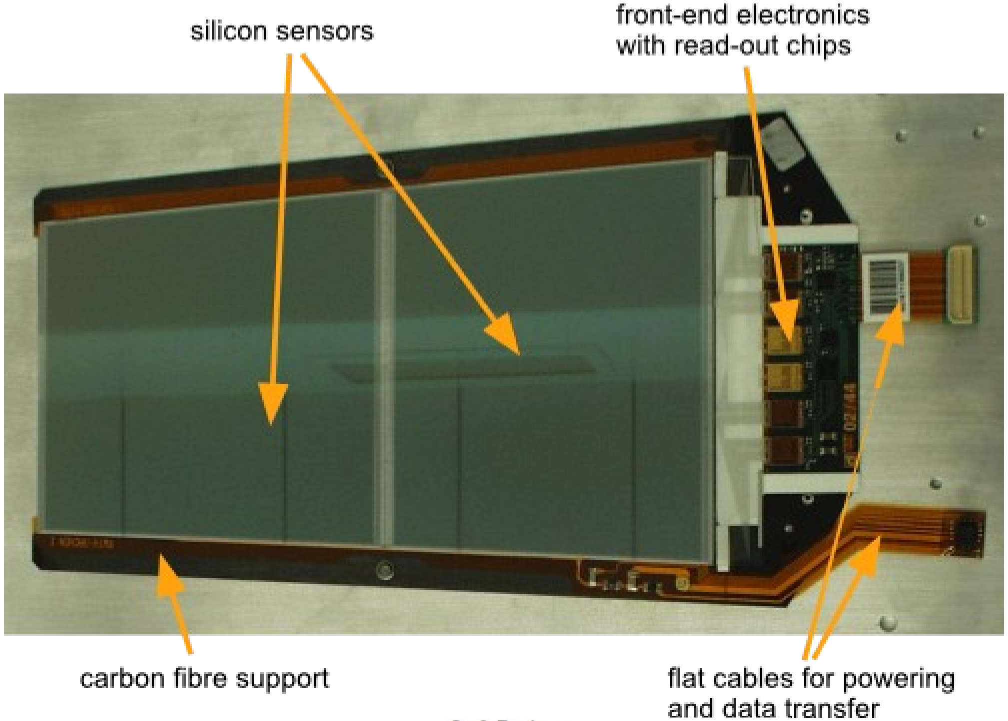
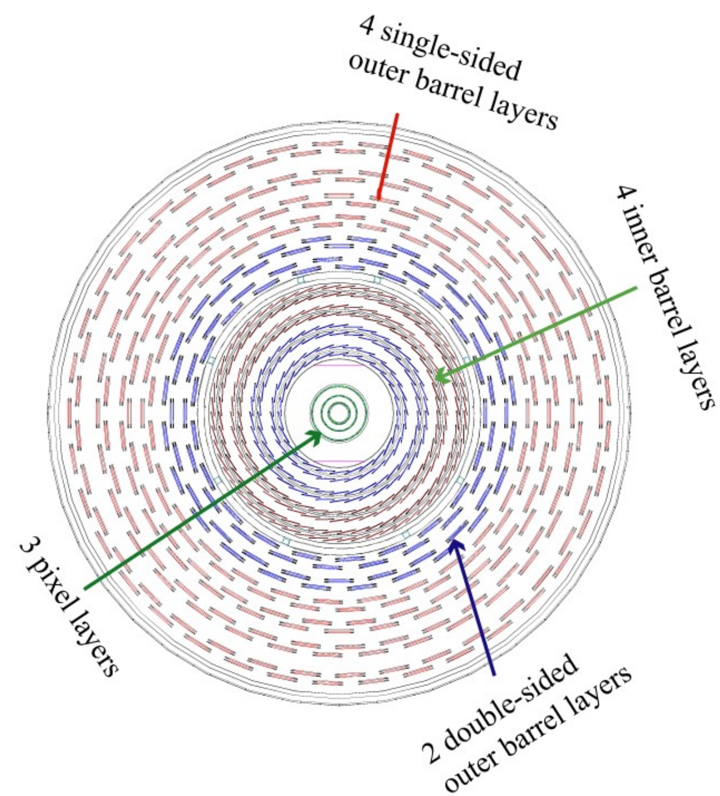


Some Implementations



http://cms.desy.de/e53612/e155175/e155179/

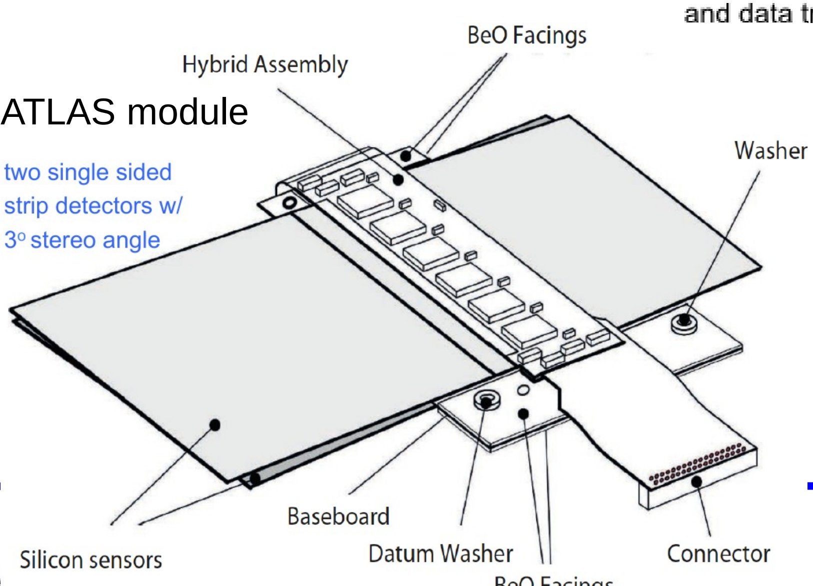




http://cms.web.cern.ch/news/silicon-strips

ATLAS module

two single sided strip detectors w/ 3° stereo angle



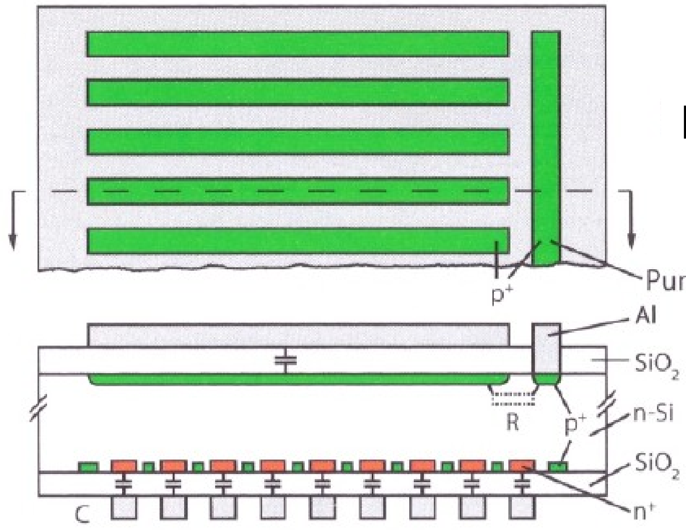
Single sided strip detectors are easier and cheaper to produce, but for having a tack point you need a stereo angle (few mrad) → doubles the material

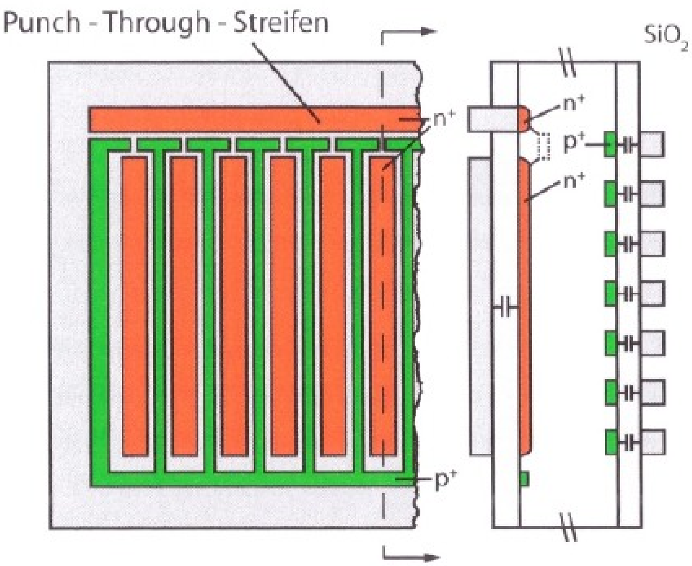
Double sided Microstrip Detectors

Great idea:
1.) Reduce material since signal induced on both sides is used
2.) Same induced charge → correlation between the signal heights of both sides

But these detectors are difficult to build, because the first side has to carefully handled and protected during the patterning of the second side.

Also which implants on the back side?
p in *n* doesn't work → two reverse diodes
n^+ in n – works, if detector is fully depleted from the front side, but there is no insulation between the n^+ strips.
Besides, electrons will accumulate on the boundary to the SiO_2 protection layer and form a conductive channel.





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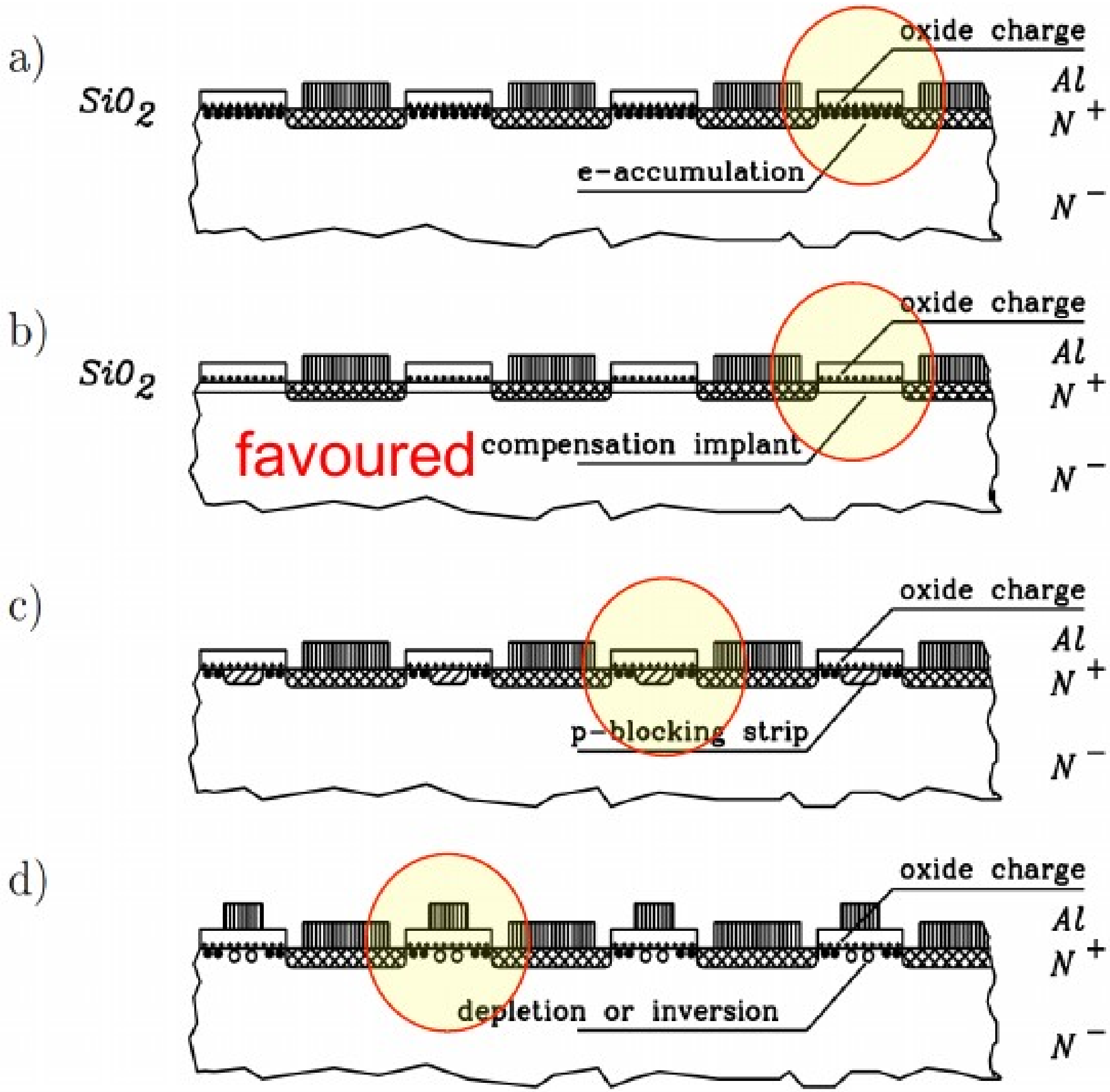
Double sided Microstrip Detectors



No protection

p-spray

p-stop

p-field plate

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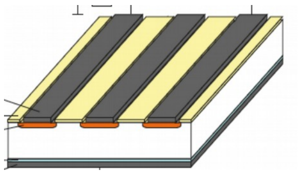
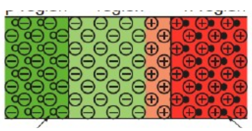
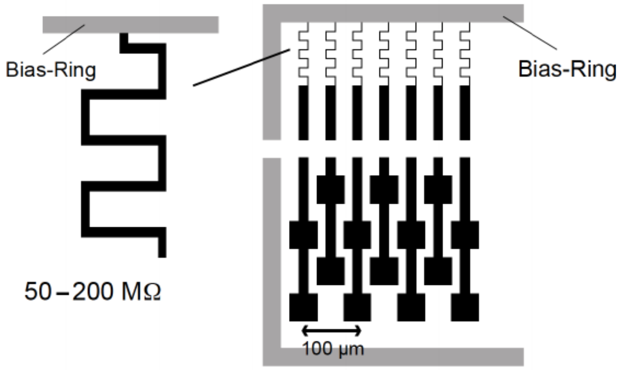


Biasing

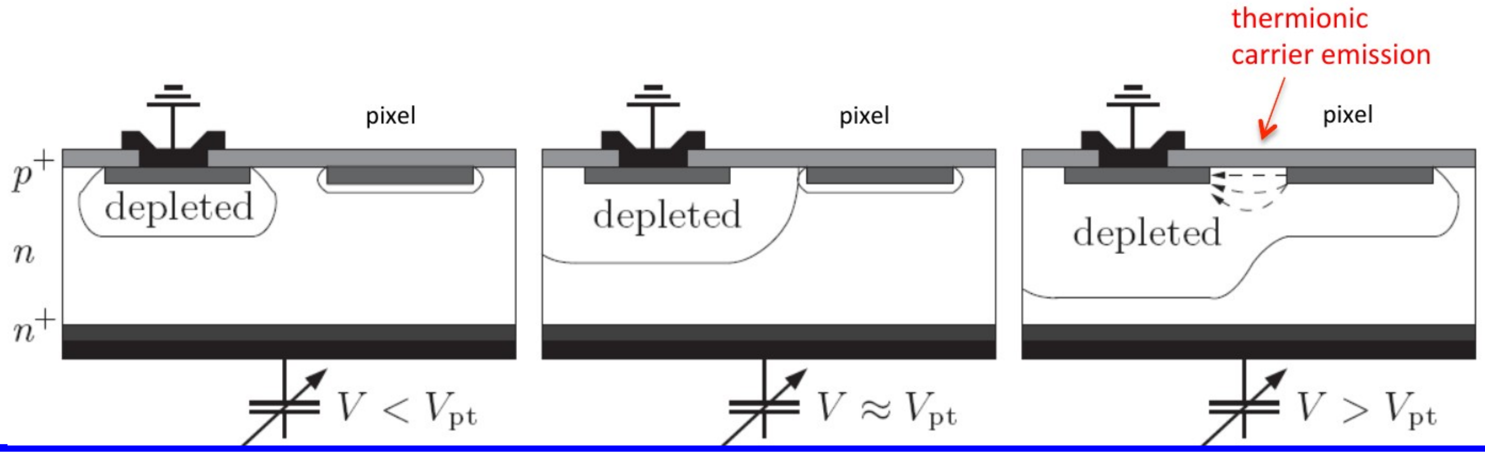


Contacting a single sided strip detector with HV on the backside is quite easy, however, for doublesided strip detectors and pixel detectors this is more complicated.
HV must be contacted via a high ohmic resistor to limit the current and thus the addition noise acquired on the readout.
Options are:

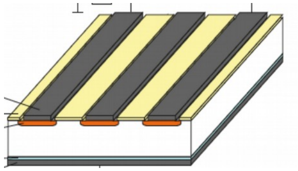


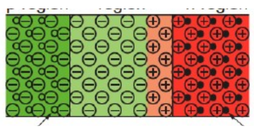
1.) Polycrystalline resistors of Si or SiO_2 which has a surface resistance of up to 100 kΩ/□.

2.) Punch-through-Biasing: The lateral extension of the depletion zone is exploited to the connection between bias pad and r/o.



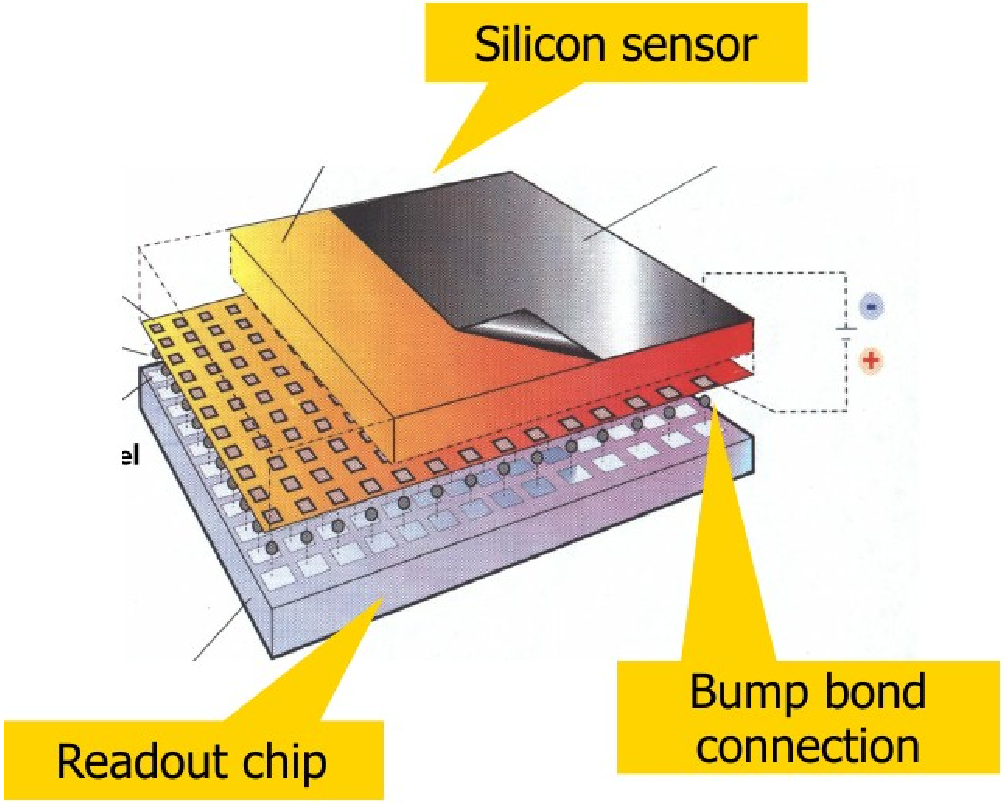
Kolanoski, Wermes 2015

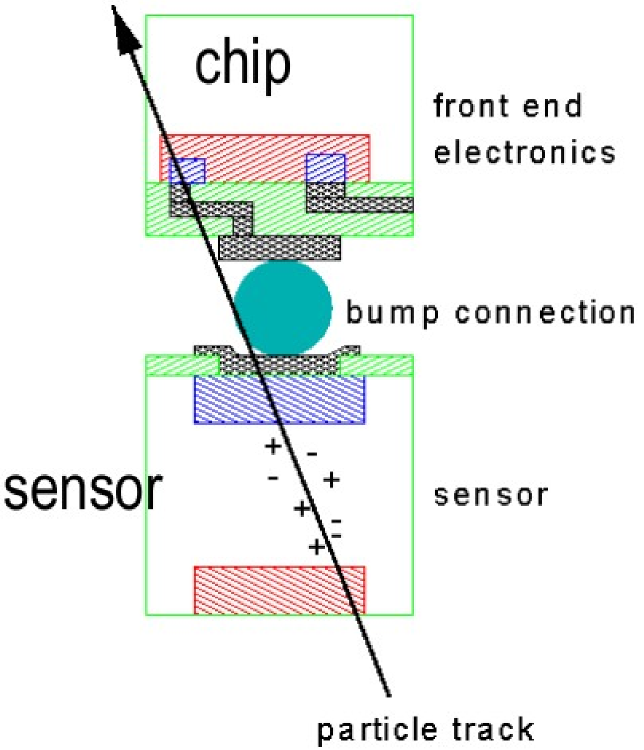


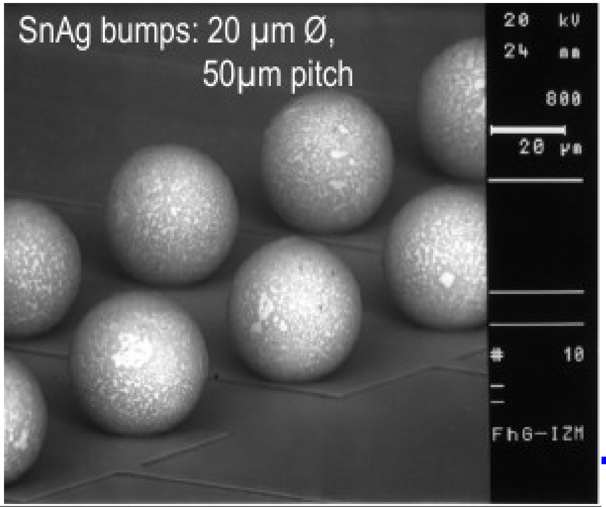


Silicon Pixel Detectors

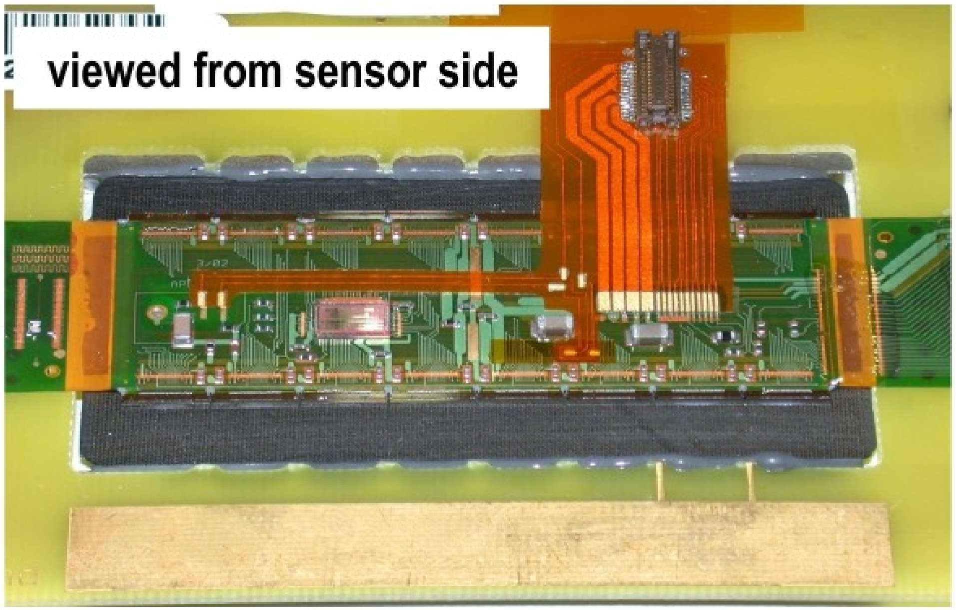
Hybrid Pixel Detectors

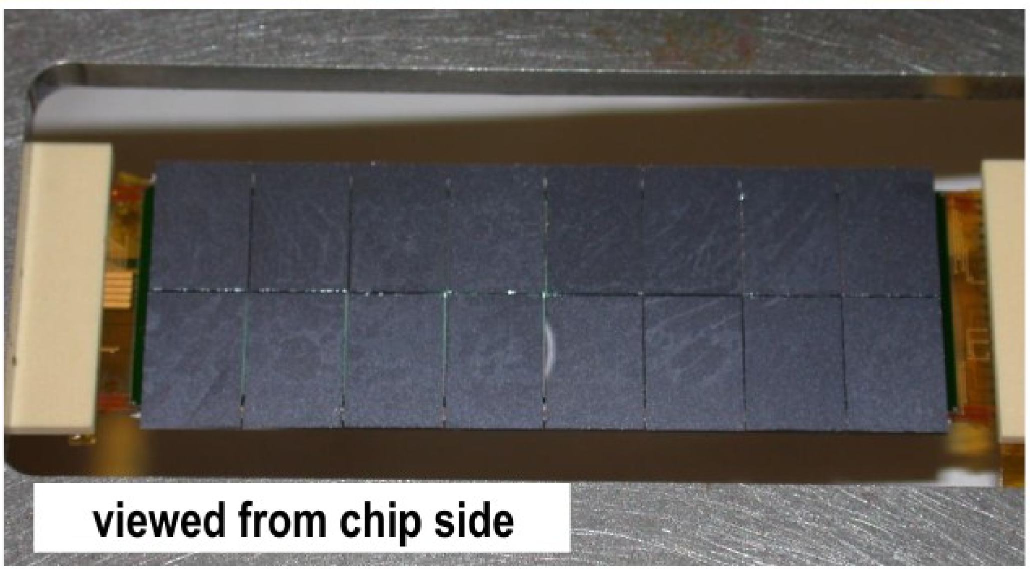


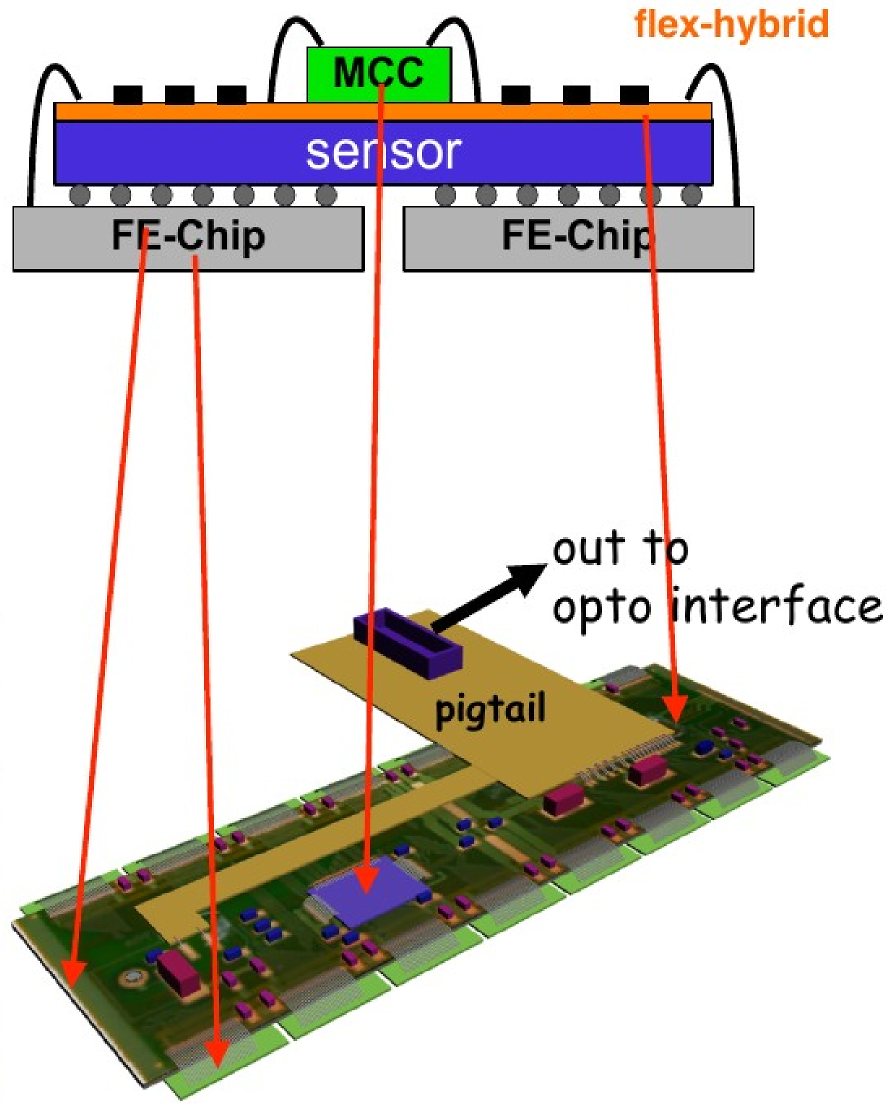




ATLAS Pixel Module





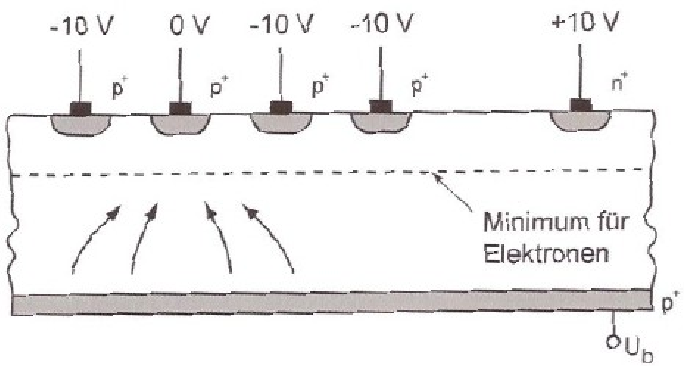


16 IC, 46080 pixels

ATLAS Pixel - Detector

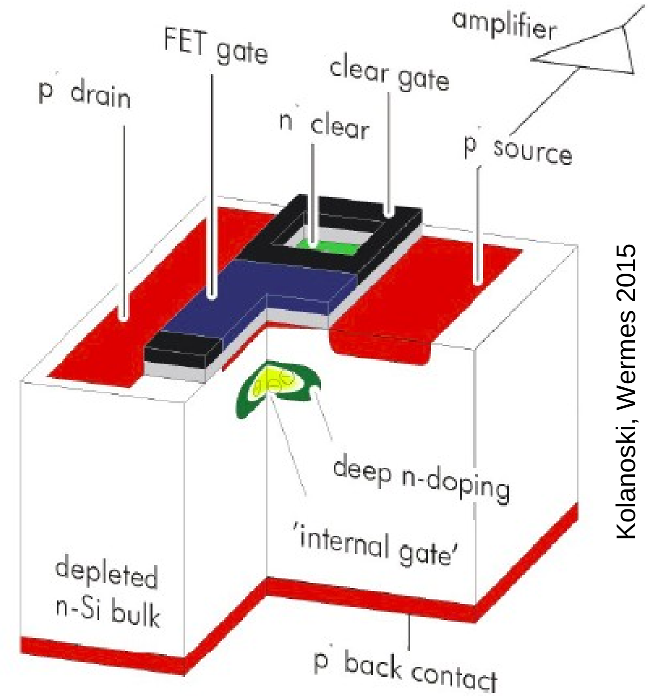
Monolithic Detectors

To simplify production and reduce the material in the detector, the readout ASIC and sensor can be unified.

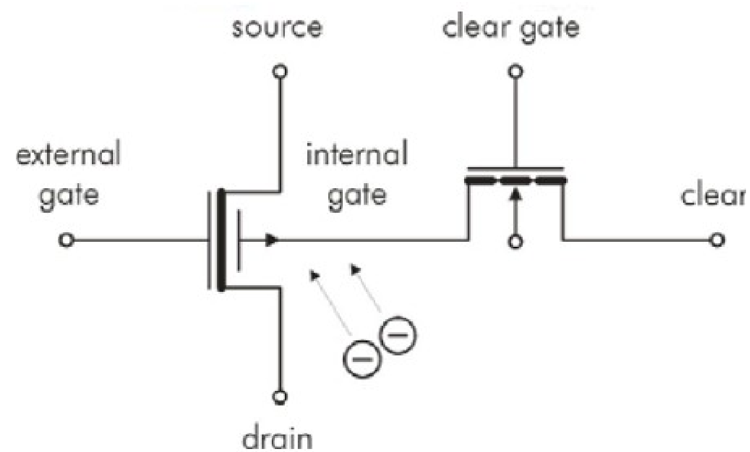


There are several approaches
And technologies, which are
Addressing this idea:

1.) DEPFET
2.) MAPS
3.) DMAPS



Kolanoski, Wermes 2015



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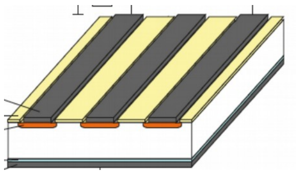

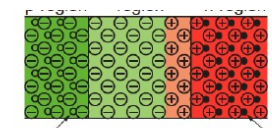

3D

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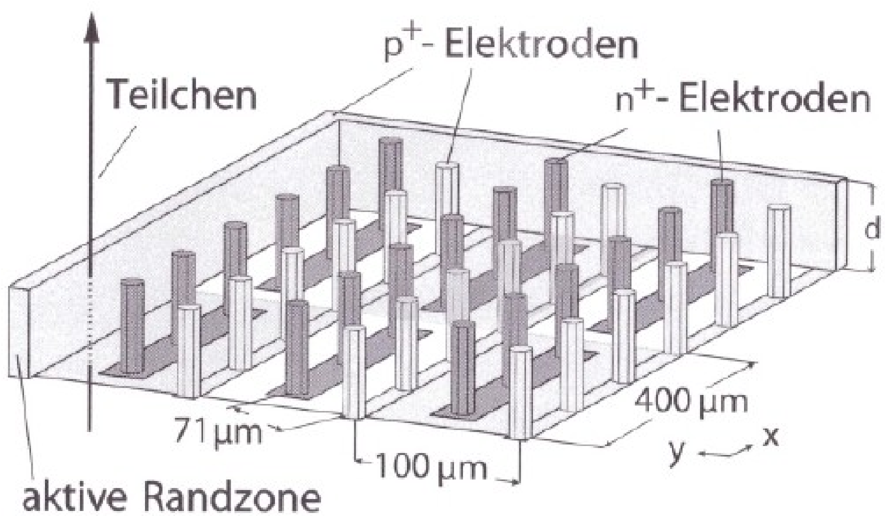
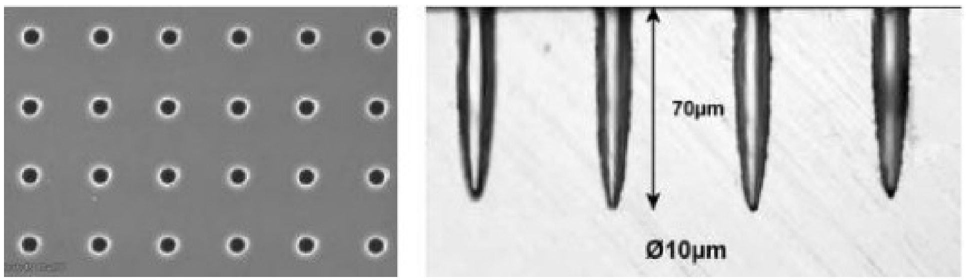
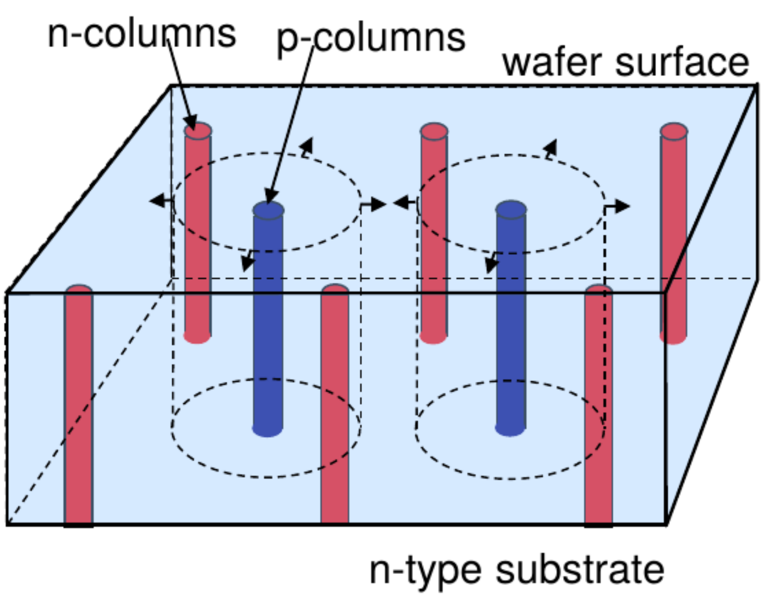
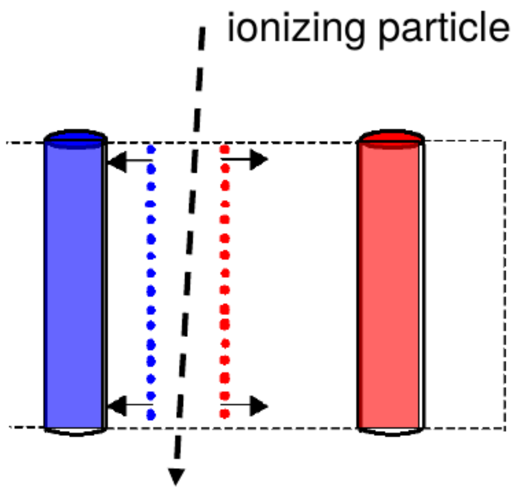


Shorter drift distances
→ faster drift times
→ higher radiation hardness



[Parker et al., NIMA395 (1997)]





Lateral depletion
and carrier drift,
charge collection
in a very short time

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Radiation Damage

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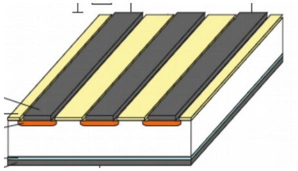
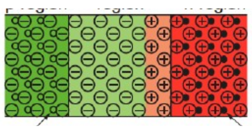


Aging



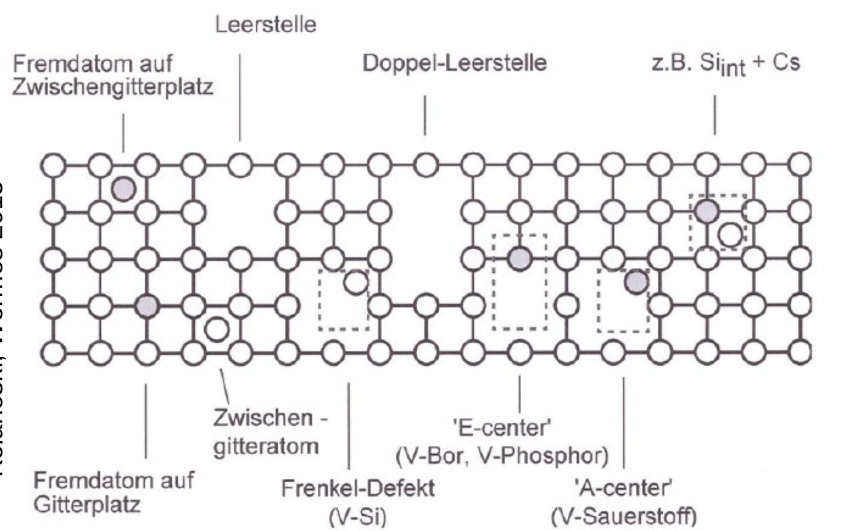
Radiation is causing damage to the detectors. One distinguishes two types of damages:

1.) Damages at the surfaces and boundaries caused by ionizing energy losses (IEL)

→ degrades performance of electronics (thresholds, leakage currents between transistors,...)

2.) Bulk damages, where particles react with nuclei and cause damage to the lattice by non-ionizing energy loss (NIEL)

→ degrades charge collection efficiency



Kolanoski, Wermes 2015

Different particle have different means of causing damages. To compare the effects, the fluences are compared to the damage 1 MeV neutrons do.

=> n_{eq}/cm²

LHC vertex detector $\phi_{eq} \sim 10^{14}\,n_{eq}/cm^2$

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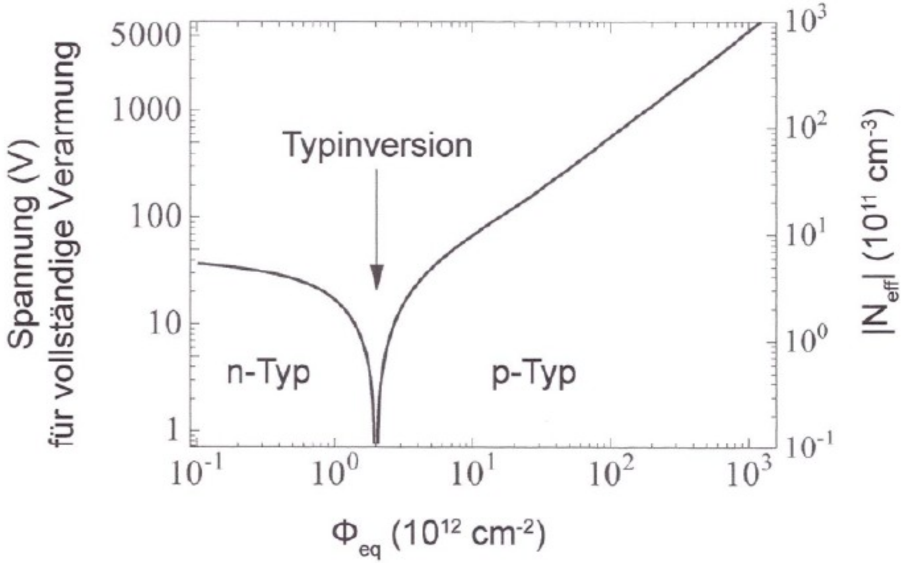
Model for Aging Behavior of Detectors

Bulk damage can have three different effects on the detector behavior:

1) Production of addition acceptor or donor level. This can even lead to a type inversion of the bulk material *n* type becomes a *p*-type and the depletion voltage has to change its sign.



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2) Generation and recombination centers: their energy level is in the center of the band gap, so they don't contribute to the acceptor/donor levels, but facilitate generation and recombination of e^-/hole pair. This increases the leakage current in the bulk

3) Long lived traps, which attract charge and release it significantly later, so that the charge is lost for the signal

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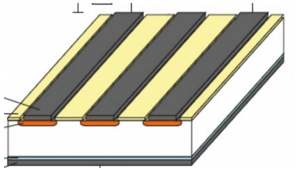

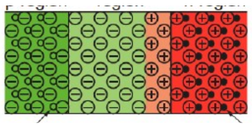

Comparison between Gaseous and Silicon Detectors

Comparison

	Gas	Silicon
Spatial resolution	50 µm – 500 µm	10 µm – 50 µm
If you try hard	10 µm - 20 µm	2 µm – 5 µm
Rate/Speed	1-50 µs	5-20 ns
Radiation length	% X_0	20-50 % X_0
Radiation damage	(no)	yes for high fluences
Size	large volumes	small- medium areas
Number of track points	30 - 250	5 – 15
PID by *dE*/*dx*	rel. rise 40-70%	10%
Cost	low	high

Pro gas: Covering a large volume with many channels make your track finding more robust, in particular in pathological cases:
Long lived (neutral) particles decaying in the central tracker, kinks of e^--tracks due to Bremsstrahlungsphotons, etc.

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About Cost

Belle TDR

arXiv:1011.0352

Component	Estimated cost (Oku yen)
Beam pipe	1.0
PXD	3.5
SVD	3.0
CDC	3.8
B-PID	7-8
E-PID	4-5
ECL (no crystals)	3.5
KLM	1.4
TRG	0.9
DAQ	4.3
Structure	4.5
Total	37.9

PiXel Detector: 2 layers -
r = 1.3 cm, l = 9 cm
r = 2.2 cm, l = 12 cm

Si strip detector: 4 layers -
r = 3.8/8.0/11.5/14.0 cm
l = 25 - 60 cm

Central Drift Chamber: 56 layers
r = 0.16 m -1.2 m
l = up to 2.4 m

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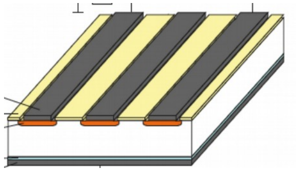

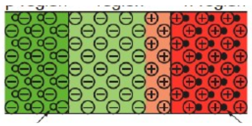

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5.) Various web pages for pictures