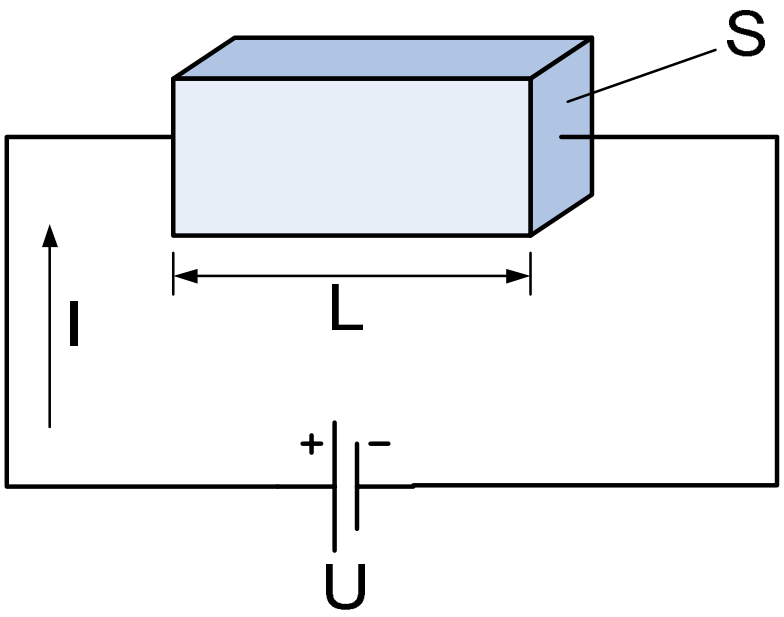
Unipolarni tranzistor

Elektronika – 5. predavanje



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

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

Field Effect Transistor **(FET)**

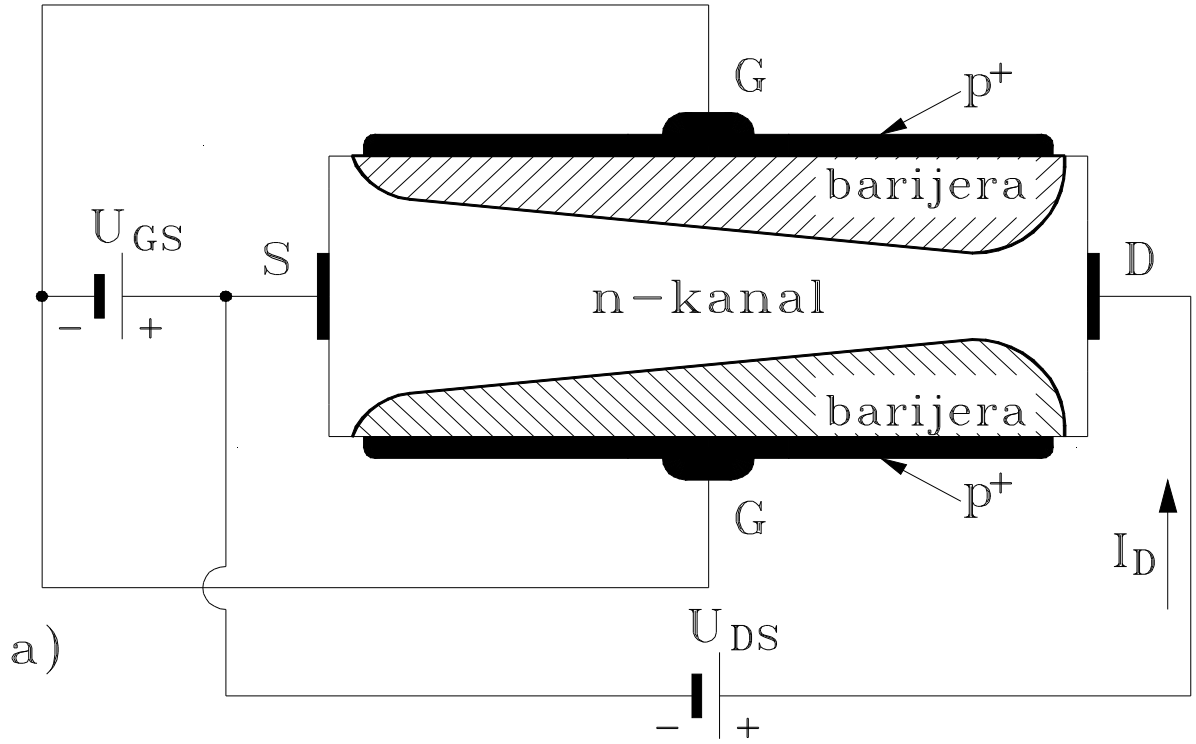
Metal Oxide Semiconductor FET **(MOSFET)**

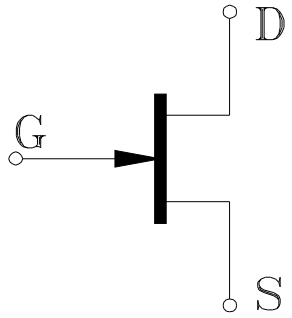
Insulated Gate FET **(IGFET)**

Unipolarni tranzistor (Tranzistor s efektom polja)

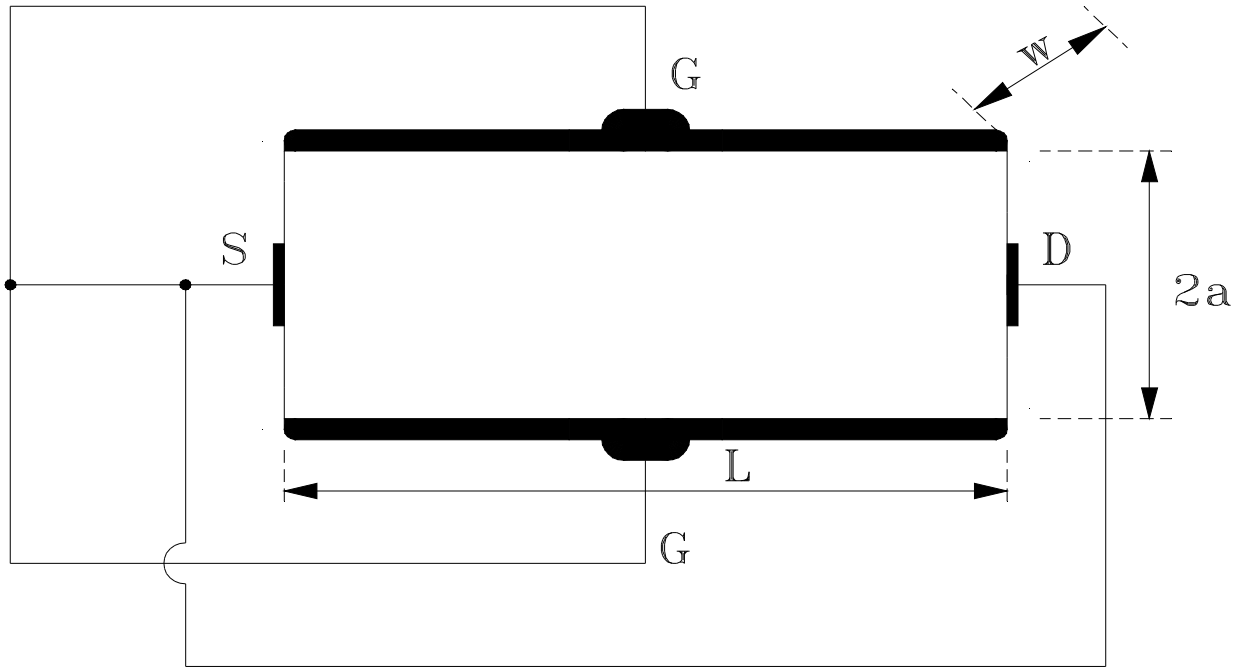
- U vođenju struje sudjeluju ili elektroni ili šupljine.
- Dio poluvodiča kroz koji teče struja naziva se KANAL:
  - p-kanalni
  - n-kanalni
- Protjecanjem struje kroz kanal upravlja se vanjskim naponom, tj. električnim poljem – tranzistor s efektom polja.
- Prvi unipolarni tranzistori bili su spojni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

Tranzistor s efektom polja (JFET)



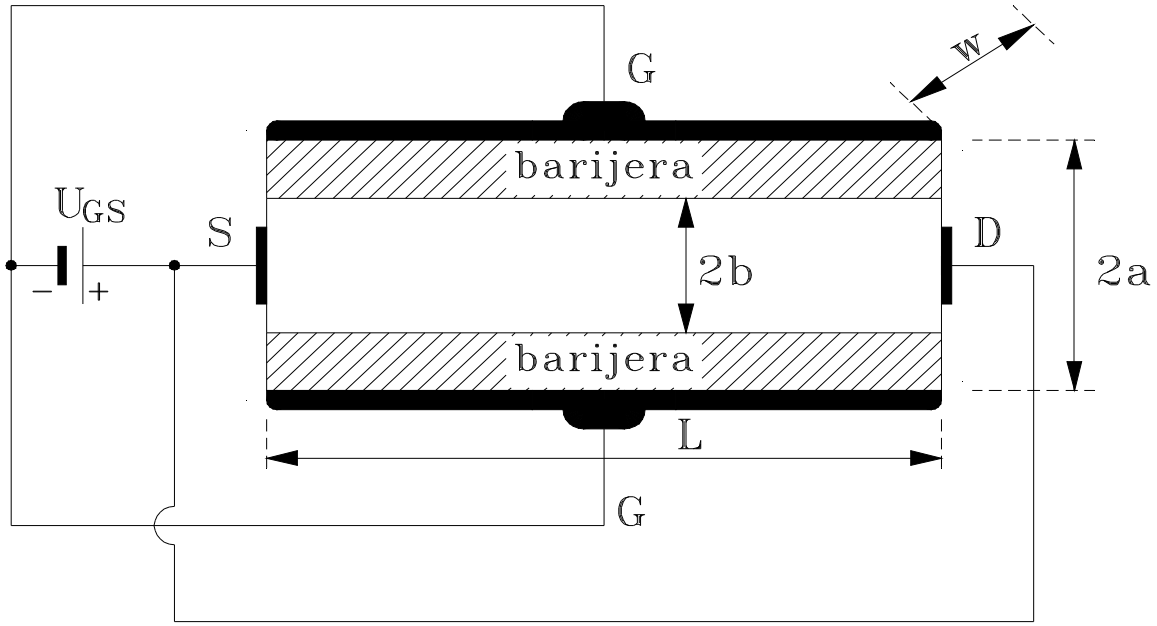


a) n-kanalni spojni FET; b) električni simbol za n-kanalni spojni FET



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

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



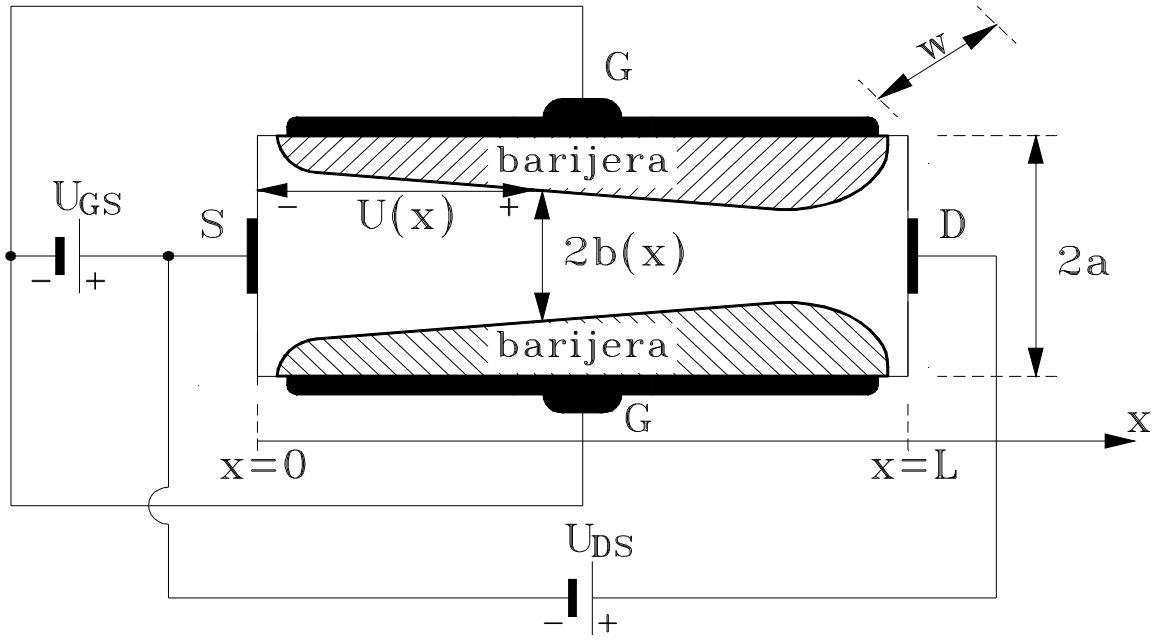
Širina kanala pri nekom naponu U_{GS} i U_{DS}=0

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

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

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

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



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

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

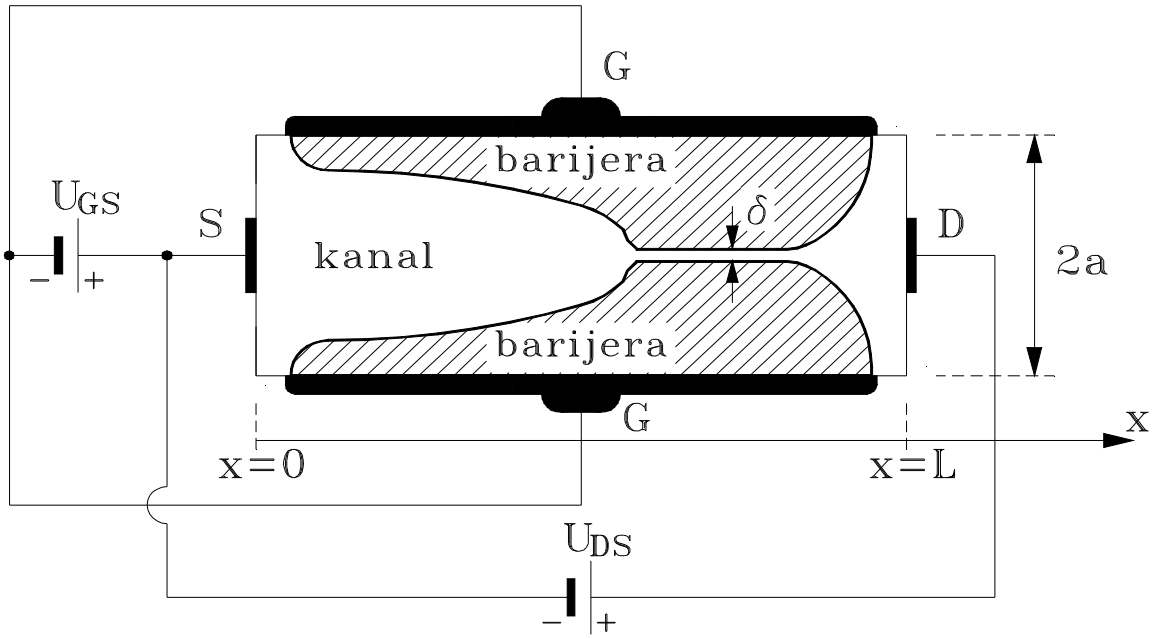
$$I_D(x) = I_D = 2b(x) \cdot w \cdot q \cdot N_D \frac{dU(x)}{dx}$$

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

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

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

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



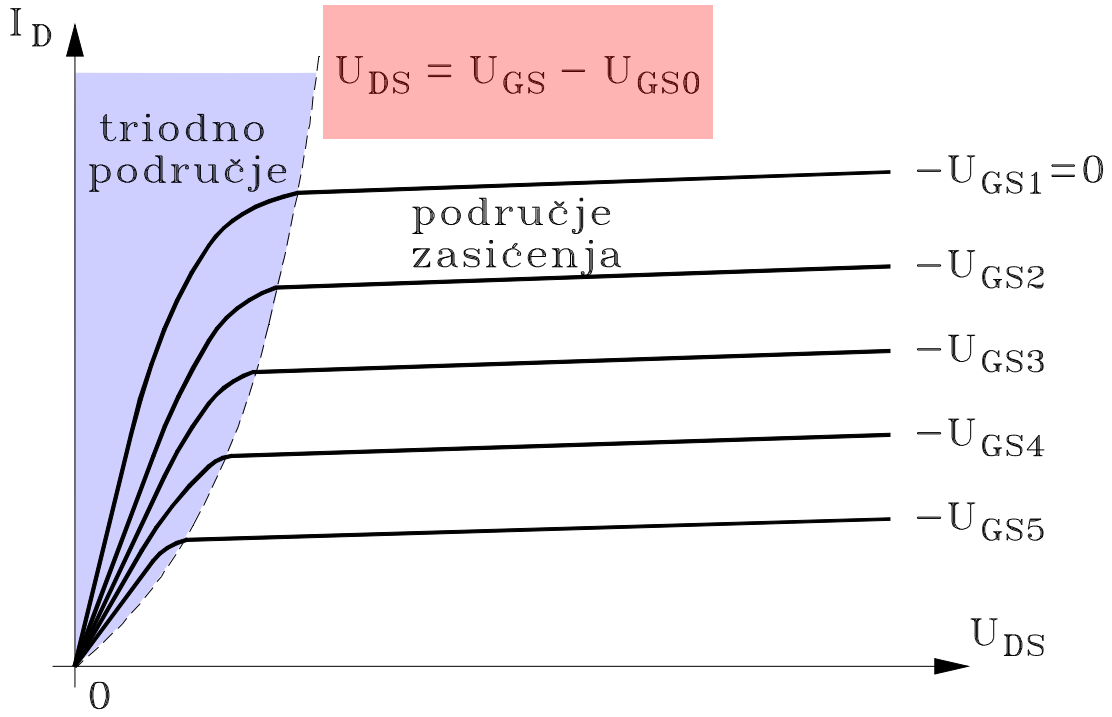
Širina kanala uz napon $U_{DS}>U_{GS}-U_{GS0}$

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

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}

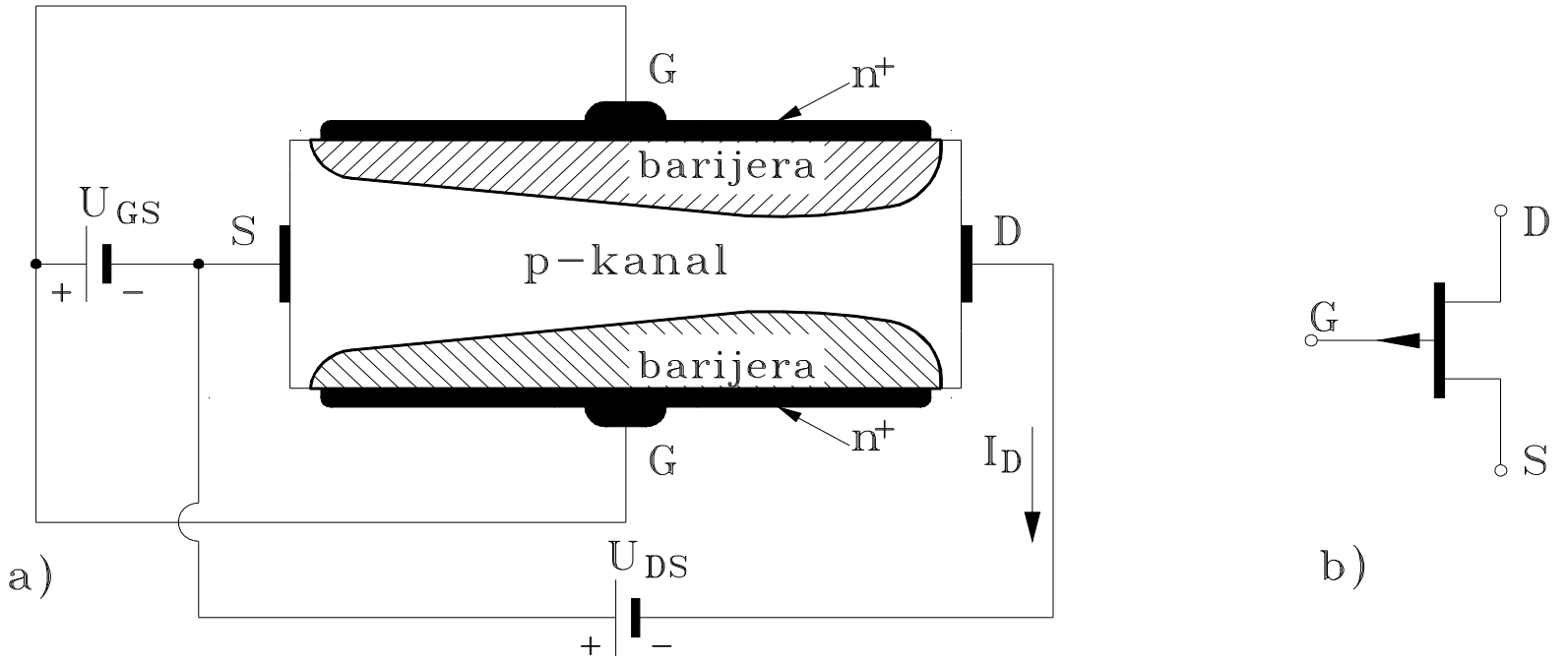
Dinamički otpor r_d je recipročna veličina g_d.

- 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 FET



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

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

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

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

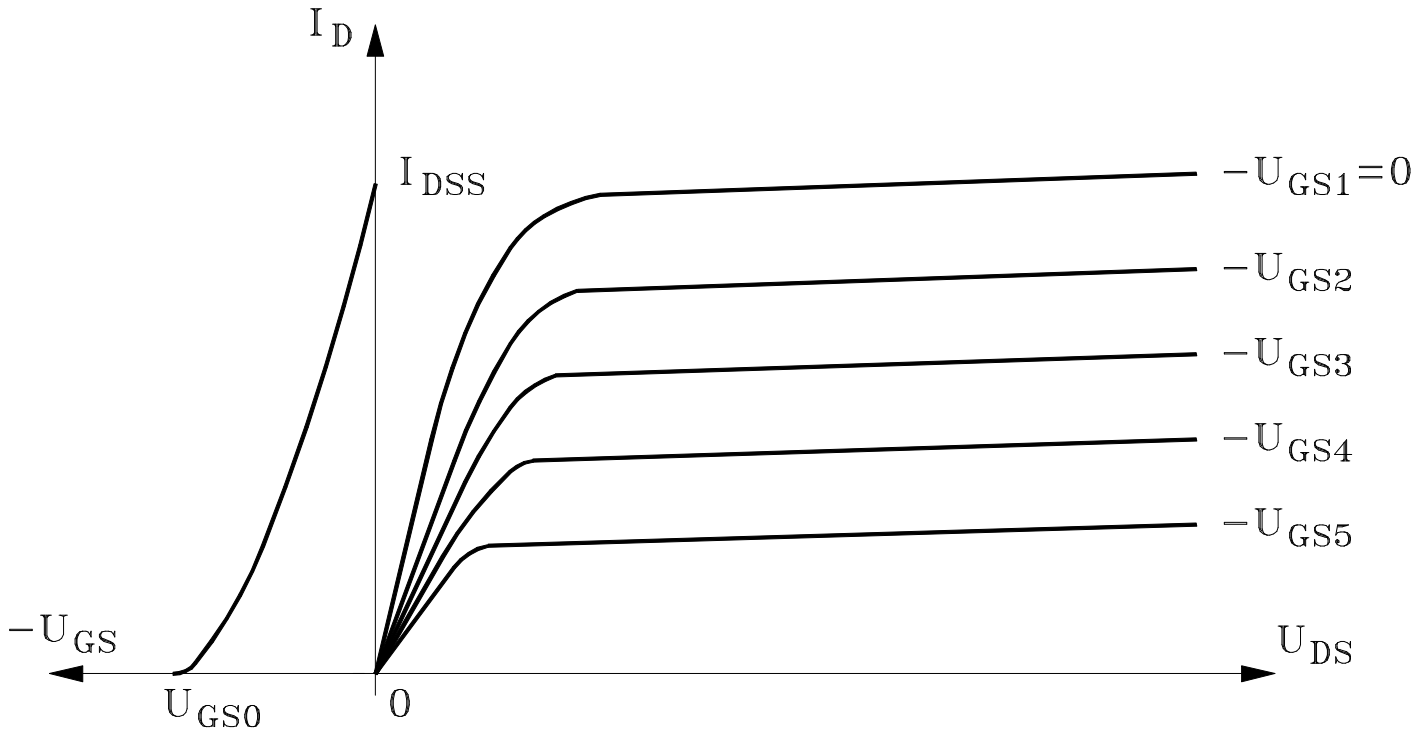
$$-I_D = G_0 \cdot \left[-U_{DS} - \frac{2}{3} \cdot \frac{(U_k + U_{GS} - U_{DS})^{\frac{3}{2}} - (U_k + U_{GS})^{\frac{3}{2}}}{\sqrt{U_k + U_{GS0}}}\right]$$

$$|U_{DS}| = |U_{GS} - U_{GS0}|$$

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

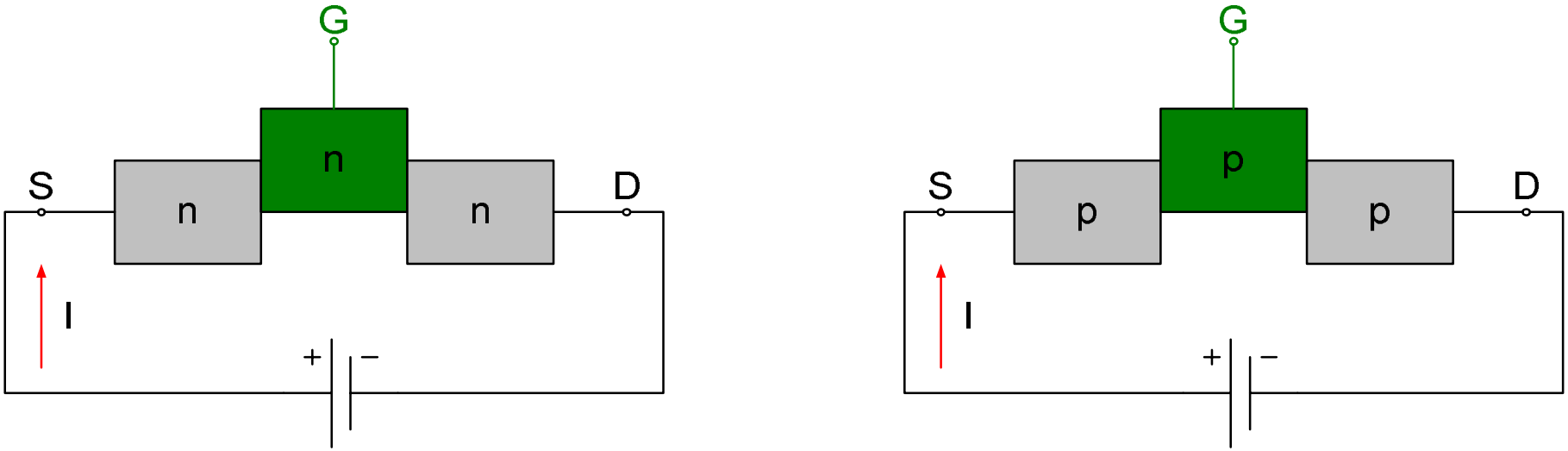
Statičke karakteristike FET-a

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



Statičke karakteristike n-kanalnog FET-a

MOSFET

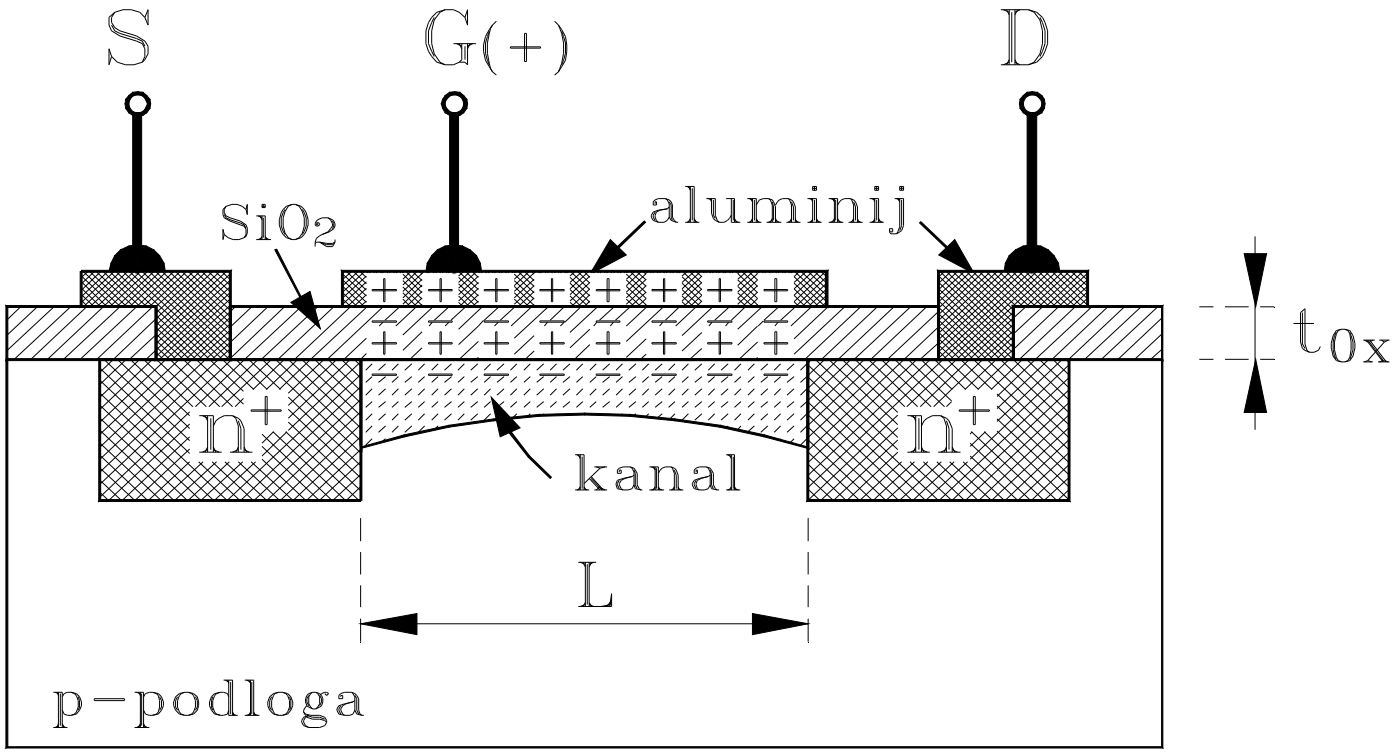


- MOSFET – Metal Oxide Semiconductor Field Effect Transistor

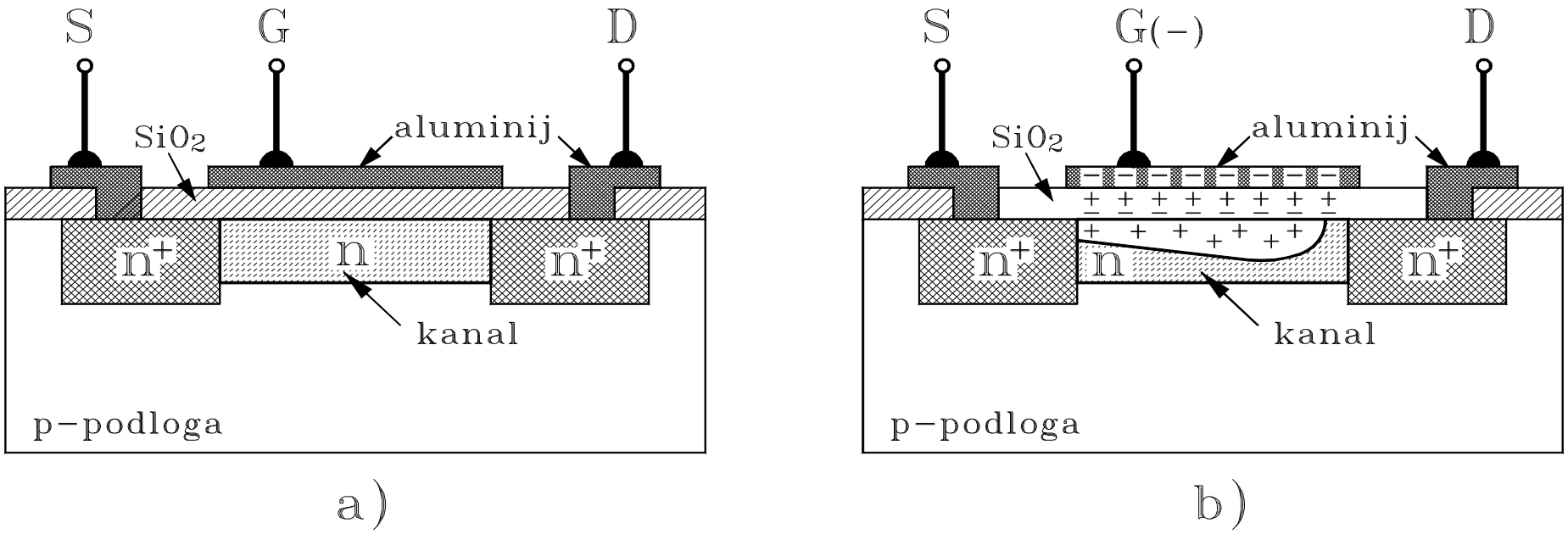
- IGFET – Insulated Gate Field Effect Transistor

- MOSFET može biti:
  - p-kanalni na n-podlozi
  - n-kanalni na p-podlozi

- Presjek n-kanalnog MOSFET-a



- I p-kanalni i n-kanalni MOSFET može biti:
  - Obogaćenog tipa
  - Osiromašenog tipa



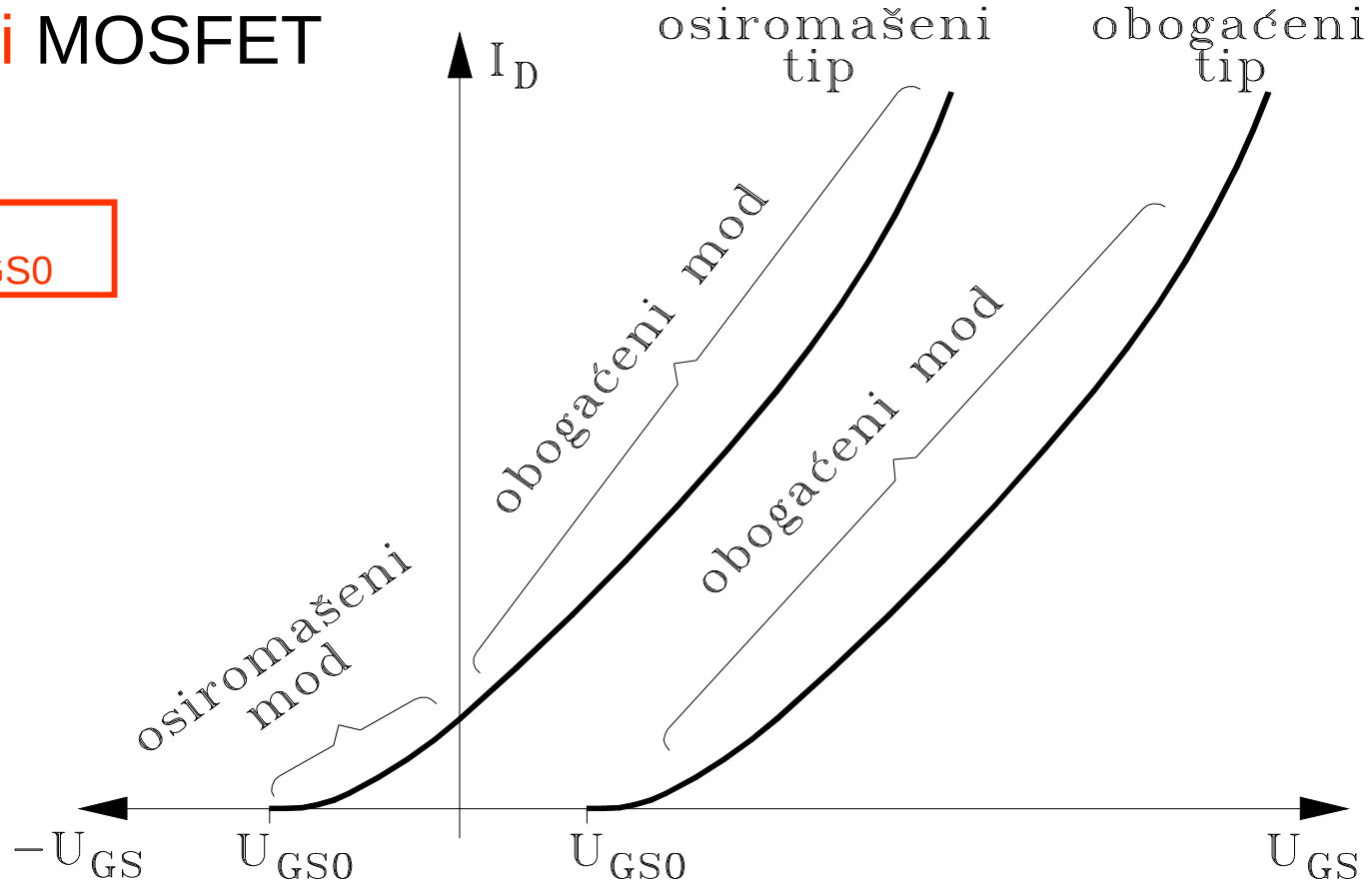
Presjek n-kanalnog MOSFET-a osiromašenog tipa:

a) uz napon $U_{GS}=0$, b) uz napon $U_{GS}<0$

Prijenosne karakteristike MOSFET-a

- n-kanalni MOSFET

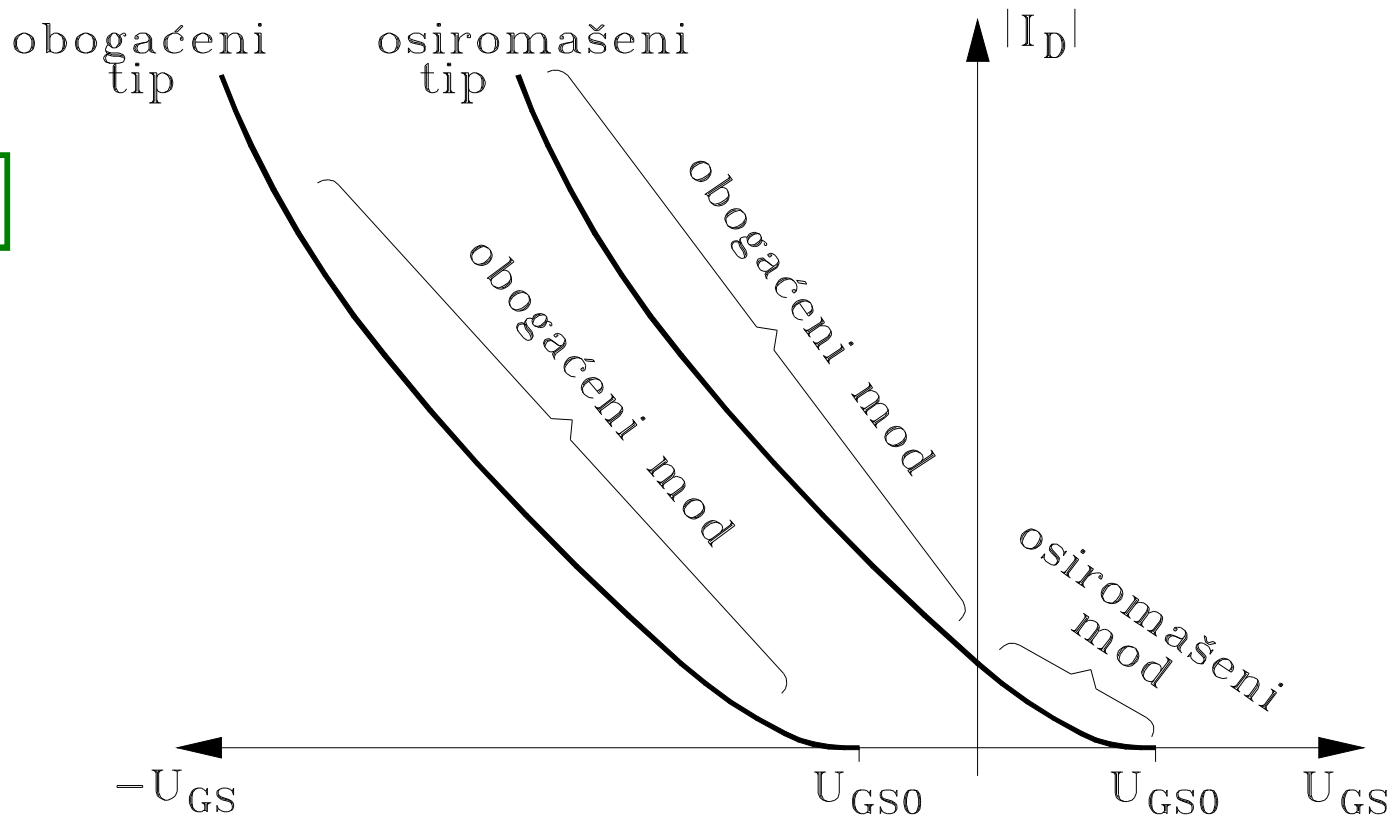
$U_{GS} \geq U_{GS0}$



Prijenosne karakteristike n-kanalnog MOSFET-a

p-kanalni MOSFET

$U_{GS} \leq U_{GS0}$

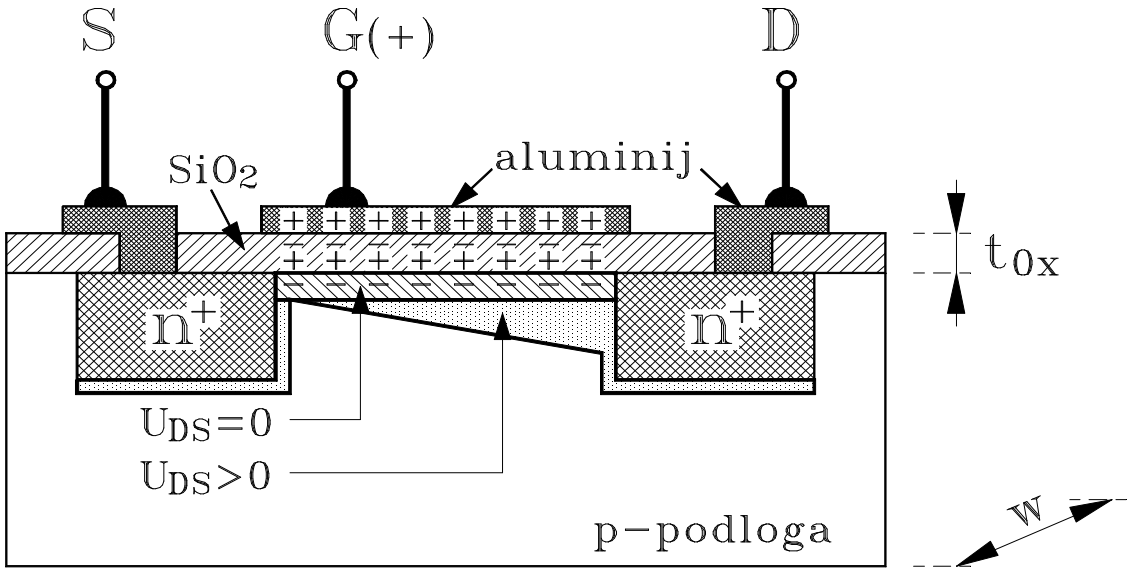


Prijenosne karakteristike p-kanalnog MOSFET-a

Izlazne karakteristike MOSFET-a

$$\sigma_m = \frac{\varepsilon_0 \cdot \varepsilon'_{0x}}{t_{0x}} \cdot (U_{GS} - U_{GS0}) \qquad \sigma_m(x) = \frac{\varepsilon_0 \cdot \varepsilon'_{0x}}{t_{0x}} \cdot (U_{GS} - U(x) - U_{GS0})$$

$$G(x) = \mu_{nk} \cdot \sigma_m(x) \cdot w$$



Geometrijsko ustrojstvo MOSFET-a

$$I_D = G(x) \cdot \frac{dU(x)}{dx}$$

$$I_D \int_0^L dx = \frac{\mu_{nk} \cdot \varepsilon_0 \cdot \varepsilon'_{0x}}{t_{0x}} \cdot w \int_0^{U_{DS}} (U_{GS} - U_{GS0} - U(x)) dU$$

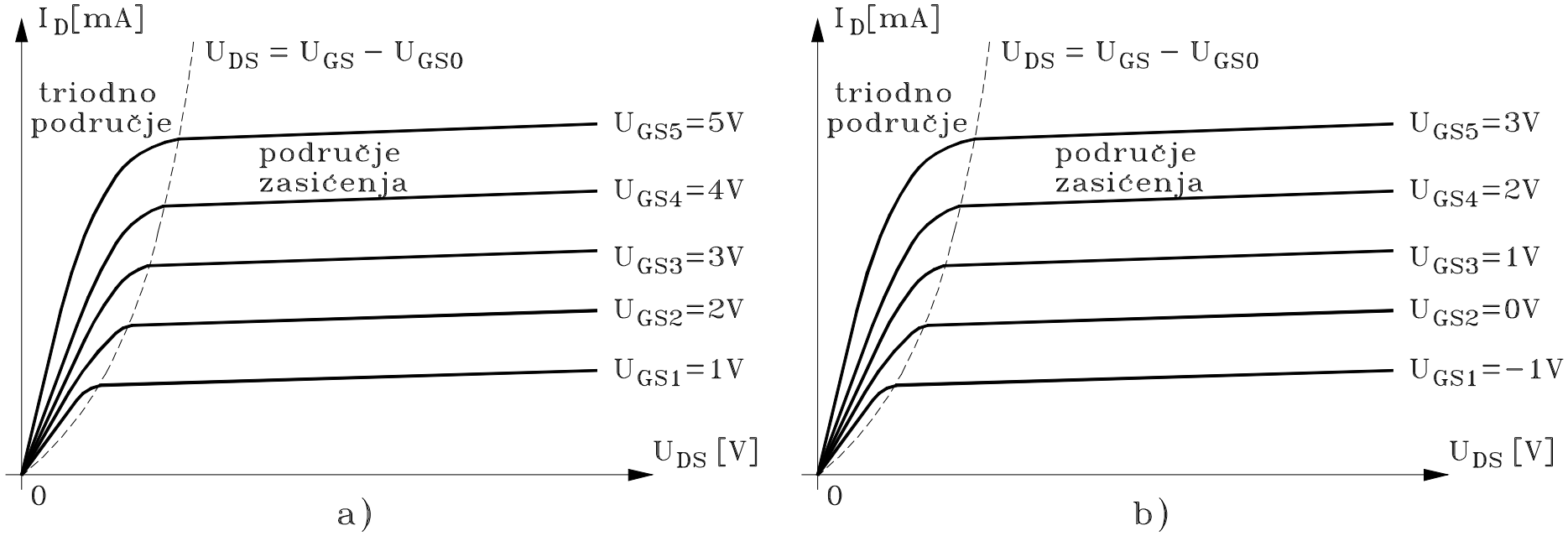
$$I_D = K\left[(U_{GS} - U_{GS0}) \cdot U_{DS} - \frac{1}{2} \cdot U_{DS}^2 \right]$$

Opisuje triodno područje

$$K = \frac{\mu_{nk} \cdot \varepsilon_0 \cdot \varepsilon'_{0x} \cdot w}{t_{0x}}$$

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

Za područje zasićenja



Izlazne karakteristike n-kanalnog MOSFET-a:

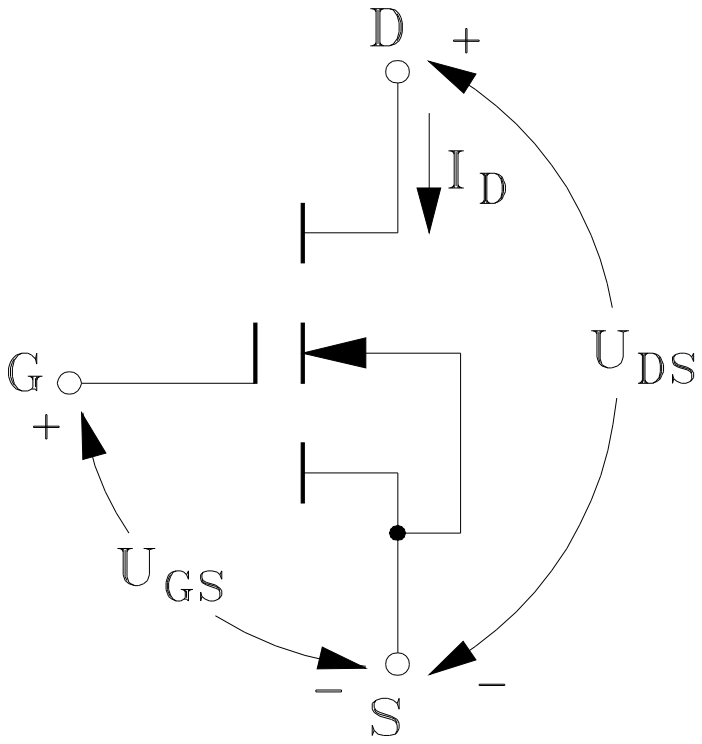
a) obogaćenog tipa, b) osiromašenog tipa

$$I_D = I_{Dzas} \cdot (1 + \lambda \cdot U_{DS})$$

($0{,}001\ V^{-1} < \lambda < 0{,}01\ V^{-1}$)

Empirijska relacija, vrijedi za područje zasićenja (izmjeren je porast struje odvoda pri povećanju iznosa napona U_{DS})

- Definicija polariteta napona i smjera struje za n-kanalni MOSFET obogaćenog tipa:

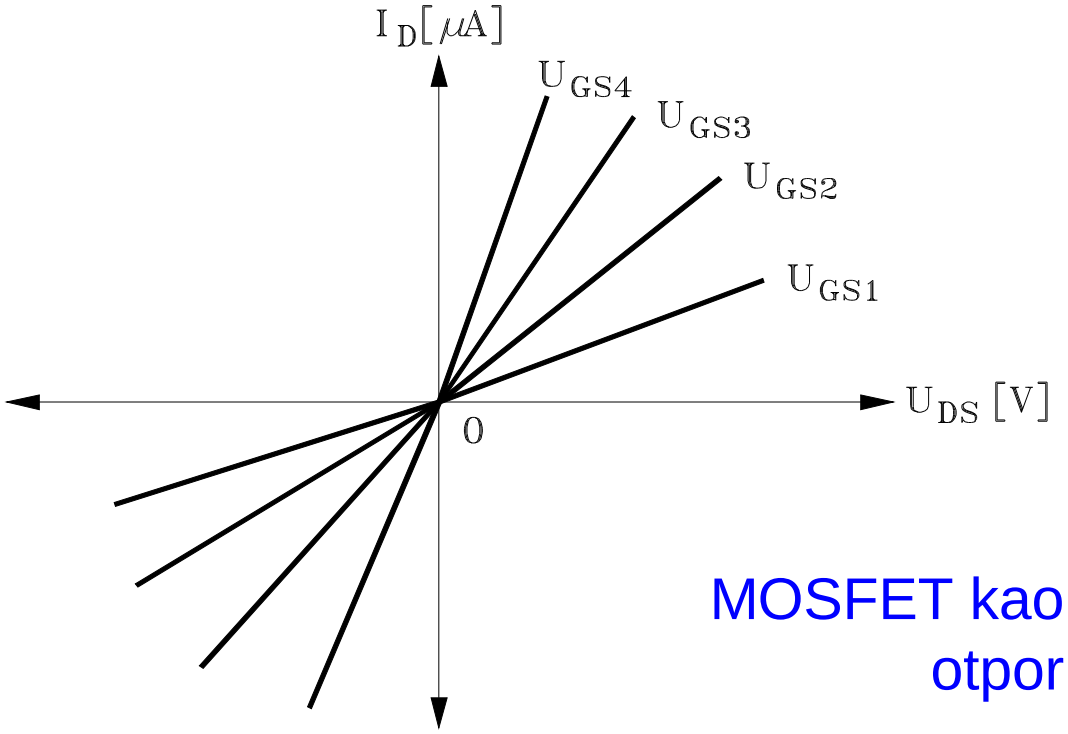


Za sve ostale tipove MOSFET-ova vrijede iste jednadžbe, ali potrebno je voditi računa o predznacima odgovarajućih električnih veličina!

Parametri MOSFET-a

- U triodnom se području MOSFET može upotrijebiti kao linearni otpornik čiji se iznos upravlja naponom U_{GS}.

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



MOSFET kao promjenjivi otpornik

- Dinamički otpor r_d:

$$r_d = \left.\frac{\partial U_{DS}}{\partial I_D}\right|_{U_{GS}=konst.} = \frac{1}{K\cdot(U_{GS}-U_{GS0}-U_{DS})}$$ Triodno područje

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

- Strmina g_m:

$$g_m = \frac{\partial I_D}{\partial U_{GS}} = K\cdot U_{DS}$$ Triodno područje

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

- Faktor pojačanja μ:

$$\mu = g_m\cdot r_d$$

Nadomjesni sklop za unipolarni tranzistor

- Za male promjene iznosa signala i srednje frekvencije.

$$i_D = f(u_{GS}, u_{DS})$$

$$di_D = \frac{\partial i_D}{\partial u_{GS}} \cdot du_{GS} + \frac{\partial i_D}{\partial u_{DS}} \cdot du_{DS}$$

$$\left\{ \begin{array}{l} i_D = I_D + i_d, \\ u_{GS} = U_{GS} + u_{gs}, \\ u_{DS} = U_{DS} + u_{ds}. \end{array} \right\}$$

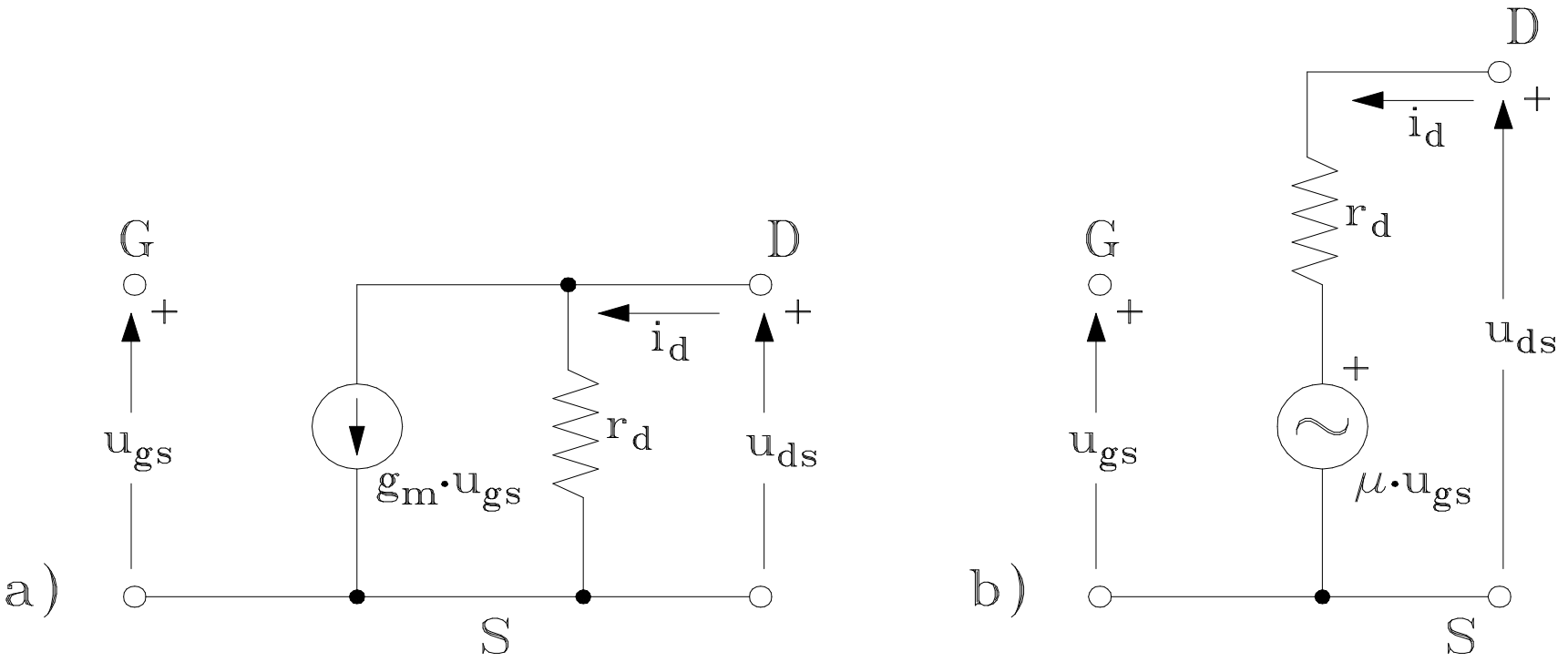
Režim malih promjena signala => $I_D >> i_d$; $U_{GS} >> u_{gs}$, $U_{DS} >> u_{ds}$.

U skladu s definicijom dinamičkih parametara:

$$g_m = \frac{\partial i_D}{\partial u_{GS}} = \frac{i_d}{u_{gs}} \qquad \frac{1}{r_d} = \frac{\partial i_D}{\partial u_{DS}} = \frac{i_d}{u_{ds}}$$

- Može se pisati:

$$i_d = g_m \cdot u_{gs} + \frac{1}{r_d} \cdot u_{ds} \qquad u_{ds} = -\mu \cdot u_{gs} + i_d \cdot r_d$$



Nadomjesni sklop unipolarnog tranzistora

a) sa strujnim izvorom, b) s naponskim izvorom