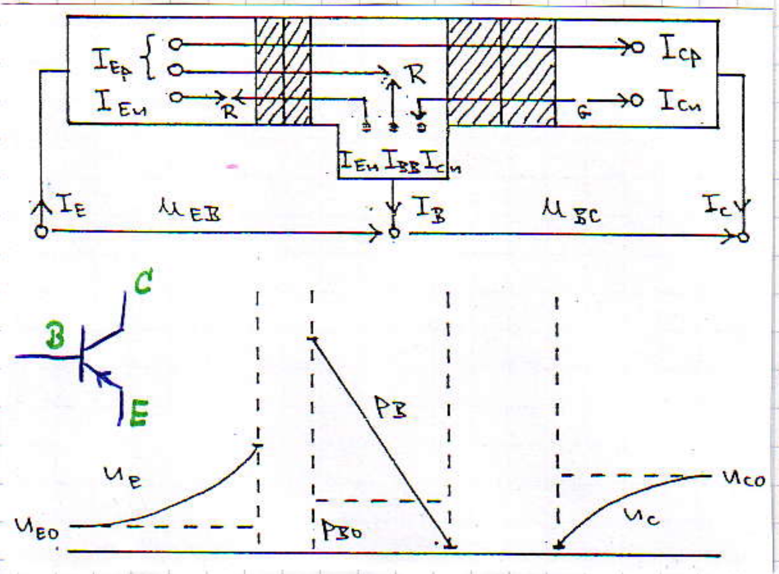
NPN - Transistor



$$I_E = I_{Ep} + I_{En} \cong I_{Ep} \cong I_{cp}$$

$$I_c = I_{cp} + I_{cn} \cong I_{cp}$$

$$I_B = I_E - I_c = I_{En} + \overbrace{(I_{Ep} - I_{cp})}^{I_{BB}} - I_{cn} \approx I_{En} + I_{BB}$$

$$I_c \cong I_E \cong I_{cp} \cong I_{cps} \cdot e^{U_{EB}/U_T} = e \cdot A \cdot \frac{D_{pB}}{W} \cdot \frac{n_i^2}{N_{DB}} \cdot e^{U_{EB}/U_T}$$

$$I_{En} \cong I_{Ens} \cdot e^{U_{EB}/U_T} = e \cdot A \cdot \frac{D_{nE}}{L_{nE}} \cdot \frac{n_i^2}{N_{AE}} \cdot e^{\frac{U_{EB}}{U_T}}$$

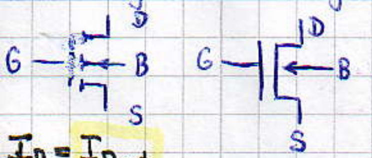
$$I_{BB} \cong I_{BBs} \cdot e^{U_{EB}/U_T} = e \cdot A \cdot W \cdot \frac{D_{pB}}{2 L_{pB}^2} \cdot \frac{n_i^2}{N_{DB}} \cdot e^{\frac{U_{EB}}{U_T}}$$

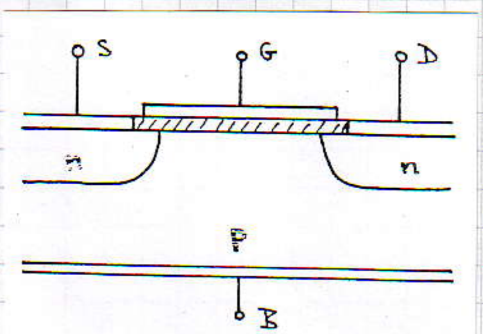
Kennlinien:

- Stromsteuerkl. $I_c = f(I_B)$
- Übertragungskl. $I_c = f(U_{BE})$

MOS-FET

Anreicherungs. Verarmungs.



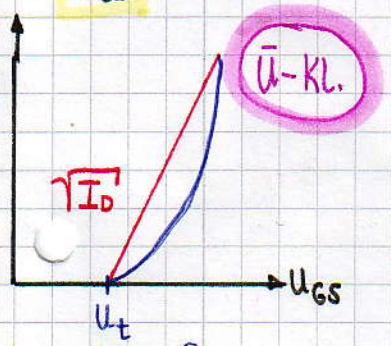


$$U_{DS\,sat} = U_{GS} - U_t$$

$$U_t = \frac{\sqrt{2 \cdot \varepsilon_{Si} \cdot e \cdot N_A \, (2\Phi_B - U_{BS})}}{\varepsilon_{ox} / d_{ox}} + 2\Phi_B + U_{FB}$$

$$I_D = \underbrace{\mu_n \cdot \varepsilon_0 \cdot \varepsilon_r \cdot \frac{1}{d_{ox}} \cdot \frac{W}{L}}_{\beta} \cdot \left[(U_{GS} - U_{TN}) \cdot U_{DS} - \frac{1}{2} \cdot U_{DS}^2 \right]$$

$I_D = I_{Dsat}$



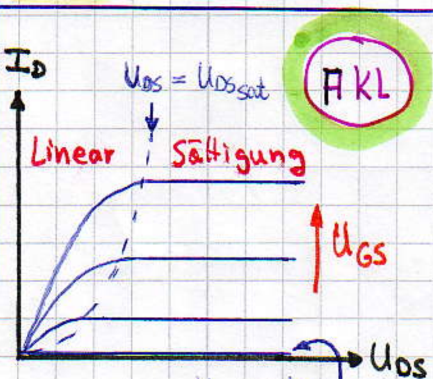
Erreichen der $U_{DS\,sat} = U_{GS} - U_t$: $I_{DS\,sat} = \frac{1}{2} \cdot \beta \cdot U_{DS\,sat}^2$

gesättigter Bereich (mit Kanallängenmodulation):

$$\Rightarrow I_D = \text{konst.} = \frac{1}{2}\beta \cdot (U_{GS} - U_t)^2 \cdot \left[1 + \frac{U_{DS} - U_{DS\,sat}}{U_{eA}}\right]$$

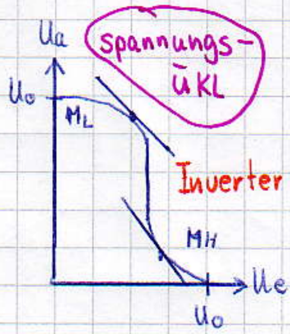
$$I_{Dsat} = \frac{\beta}{2} \cdot U_{DS\,sat}^2$$

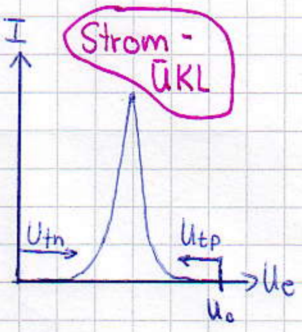
$$R_{DSon} = \left.\frac{dU_{DS}}{dI_D}\right|_{I_D = 0} \cong \boxed{\frac{\Delta U_{DS}}{\Delta I_D}} \qquad \beta = \left(\frac{\sqrt{I_D}}{U_{GS} - U_t}\right)^2 \cdot 2$$

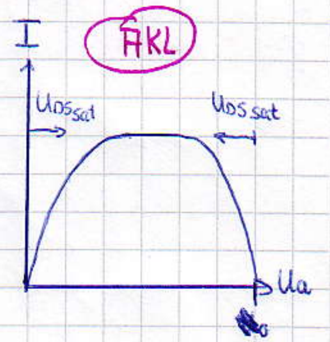


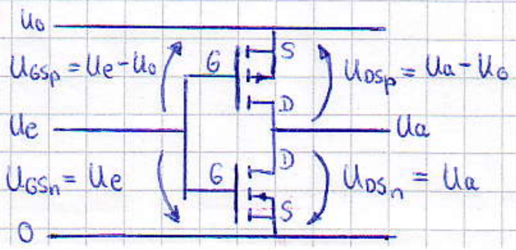
$U_{GS} \leq U_t$

$\Rightarrow I_D \cong 0$



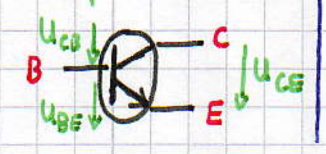


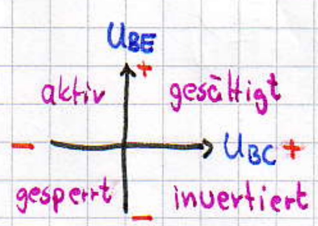


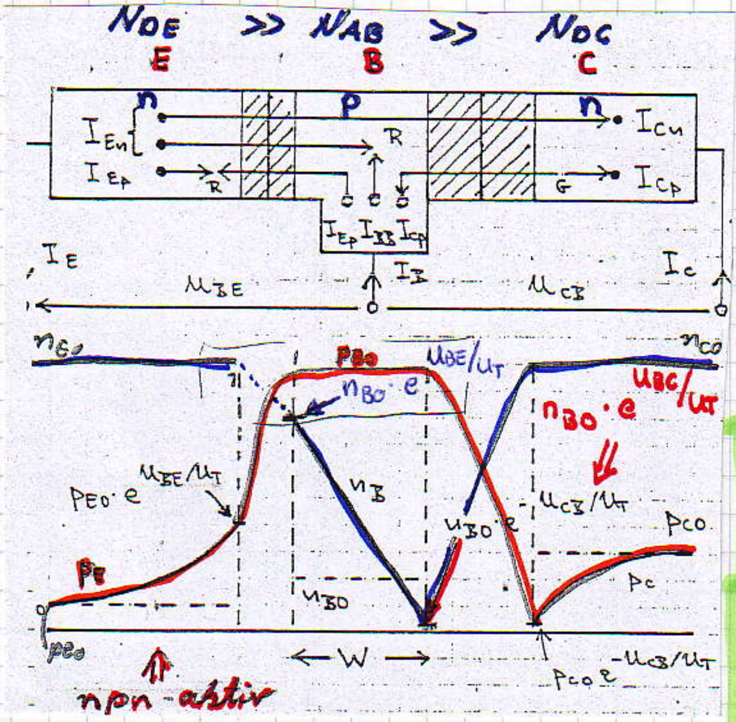


Bipolartransistor

• npn - Trans.







Ströme:

$$I_E = I_{En} + I_{Ep} \approx I_{En} \approx I_{Cn}$$

$$I_C = I_{Cn} + I_{Cp} \approx I_{Cn}$$

$$I_B = I_E - I_C = I_{Ep} + \underbrace{[I_{En} - I_{Cn}]}_{I_{BB}} - I_{Cp}$$

$$I_C \cong I_E \cong I_{Cns} \cdot e^{U_{BE}/U_T} = e \cdot A \cdot D_{nB} \cdot \frac{n_B(x=0)}{W} =$$

$$= e \cdot A \cdot \frac{D_{nB}}{W} \cdot \left(\frac{n_i^2}{N_{AB}} \cdot e^{U_{BE}/U_T} \right) =$$

$$I_{BB} = e \cdot A \cdot \frac{D_{nB}}{2 L_{nB}^2} \cdot W \cdot \frac{n_i^2}{N_{AB}} \cdot e^{U_{BE}/U_T} = I_C \cdot \frac{1}{2} \cdot \left(\frac{W}{L_{nB}} \right)^2$$

$$I_{Ep} = e \cdot A \cdot \frac{D_{pE}}{L_{pE}} \cdot \frac{n_i^2}{N_{DE}} \cdot e^{U_{BE}/U_T} \cong I_{Eps} \cdot e^{U_{BE}/U_T}$$

$$I_C \cong I_E \Rightarrow B = \frac{I_C}{I_B}, \quad \beta = \frac{\Delta I_C}{\Delta I_B}$$

AP-Einstellen:

$$U_0 = I_C \cdot R_C + U_{CE} \Rightarrow R_C = \frac{U_0 - U_{CE}}{I_C}$$

$$U_0 = I_B \cdot R_B + U_{BE} \Rightarrow R_C \text{ mit } U_{BE} = 0{,}7$$

Kleinsignalgrößen:

$$|V_u| = g_m \cdot (R_C \| r_{CE}) = \frac{\Delta U_{CE}}{\Delta U_{BE}} = \boxed{g_m \cdot R_C} \text{ (ohne } r_{CE})$$

$$r_{BE} = \frac{1}{g_{BE}} = \boxed{\frac{dU_{BE}}{dI_B}} = \frac{U_T}{I_B} \qquad g_m = \frac{V_u}{R_C} = \frac{I_C}{U_{BE}} = \boxed{\frac{I_C}{U_T}} = \frac{\beta}{r_{BE}}$$

$$r_{CE} = \frac{1}{g_{CE}} = \frac{U_{CE}}{I_C} \cong \frac{U_{EA}}{I_C} = \boxed{\frac{dU_{CE}}{dI_C}} \qquad \beta = \frac{\Delta I_C}{\Delta I_B} \approx \frac{I_C}{I_B}$$

EKL : $I_B = I_{BS} \cdot e^{U_{BE}/U_T}$, $g_{BE} = \left.\frac{dI_B}{dU_{BE}}\right|_{U_{CE}} = \frac{I_B}{U_T}$

AKL : $I_C = B \cdot I_B = \beta \cdot I_B$

ÜKL : $I_C \cong I_{Cns} \cdot e^{U_{BE}/U_T}$ $\quad g_m = \frac{dI_C}{dU_{BE}} = \frac{I_C}{U_T}$

Stromü. KL : $I_C \cong B \cdot I_B$, $\quad B = \frac{I_C}{I_B}$

Achtung: m berücksichtigen ⇒ $m \cdot U_T$

Ladungsträgerdichten: in Basis

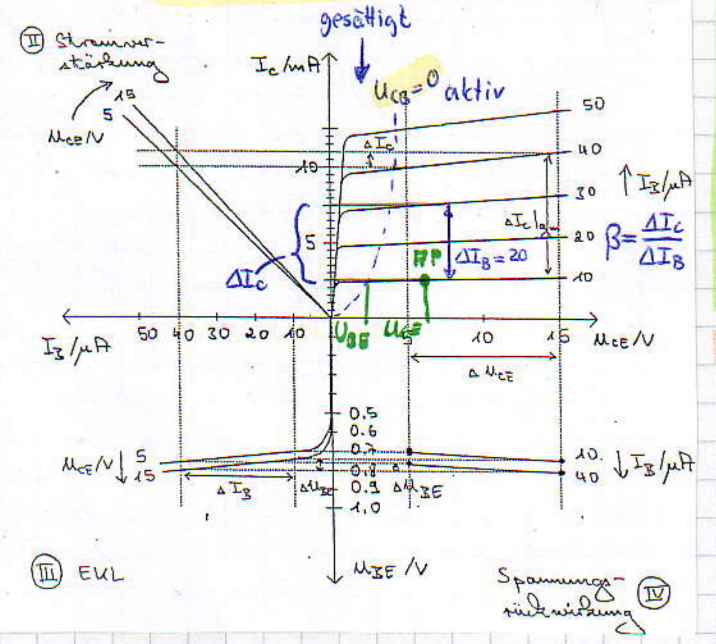
$$n_0 = \frac{n_i^2}{N_A} \qquad p_0 = \frac{n_i^2}{N_D}$$

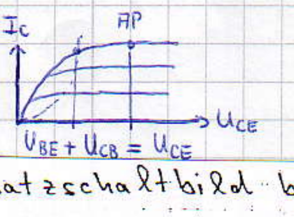
$$n_{B(x=0)} = \frac{I_C \cdot W}{e \cdot A \cdot D_{nB}} = n_{B0} \cdot e^{\frac{U_{BE}}{U_T}} \qquad n_{B(W)} = n_{B0} \cdot e^{\frac{U_{BC}}{U_T}} = n_{B(x=0)} - \Delta n_B$$

Emitterschaltung : Kennlinien

Bei Grenze im AKL bei $U_{CB} = 0$: $U_{BE} = U_{CE}$

ansonsten: $U_{CE} = U_{BE} + U_{CB} = U_{BE} - U_{BC}$

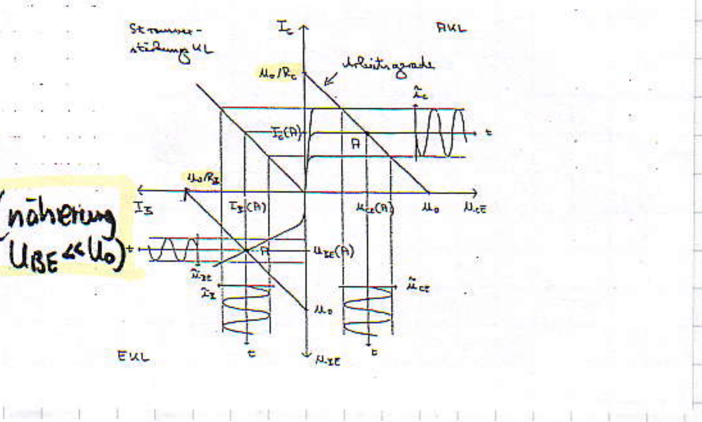




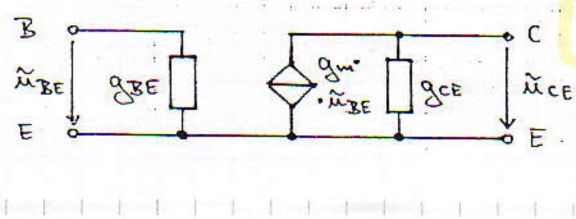
$$C_{BE} = \varepsilon_0 \varepsilon_r \cdot \frac{A}{L_{BE}}$$

$$C_{BC} = \varepsilon_0 \varepsilon_r \cdot \frac{A}{L_{BC}}$$

Kleinsignal-Übertragung



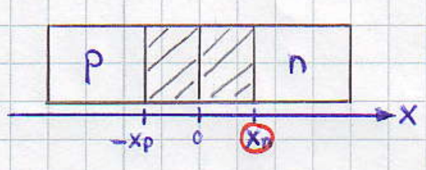
Ersatzschaltbild bei kleinen Frequenzen



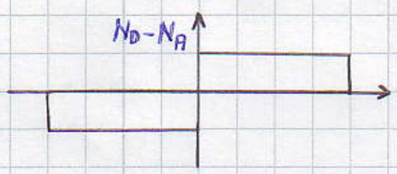
$$R_B \approx \frac{U_0}{I_B} \text{ (Näherung } U_{BE} \ll U_0)$$

PN - Übergang

thermisches Gleichgewicht

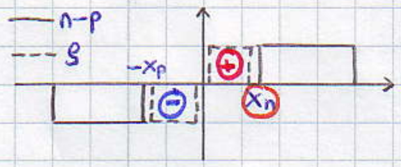


$$N_A = \frac{n_i^2}{N_D} \cdot e^{(U_D/U_T)}$$

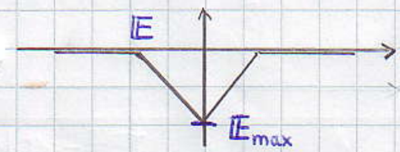


$$n_{p_0} = \frac{n_i^2}{N_A}$$

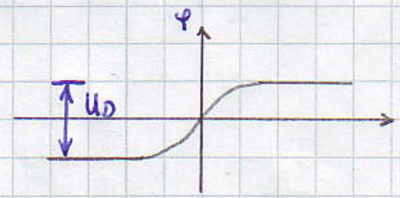
$$p_{n_0} = \frac{n_i^2}{N_D}$$



RLZ: $L = x_n + x_p = \left[\frac{2\varepsilon}{e} \cdot \left(\frac{N_A + N_D}{N_A \cdot N_D}\right) \cdot U_D\right]^{1/2}$



$$E_{max} = \frac{e \cdot N_D \cdot x_n}{\varepsilon} = \frac{e \cdot N_A \cdot x_p}{\varepsilon}$$

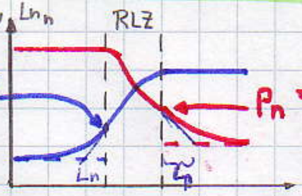


$$U_D = \frac{k \cdot T}{e} {}^{*} \cdot \ln\left(\frac{N_D \cdot N_A}{n_i^2}\right) = \frac{1}{2} E_{max} \cdot L$$

mit angelegter Spg. $U = \varphi_p - \varphi_n$

$U \begin{cases} > 0 \sim \text{Injektion} \\ < 0 \sim \text{Extraktion} \end{cases}$ von Minoritäts-LT

Minoritäts-LT am Rand von RLZ

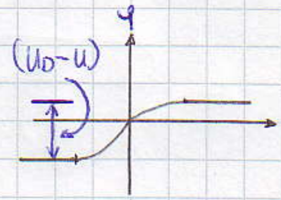


$n_p = n_{p_0} \cdot e^{U/U_T}$ $p_n = p_{n_0} \cdot e^{U/U_T}$

$$\rightarrow L = x_n + x_p = \left[\frac{2\varepsilon}{e} \cdot \left(\frac{N_A + N_D}{N_A \cdot N_D}\right) \cdot (U_D - U)\right]^{1/2}$$

$$\rightarrow E_{max} = \frac{e \cdot N_D \cdot x_n}{\varepsilon} = \frac{e \cdot N_A \cdot x_p}{\varepsilon}$$

$$\rightarrow (U_D - U) = \frac{1}{2} \cdot E_{max} \cdot L$$



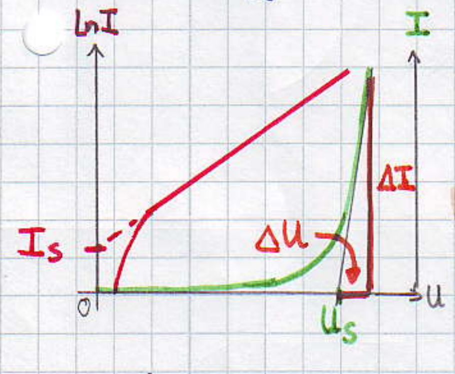
KL.: $I = I_S \cdot \left(e^{U/U_T} - 1\right)$

$e \cdot A \cdot n_i^2 \cdot \left(\frac{D_n}{L_n \cdot N_A} + \frac{D_p}{L_p \cdot N_D}\right) = I_S = e \cdot A \cdot \left(\frac{D_n \cdot n_{p0}}{L_n} + \frac{D_p \cdot p_{n0}}{L_p}\right)$

für $U \gg U_T \Rightarrow I = I_S \cdot e^{U/U_T}$

für $U \ll U_T \Rightarrow I = -I_S$

Durchbruchspg.: bei Lawineneffekt: $U_{Br} > 5V \;\hat{=}\; \frac{E_{Br} \cdot L}{2} - U_D$ | Tunneleffekt: $U_{Br} < 5V$

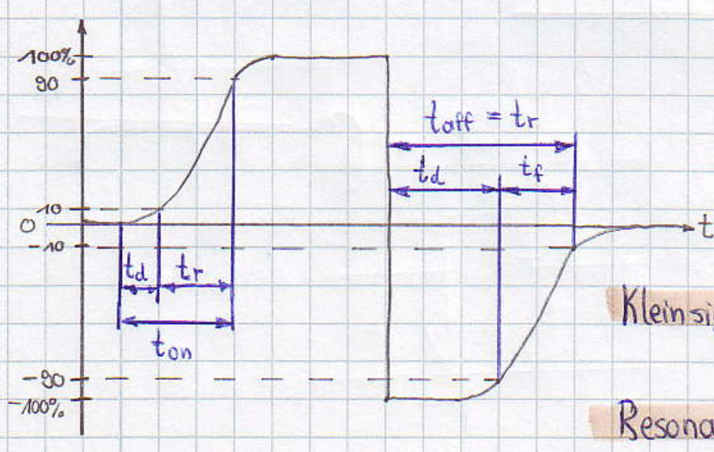


$$R_D = \frac{\Delta U}{\Delta I}$$

Kennlinie für $\frac{1}{C_S^2}$: $\frac{1}{C_S^2} = \underbrace{\frac{1}{A^2} \cdot \frac{2}{\varepsilon_0 \varepsilon_r \cdot e \cdot N_D}}_{\text{Steigung!}} (U_D - U)$

Durchlass: $n_{(0)} = n_{p_0} \cdot e^{U/U_T}$ $p_{n(0)} = n_{p_0} \cdot e^{U/U_T}$

Sperrricht.: $n_{(0)} = n_{p_0} \cdot e^{-U/U_T}$ $p_{n(0)} = n_{p_0} \cdot e^{-U/U_T}$



Kapazitäten: $C_S = A \sqrt{\frac{\varepsilon_0 \cdot \varepsilon_r \cdot e \cdot N_D}{2 \cdot (U_D - U_R)}}$

* normal $U_R = 0$!

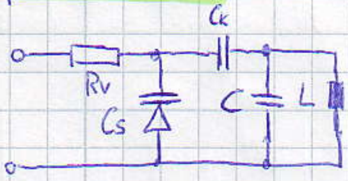
$U_D = U_T \cdot \ln\left(\frac{N_A \cdot N_D}{n_i^2}\right)$ (auch für C-Diode)

Kleinsignalmodell: $g_d = \frac{dI}{dU} \cong \frac{I}{m U_T}$

Resonanz: $f_g = \frac{1}{2\pi \cdot \sqrt{L \cdot C}}$ mit $C = C + C_S$

Ideale Solarzelle: $I = I_S\left[e^{U/U_T} - 1\right] - I_{Ph}$

Kapazitätsdiode:



$$C_S = \varepsilon \cdot \frac{A}{L} = A \cdot \sqrt{\frac{e \cdot \varepsilon_0 \cdot \varepsilon_r \cdot N_D}{2(U_D - U)}} = \underbrace{A \cdot \sqrt{\frac{e \cdot \varepsilon_0 \cdot \varepsilon_r \cdot N_D}{2U_D}}}_{C_{S0}} \cdot \left[1 - \frac{U}{U_D}\right]^{1/2}$$

$$N_A = \frac{n_i^2}{N_D} \cdot e^{U_D/U_T}$$

Z-Diode:

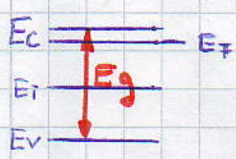
Zener-Effekt: $U_Z < 5V$, $N_D > 3 \cdot 10^{17}\ cm^{-3}$, $\alpha < 0$

Lawinen- " : $U_Z > 5V$, $N_D < 3 \cdot 10^{17}\ cm^{-3}$, $\alpha > 0$

Differentieller Widerstand im Durchbruchbereich: $r_Z = \frac{dU_Z}{dI_Z}$, $R_{Z0} = \frac{\Delta U}{\Delta I}$, $\alpha = \frac{1}{U_{Z0}} \cdot \frac{\Delta U_Z}{\Delta T}$

Leitung im HL

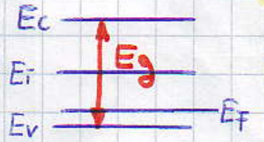
n-HL



$$n_0 = n_i \cdot e^{\frac{E_F - E_i}{kT}}$$

$$p_{n0} = n_i \cdot e^{\frac{E_i - E_F}{kT}} = \boxed{\frac{n_i^2}{N_D}}$$

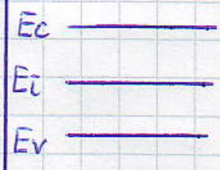
p-HL



$$p_0 = n_i \cdot e^{\frac{E_i - E_F}{k \cdot T}}$$

$$n_{p0} = n_i \cdot e^{\frac{E_F - E_i}{k \cdot T}} = \boxed{\frac{n_i^2}{N_A}}$$

intrinsischer HL



$n_0 = p_0 = n_i$

Fermiverteilung

allg.: $F_{(E)} = \frac{1}{1 + \exp\left[\frac{E - E_F}{k \cdot T}\right]}$

im intrinsischen HL

für Ec Bandkante: $F_{(E_C)} = \frac{1}{1 + \exp\left[\frac{E_g}{2k \cdot T}\right]}$

für Ev Bandkante: $F_{(E_V)} = \frac{1}{1 + \exp\left[\frac{-E_g}{2k \cdot T}\right]}$

Zustandsdichten

$n_0 = N_C \cdot \exp\left[-\frac{E_C - E_F}{k \cdot T}\right]$ $\quad N_C = 2\left[\frac{2\pi \cdot m_n \cdot k \cdot T}{h^2}\right]^{3/2} \overset{Si}{\underset{300K}{\cong}} 2{,}8 \cdot 10^{19}\ cm^{-3}$

$p_0 = N_V \cdot \exp\left[-\frac{E_F - E_V}{k \cdot T}\right]$ $\quad N_V = 2\left[\frac{2\pi \cdot m_p \cdot k \cdot T}{h^2}\right]^{3/2} \overset{Si}{\underset{300K}{\cong}} 1{,}04 \cdot 10^{19}\ cm^{-3}$

	Bandabstand E_g	$n_i\ [cm^{-3}]$
Ge	0,67	$2{,}5 \cdot 10^{13}$
Si	1,12	$1{,}5 \cdot 10^{13}$
GaAs	1,43	$1{,}8 \cdot 10^{6}$

Stromkomponenten

Leitfähigkeit σ

- Driftstrom: $\vec{J}_{drift} = e \cdot (n \cdot \mu_n + p \cdot \mu_p) \cdot \vec{E} = \sigma \cdot \vec{E}$
- Diffusionstrom: $\vec{J}_{diff} = e \cdot D_n \cdot \frac{dn}{dx} - e \cdot D_p \cdot \frac{dp}{dx}$

Stationäre Injektion:

$\tau_p = \frac{1}{n_0 \cdot r}$ $\quad L_p = \sqrt{D_p \cdot \tau_p}$

$$p_{(x)} = p_0 + p'_{(0)} \cdot e^{\left(-\frac{x}{L_p}\right)}$$