Bändermodell

$W_g(T)=W_g(0)-\alpha\frac{T^2}{T+\beta}$

Halbleiter $W_g<5\,eV$

Isolator $W_g>5\,eV$

$W_{g_{Si}}(300\,K)=1{,}12\,eV$

$W_{g_{GaAs}}(300\,K)=1{,}42\,eV$

$m\,stern^{-1}=\frac{1}{h^2}\frac{\partial^2 W}{\partial k^2}$

$\frac{m_{e_{Si}}}{m_0}=0{,}26$ $\frac{m_{h_{Si}}}{m_0}=0{,}386$

$\varepsilon_{r_{Si}}=12$ $\varepsilon_{Si}=1{,}06\cdot 10^{-12}\frac{As}{V\,cm}$

Intrinsische Halbleiter

Zustandsdichte

$D(W)=\frac{dZ}{dW}=\frac{\sqrt{2\,m^3 W}}{2\,h^3\pi^2}$

Fermiverteilung

$f(W)=\frac{1}{1+\exp\left(\frac{W-W_F}{kT}\right)}$

intrinsisches Ferminiveau

$W_{F_i}=\frac{W_C+W_V}{2}+\frac{kT}{2}\ln\left(\frac{N_V}{N_C}\right)$

Ladungsträgerdichten

Leitungsband $n_0=\int_{W_C}^{\infty} f(W)D(W)\,dW=N_C\exp\left(\frac{W_F-W_C}{kT}\right)$

$N_C=2\left(\frac{2\pi m_e kT}{h^2}\right)^{\frac{3}{2}}$

Valenzband $p_0=\int_{0}^{W_V}(1-f(W))D(W)\,dW=N_V\exp\left(\frac{W_V-W_F}{kT}\right)$

$N_V=2\left(\frac{2\pi m_h kT}{h^2}\right)^{\frac{3}{2}}$

$n_i^2=p_i^2=n_0 p_0=N_C N_V\exp\left(-\frac{W_g}{kT}\right)$

Dotierte Halbleiter

Akzeptorendichte

$N_A^+=\frac{N_A}{1+\exp\left(\frac{W_A-W_F}{kT}\right)}$

Donatorendichte

$N_D^+=\frac{N_D}{1+\exp\left(\frac{W_F-W_D}{kT}\right)}$

Neutralitätsbedingung

$N_A^+ + n_0=N_D^+ + p_0$

$p_0=\frac{N_A-N_D}{2}+\sqrt{\left(\frac{N_A-N_D}{2}\right)^2+n_i^2}$

$n_0=\frac{N_D-N_A}{2}+\sqrt{\left(\frac{N_D-N_A}{2}\right)^2+n_i^2}$

p-Halbleiter $n_0=\frac{n_i^2}{N_A}$ $p_0=N_A$ $W_F-W_V=kT\ln\left(\frac{N_V}{N_A}\right)$ $W_{F_i}-W_F=kT\ln\left(\frac{p_0}{n_i}\right)$

n-Halbleiter $n_0=N_D$ $p_0=\frac{n_i^2}{N_D}$ $W_C-W_F=kT\ln\left(\frac{N_C}{N_D}\right)$ $W_F-W_{F_i}=kT\ln\left(\frac{n_0}{n_i}\right)$

Stromdichte

Driftgeschwindigkeit

$v_{D_p}=\mu_p E$ $v_{D_n}=-\mu_n E$

Elektronenbeweglichkeit

$\mu=\frac{e\tau}{m_{e|h}}$

spez. Leitfähigkeit

$\gamma=\frac{1}{\rho}=p\,e\,\mu_p+n\,e\,\mu_n$

Stromdichte

$J=J_p+J_n=J_D+J_{Diff}$

$J_{p|n}=J_{D_{p|n}}=J_{Diff_{p|n}}$

Drift-Strom

$J_D=J_{D_p}+J_{D_n}$

$J_{D_{p|n}}=(p|n)\,e\,\mu_{p|n}E$

Diffusions-Strom

$J_{Diff}=J_{Diff_p}+J_{Diff_n}$

$J_{Diff_{p|n}}=\mp e\,D_{p|n}\,\mathrm{grad}(p|n)$

Diffusionskonstante $D_{p|n}=U_T\mu_{p|n}$

Diffusionslänge $L_{p|n}=\sqrt{D_{p|n}\tau_{p|n}}$

Kontinuitätsgleichung $\frac{\partial(p|n)}{\partial t}=\pm\frac{1}{e}\frac{\partial J_{p|n}}{\partial x}+(g_{p|n}-r_{p|n})$

Hallspannung $\vec{U}_H=\pm\mu_{p|n}d\,\vec{E}\times\vec{B}$

pn-Übergang

$$U_D=\frac{W_g}{e}-U_n-U_p=U_T\left(\ln\left(\frac{N_C N_V}{n_i^2}\right)-\ln\left(\frac{N_C}{n_{n_0}}\right)-\ln\left(\frac{N_V}{p_{p_0}}\right)=\ln\left(\frac{n_{n_0}p_{p_0}}{n_i^2}=\frac{N_A N_D}{n_i^2}=\frac{p_{p_0}}{p_{n_0}}=\frac{n_{n_0}}{n_{p_0}}\right)\right)=\frac{1}{2}E_m w$$

$$w=w_p+w_n=\sqrt{\frac{2\varepsilon}{e}\left(\frac{1}{N_A}+\frac{1}{N_D}\right)(U_D-U)}$$

$$N_A w_p=N_D w_n$$

p-Gebiet

$$w_p=w\frac{N_D}{N_D+N_A}$$

$$-\frac{\partial^2\phi}{\partial x^2}=\frac{\partial E}{\partial x}=\frac{-eN_A}{\varepsilon}$$

$$-\frac{\partial\phi}{\partial x}=E=\frac{-eN_A}{\varepsilon}(x+w_p)=-E_m\left(1+\frac{x}{w_p}\right)$$

$$\phi=E_m\frac{(x+w_p)^2}{2w_p} \qquad |E_m|=\frac{eN_A w_p}{\varepsilon}$$

$$p_{p_0}=N_V\exp\left(\frac{W_V-W_F}{kT}\right)=N_V\exp\left(-\frac{U_p}{U_T}\right)$$

$$n_{p_0}=n_{n_0}\exp\left(-\frac{U_D}{U_T}\right)$$

$$n_p(x)=n_{p_0}\left(\exp\left(\frac{U}{U_T}\right)-1\right)\exp\left(\frac{w_p+x}{L_n}\right)+n_{p_0}$$

$$\frac{Q_n}{eA}=\int_{-\infty}^{-w_p}\left(n_p(x,t)-n_{p_0}\right)dx=n_{p_0}L_n\left(\exp\left(\frac{U}{U_T}\right)-1\right)$$

$$J_n(-w_p)=\frac{eD_n}{L_n}n_{p_0}\left(\exp\left(\frac{U}{U_T}\right)-1\right)=\frac{dQ_n}{dt}+\frac{Q_n}{\tau_n}$$

n-Gebiet

$$w_n=w\frac{N_A}{N_D+N_A}$$

$$-\frac{\partial^2\phi}{\partial x^2}=\frac{\partial E}{\partial x}=\frac{eN_D}{\varepsilon}$$

$$-\frac{\partial\phi}{\partial x}=E=\frac{eN_D}{\varepsilon}(x-w_n)=-E_m\left(1-\frac{x}{w_n}\right)$$

$$\phi=E_m\left(x-\frac{x^2}{2w_n}+\frac{w_p}{2}\right) \qquad |E_m|=\frac{eN_D w_n}{\varepsilon}$$

$$n_{n_0}=N_C\exp\left(\frac{W_F-W_C}{kT}\right)=N_C\exp\left(-\frac{U_n}{U_T}\right)$$

$$p_{n_0}=p_{p_0}\exp\left(-\frac{U_D}{U_T}\right)$$

$$p_n(x)=p_{n_0}\left(\exp\left(\frac{U}{U_T}\right)-1\right)\exp\left(\frac{w_n-x}{L_p}\right)+p_{n_0}$$

$$\frac{Q_p}{eA}=\int_{w_n}^{\infty}\left(p_n(x,t)-p_{n_0}\right)dx=p_{n_0}L_p\left(\exp\left(\frac{U}{U_T}\right)-1\right)$$

$$J_p(w_n)=\frac{eD_p}{L_p}p_{n_0}\left(\exp\left(\frac{U}{U_T}\right)-1\right)=\frac{dQ_p}{dt}+\frac{Q_p}{\tau_p}$$

$$J=J_n+J_p=J_S\left(\exp\left(\frac{U}{\eta U_T}\right)-1\right)$$

Idealitätsfaktor $1<0\eta\leq 2$

$$J_S=\frac{eD_n}{L_n}n_{p_0}+\frac{eD_p}{L_p}p_{n_0}=e n_i^2\left(\frac{1}{N_A}\sqrt{\frac{D_n}{\tau_n}}+\frac{1}{N_D}\sqrt{\frac{D_p}{\tau_p}}\right)=e\left(L_n\frac{n_{p_0}}{\tau_n}+L_p\frac{p_{n_0}}{\tau_p}\right)$$

Kleinsignalverhalten

Raumladungskapazität $C_S=A\sqrt{\frac{\varepsilon e N_A N_D}{2(N_A+N_D)(U_D-U)}}$

Diffusionskapazität (p^+n) $C_d=\frac{dQ_p}{dU_F}=\tau_p\frac{dI_F}{dU_F}=\tau_p g_d$

Kleinsignalleitwert (p^+n) $g_d=\frac{dI_F}{dU_F}=\frac{I_F}{U_T}$

Speicherzeit (p^+n) $t_s=\tau_p\ln\left(1+\frac{I_F}{I_R}\right)$

npn-Transistor

$$-I_E = a_{11}\left(\exp\left(\frac{U_{BE}}{U_T}\right)-1\right)+a_{12}\left(\exp\left(\frac{U_{BC}}{U_T}\right)-1\right)$$

$$I_C = a_{21}\left(\exp\left(\frac{U_{BE}}{U_T}\right)-1\right)+a_{22}\left(\exp\left(U_{BC}U_T\right)-1\right)$$

$$I_B = \left(a_{11}-a_{21}\right)\left(\exp\left(\frac{U_{BE}}{U_T}\right)-1\right)+\left(a_{12}-a_{22}\right)\left(\exp\left(\frac{U_{BC}}{U_T}\right)-1\right) = -I_C - I_E = I_{BE}+I_{BB}-I_{BC}$$

$$a_{11} = A\,e\left(\frac{D_{n_B} n_{B_0}}{L_{n_B}}\coth\left(\frac{w_B}{L_{n_B}}\right)+\frac{D_{p_E} p_{E_0}}{L_{p_E}}\right) \qquad a_{12} = -A\,e\frac{D_{n_B} n_{B_0}}{L_{n_B}}\sinh\left(\frac{w_B}{L_{n_B}}\right)$$

$$a_{21} = A\,e\frac{D_{n_B} n_{B_0}}{L_{n_B}}\frac{1}{\sinh\left(\frac{w_B}{L_{n_B}}\right)} \qquad a_{22} = A\,e\left(-\frac{D_{n_B} n_{B_0}}{l_{n_B}}\coth\left(\frac{w_B}{L_{n_B}}\right)+\frac{D_{p_C} p_{C_0}}{L_{p_C}}\right)$$

$$I_{BE} = A\,e\frac{D_{p_E} p_{E_0}}{L_{p_E}}\left(\exp\left(\frac{U_{BE}}{U_T}\right)-1\right) \qquad I_{BC} = -A\,e\frac{D_{p_C} p_{C_0}}{L_{p_C}}\left(\exp\left(\frac{U_{BC}}{U_T}\right)-1\right) \qquad I_{BB} = I_B - I_{BE} + I_{BC}$$

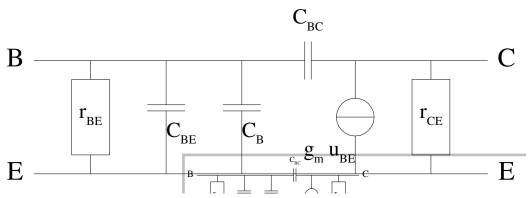
Kleinsignalverhalten

Diffusionskapazität

$$C_B = \frac{q_B}{u_{BE}} = \tau_{FT}\, g_m$$

Sperrschichtkapazitäten

$$C_{BE} = \frac{C_{BE_0}}{\left(1-\frac{U_{BE}}{U_{D_{BE}}}\right)^{m_e}} \qquad C_{BC} = \frac{C_{BC_0}}{\left(1+\frac{U_{CB}}{U_{D_{CB}}}\right)^{m_C}}$$



Eingangswiderstand

$$r_{BE} = \frac{u_{BE}}{i_B} = \frac{U_T}{|I_B|} = \frac{\beta}{g_m}$$

Stromverstärkung

$$\beta = \frac{i_C}{i_B} = \frac{|I_C|}{|I_B|} = \frac{\alpha}{1-\alpha} = g_m\, r_{BE}$$

Basistransportfaktor

$$\alpha = \frac{i_C}{i_E}$$

Ausgangsleitwert

$$g_{CE} = \frac{i_C}{u_{CE}} = \frac{|I_C|}{U_{ea}} = g_m\, v_r$$

Steilheit

$$g_m = \frac{i_C}{u_{BE}} = \frac{|I_C|}{U_T} = \frac{\beta}{r_{BE}}$$

Spannungsrückwirkung

$$v_r = \frac{u_{BE}}{u_{CE}} = \frac{U_T}{U_{ea}} = \frac{g_{CE}}{g_m}$$

Forward-Basis-Transitzeit

$$\tau_{FT} = \frac{w^2}{2D_{n_B}}$$

Grenzfrequenz

$$\omega_g = \frac{1}{r_{BE}\left(C_B + C_{BE} + C_{BC}\right)}$$

Transitfrequenz

$$\omega_T = \frac{g_m}{\left(C_B + C_{BE} + C_{BC}\right)}$$

Gleichstromverstärkung

$$h_{fe} = \frac{\beta}{1 + j\omega\, r_{BE}\left(C_B + C_{BE} + C_{BC}\right)}$$

Vierpolmatrix

$$\underline{H} = \begin{pmatrix} r_{BE} & v_r \\ \beta & g_{CE} \end{pmatrix} \qquad |I_B| = I_{B_0}\exp\left(\frac{|U_{BE}|}{U_T}\right) \qquad |I_C| = I_{C_0}\exp\left(\frac{|U_{BE}|}{U_T}\right)$$

MOS-FET

Kapazitäten

$$C'=\left(\frac{1}{C'_{ox}}+\frac{1}{C'_{si}}\right)^{-1}\qquad C'_{ox}=\frac{\varepsilon_{ox}}{x_{ox}}\qquad C'_{si}=\frac{\varepsilon_{si}}{x_{si}=\left(w,L_D,0\right)}$$

Debeye-Länge

$$L_D=\sqrt{\frac{\varepsilon_{si}U_T}{e N_A}}$$

Raumladungszonenweite

$$w=\sqrt{\frac{2U_{si}\varepsilon_{si}}{e N_A}}$$

Spannungen

$$U_{MS}=\phi_{0_S}-\phi_{0_M}=U_{ox}+U_{si}$$

$$U_{ox}=E_{ox}x_{ox}=Q'\frac{}{C'_{ox}}\qquad E_{ox}=\frac{e N_A w}{\varepsilon_{ox}}\qquad Q'=\varepsilon_{ox}E_{ox}=\sqrt{2U_{si}e N_A\varepsilon_{si}}$$

Flachbandspannung

$$U_{FB}=-U_{MS}-\frac{1}{C'_{ox}}\left(\rho_F+\int_0^{x_{ox}}\frac{x}{x_{ox}}\rho_v(x)\,dx\right)$$

Schwellspannung

$$U_S=U_{FB}+\frac{2}{e}\left|W_{F_i}-W_{F_s}\right|+U_{ox}\left(U_{si}=\frac{2}{e}\left|W_{F_i}-W_{F_s}\right|\right)\qquad W_{F_i}-W_{F_s}=kT\ln\left(\frac{N_A}{n_i}\right)$$

Kennlinien

Drainstrom

$$I_D(U_{DS})=\begin{matrix}+(n-\text{Kanal})\\-(p-\text{Kanal})\end{matrix}\left[\begin{matrix}2K\left((U_{GS}-U_S)U_{DS}-\frac{U_{DS}^2}{2}\right) & \text{Triodenbereich} & \pm U_{DS}\le\pm(U_{GS}-U_S)\\ K\left(1+\frac{U_{DS}}{U_A}\right)(U_{GS}-U_S)^2 & \text{Sättigungsbereich} & \pm U_{DS}\ge\pm(U_{GS}-U_S)\end{matrix}\right]\qquad K=\frac{\varepsilon_{ox}\mu_{n_{si}}A}{2x_{ox}L^2}$$

Kleinsignal

Ausgangsleitwert

$$g_d=\frac{i_D}{u_{DS}}=\left[\begin{matrix}2K(U_{GS}-U_{DS}-U_S)\\ \frac{I_D}{U_A}\end{matrix}\right]$$

Steilheit

$$g_m=\frac{i_D}{u_{GS}}=\left[\begin{matrix}2KU_{DS}\\ \frac{2I_D}{U_{GS}-U_S}\end{matrix}\right]$$