SEMICONDUCTOR DEVICES

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Quadripole (four-pole network):

$\underline{y}_{mn} = g_{mn} + jb_{mn}$ $\underline{z}_{mn} = r_{mn} + jx_{mn}$ $\underline{I}_1 = \underline{y}_{11}\underline{U}_1 + \underline{y}_{12}\underline{U}_2$ $\underline{U}_1 = \underline{z}_{11}\underline{I}_1 + \underline{z}_{12}\underline{I}_2$ $\underline{U}_1 = \underline{h}_{11}\underline{I}_1 + \underline{h}_{12}\underline{U}_2$

$\underline{h}_{mn} = \mathrm{Re}\left[\underline{h}_{mn}\right] + j\,\mathrm{Im}\left[\underline{h}_{mn}\right]$ $\underline{I}_2 = \underline{y}_{21}\underline{U}_1 + \underline{y}_{22}\underline{U}_2$ $\underline{U}_2 = \underline{z}_{21}\underline{I}_1 + \underline{z}_{22}\underline{I}_2$ $\underline{I}_2 = \underline{h}_{21}\underline{I}_1 + \underline{h}_{22}\underline{U}_2$

Semiconductor:

$$n = N_C e^{-\frac{E_C - E_F}{kT}} = n_i e^{\frac{E_F - E_{Fi}}{qU_T}} = n_i e^{\frac{V_{Fi} - V_F}{U_T}} \quad J_n = q\mu_n nE + qD_n \frac{dn}{dx} \quad \frac{\partial n}{\partial t} = -\frac{n - n_0}{\tau_n} + \frac{1}{q}\frac{\partial j_n}{\partial x} \quad \rho = q(p - n + N_D - N_A) \quad L = \sqrt{D\tau}$$

$$p = N_V e^{-\frac{E_F - E_V}{kT}} = n_i e^{\frac{E_{Fi} - E_F}{qU_T}} = n_i e^{\frac{V_F - V_{Fi}}{U_T}} \quad J_p = q\mu_p pE - qD_p \frac{dp}{dx} \quad \frac{\partial p}{\partial t} = -\frac{p - p_0}{\tau_p} - \frac{1}{q}\frac{\partial j_p}{\partial x} \quad -\frac{d^2V}{dx^2} = \frac{dE}{dx} = \frac{\rho}{\varepsilon} \quad \frac{D}{\mu} = \frac{kT}{q} = U_T$$

***pn* diode:**

$$I = AJ = Aq\left(\frac{D_p p_{n0}}{L_p} + \frac{D_n n_{p0}}{L_n}\right)\left(e^{\frac{U}{U_T}} - 1\right) = Aqn_i^2\left(\frac{D_p}{L_p N_D} + \frac{D_n}{L_n N_A}\right)\left(e^{\frac{U}{U_T}} - 1\right) = I_S\left(e^{\frac{U}{U_T}} - 1\right)$$

$$U_D = V_{Fin} - V_{Fip} = U_T \ln\frac{p_{p0}}{p_{n0}} = U_T \ln\frac{n_{n0}}{n_{p0}} = U_{Fp} + U_{Fn} = U_T \ln\frac{p_{p0} n_{n0}}{n_i^2} \cong$$

$$\cong U_T \ln\frac{N_A N_D}{n_i^2} = U_p + U_n = \frac{q}{2\varepsilon}\left(N_A x_p^2 + N_D x_n^2\right)$$

$$x_n = \sqrt{\frac{2\varepsilon}{q}\frac{N_A}{N_D}\frac{(U_D + U_R)}{(N_A + N_D)}} \qquad x_p = \sqrt{\frac{2\varepsilon}{q}\frac{N_D}{N_A}\frac{(U_D + U_R)}{(N_A + N_D)}}$$

$$D = x_p + x_n = \sqrt{\frac{2\varepsilon}{q}\left(\frac{1}{N_A} + \frac{1}{N_D}\right)(U_D + U_R)}$$

Small-signal model of a *pn* diode:

$$C_T = \frac{\varepsilon A}{D}$$

N_A » N_D & $u = U_F$:

$$\underline{y} = \frac{\underline{I}}{\underline{U}} = \frac{I}{U_T}\sqrt{1 + j\omega\tau_p} = g + jb$$

$$g\big|_{NF} = \frac{I}{U_T} \qquad C_d\big|_{NF} = \frac{g\big|_{NF}\,\tau_p}{2}$$

$$g\big|_{VF} = g\big|_{NF}\sqrt{\frac{\omega\tau_p}{2}} \qquad C_d\big|_{VF} = \frac{g\big|_{VF}}{\omega}$$

Ebers-Moll model of a bipolar transistor (*pnp*):

$$I_E = I_F - \alpha_R I_R \qquad I_F = I_{ES}\left(e^{\frac{U_{EB}}{U_T}} - 1\right) \qquad I_E = I_{E0}\left(e^{\frac{U_{EB}}{U_T}} - 1\right) - \alpha_R I_C$$

$$I_C = -\alpha_F I_F + I_R \qquad I_R = I_{CS}\left(e^{\frac{U_{CB}}{U_T}} - 1\right) \qquad I_C = -\alpha_F I_E + I_{C0}\left(e^{\frac{U_{CB}}{U_T}} - 1\right)$$

$$I_{E0} = I_{ES}(1 - \alpha_F\alpha_R) \qquad I_{C0} = I_{CS}(1 - \alpha_F\alpha_R) \qquad \alpha_F I_{ES} = \alpha_R I_{CS}$$

Small-signal model of a bipolar transistor:

$$g_m = \alpha_0 g_e = \frac{I_C}{U_T} \qquad g_e = \frac{I_E}{U_T} \qquad r_{be} = \frac{\beta}{g_m}$$

$$\underline{A}_i\big|_{\underline{U}_{CB}=0} = -\frac{\underline{I}_C}{\underline{I}_E}\bigg|_{\underline{U}_{CB}=0} = \frac{\alpha_0}{1 + \frac{j\omega}{\omega_\alpha}} = \frac{\alpha_0}{1 + \frac{jf}{f_\alpha}} = \underline{\alpha}(f)$$

Junction FET (*n* channel):

$$I_{DS} = I_{DSS}\left(1 - \frac{U_{GS}}{U_P}\right)^2 \qquad U_P = U_D - \frac{qN_D D^2}{8\varepsilon} \qquad U_{DSsat} = U_{GS} - U_P$$

MOS transistor (*n* channel):

$$I_D = \frac{C_0 W\mu_n}{L}\left[(U_{GS} - U_T)U_{DS} - \frac{U_{DS}^2}{2}\right]$$

$$I_{DS} = \frac{C_0 W\mu_n}{2L}U_T^2\left(1 - \frac{U_{GS}}{U_T}\right)^2 \qquad U_{DSsat} = U_{GS} - U_T$$

Four-layer diode: $I = \dfrac{MI_{C0}}{1 - M\alpha_1 - M\alpha_2}$

Thyristor: $I = \dfrac{MI_{C0} + M\alpha_2 I_G}{1 - M\alpha_1 - M\alpha_2}$

Photodiode: $I = -I_S\left(e^{-\frac{U}{nU_T}} - 1\right) + I_L$

Fototransistor: $-I_C = -I_B\dfrac{\alpha_F}{1 - \alpha_F} + \dfrac{I_{C0} + I_L}{1 - \alpha_F}$

Table of physical constants

Boltzmann constant	$k = 1.38\times10^{-23}$ J/K
Absolute electron charge	$q = 1.6\times10^{-19}$ As
Planck constant	$h = 6.625\times10^{-34}$ Ws^2
Electron mass	$m = 9.11\times10^{-31}$ kg
Thermal voltage	$U_T = kT/q = 25.66$ mV (T = 297.8 K = 24.8 °C)
Intrinsic concentration in Si	$n_i = 10^{10}$ cm^{-3} (T = 297.8 K = 24.8 °C)
Dielectric constant	$\varepsilon_0 = 8.854\times10^{-12}$ As/(Vm) = 8.854×10^{-14} As/(Vcm)
Relative dielectric constant for Si	ε_r(Si) = 11.7 $\varepsilon_0\,\varepsilon_{rSi} = 10^{-12}$ As/(Vcm)
Relative dielectric constant for SiO_2	$\varepsilon_r(SiO_2) = 3.85$