Formularium

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Basics

Symbols

- Absolute temperature: T
- Boltzmann constant: $k = 1.38064852 \times 10^{-23}\ \mathrm{m^2\ kg\ s^{-2}\ K^{-1}}$
- Intrinsic free carrier concentration: n_i
- Electron concentration: n
- Hole concentration: p
- Effective density of states in conduction band: N_c
- Effective density of states in valence band: N_v
- Fermi level: ϕ_f
- Fermi energy: E_f
- Quasi Fermi energy for electrons (no equilibrium): E_{fn}
- Quasi Fermi energy for holes (no equilibrium): E_{fp}
- Intrinsic Fermi energy: E_i
- Valence band energy: E_v
- Conduction band energy: E_c
- Donor ionization energy: E_D
- Acceptor ionization energy: E_A
- Band gap energy: $E_g \triangleq E_c - E_f$
- Number of ionized donor ions: N_D
- Number of ionized acceptor ions: N_A
- Number of equivalent energy minima in conduction band: M_c
- Density-of-state effective electron mass: m_{de}
- Density-of-state effective hole mass: m_{dh}
- Recombination: R
- Thermal generation: G_{th}
- External generation: G
- Net recombination rate of electrons and holes: $U \triangleq R - G_{th}$
- Equilibrium electron concentration: n_{po}
- Equilibrium hole concentration: p_{no}
- Minority carrier effective lifetimes: τ_n, τ_p

Concentration

$$n = N_c \exp\left(\frac{E_f - E_c}{kT}\right)$$
$$p = N_v \exp\left(\frac{E_v - E_f}{kT}\right)$$

$$N_c = 2\left(\frac{2\pi m_{de} kT}{h^2}\right)^{3/2} M_c$$
$$N_v = 2\left(\frac{2\pi m_{dh} kT}{h^2}\right)^{3/2}$$

Pure Semiconductor in Equilibrium

$$n = p = n_i$$
$$n_i^2 = np = N_c N_v \exp\left(\frac{-E_g}{kT}\right)$$
$$E_f = E_i = \frac{E_c + E_v}{2} + \frac{kT}{2} \ln\left(\frac{N_v}{N_c}\right)$$

Doped Semiconductor in Equilibrium

Charge neutrality:

$$N_D + p = N_A + n$$

N-type

$$\begin{aligned}
&N_D > N_A \\
n &= \frac{1}{2}\left(N_D - N_A + \sqrt{(N_D - N_A)^2 + 4n_i^2}\right) \\
&\approx N_D - N_A \\
p &= \frac{n_i^2}{n} \\
&\approx \frac{n_i^2}{N_D - N_A} \\
E_f &\approx E_i + kT\ln\left(\frac{N_D - N_A}{n_i}\right) > E_i
\end{aligned}$$

P-type

$$\begin{aligned}
&N_A > N_D \\
p &= \frac{1}{2}\left(N_A - N_D + \sqrt{(N_A - N_D)^2 + 4n_i^2}\right) \\
&\approx N_A - N_D \\
n &= \frac{n_i^2}{p} \\
&\approx \frac{n_i^2}{N_A - N_D} \\
E_f &\approx E_i - kT\ln\left(\frac{N_A - N_D}{n_i}\right) < E_i
\end{aligned}$$

Semiconductor out of Equilibrium

$$pn > n_i^2$$

$$\begin{aligned}
n &= N_c \exp\left(\frac{E_{fn} - E_c}{kT}\right) \\
&= n_i \exp\left(\frac{E_{fn} - E_i}{kT}\right) \\
p &= N_v \exp\left(\frac{E_v - E_{fp}}{kT}\right) \\
&= n_i \exp\left(\frac{E_i - E_{fp}}{kT}\right) \\
np &= N_c N_v \exp\left(\frac{(E_v - E_c) + (E_{fn} - E_{fp})}{kT}\right) \\
&= n_i^2 \exp\left(\frac{E_{fn} - E_{fp}}{kT}\right)
\end{aligned}$$

Carrier Recombination and Generation Mechanisms

$$\begin{aligned}
U_n &\approx \frac{n - n_{po}}{\tau_n} \\
U_p &\approx \frac{p - p_{no}}{\tau_p} \\
\frac{dn}{dt} &= \frac{dp}{dt} = -U + G = G_{th} + G - R
\end{aligned}$$

Shockley-Read-Hall generation and recombination

Impurities with energy levels within the forbidden gap.

$$U_{SRH} = \text{staat hopelijk in het formularium}$$

Effectieve levensduur

$$\frac{1}{\tau_p} = \frac{1}{\tau_{p,\text{rad}}} + \frac{1}{\tau_{\text{p,Auger}}}$$

$$\tau_{\text{rad}} = \frac{1}{BN_D}$$

$$\tau_{\text{Auger}} = \frac{1}{G_{A,n}N_D^2}$$

PN-junction

Symbols

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MOS-cap

MOSFET

N-FET

Fermi level

$$\phi_f = V_t \ln\left(\frac{N_A}{n_i}\right)$$

Threshold voltage

$$V_T = V_{FB} + 2\phi_f + \frac{\sqrt{2q\epsilon_s N_A}}{C_{ox}}\sqrt{2\phi_f - V_{BS}}$$

Drain-Source current:

$$\begin{aligned} I_{DS,\mathrm{lin}} &= \frac{\mu C_{ox} W}{L}\left(V_{GS} - V_T + \frac{V_{DS}}{2}\right) V_{DS} \\ I_{DS,\mathrm{sat}} &= \frac{\mu C_{ox} W}{2L}(V_{GS} - V_T)^2 \end{aligned}$$

BJT

PV cell

$$V_{oc} = V_t \ln\left(\frac{J_{sc}}{J_0}\right)$$

$$J_0 = q\sqrt{\frac{V_t \mu_p}{\tau_p}}\frac{n_i^2}{N_D}$$

$$I_{np} = I_{sc} - I_S\left[\exp\left(\frac{V_{pn}}{V_t}\right) - 1\right]$$