SVEUČILIŠTE U SPLITU

FAKULTET ELEKTROTEHNIKE, STROJARSTVA I BRODOGRADNJE

ELEKTRONIČKI ELEMENTI I SKLOPOVI

Predavanje 6

BIPOLARNI TRANZISTOR – Ebers-Mollov model

UNIPOLARNI TRANZISTOR

Ebers-Mollove jednadžbe i model tranzistora

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

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

$$a_{11} = S\cdot q\cdot\left(\frac{D_{nB}\cdot n_{0B}}{w_B}+\frac{D_{pE}\cdot p_{0E}}{L_{pE}}\right)$$

$$a_{22} = S\cdot q\cdot\left(\frac{D_{nB}\cdot n_{0B}}{w_B}+\frac{D_{pC}\cdot p_{0C}}{L_{pC}}\right)$$

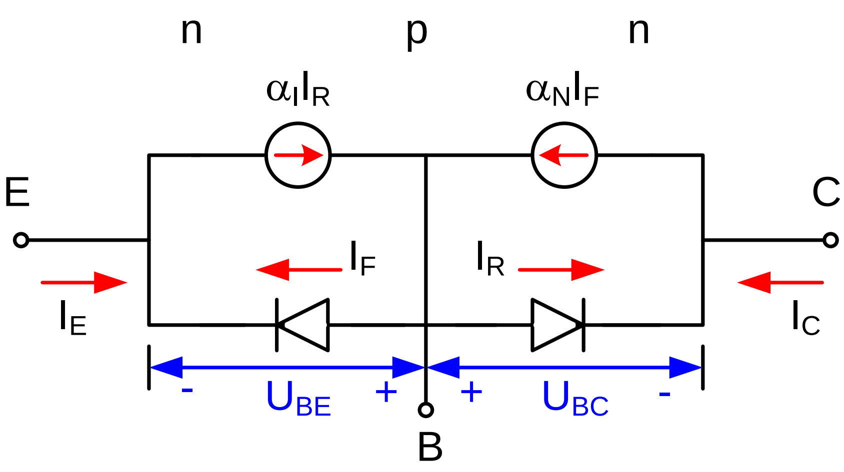
$$a_{12} = a_{21} = -S\cdot q\cdot D_{nB}\cdot\frac{n_{0B}}{w_B}$$

(svojstvo recipročnosti!)

a_{11} jest struja I_E=I_{ES} pri U_{BC}=0 i U_{BE}<0

a_{22} jest struja I_C=I_{CS} pri U_{BE}=0 i U_{BC}<0

Injekcijski Ebers-Mollov model



$$I_E - \alpha_I I_R + I_F = 0 \quad (1)$$

$$I_C - \alpha_N I_F + I_R = 0 \quad (2)$$

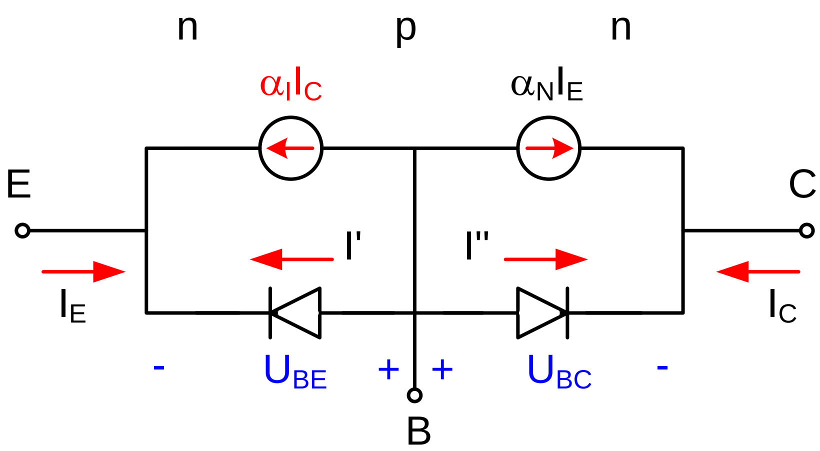
$$I_F = I_{ES}\left[\exp\left(\frac{U_{BE}}{U_T}\right) - 1\right] \quad (3)$$

$$I_R = I_{CS}\left[\exp\left(\frac{U_{BC}}{U_T}\right) - 1\right] \quad (4)$$

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

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

Ebers-Mollov model npn tranzistora



$$I_E + \alpha_I I_C + I' = 0$$

$$I_C + \alpha_N I_E + I'' = 0$$

$$I' = I_{EB0}\left[\exp\left(\frac{U_{BE}}{U_T}\right) - 1\right]$$

$$I'' = I_{CB0}\left[\exp\left(\frac{U_{BC}}{U_T}\right) - 1\right]$$

$$I_E = -\frac{I_{EB0}}{1-\alpha_I\alpha_N}\left[\exp\left(\frac{U_{BE}}{U_T}\right) - 1\right] + \frac{\alpha_I I_{CB0}}{1-\alpha_I\alpha_N}\left[\exp\left(\frac{U_{BC}}{U_T}\right) - 1\right]$$

$$I_C = \frac{\alpha_N I_{EB0}}{1-\alpha_I\alpha_N}\left[\exp\left(\frac{U_{BE}}{U_T}\right) - 1\right] - \frac{I_{CB0}}{1-\alpha_I\alpha_N}\left[\exp\left(\frac{U_{BC}}{U_T}\right) - 1\right]$$

$$I_C = \alpha_N I_E + I_{CB0}$$

$$I_E = \alpha_I I_C + I_{EB0}$$

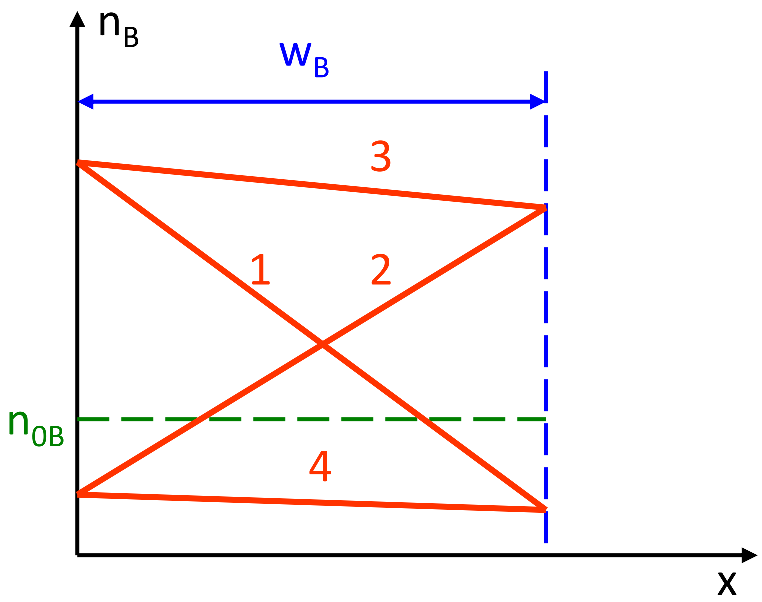
$$I_{CB0} = I_C \quad (uz\; I_E = 0)$$

$$I_{EB0} = I_E \quad (uz\; I_C = 0)$$

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

Područja rada tranzistora

- Raspodjela manjinskih nosilaca u bazi npn tranzistora u različitim područjima rada:



1 – normalno aktivno područje

2 – inverzno aktivno područje

3 – područje zasićenja

4 – zaporno područje

Normalno aktivno područje

$U_{BE} >> U_T$, $U_{BC} < 0$

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

$$I_C = \alpha_N I_{ES}\left[\exp\left(\frac{U_{BE}}{U_T}\right)-1\right]+I_{CS} \qquad (2)$$

Iz (1) i (2) slijedi funkcija $I_C = f(I_E)$:

$$I_C = -\alpha_N I_E + \underbrace{I_{CS}\left(1-\alpha_N \alpha_I\right)}_{I_{CB0}}$$

$$I_C = -\alpha_N I_E + I_{CB0}$$

Inverzno aktivno područje

U_{BE}<0, U_{BC}>> U_T

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

$$I_C = \alpha_N I_{ES} - I_{CS}\left[\exp\left(\frac{U_{BC}}{U_T}\right)-1\right] \qquad (2)$$

Iz (1) i (2) slijedi funkcija $I_E=f(I_C)$:

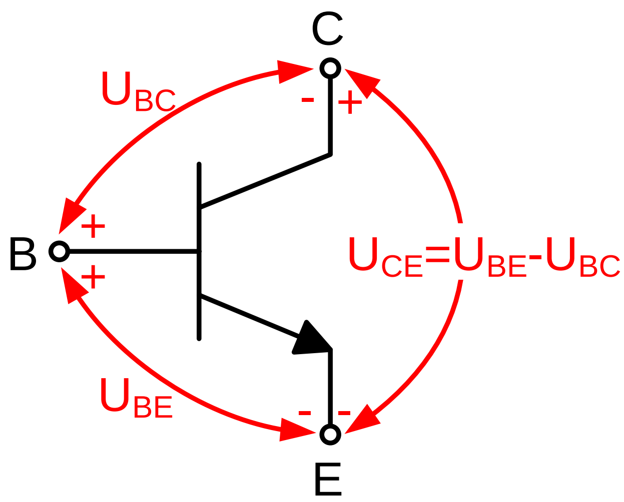
$$I_E = -\alpha_I I_C + I_{EB0}$$

Područje zasićenja

$U_{BE}>0$, $U_{BC}>0$

$$U_{BC} = U_T \cdot \ln \frac{I_C + \alpha_N I_E - I_{CB0}}{-I_{CB0}}$$

$$U_{BE} = U_T \cdot \ln \frac{I_E + \alpha_I I_C - I_{EB0}}{-I_{EB0}}$$



$$U_{CE} = U_T \cdot \ln \frac{\left(I_E + \alpha_I I_C - I_{EB0}\right) \cdot \alpha_N}{\left(I_C + \alpha_N I_E - I_{CB0}\right) \cdot \alpha_I}$$

Zaporno područje

U_{BE}<0, U_{BC}<0

$$I_E = \frac{I_{EB0}}{1-\alpha_N\alpha_I}\left(1-\alpha_N\right)$$

$$I_C = \frac{I_{CB0}}{1-\alpha_N\alpha_I}\left(1-\alpha_I\right)$$

Unatoč nepropusnoj polarizaciji kroz oba spojišta teku male struje emitera i kolektora.

Stoga se zaporno područje definira uvjetom: I_E=0; U_{BC}<0 te je I_C=I_{CB0}

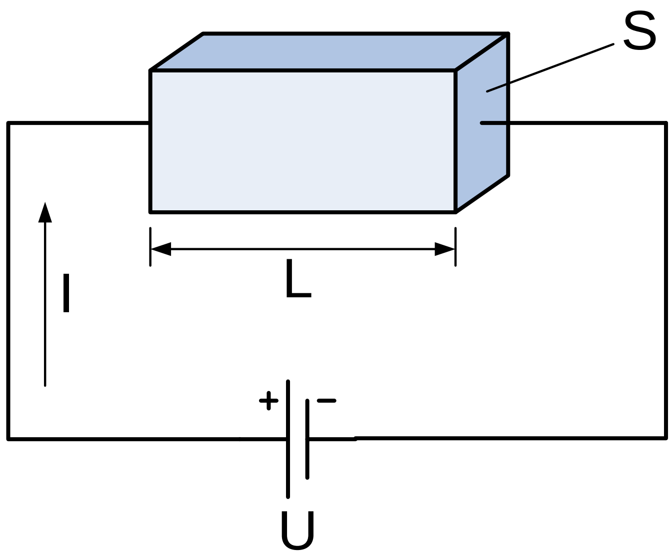
Uz ove uvjete iz Ebers-Mollovih jednadžbi dobiva se odgovarajući napon U_{BE}:

$$U_{BE} = U_T \cdot \ln\left(1-\alpha_N\right)$$

Npr. za α=0,9 pri T=300 K

U_{BE}=-59,5 mV

UNIPOLARNI TRANZISTOR



$$R = \rho \cdot \frac{L}{S} \qquad I = \frac{U}{R}$$

$$\frac{1}{\rho} = \sigma = n \cdot q \cdot \mu$$

Field Effect Transistor **(FET)**

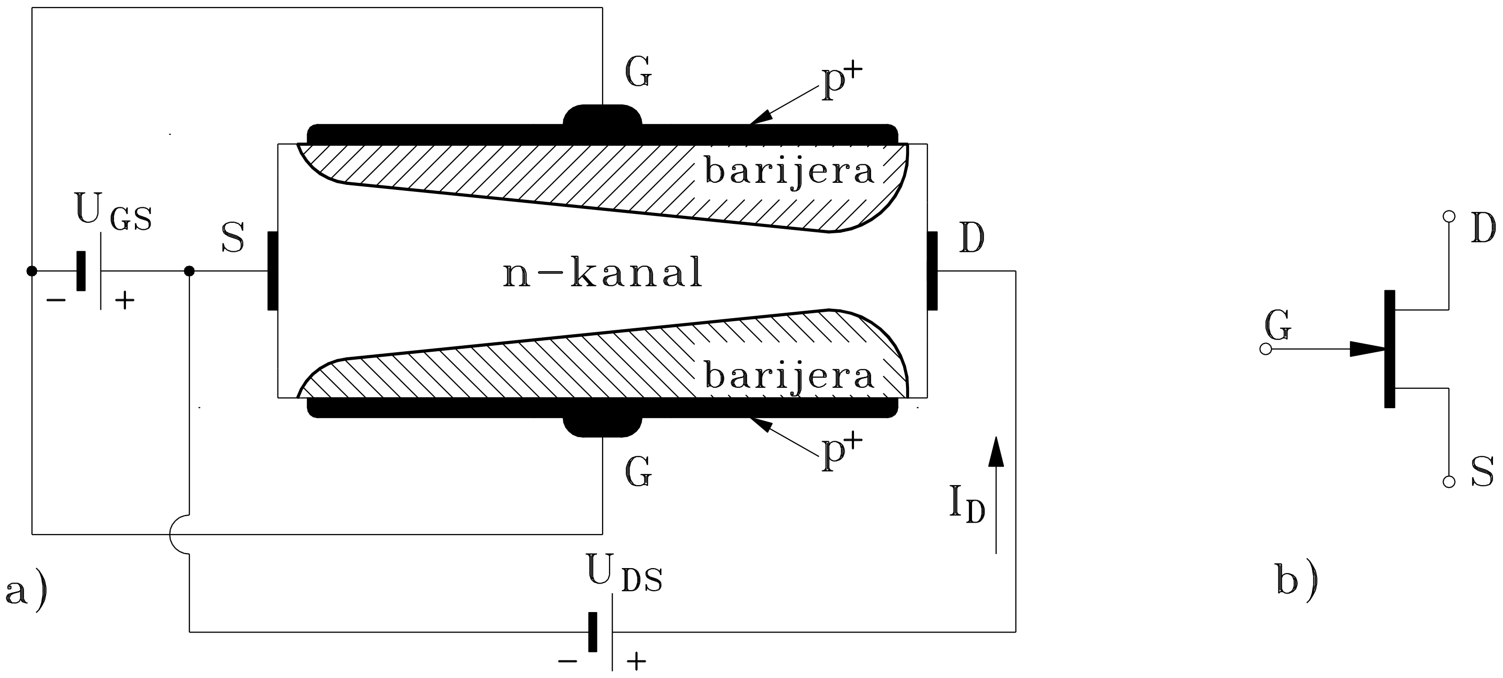
Metal Oxide Semiconductor FET **(MOSFET)**

Insulated Gate FET **(IGFET)**

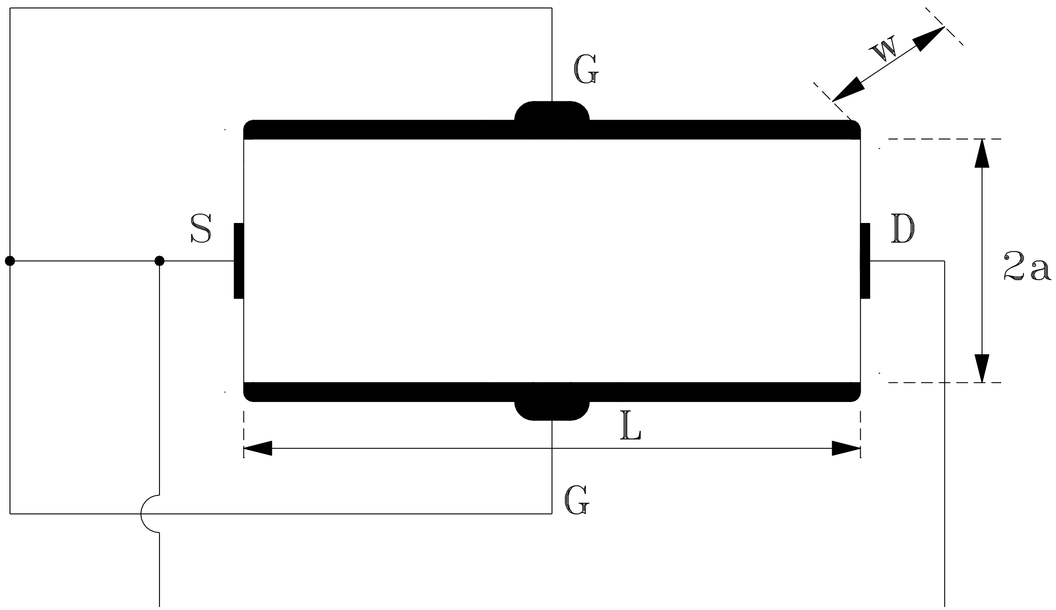
Unipolarni tranzistor (Tranzistor s efektom polja)

- U vođenju struje sudjeluju ili elektroni ili šupljine.
- Dio poluvodiča kroz koji teče struja naziva se KANAL:
  - p-kanalni
  - n-kanalni
- Protjecanjem struje kroz kanal upravlja se vanjskim naponom, tj. električnim poljem – tranzistor s efektom polja.
- Prvi unipolarni tranzistori bili su spojni unipolarni tranzistori – JFET (Junction Field Effect Transistor).

Tranzistor s efektom polja (JFET)

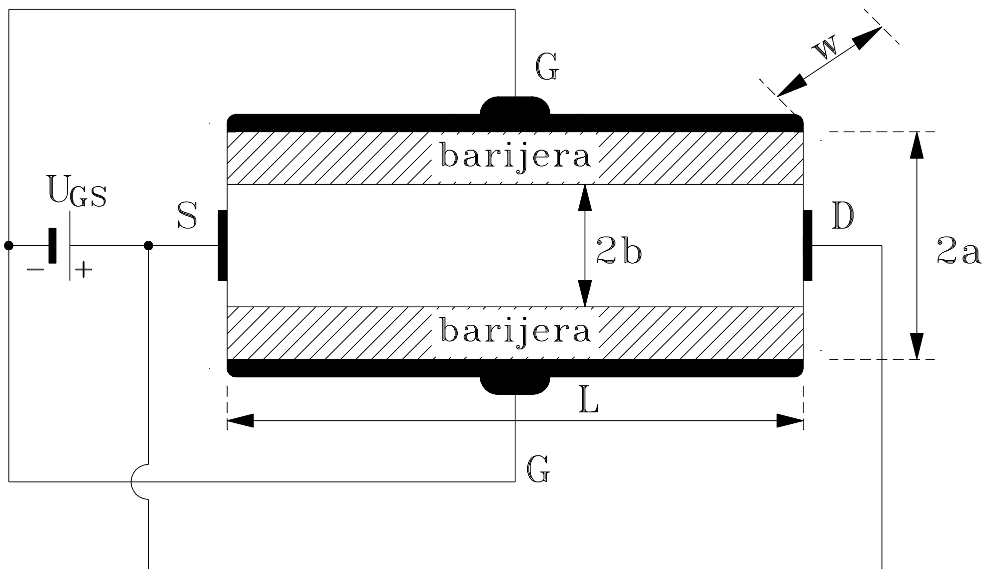


a) n-kanalni spojni FET; b) električni simbol za n-kanalni spojni FET



Širina potpuno otvorenog kanala pri U_{DS}=0 i U_{GS}=0

$$G_0 = \frac{1}{R_0} = \frac{q \cdot \mu_n \cdot N_D \cdot 2a \cdot w}{L} = \sigma \cdot \frac{2a \cdot w}{L}$$



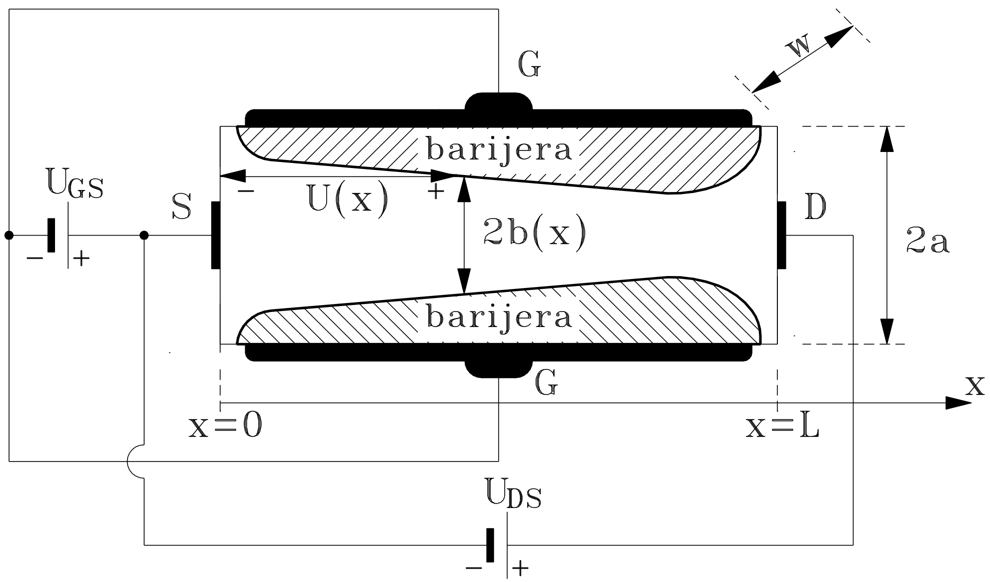
Širina kanala pri nekom naponu U_{GS} i U_{DS}=0

$$a-b=\sqrt{\frac{2\cdot\varepsilon\cdot(U_k-U_{GS})}{q\cdot N_D}}$$

$$U_{GS0}=U_k-\frac{a^2\cdot q\cdot N_D}{2\cdot\varepsilon}$$

$$a^2=\frac{2\cdot\varepsilon\cdot(U_k-U_{GS0})}{q\cdot N_D}$$

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



Širina kanala pri nekom naponu $U_{GS}\neq 0$ i $U_{DS}\neq 0$

$$b(x) = a \cdot \left(1 - \sqrt{\frac{U_k - U_{GS} + U(x)}{U_k - U_{GS0}}}\right)$$

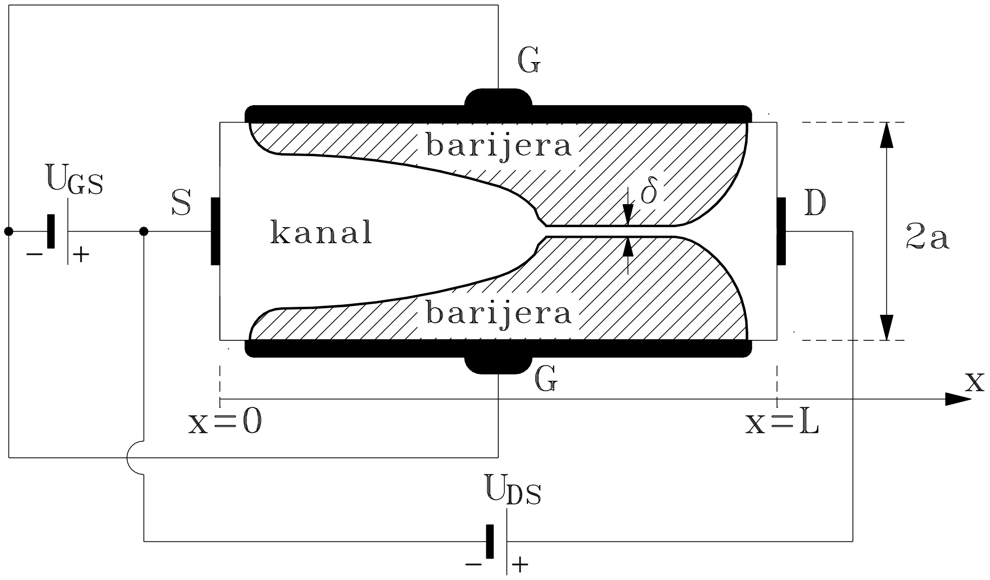
$$I_D(x) = I_D = 2b(x) \cdot w \cdot q \cdot N_D \frac{dU(x)}{dx}$$

$$I_D = 2a \cdot w \cdot q \cdot N_D \cdot \mu_n \cdot \left(1 - \sqrt{\frac{U_k - U_{GS} + U(x)}{U_k - U_{GS0}}}\right) \cdot \frac{dU(x)}{dx}$$

$$I_D \cdot dx = 2a \cdot w \cdot q \cdot N_D \cdot \mu_n \cdot \left(1 - \sqrt{\frac{U_k - U_{GS} + U(x)}{U_k - U_{GS0}}}\right) \cdot dU(x)$$

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

$$G_0 = \frac{2a \cdot w \cdot q \cdot N_D \cdot \mu_n}{L}$$



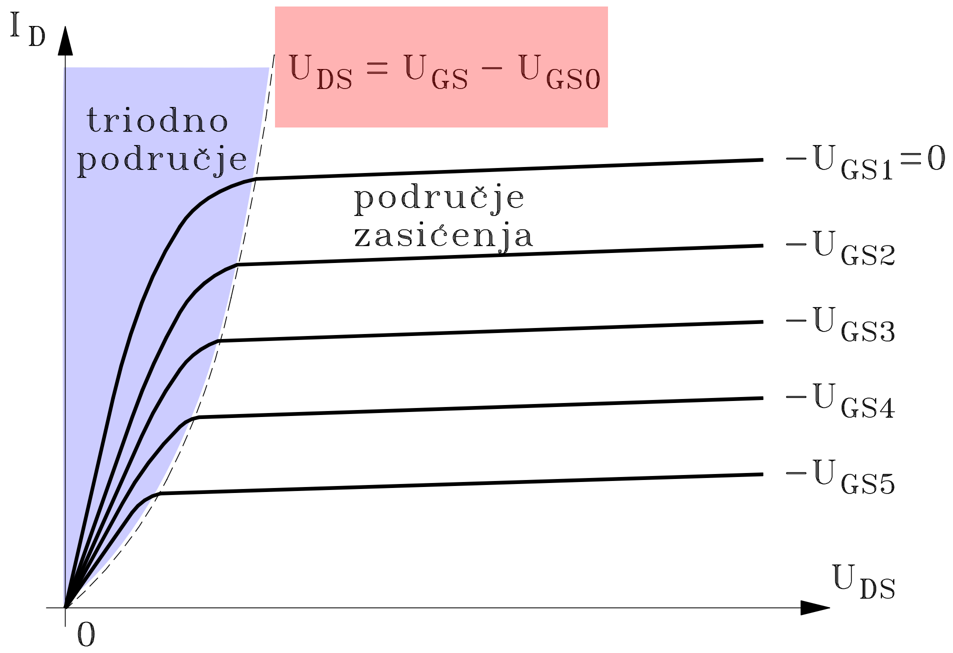
Širina kanala uz napon $U_{DS}>U_{GS}-U_{GS0}$

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

Izlazne karakteristike FET-a

- Dva područja rada:
  - Triodno područje
  - Područje zasićenja

Jednadžba krivulje koja odvaja triodno i područje zasićenja



Dinamički parametri FET-a

- Strmina g_m:

$$g_m = \left.\frac{\partial I_D}{\partial U_{GS}}\right|_{U_{DS}=konst.}$$

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

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

- Izlazna dinamička vodljivost g_d:

$$g_d = \left.\frac{\partial I_D}{\partial U_{DS}}\right|_{U_{GS}=konst.}$$

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

U području zasićenja može se upotrijebiti empirijski izraz za struju odvoda I_D: $$I_D = I_{Dzas} \cdot (1 + \lambda \cdot U_{DS})$$

pa je tada izlazna dinamička vodljivost:

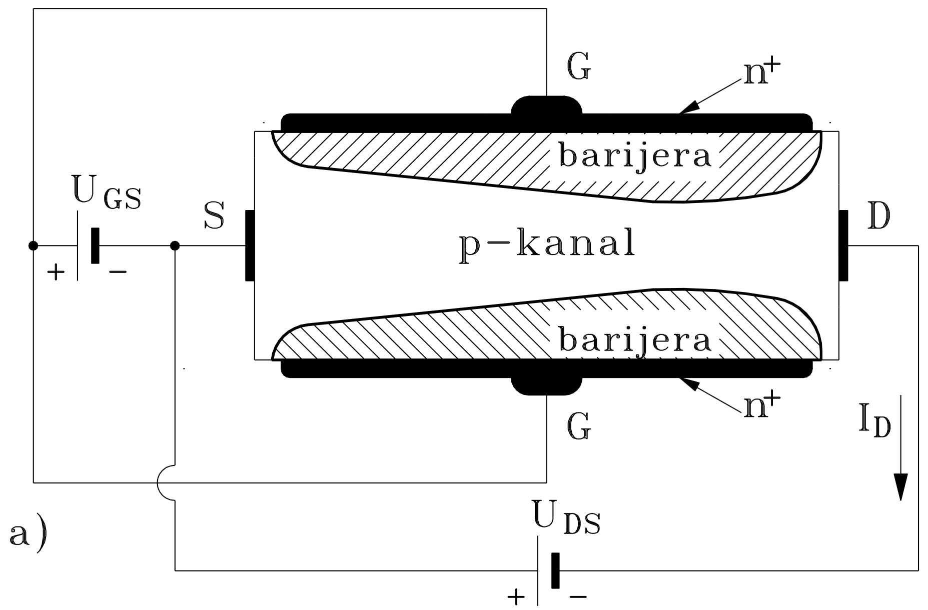
$g_{dzas} = \lambda \cdot I_{Dzas}$, gdje je λ parametar iznosa između 0,01 i 0,001 V^{-1}

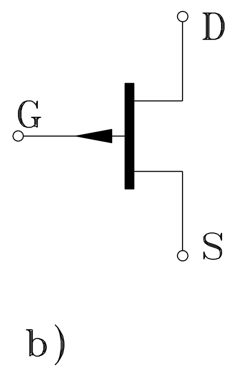
- Dinamički otpor r_d je recipročna veličina g_d.
- Faktor pojačanja μ:

$$\mu = \left.\frac{\partial U_{DS}}{\partial U_{GS}}\right| I_D = konst.$$

$$\mu = \frac{\partial U_{DS}}{\partial U_{GS}} = \frac{\partial U_{DS}}{\partial I_D} \cdot \frac{\partial I_D}{\partial U_{GS}} = \frac{g_m}{g_d} = r_d \cdot g_m$$

p-kanalni JFET





a) p-kanalni spojni FET; b) električni simbol za p-kanalni spojni FET

$$a-b=\sqrt{\frac{2\cdot\varepsilon\cdot(U_k+U_{GS})}{q\cdot N_A}}$$

$$U_{GS0}=\frac{a^2\cdot q\cdot N_A}{2\cdot\varepsilon}-U_k$$

$$b=a\cdot\left(1-\sqrt{\frac{U_k+U_{GS}}{U_k+U_{GS0}}}\right)$$

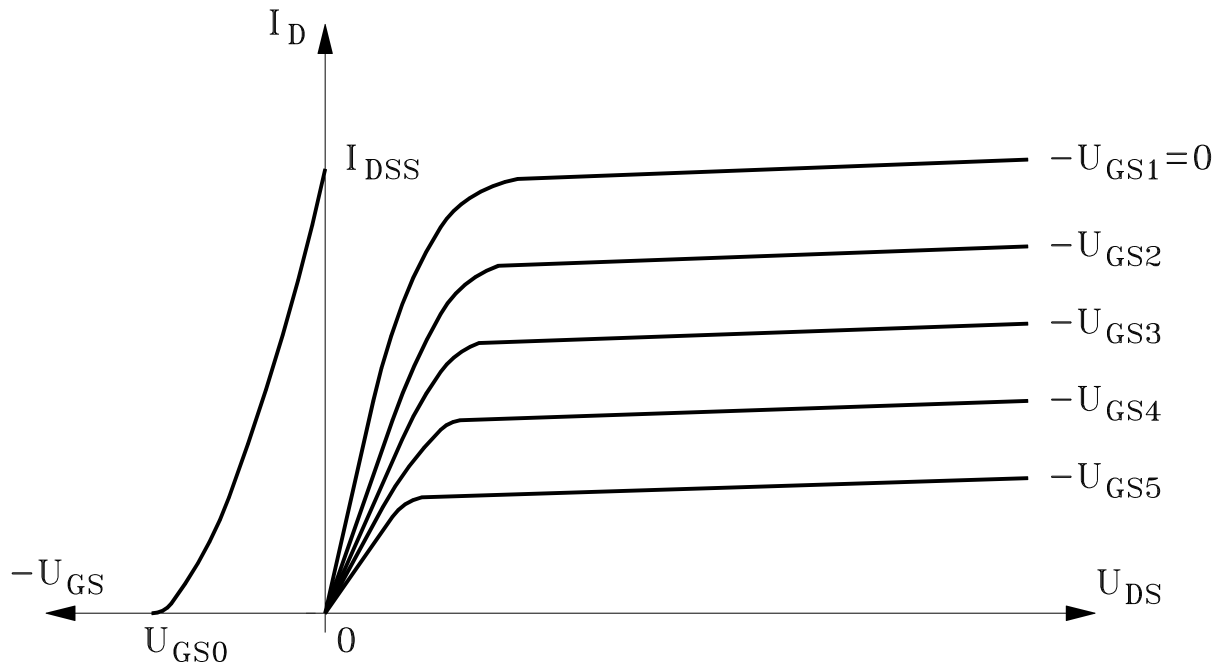
$$-I_D=G_0\cdot\left[-U_{DS}-\frac{2}{3}\cdot\frac{\left(U_k+U_{GS}-U_{DS}\right)^{\frac{3}{2}}-\left(U_k+U_{GS}\right)^{\frac{3}{2}}}{\sqrt{U_k+U_{GS0}}}\right]$$

$$\left|U_{DS}\right|=\left|U_{GS}-U_{GS0}\right|$$

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

Statičke karakteristike JFET-a

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



Statičke karakteristike n-kanalnog FET-a