electrical resistance $R = \rho \frac{l}{A}$ [length l, cross section A] , electrical resistivity ρ , electrical conductivity $\sigma = \frac{1}{\rho}$, electrical conductance $G = \frac{1}{R}$.

Drude-modell: $\sigma = e^- n \mu$, charge of an electron e^-, charge carrier density n, mobility of the charge carriers μ.

For hole- [density p, mobility μ^+] and electron-conduction: $\sigma_{\text{tot}} = e^- n \mu^- + e^- p \mu^+$.

Matthiesen-rule: $\frac{1}{\tau_{\text{tot}}} = \sum_i \frac{1}{\tau_i}$, total collision time τ_{tot}, collision times of the involved processes τ_i.

$\mu = \frac{q \tau_{\text{tot}}}{m^*}$, charge q, effective mass $m^* = \frac{\hbar^2}{\frac{\mathrm{d}^2 E}{\mathrm{d}k^2}}$.

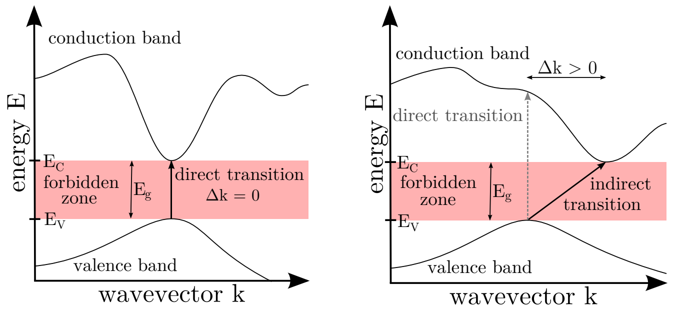
Typical band structures of semiconductors:

conduction band edge E_C ,

valence band edge E_V ,

energy gap $E_g = E_C - E_V$

direct semiconductors indidirect semiconductors

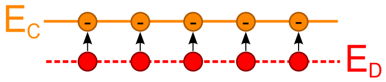


In direct semiconductors the excitation is a two-particle process [→ electron, photon]; in indirect semiconductors a transition is a three-particle process [→ electron, photon, phonon] and thus much less propable.

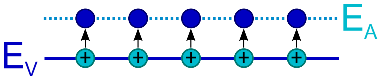
Energetic state densities: conduction band [CB] $D_{CB}(E)\,\mathrm{d}E = \frac{1}{2\pi^2}\left[\frac{2m_e^*}{\hbar^2}\right]^{\frac{3}{2}} [E - E_C]^{\frac{1}{2}}\,\mathrm{d}E$,

valence band [VB] $D_{VB}(E)\,\mathrm{d}E = \frac{1}{2\pi^2}\left[\frac{2m_p^*}{\hbar^2}\right]^{\frac{3}{2}} [E_V - E]^{\frac{1}{2}}\,\mathrm{d}E$.

Occupation propability is described via the Fermi-Dirac distribution: $f(E) = \frac{1}{1+\mathrm{e}^{\frac{E-\mu}{k_B T}}}$, chemical potential μ.



$[E_F \approx \frac{E_C + E_V}{2}$, $\mu(T) = E_F - [k_B T]^2 \frac{\pi^2}{6} \frac{\left.\frac{\mathrm{d}D(E)}{\mathrm{d}E}\right|_{E=E_F}}{D(E_F)}]$



Doping:
additional free carriers via elements with a different number of valence electrons.
n-doping: elements from the fifth group, p-doping: elements from the third group

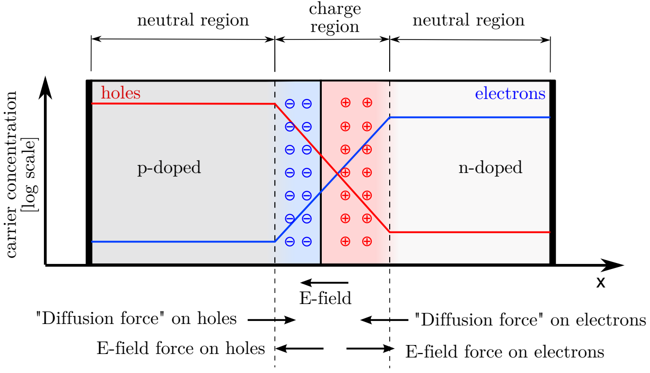
donor concentration $N_D = \underbrace{N_D^0}_{\text{neutral donor concentration}} + \overbrace{N_D^+}^{\text{ionized donor concentration}}$, acceptor concentration $N_A = \underbrace{N_A^0}_{\text{neutral acceptor concentration}} + \overbrace{N_A^-}^{\text{ionized acceptor concentration}}$.

n - concentration of e^- in conduction band , p concentration of holes in valence band. Neutrality $n + N_A^- = p + N_D^+$.

For moderately n-doped materials: $N_D^+(T) = \frac{N_D}{2\,\mathrm{e}^{\frac{E_F - E_D}{k_B T}} + 1}$, $E_F = \frac{1}{2}[E_D + E_C] + \frac{1}{2} k_B T \ln(\frac{N_D}{2 n_0})$ and

$n = n_0\,\mathrm{e}^{-\frac{E_C - E_F}{k_B T}} + \frac{1}{2} N_D\,\mathrm{e}^{-\frac{E_F - E_D}{k_B T}}$.

pn-Junction:



Diffusion voltage $V_{\text{Diff}} = \frac{k_B T}{e^-} \ln\left(\frac{N_D}{N_A}\right)$.

The free majority carriers in each region [e^- in n-doped region, h in p-doped region] diffuse into the other region [there they are the minority charge carriers]; thereby an electrical field is build up that counteracts the diffusion and thus eventually an equilibrium.

[space charged region = depletion layer]

Forward bias → + to p-doped and − to n-doped region.

Current $j = \left[\frac{e^- D_p}{l_p} p_n + \frac{e^- D_n}{l_n} n_p\right] [\mathrm{e}^{\frac{e^- V}{k_B T}} - 1]$

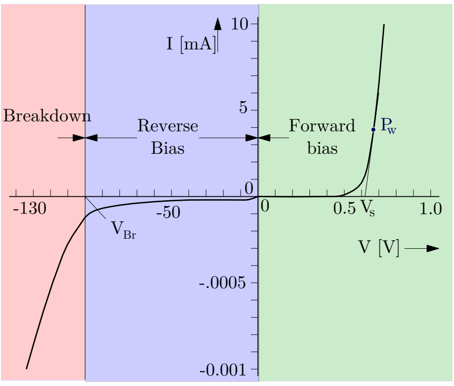
D_n,D_p - diffusion coeff., l_n,l_p - diffusion lengths, [subscripts → carriers]

n_p,p_n - minority carrier concentrations [subscripts → region]

V_S - threshold voltage, I_S - leakage current, V_{Br} - breakthrough voltage, P_w - working point, $R_d = \frac{\mathrm{d}V}{\mathrm{d}I}\Big|_{P_w}$ - differential resistance.

depletion layer thickness $d = \sqrt{\frac{2\varepsilon_0\varepsilon_r[V_D - V]}{e^-}\left[\frac{1}{N_A} + \frac{1}{N_D}\right]}$

$$\frac{\partial V_S}{\partial T}\Big|_{T\approx 300\,\mathrm{K}} \approx -\frac{2\,\mathrm{mV}}{\mathrm{K}}$$



In a semiconductor without an externally applied voltage the Fermi energy is the same everywhere.

$$V_D \approx \frac{1}{e^-}[E_{C_p} - E_{C_n}] \approx \frac{1}{e^-}[E_{V_p} - E_{V_n}] \approx \frac{k_BT}{e^-}\ln\left(\frac{n_n}{n_p}\right) \approx \frac{k_BT}{e^-}\ln\left(\frac{p_p}{p_n}\right)$$

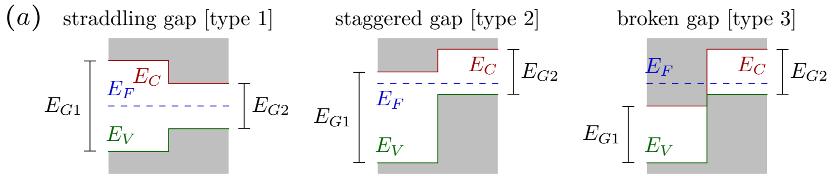
is the diffusion induced voltage in a $p-n$-junction with the band-edge-energies E_{C_p}, E_{V_p} in the p-doped and E_{C_n}, E_{V_n} in the n-doped region.

Breakdown in reverse bias mode via (a) avalanche effect [accelerated free charge collides with other charges and sets them free; these are accelerated and set others free → avalanche; low doping] or (b) Zener breakdown [high doping → thin depletion layer → tunnerling current].

Heterojunctions: contact of two different materials [(a) 2 different semiconductors: (a_i) pn-junction, (a_{ii}) iso-junction; (b) semiconductor and metal: (b_i) $\Phi_M \approx \Phi_{\mathrm{sc}}$ [„ohmic contact“], (b_{ii}) $\Phi_M > \Phi_{\mathrm{sc}}$ [„Schottky contact“], (b_{ii}) $\Phi_M < \Phi_{\mathrm{sc}}$].

electron affinity $\chi = E_{\mathrm{vacuum}} - E_C$

work function $\Phi = E_{\mathrm{vacuum}} - E_F$


(a) straddling gap [type 1] staggered gap [type 2] broken gap [type 3]

For pn-junctions potentially discontinuities in the conduction [ΔE_C] and in the valence band [ΔE_V] can occur [notches, spikes], as in the depletion layer of the n-side a band bending to higher energies and in the depletion layer of the p-side a band bending to lower energies occurs. [$\Delta E_C =$]

Optical devices

Lambert's law: $I = I_0\,\mathrm{e}^{-\alpha_{\mathrm{ab}} z}$, absorption coefficient α_{ab}.

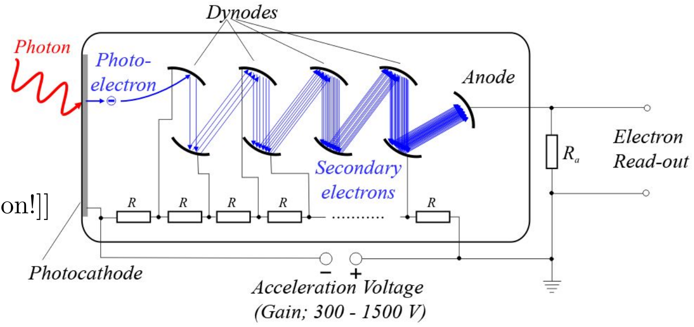
Absorption processes: [all of them are saturated for high intensities!]

- fundamental absorption [α_{VC}; between valence and conduction band → $E_{\mathrm{photon}} \geq E_g$ [$-E_{\mathrm{phonon}}$]]
- impurity absorption [α_{il}; between, from and to impurity levels; shoulders for $E_{\mathrm{photon}} < E_g$]
- exciton absorption [α_{ex}; excitons are Coulomb-bound electron-hole-pairs, single line for $E_{\mathrm{photon}} < E_g$]
- intraband transition [α_{ib}; in doped materials within one band; light hole, heavy hole or split off band]
- free carrier absorption [α_{FC}; an already excited free carrier is excited even further; $E_{\mathrm{photon}} \ll E_g$]

It is $\alpha_{\mathrm{ab}} = \alpha_{VC} + \alpha_{il} + \alpha_{ex} + \alpha_{ib} + \alpha_{FC}$.

Photomultiplier:

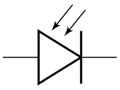
- high gain / amplification [~ $10^6 e^-/\text{photo} - e^-$]
- low noise
- broad frequency response [110 nm . . . 1100 nm, photocathode-material-dependend [work-function!]]
- high sensitivity [~ 1 A/µW]
- quantum efficiency [1 % . . . 20 %]
- small response time [1 ns . . . 20 ns]
- maximum anode current limited [≲ 1 mA]
- dark current [thermal → cooling]

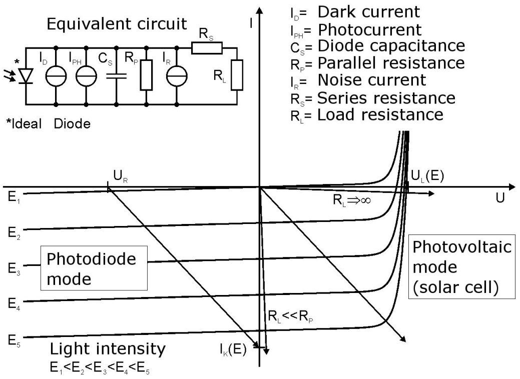


Photoresistor:

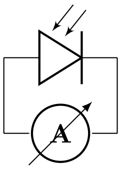
- high electric resistance [dark ~ $10^6\,\Omega \dots 10^7\,\Omega$, lit ~ $10^2\,\Omega \dots 10^3\,\Omega$]
- strong wavelength dependence
- slow repetitive measurements [ms…s; for special materials down to µs]
- high sensitivity

Photodiode [reverse bias mode]:

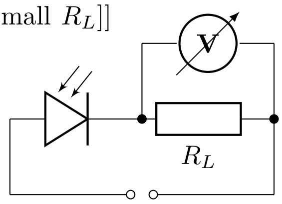




- photovoltaic effect leads to generation of electron-hole pairs in the pn-junction at illumination [→ there no recombination ⇒ current source]
- dark current
$$I_{\text{dark current}} = I_{\text{diffusion c.}} + I_{\text{surface leakage c.}} + I_{\text{generation-recombination c.}} + I_{\text{tunneling c.}}$$
- $I_{\text{diffusion c.}}$ should be the main component
- all contributions show a different temperature dependence; material [purity, structure, E_g, …] and geometry factors influence them as well
- [quantum] efficiency $\eta = \dfrac{\frac{I_{\text{photo}}}{q}}{\frac{P_{\text{incident}}}{hf}} = \overbrace{\dfrac{I_{\text{photo}}}{P_{\text{incident}}}}^{S} \overbrace{\dfrac{q}{hf}}^{\approx \frac{1}{1{,}240\,\mu\text{m}}\lambda\frac{\text{A}}{\text{W}}}$ [responsivity S] is influenced by:
  - ~ reflectivity of incident light at the surface
  - ~ recombination of photo-induced carriers at the surface and in the depletion layer
  - ~ the optical absorption outside the depletion layer

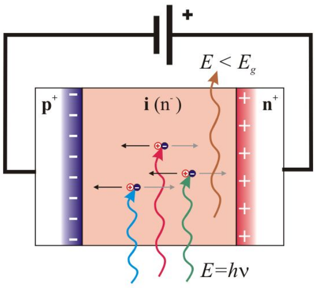


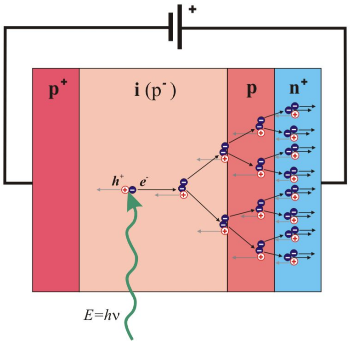
- operation modes
  - ~ photo current I_{photo}-measurement [without any additional voltage sources; small currents; rather slow]
  - ~ load resistor voltage measurement [additional voltage source necessary; rather fast [for small R_L]]



PIN-diode:

- i-layer [un- or only poorly doped layer [$i[\nu]$ [→ n^-] or $i[\pi]$ [→ p^-], ~ $10^{13}\,\text{cm}^{-3}$…$10^{16}\,\text{cm}^{-3}$] compared to p^+/n^+ layers [~ $10^{18}\,\text{cm}^{-3}$]; intrinsic conduction] between p- and n-layer
- increases depletion layer width W_{dl} [⇒ higher quantum efficiency possible]
- higher reverse bias voltage V_b [$W_{dl} \propto \sqrt{V_b}$]; if just the whole i-layer is depleted then $V_b = V_{\text{reach-through}}$
- before break-through:
  - · capacitance $C_{dl} \approx \varepsilon_0 \varepsilon_{r,dl} \dfrac{A}{W_{dl}} \propto \dfrac{1}{\sqrt{V_b}}$
  - · resistance R_D defined by residual part of the i-layer [mostly]
- cut-off frequency $f_{c,RC} \approx \dfrac{1}{2\pi C_{dl} R_{DL}}$, with $\dfrac{1}{R_{DL}} = \dfrac{1}{R_D} + \dfrac{1}{R_L}$ [load resistor R_L]
- transit time t_{tr} of a charge carrier through the depletion layer is another frequency limiting factor $f_{c,tr} = \dfrac{1}{t_{tr}}$
- anti-reflective coating for low reflectivity at surface → higher efficiency





Avalanche photodiode [APD]:

- similar to PIN-diode [i-layer for absorption], shows however an additional poorly doped layer [here p, for charge carrier avalanching]
- multiplication factor

$$M = \frac{\text{photocurrent amplified at high reverse bias in avalanche mode}}{\text{photocurrent amplified at low reverse bias in photodiode mode}}$$

- RC- and transition time cut-off frequencies limit operation bandwidth
- typical: doping of depletion region low, band gap in depletion r. large, thick layer
- for too large V_b breakthrough [avalanche [charge carriers are accelerated this fast, that they free other carriers] or Zener [tunneling of minority charge carriers]]