



## POLUVODIČI

$n_i = (N_c \cdot N_v)^{1/2} \cdot \exp\left(-\frac{E_G}{2E_T}\right)$  [cm<sup>-3</sup>]. Za Si na T=300 K izmjereno je  $n_i = 10^{10}$  cm<sup>-3</sup>. Za Si:

$$N_c = 6,2 \cdot 10^{15} \cdot T^{3/2} \text{ [cm}^{-3}\text{]}; N_v = 3,5 \cdot 10^{15} \cdot T^{3/2} \text{ [cm}^{-3}\text{]}; E_G(T) = 1,17 - 4,73 \cdot 10^{-4} \cdot \frac{T^2}{T + 636} \text{ [eV]}$$

$$E_T = k \cdot T = \frac{T}{11605} \text{ [eV]}$$

**Električna provodnost:**  $\sigma = \sigma_n + \sigma_p = q \cdot n \cdot \mu_n + q \cdot p \cdot \mu_p = q \cdot (n \cdot \mu_n + p \cdot \mu_p)$

### Pokretljivost nosilaca

Za Si na T=300 K:

$$\mu = \mu_{\min} + \frac{\mu_{\max} - \mu_{\min}}{1 + \left(\frac{N}{N_{\text{ref}}}\right)^\alpha}$$

	$N_{\text{ref}} \text{ [cm}^{-3}\text{]}$	$\mu_{\max} \text{ [cm}^2\text{V}^{-1}\text{s}^{-1}\text{]}$	$\mu_{\min} \text{ [cm}^2\text{V}^{-1}\text{s}^{-1}\text{]}$	$\alpha$
elektron	$1,12 \cdot 10^{17}$	1430	80	0,72
šupljina	$2,23 \cdot 10^{17}$	460	45	0,72

### Vrijeme života i poništavanje (rekombinacija) nosilaca;

Za Si na T=300K:

$$\tau_p = \frac{\tau_{p0}}{1 + \frac{N_D}{N_{0D}}}; \tau_{p0} = 3,52 \cdot 10^{-5} \text{ s}, N_{0D} = 7,1 \cdot 10^{15} \text{ cm}^{-3}$$

$$\tau_n = \frac{\tau_{n0}}{1 + \frac{N_A}{N_{0A}}}; \tau_{n0} = 1,7 \cdot 10^{-5} \text{ s}, N_{0A} = 7,1 \cdot 10^{15} \text{ cm}^{-3}$$

### PN SPOJ

$$U_k = U_T \ln\left(\frac{n_{0n} \cdot p_{0p}}{n_i^2}\right) = U_T \ln\left(\frac{N_D \cdot N_A}{n_i^2}\right); x_p = \frac{N_D}{N_A + N_D} d_B; x_n = \frac{N_A}{N_A + N_D} d_B; U_{TOT} = U_k - U;$$

$$d_B = \sqrt{\frac{2\varepsilon}{q} \frac{N_A + N_D}{N_A \cdot N_D} \cdot U_{TOT}}$$

$$E_{\max} = -\frac{2 \cdot U_{TOT}}{d_B}; C_T = \varepsilon \frac{S}{d_B}$$

Široka n-strana:

$$Q_p = q \cdot S \cdot (p_{n0} - p_{0n}) \cdot L_p$$

$$I_p = \frac{Q_p}{\tau_p}$$

Uska n-strana:

$$Q_p = q \cdot S \cdot (p_{n0} - p_{0n}) \cdot \frac{w_n}{2}$$

$$I_p = \frac{Q_p}{t_{pr}}$$

$$t_{pr} = \frac{(w_n)^2}{2D_p}$$

$$I_S = q \cdot n_i^2 \cdot S \cdot \left( \frac{D_n}{L_n \cdot N_A} + \frac{D_p}{L_p \cdot N_D} \right) \text{ (dioda sa širokim stranama)}$$



## BIPOLARNI TRANZISTOR

### pnp tranzistor

$$\gamma = \left[ 1 + \frac{D_{nE} \cdot N_{DB} \cdot w_B}{D_{pB} \cdot N_{AE} \cdot L_{nE}} \right]^{-1}$$

$$\beta^* = \frac{1}{1 + \frac{w_B^2}{2L_{pB}^2}} \approx 1 - \frac{1}{2} \cdot \left( \frac{w_B}{L_{pB}} \right)^2$$

### Ebbers-Mollove jednadžbe

$$I_{ES} = \frac{I_{EB0}}{1 - \alpha_N \cdot \alpha_I}; I_{CS} = \frac{I_{CB0}}{1 - \alpha_N \cdot \alpha_I}; \alpha_I \cdot I_{CS} = \alpha_N \cdot I_{ES}$$

### pnp:

$$I_E = I_{ES} \cdot \left[ \exp\left(\frac{U_{EB}}{U_T}\right) - 1 \right] - \alpha_I \cdot I_{CS} \cdot \left[ \exp\left(\frac{U_{CB}}{U_T}\right) - 1 \right]$$

$$I_C = -\alpha_N \cdot I_{ES} \cdot \left[ \exp\left(\frac{U_{EB}}{U_T}\right) - 1 \right] + I_{CS} \cdot \left[ \exp\left(\frac{U_{CB}}{U_T}\right) - 1 \right]$$

### npn tranzistor

$$\gamma = \left[ 1 + \frac{D_{pE} \cdot N_{AB} \cdot w_B}{D_{nB} \cdot N_{DE} \cdot L_{pE}} \right]^{-1}$$

$$\beta^* = \frac{1}{1 + \frac{w_B^2}{2L_{nB}^2}} \approx 1 - \frac{1}{2} \cdot \left( \frac{w_B}{L_{nB}} \right)^2$$

### npn:

$$I_E = -I_{ES} \cdot \left[ \exp\left(\frac{U_{BE}}{U_T}\right) - 1 \right] + \alpha_I \cdot I_{CS} \cdot \left[ \exp\left(\frac{U_{BC}}{U_T}\right) - 1 \right]$$

$$I_C = \alpha_N \cdot I_{ES} \cdot \left[ \exp\left(\frac{U_{BE}}{U_T}\right) - 1 \right] - I_{CS} \cdot \left[ \exp\left(\frac{U_{BC}}{U_T}\right) - 1 \right]$$

## UNIPOLARNI TRANZISTOR - JFET

### n-kanalni

$$U_{GS0} = U_k - \frac{a^2 \cdot q \cdot N_D}{2 \cdot \epsilon}, b = a \cdot \left( 1 - \sqrt{\frac{U_k - U_{GS}}{U_k - U_{GS0}}} \right), G_0 = \frac{2a \cdot w \cdot q \cdot N_D \cdot \mu_n}{L}, \mu = \frac{\partial U_{DS}}{\partial U_{GS}} = r_d \cdot g_m$$

### Triodno područje:

$$I_D = G_0 \cdot \left[ U_{DS} - \frac{2}{3} \cdot \frac{(U_k - U_{GS} + U_{DS})^{\frac{3}{2}} - (U_k - U_{GS})^{\frac{3}{2}}}{\sqrt{U_k - U_{GS0}}} \right]$$

$$g_m = G_0 \cdot \frac{\sqrt{U_k - U_{GS} + U_{DS}} - \sqrt{U_k - U_{GS}}}{\sqrt{U_k - U_{GS0}}}$$

$$g_d = G_0 \cdot \left[ 1 - \sqrt{\frac{U_k - U_{GS} + U_{DS}}{U_k - U_{GS0}}} \right]$$

### Područje zasićenja:

$$I_{Dzas} = G_0 \cdot \left[ U_{GS} - U_{GS0} - \frac{2}{3} \cdot \frac{(U_k - U_{GS0})^{\frac{3}{2}} - (U_k - U_{GS})^{\frac{3}{2}}}{\sqrt{U_k - U_{GS0}}} \right]$$

$$I_{Dzas} = I_{DSS} \cdot \left( 1 - \frac{U_{GS}}{U_{GS0}} \right)^2$$

$$g_m = G_0 \cdot \left( 1 - \sqrt{\frac{U_k - U_{GS}}{U_k - U_{GS0}}} \right)$$

$$g_d = \lambda \cdot I_{Dzas}$$

## MOSFET

### n-kanalni

$$K = \frac{\mu_{nk} \cdot \epsilon_0 \cdot \epsilon_{ox} \cdot w}{t_{ox} \cdot L}$$

### Triodno područje:

$$I_D = K \cdot \left[ (U_{GS} - U_{GS0}) \cdot U_{DS} - \frac{1}{2} \cdot U_{DS}^2 \right]$$

$$g_m = K \cdot U_{DS}$$

$$g_d = K \cdot (U_{GS} - U_{GS0} - U_{DS})$$

$$\mu = g_m \cdot r_d$$

### Područje zasićenja:

$$I_{Dzas} = \frac{K}{2} \cdot (U_{GS} - U_{GS0})^2$$

$$g_m = K \cdot (U_{GS} - U_{GS0})$$

$$\frac{1}{r_d} = g_d = I_{Dzas} \cdot \lambda$$

$$\mu = g_m \cdot r_d$$

Kod p-kanalnog unipolarnog tranzistora naponi su suprotnog polariteta, a struja odvoda teče u suprotnom smjeru.