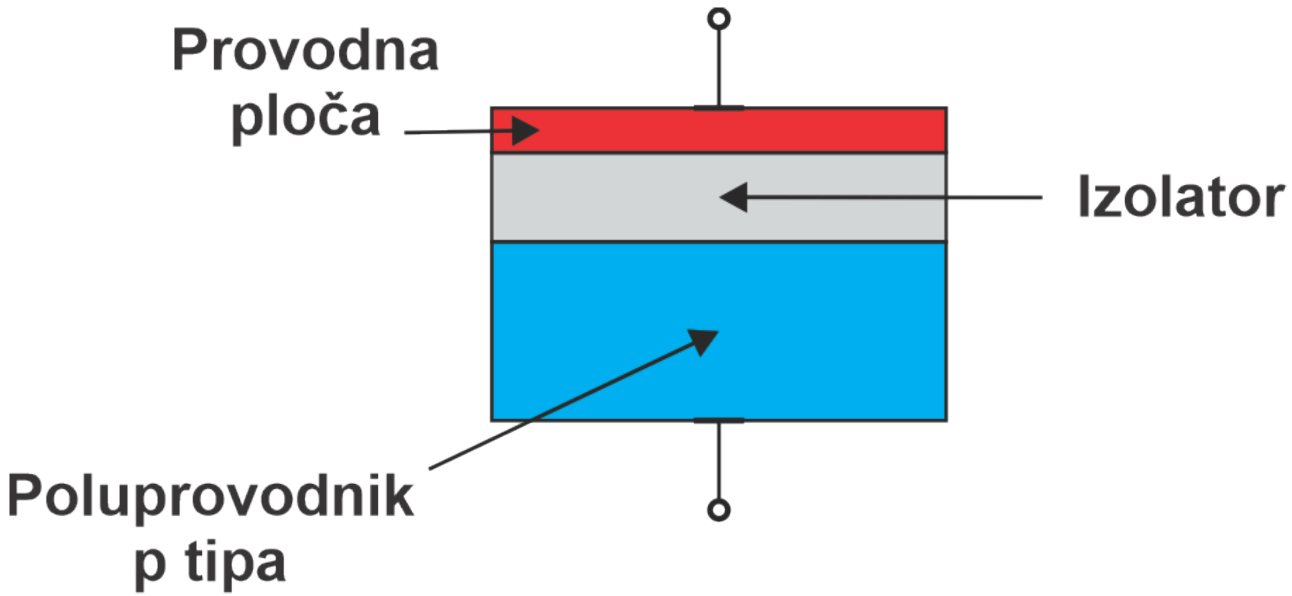
MOSFET

Struktura MOS tranzistora

- MOS struktura: metal, silicijum(IV)oksid (dielektrik), poluprovodnik
- Kondenzator *C*

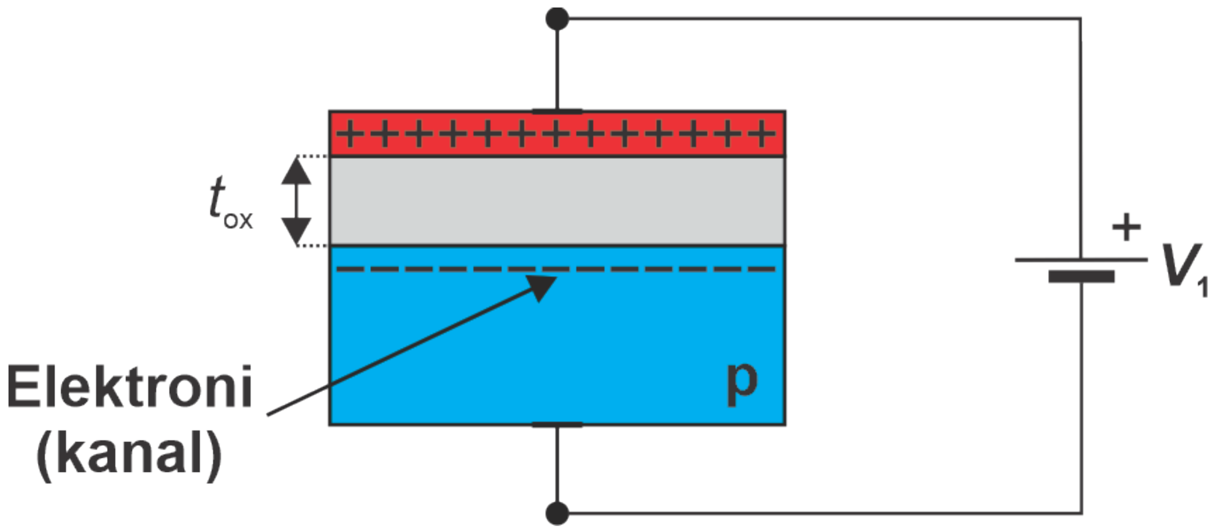


Struktura MOS tranzistora

- Količina naelektrisanja je proporcionalna naponu

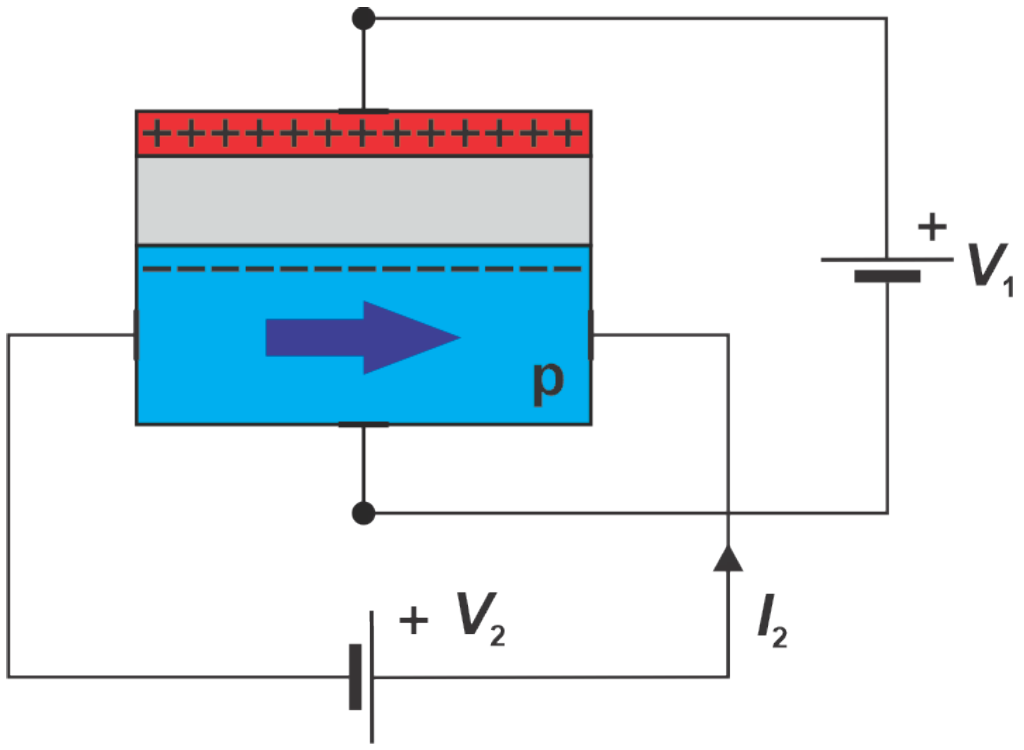
$$Q = CV_1$$

$$C = \varepsilon_{ox} \frac{S}{t_{ox}}$$

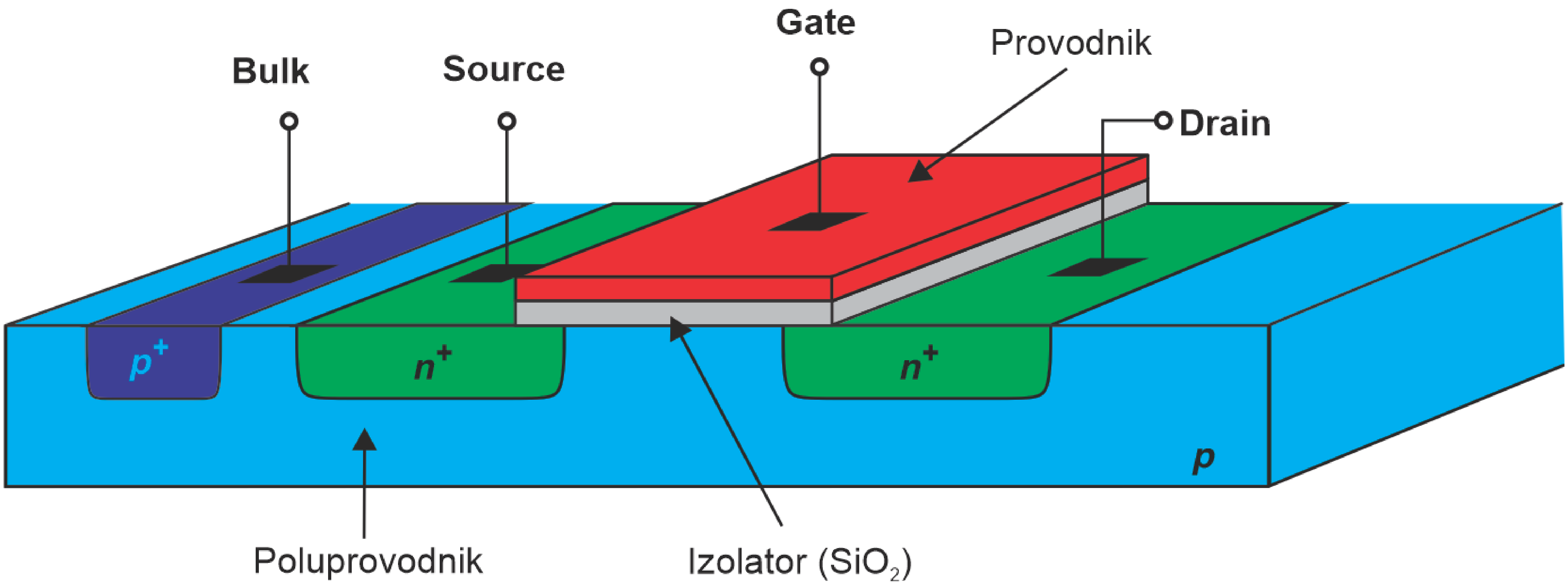


Struktura MOS tranzistora

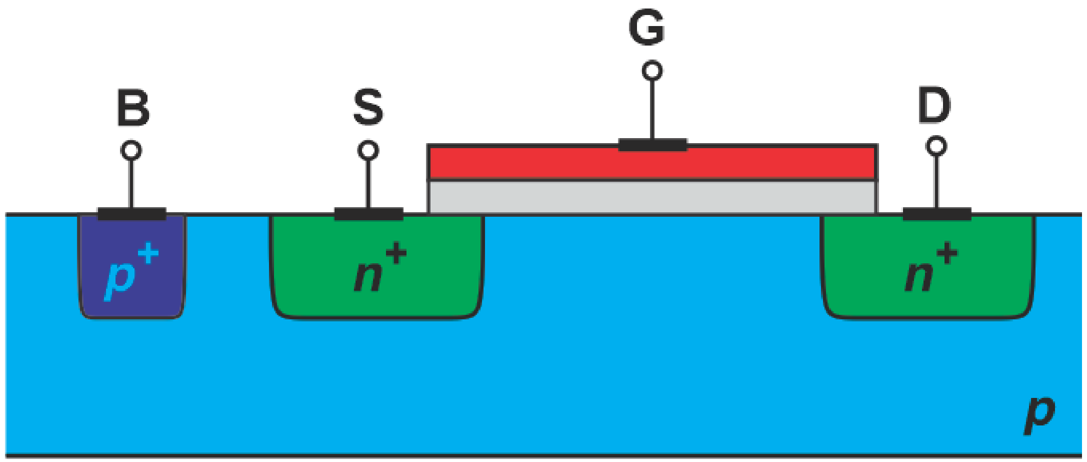
- Ukoliko se zatvori kolo, protiče struja I_2
- Struja zavisi od gustine naelektrisanja

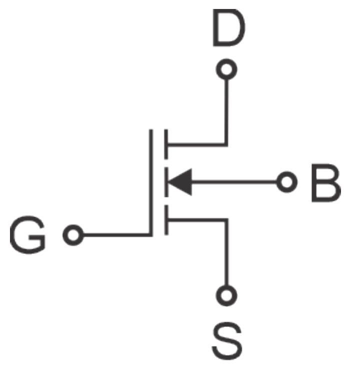


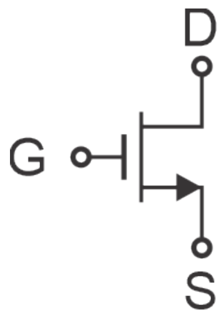
Struktura MOS tranzistora (n-kanalni)



2D struktura MOS tranzistora i simboli (n-kanalni)



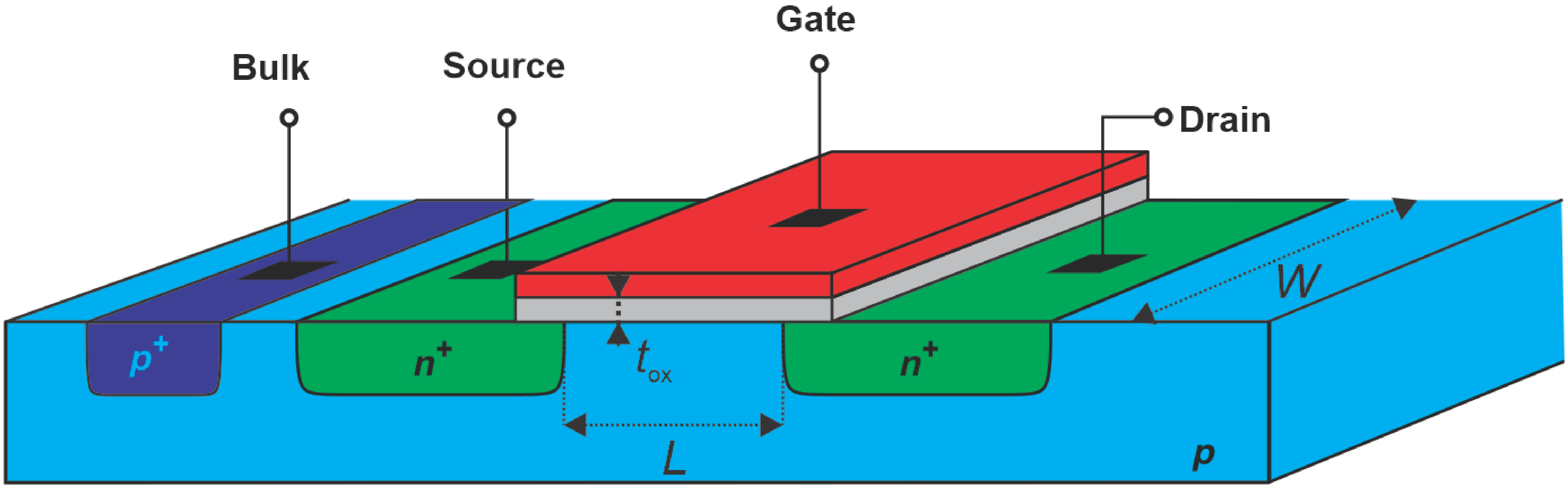




Osobine MOS tranzistora

- **M**etal **O**xide **S**emiconductor **F**ield **E**ffect **T**ransistor
- MOS tranzistor ima četiri priključka (**S**ource, **D**rain, **G**ate, **B**ulk)
- Struktura je simetrična (source – drain)
- Supstrat (Bulk) se obično povezuje sa sorsom
- Struja gejta je jednaka nuli
- Napon na gejtu može da kontroliše struju sorsa/drejna

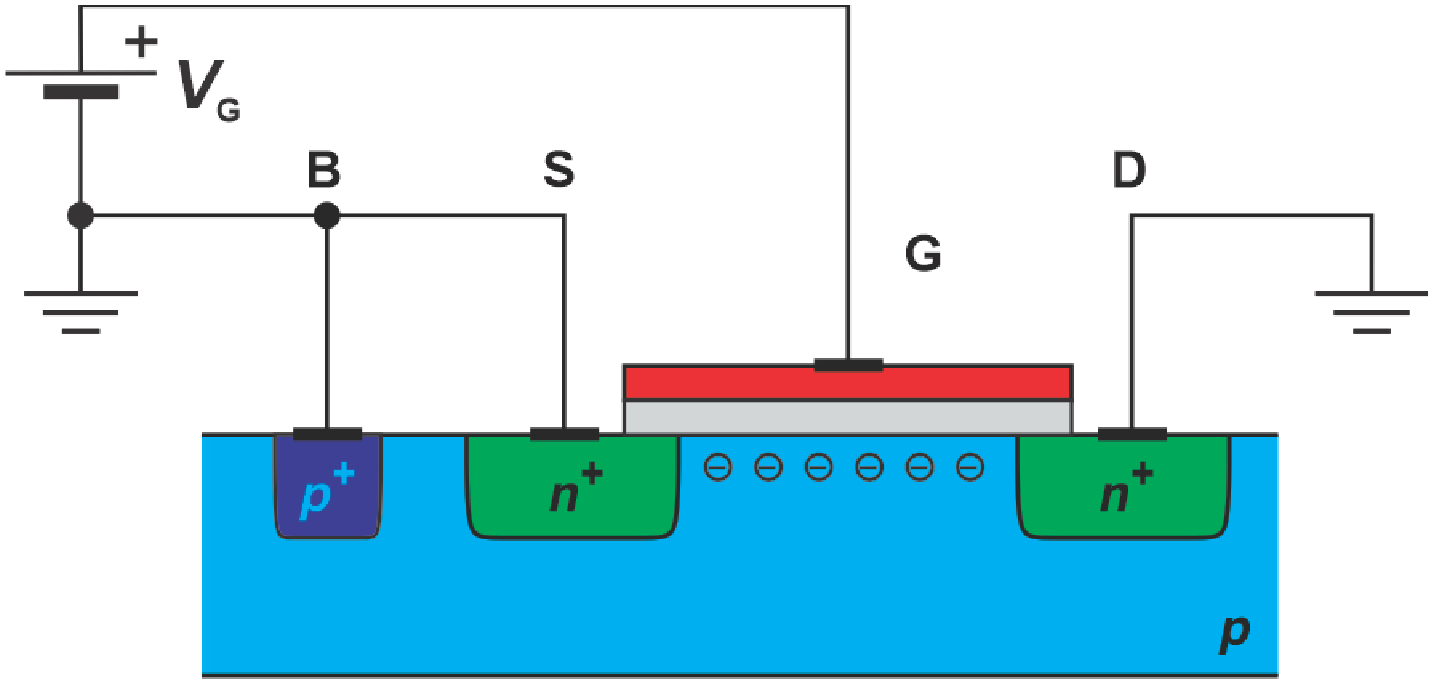
Tipične dimenzije

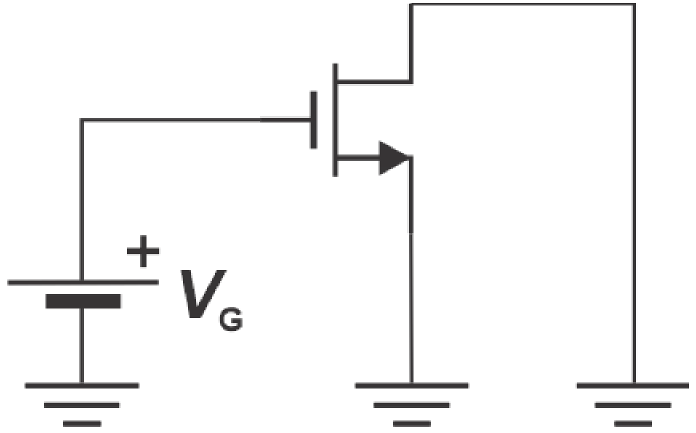


t_{ox}≈1.8nm, L≈90nm

$$C_{ox} = \varepsilon_{ox}\frac{L\cdot W}{t_{ox}}$$

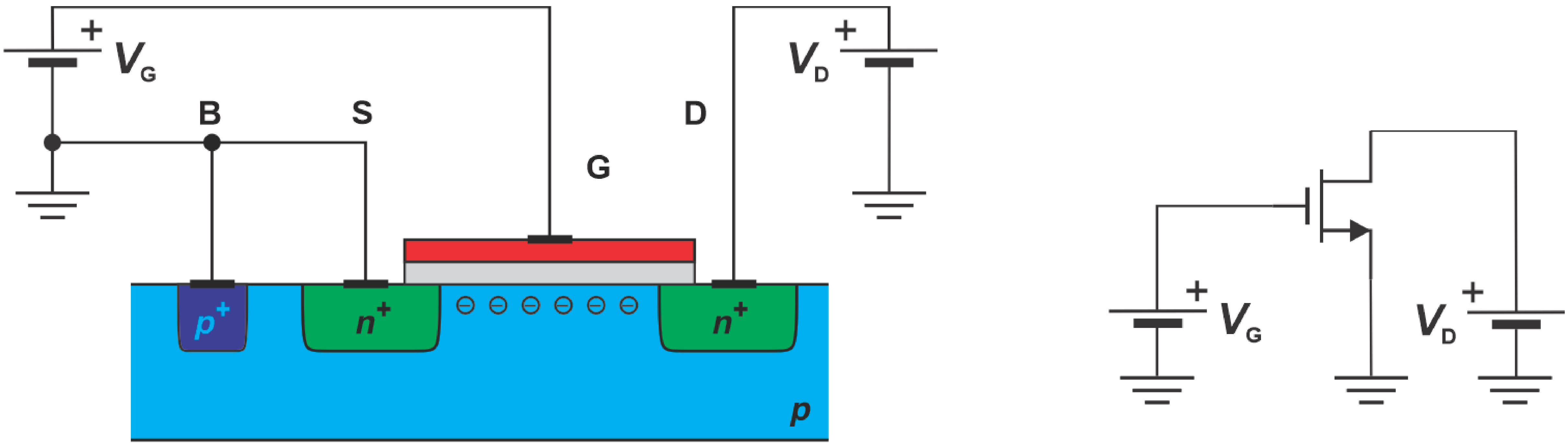
Tranzistorski efekat





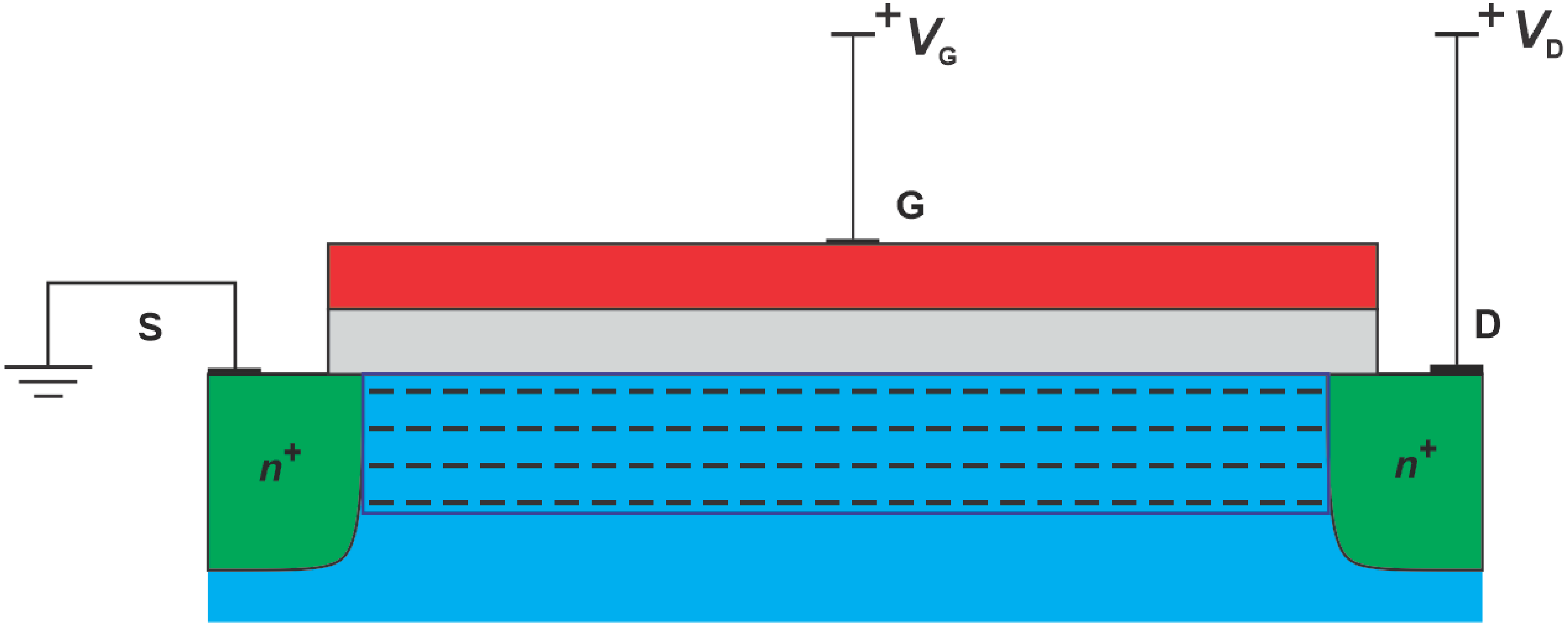
- Kada je $V_G > V_{TH}$, u supstratu se formira kanal koga čine slobodni elektroni

Tranzistorski efekat



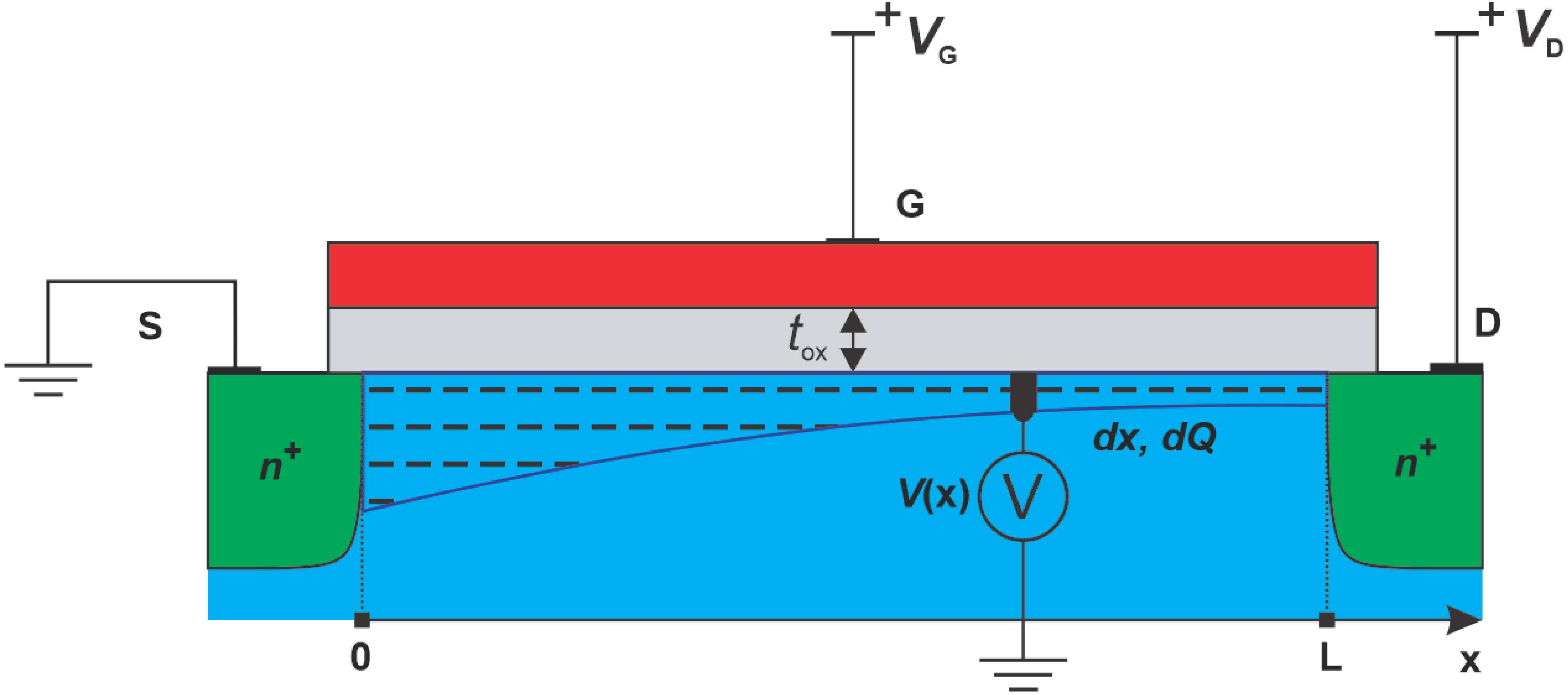
- Kada je $V_D > V_S$, protiče struja drejna koja zavisi od V_D i V_G.

Tranzistorski efekat



- V_D=0, kanal je uniforman

Tranzistorski efekat



- $V_D>0$, $V(0)=0$, $V(L)=V_D$

Tranzistorski efekat

- Količina naelektrisanja *dQ* u delu kanalu dužine *dx* je

$$dQ = C'_{\mathrm{ox}} dx \cdot \left(V_{\mathrm{G}} - V_{\mathrm{TH}} - V(x)\right)$$

$$dQ = \varepsilon_{\mathrm{ox}} \frac{W}{t_{\mathrm{ox}}} dx \cdot \left(V_{\mathrm{G}} - V_{\mathrm{TH}} - V(x)\right)$$

- Elektroni se u poluprovodniku pod dejstvom električnog polja kreću konstantnom brzinom

$$v_{\mathrm{e}} = -\mu_{\mathrm{n}} E$$

Tranzistorski efekat

- U vremenskom intervalu *dt*, elektroni pređu distancu *dx*

$$dx = v_{\mathrm{e}} dt$$

$$dx = -\mu_{\mathrm{n}} E dt$$

- Električno polje se može izraziti kao negativni gradijent napona

$$E = -\frac{dV(x)}{dx}$$

Tranzistorski efekat

- Pređeni put *dx*, je prema tome

$$dx = \mu_{\mathrm{e}} \frac{dV(x)}{dx} dt$$

- Količina naelektrisanja *dQ* u elementu *dx* je

$$dQ = \mu_{\mathrm{e}} C'_{\mathrm{ox}} \cdot \left(V_{\mathrm{G}} - V_{\mathrm{TH}} - V(x)\right) \cdot \frac{dV(x)}{dx} dt$$

Tranzistorski efekat

- Ukoliko infinitezimalne veličine *dx* i *dt* grupišemo na levoj strani

$$\frac{dQ}{dt}dx = \mu_n C'_{ox} \cdot \left(V_G - V_{TH} - V(x)\right) \cdot dV(x)$$

- Priraštaj naelektrisanja u vremenu je struja I_{DS}

$$I_{DS}dx = \mu_n C'_{ox} \cdot \left(V_G - V_{TH} - V(x)\right) \cdot dV(x)$$

Tranzistorski efekat

- Integracijom jednačine u granicama od 0 do *L*, dobija se

$$I_{\mathrm{DS}}\int_0^L dx=\mu_{\mathrm{n}}C'_{\mathrm{ox}}\cdot\int_{V(0)=0}^{V(L)=V_{\mathrm{D}}}\left(V_{\mathrm{G}}-V_{\mathrm{TH}}\right)dV-\mu_{\mathrm{n}}C'_{\mathrm{ox}}\cdot\int_{V(0)=0}^{V(L)=V_{\mathrm{D}}}V(x)\cdot dV$$

$$I_{\mathrm{DS}}\cdot L=\mu_{\mathrm{n}}C'_{\mathrm{ox}}\cdot\left(V_{\mathrm{G}}-V_{\mathrm{TH}}\right)\cdot V_{\mathrm{D}}-\frac{1}{2}\mu_{\mathrm{n}}C'_{\mathrm{ox}}\cdot V_{\mathrm{D}}^2$$

$$I_{\mathrm{DS}}=\frac{1}{2}\mu_{\mathrm{n}}\frac{\varepsilon_{\mathrm{ox}}}{t_{\mathrm{ox}}}\frac{W}{L}\cdot\left(2\left(V_{\mathrm{G}}-V_{\mathrm{TH}}\right)\cdot V_{\mathrm{D}}-V_{\mathrm{D}}^2\right)$$

Tranzistorski efekat – triodni režim

- Struja drejna zavisi od električnih osobina poluprovodnika i dielektrika (oksida), ali i od dimenzija tranzistora, konkretno odnosa širine i dužine kanala *W*/*L*
- Struja drejna ima kvadratnu zavisnost od napona V_D
- Maksimalna struja drejna se može naći ukoliko se izvod I_{DS} po V_D izjednači sa nulom:

$$\frac{dI_{DS}}{dV_D} = \frac{1}{2}\mu_n \frac{\varepsilon_{ox}}{t_{ox}} \frac{W}{L} \cdot \left(2\left(V_G - V_{TH}\right) - 2V_D\right)$$

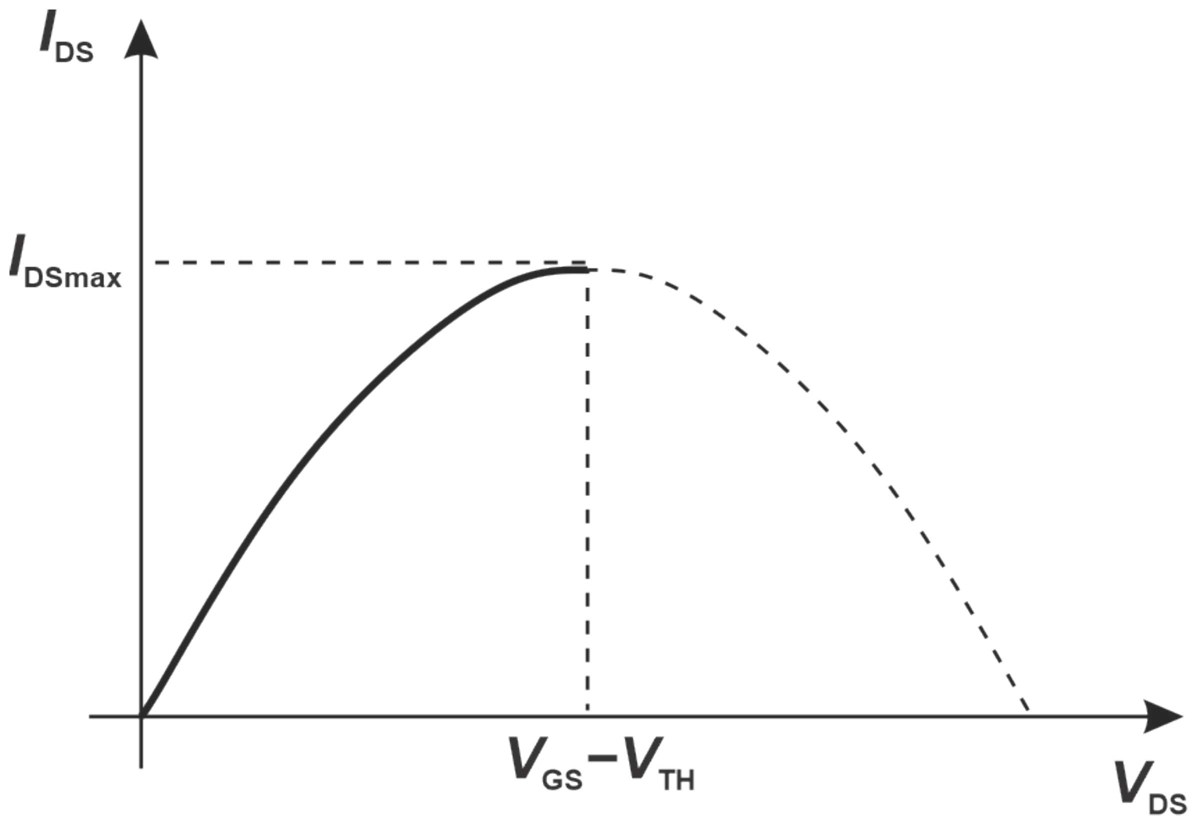
$$V_G - V_{TH} - V_D = 0$$

Tranzistorski efekat – triodni režim

- Sors je vezan za masu, tako da je $V_G = V_{GS}$, $V_D = V_{DS}$

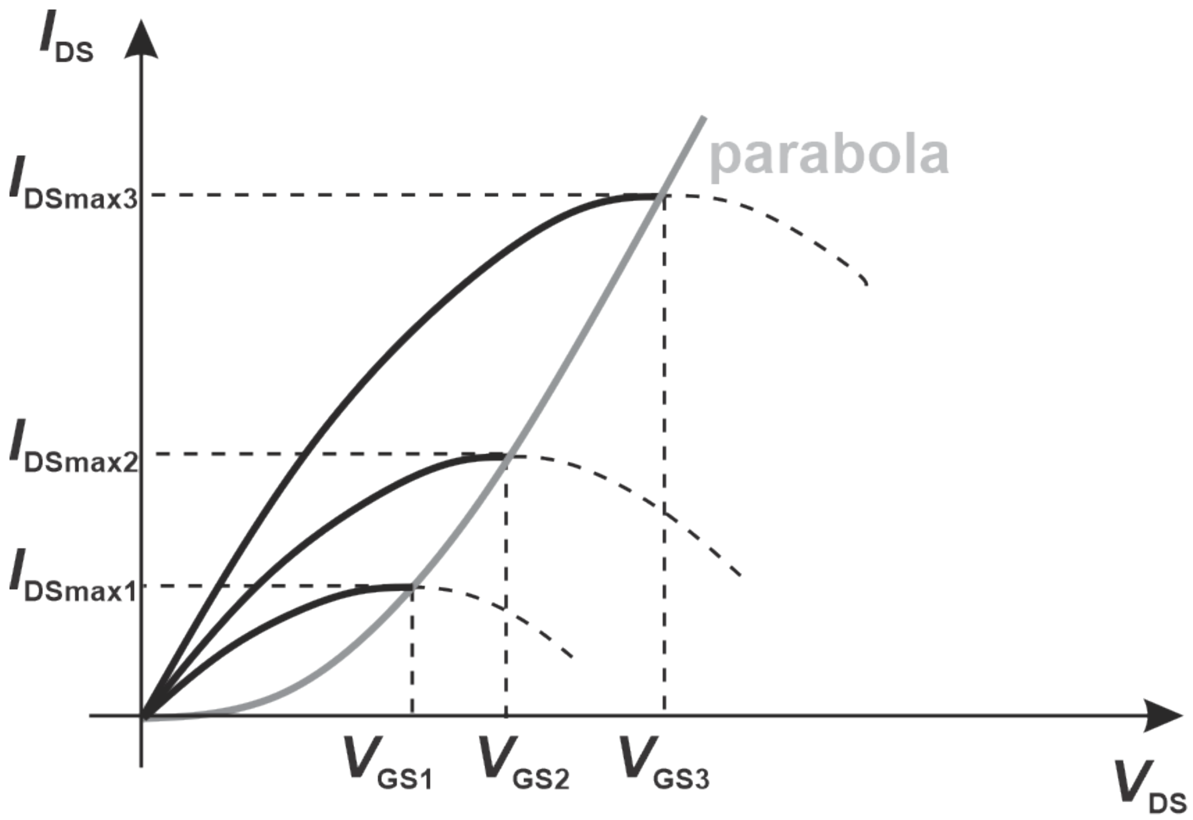
$$V_{DS} = V_{GS} - V_{TH}$$

$$I_{DSmax} = \frac{1}{2}\mu_n \frac{\varepsilon_{ox}}{t_{ox}} \frac{W}{L} \cdot \left(V_{GS} - V_{TH}\right)^2$$



Tranzistorski efekat – triodni režim

- Familija karakteristika, maksimumi se nalaze na paraboli
- Za male vrednosti $V_{DS} << V_{GS} - V_{TH}$, kvadratni član u jednačini za struju drejna možemo da zanemarimo



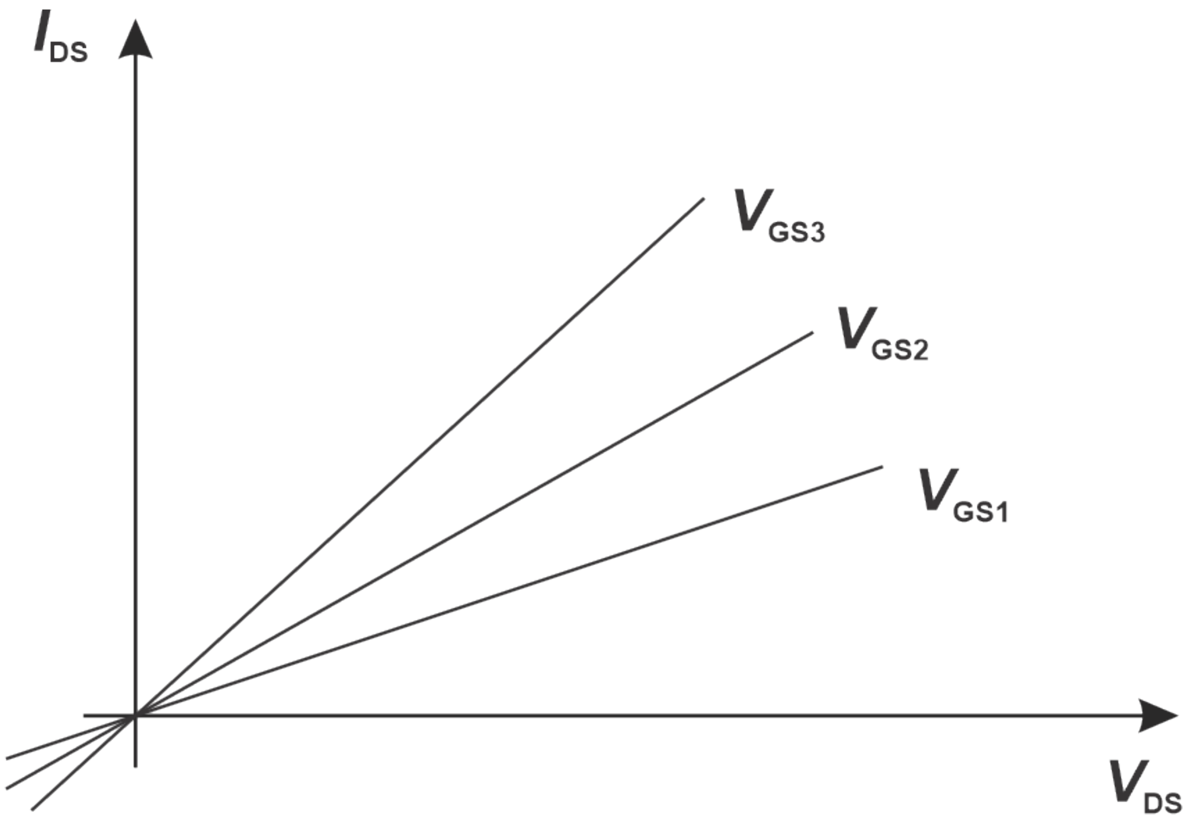
Tranzistorski efekat – triodni režim

$$I_{DS} = \frac{1}{2}\mu_n \frac{\varepsilon_{ox}}{t_{ox}} \frac{W}{L} \cdot \left(2\left(V_{GS} - V_{TH}\right) \cdot V_{DS} - V_{DS}^2\right)$$

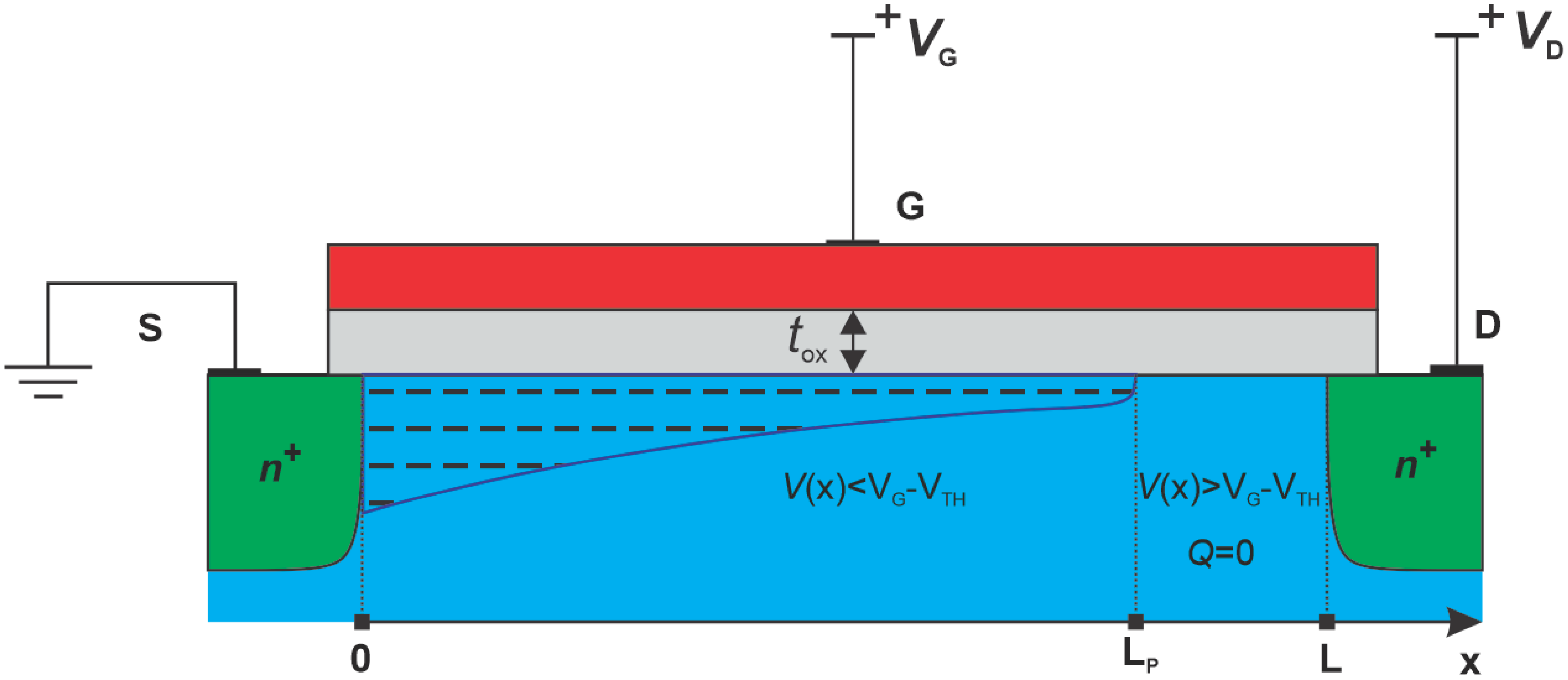
$$I_{DS} = \mu_n \frac{\varepsilon_{ox}}{t_{ox}} \frac{W}{L} \cdot \left(V_{GS} - V_{TH}\right) \cdot V_{DS}$$

$$I_{DS} = \frac{V_{DS}}{R_D}$$

$$R_D = \frac{1}{\mu_n \frac{\varepsilon_{ox}}{t_{ox}} \frac{W}{L} \cdot \left(V_{GS} - V_{TH}\right)}$$



Tranzistorski efekat – saturacija



- $V_D > V_G - V_G$, prekid kanala, MOSFET ulazi u zasićenje

Tranzistorski efekat – saturacija

- Zbog prekinutog kanala, gornja granica integracije je $V_{GS}-V_{TH}$

$$I_{DS}\int_0^{L_P} dx = \mu_n C'_{ox}\cdot \int_0^{V_{GS}-V_{TH}} \left(V_{GS}-V_{TH}\right) dV - \mu_n C'_{ox}\cdot \int_0^{V_{GS}-V_{TH}} V(x)\cdot dV$$

$$I_{DS}\cdot L_P = \mu_n C'_{ox}\cdot\left(V_{GS}-V_{TH}\right)^2 - \frac{1}{2}\mu_n C'_{ox}\cdot\left(V_{GS}-V_{TH}\right)^2$$

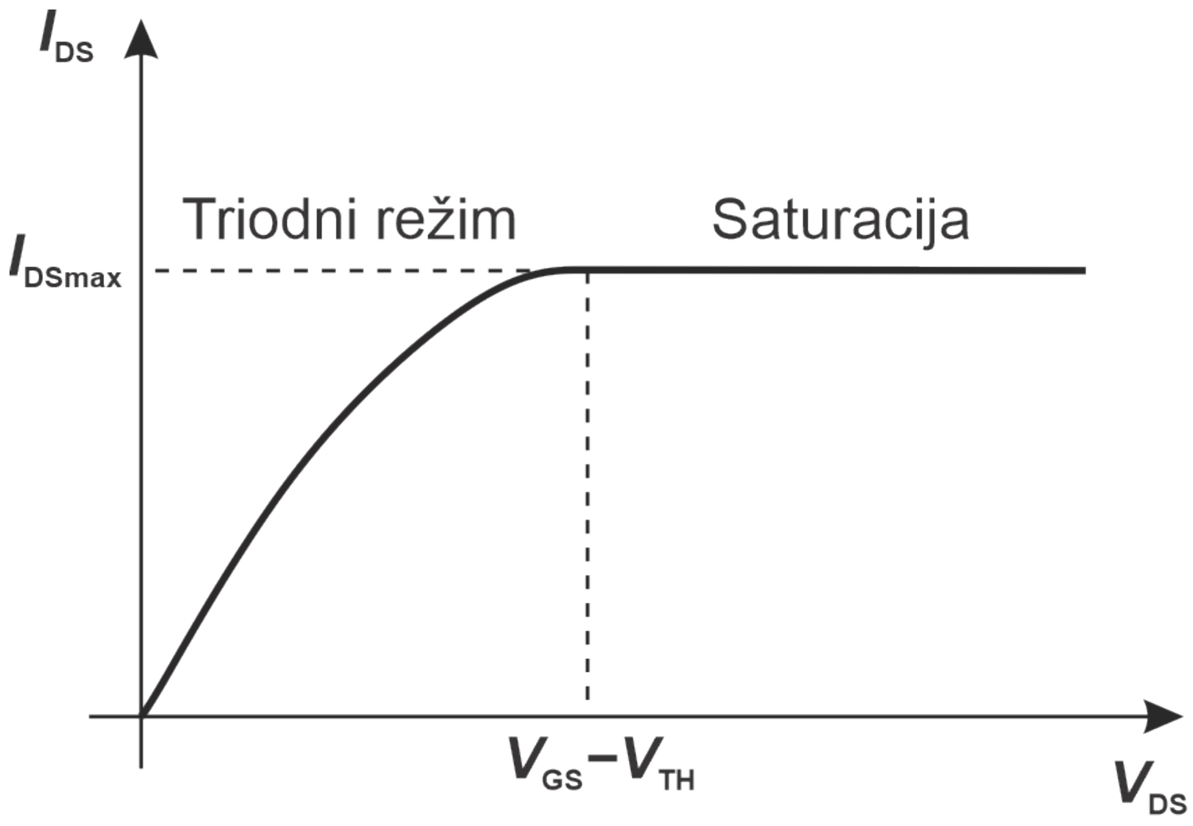
$$I_{DS} = \frac{1}{2}\mu_n \frac{\varepsilon_{ox}}{t_{ox}}\frac{W}{L_P}\cdot\left(V_{GS}-V_{TH}\right)^2$$

Tranzistorski efekat – modulacija dužine kanala

- Za $V_{DS} > V_{GS} - V_{TH}$, struja drejna je **približno** konstantna, MOSFET je u zasićenju

$$V_{DS} > V_{GS} - V_{TH}$$

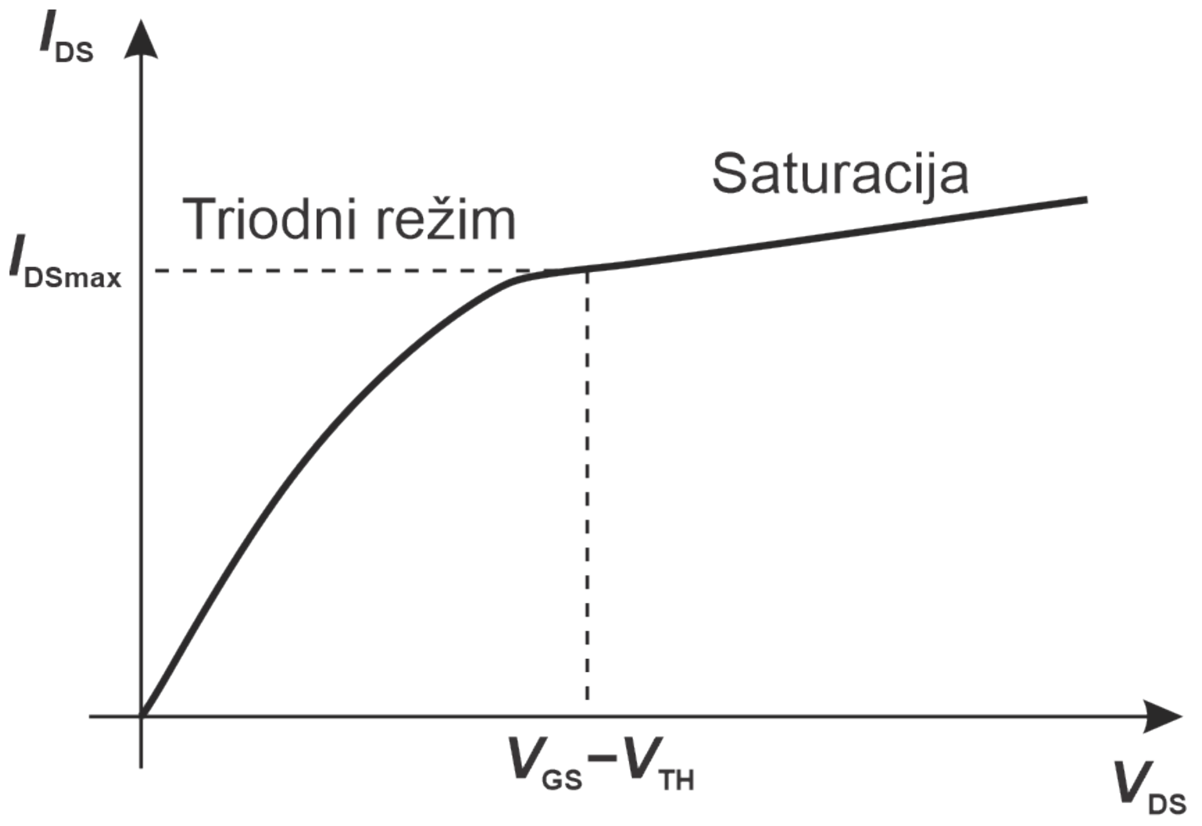
$$I_{DS} = \frac{1}{2}\mu_n \frac{\varepsilon_{ox}}{t_{ox}} \frac{W}{L_P} \cdot \left(V_{GS} - V_{TH}\right)^2$$



Tranzistorski efekat – modulacija dužine kanala

- L_P je dužina prekinutog kanala, zavisi od napona V_{DS}
- Parametar λ je koeficijent modulacije dužine kanala

$$L_P = \frac{L}{1 + \lambda \cdot V_{DS}}$$



Struja drejna

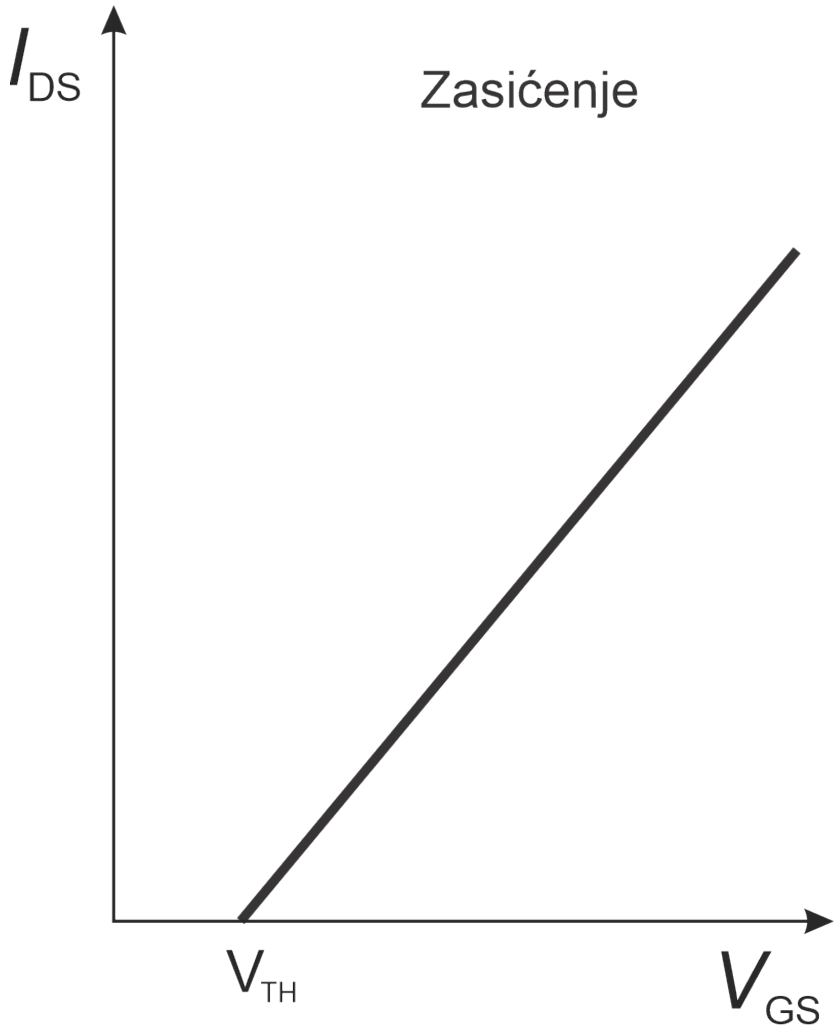
- Pojednostavljenje izraza

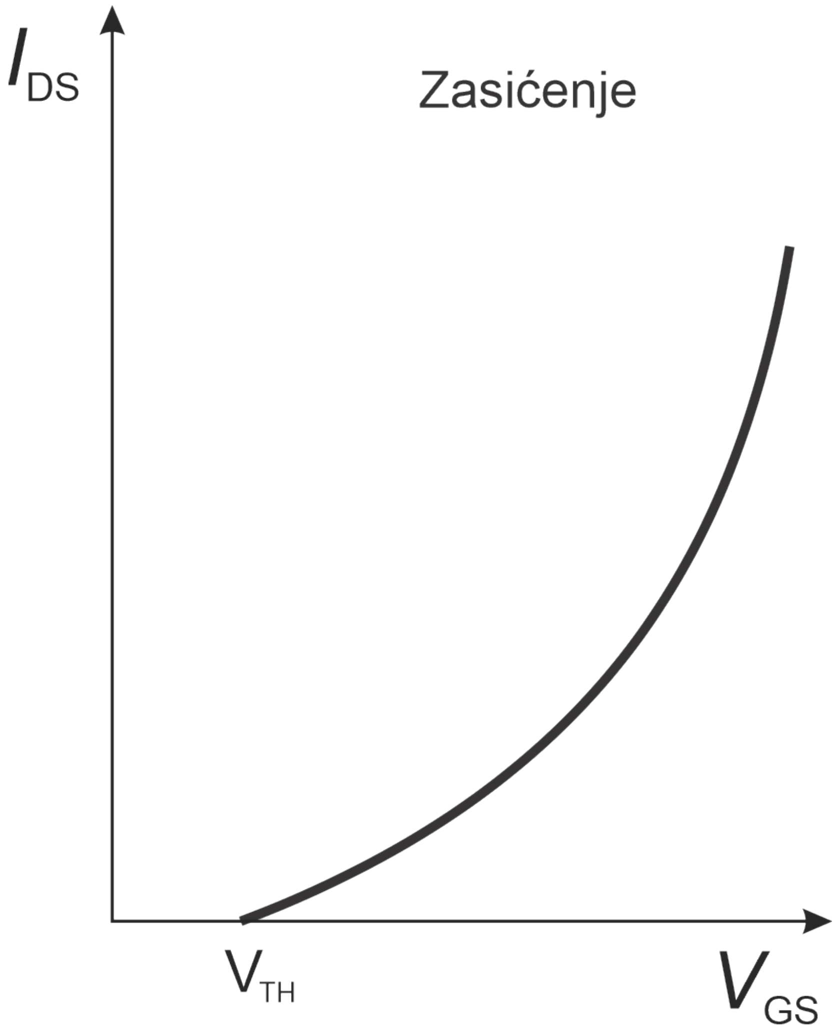
$$I_{DS} = \frac{1}{2}\mu_n \frac{\varepsilon_{ox}}{t_{ox}}\frac{W}{L}\cdot\left(V_{GS} - V_{TH}\right)^2 \cdot\left(1 + \lambda V_{DS}\right)$$

$$I_{DS} = \frac{1}{2}\mu_n \cdot V_{TH}^2 \cdot \frac{\varepsilon_{ox}}{t_{ox}}\frac{W}{L}\cdot\left(\frac{V_{GS}}{V_{TH}} - 1\right)^2 \cdot\left(1 + \lambda V_{DS}\right)$$

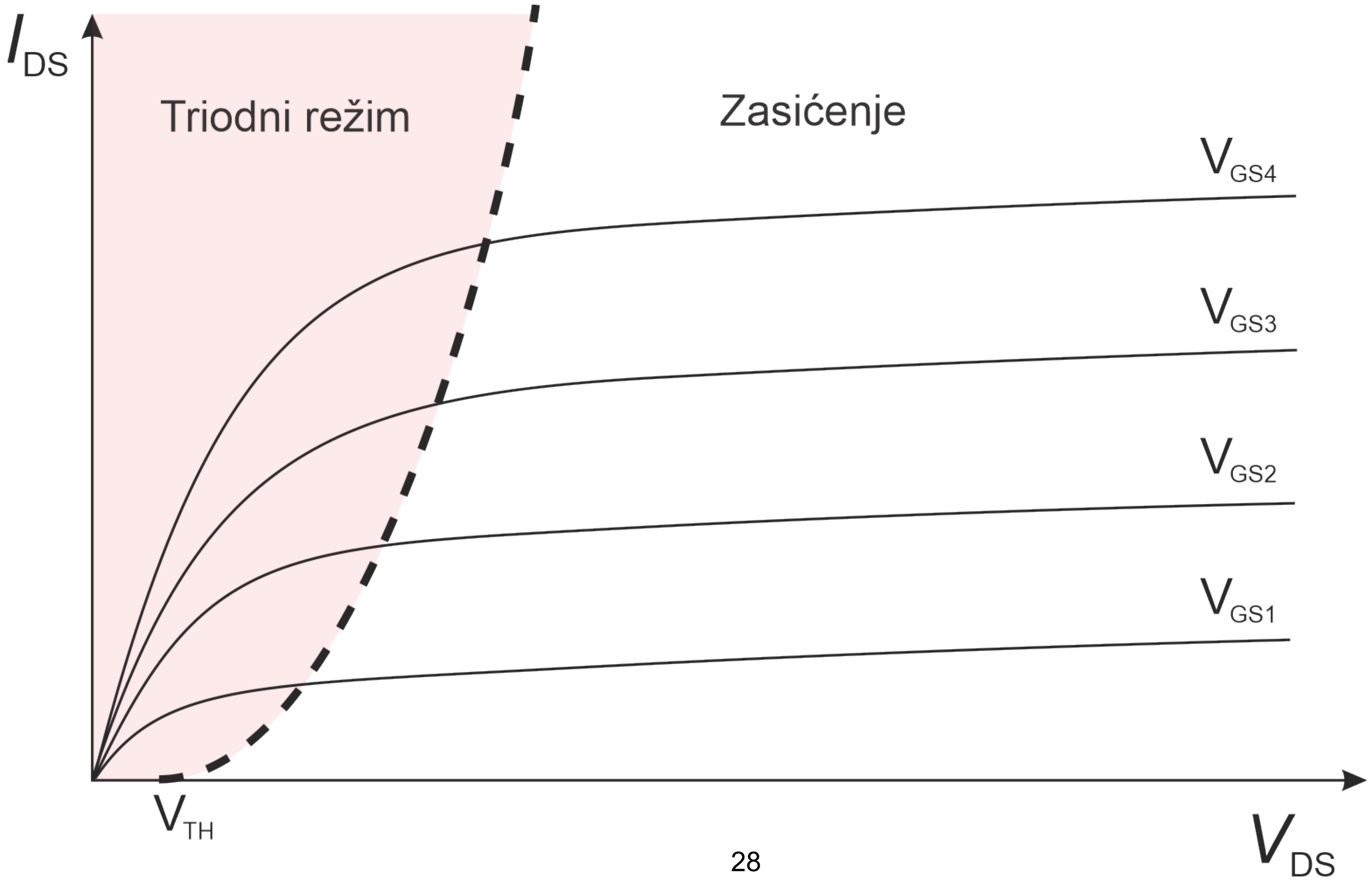
$$I_{DS} = I_{DSS}\cdot\left(\frac{V_{GS}}{V_{TH}} - 1\right)^2 \cdot\left(1 + \lambda V_{DS}\right)$$

Prenosna karakteristika



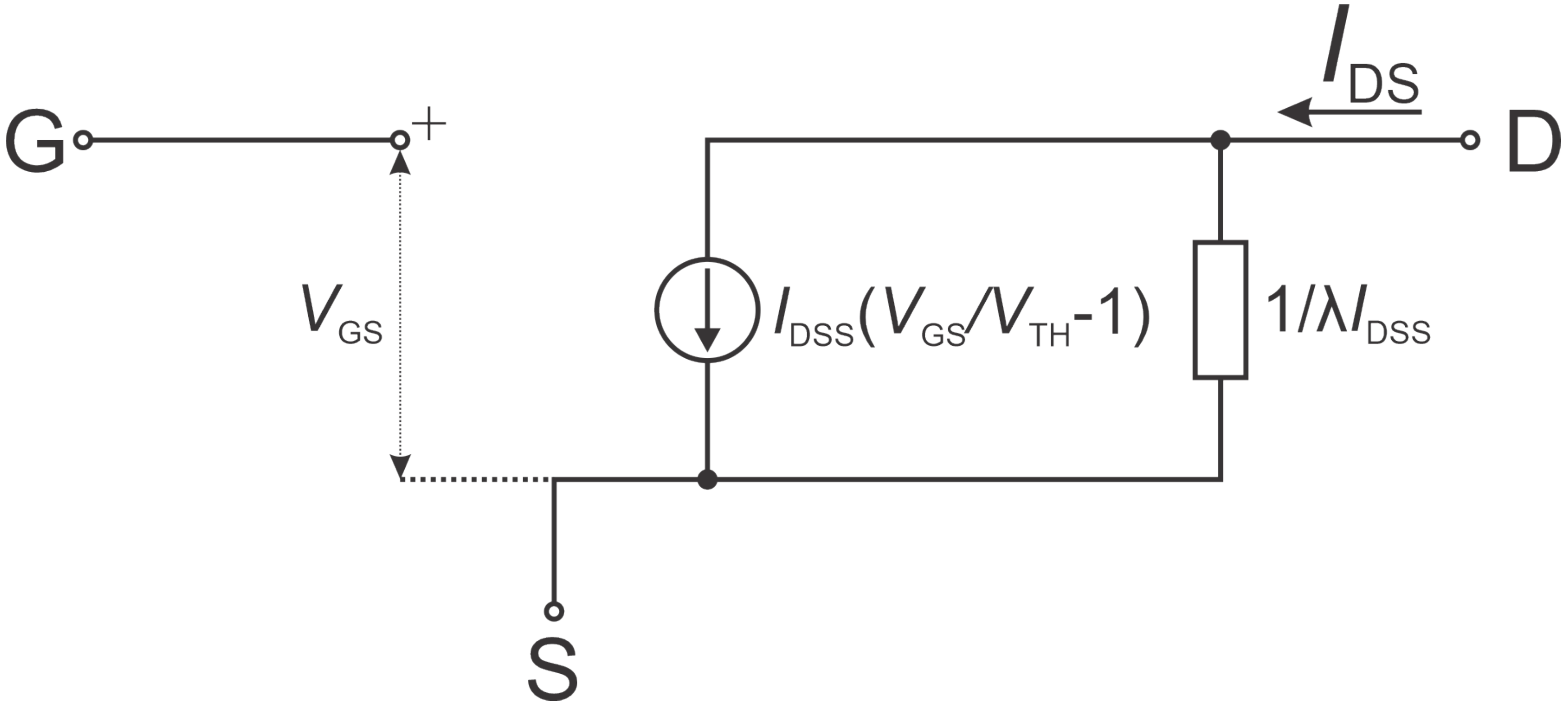


Izlazna karakteristika

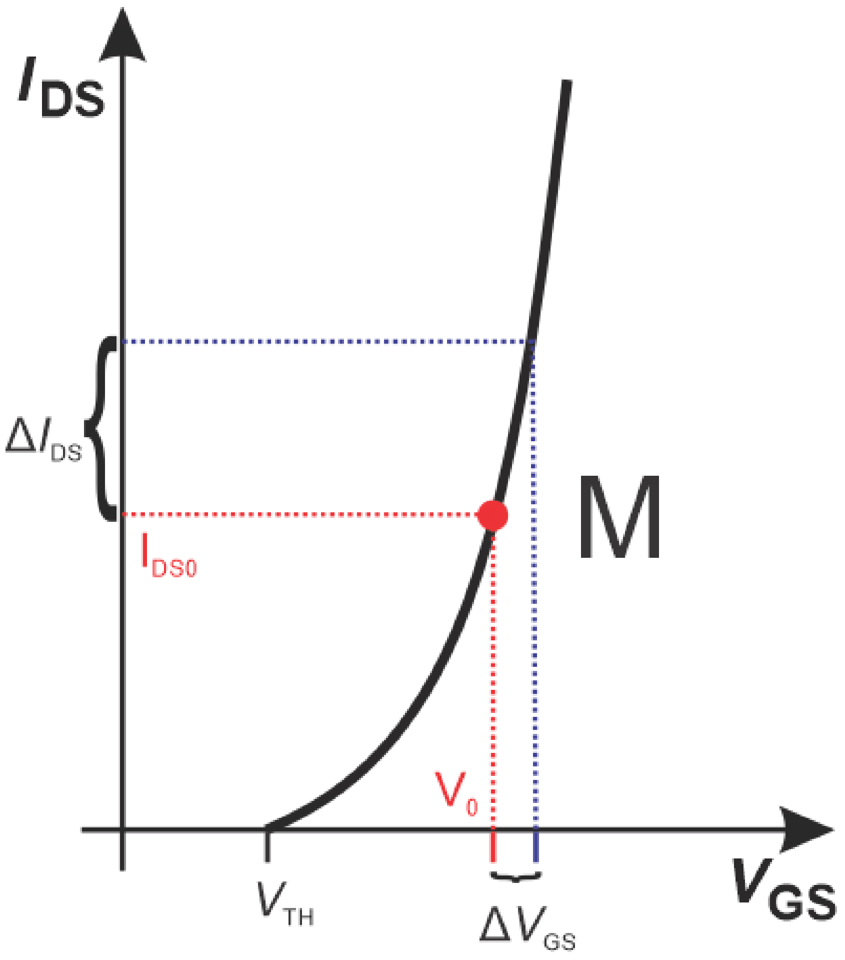


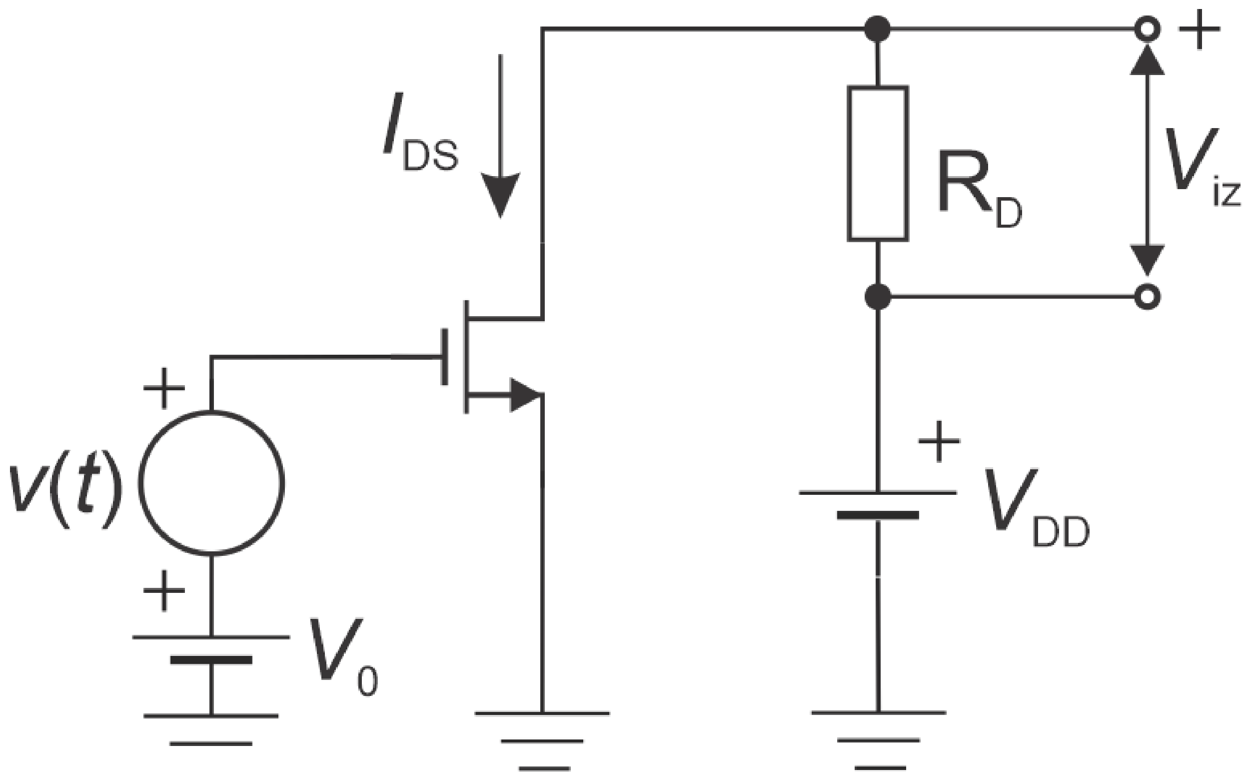
Model za velike signale

- Parametri modela: I_{DSS}, V_{TH}, λ



Polarizacija i radna tačka



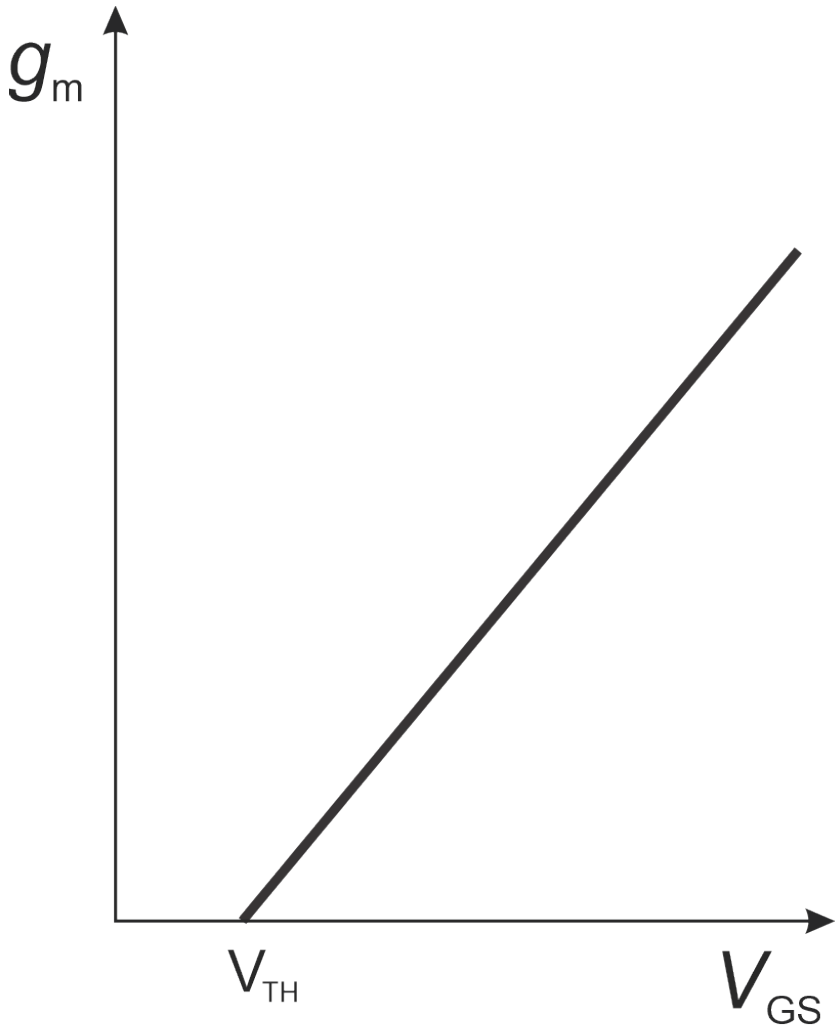


Transkonduktansa MOS tranzistora

$$I_{DS} = \frac{1}{2}\mu_n \cdot \frac{\varepsilon_{ox}}{t_{ox}}\frac{W}{L}\left(V_{GS} - V_{TH}\right)^2$$

$$g_m = \frac{dI_{DS}}{dV_{GS}}$$

$$g_m = \mu_n \cdot \frac{\varepsilon_{ox}}{t_{ox}}\frac{W}{L}\left(V_{GS} - V_{TH}\right)$$



Transkonduktansa

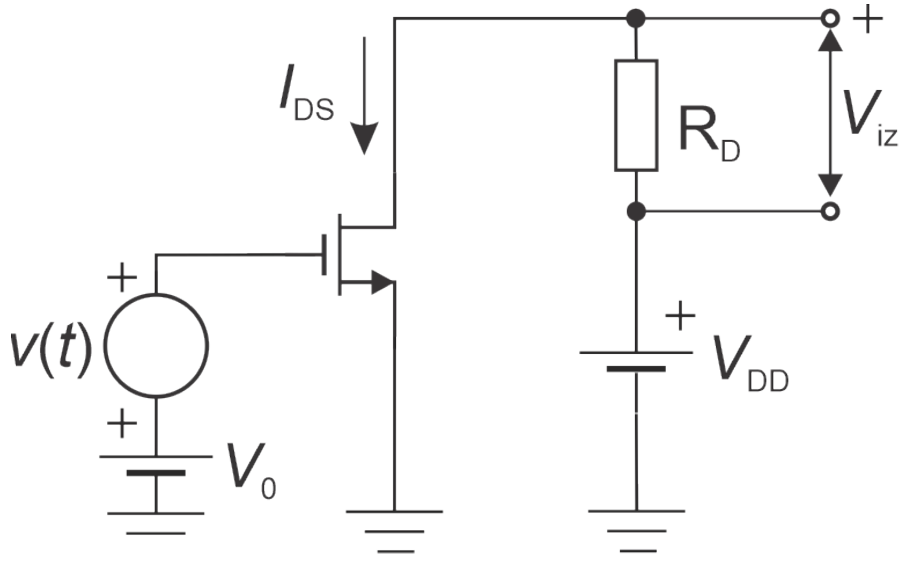
$$g_{m} = \frac{2I_{DS}}{V_{GS} - V_{TH}}$$

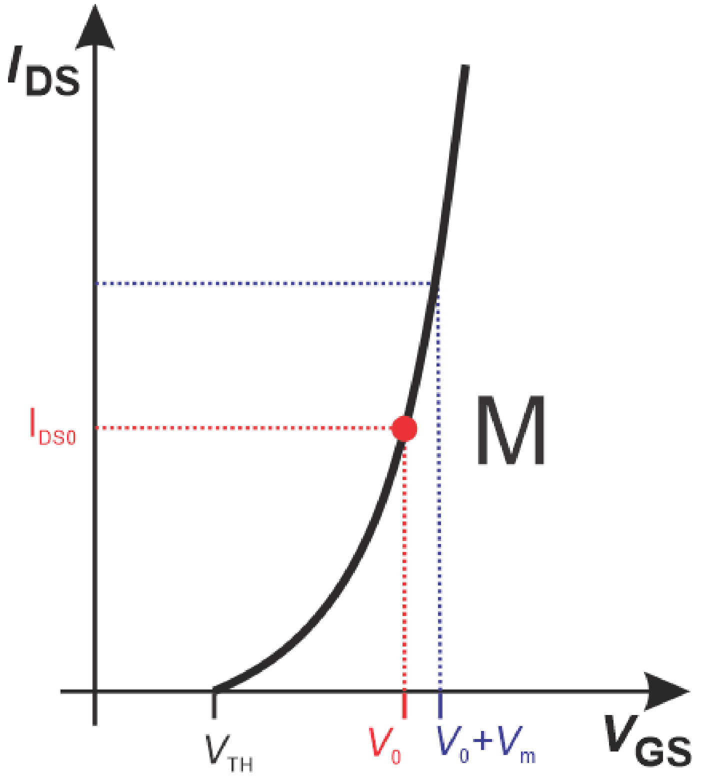
$$g_{m} = \sqrt{2I_{DS} \cdot \mu_{n} \cdot \frac{\varepsilon_{ox}}{t_{ox}} \frac{W}{L}}$$

Model MOS tranzistora za male signale

- Signal $v(t)$ je superponiran jednosmernom naponu V_0, promena napona V_{GS} je mala ($V_m \ll V_{TH}$):

$$V_{GS} = V_0 + v(t) = V_0 + V_m \cdot \sin \omega t$$





Model MOS tranzistora za male signale

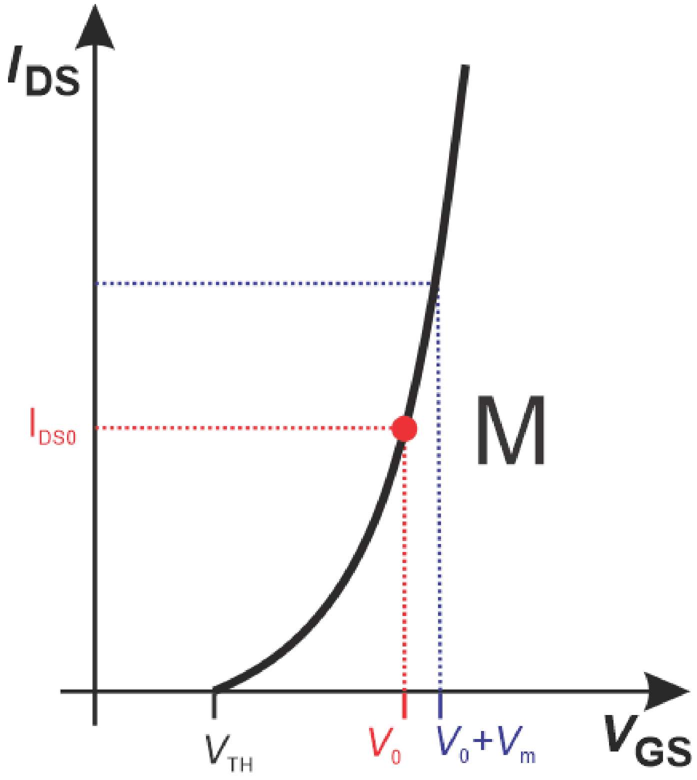
$$I_{DS} = I_{DSS} \cdot \left(\frac{V_{GS}}{V_{TH}} - 1 \right)^2$$

$$I_{DS} = I_{DSS} \cdot \left(\frac{V_0 + v(t)}{V_{TH}} - 1 \right)^2$$

$$I_{DS} = I_{DSS} \cdot \left(\frac{V_0}{V_{TH}} - 1 \right)^2 + 2I_{DSS} \cdot \left(\frac{V_0}{V_{TH}} - 1 \right) \cdot \frac{v(t)}{V_{TH}} + I_{DSS} \cdot \left(\frac{v(t)}{V_{TH}} \right)^2$$

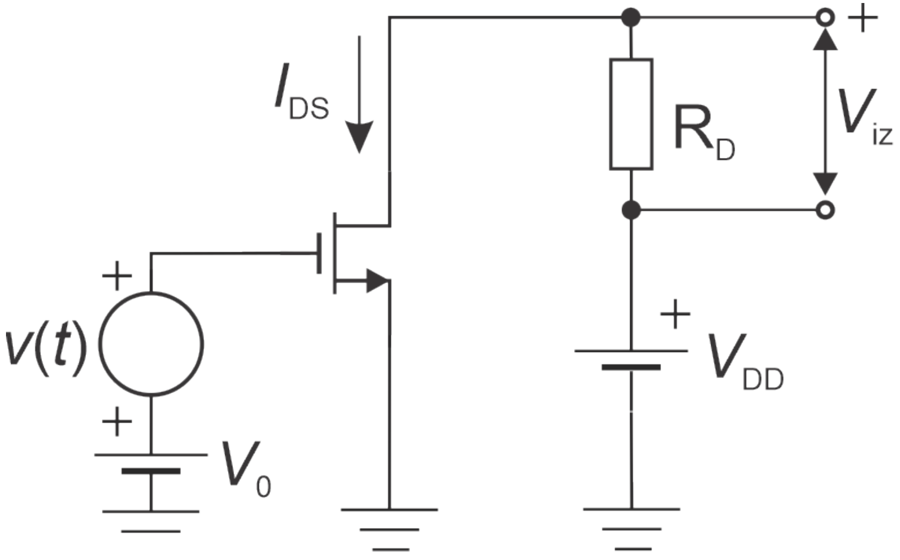
$$I_{DS} = I_{DS0} + \frac{2I_{DSS}}{V_{TH}} \cdot \left(\frac{V_0}{V_{TH}} - 1 \right) \cdot v(t)$$

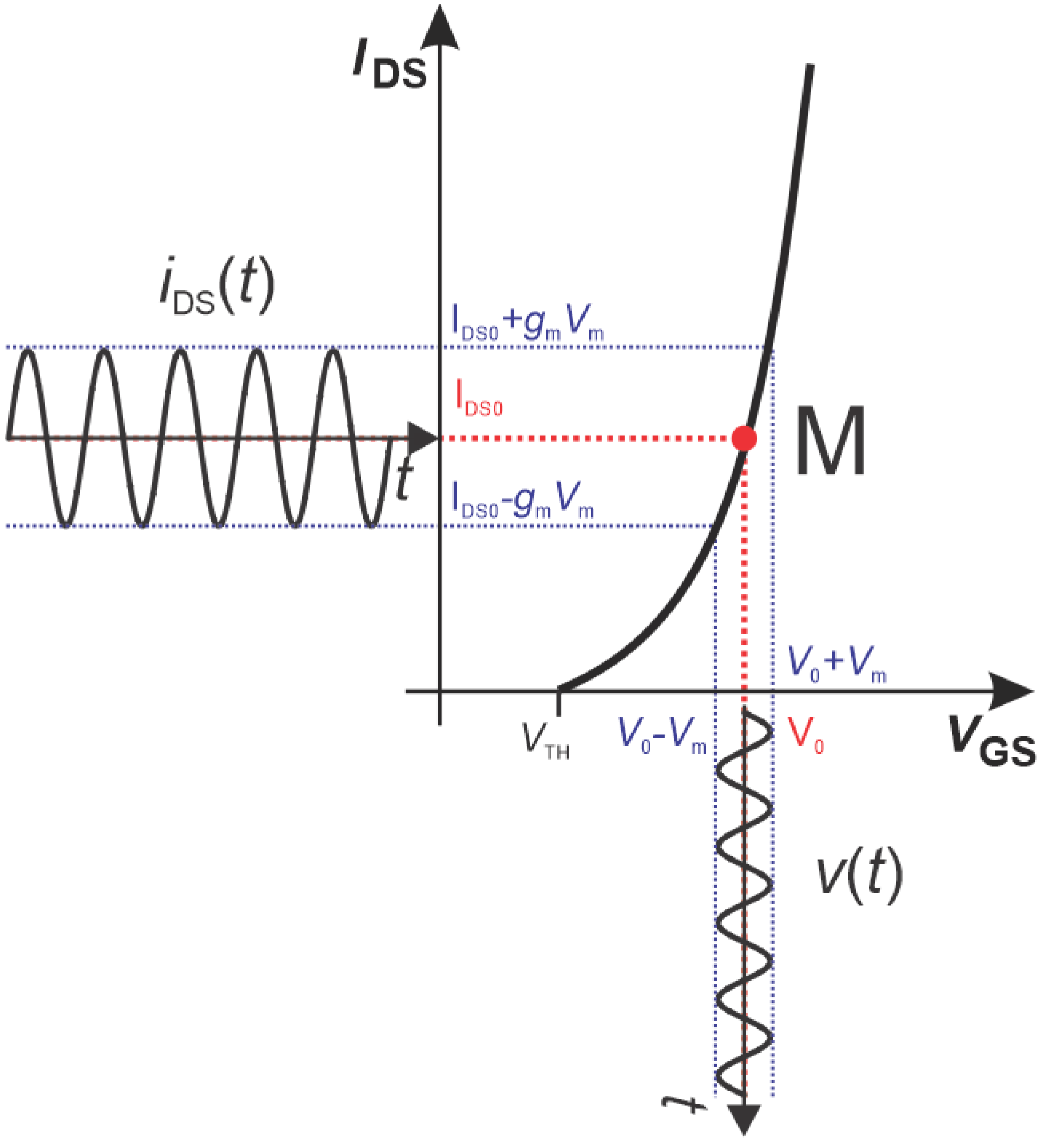
$$I_{DS} = I_{DS0} + g_m \cdot v(t)$$



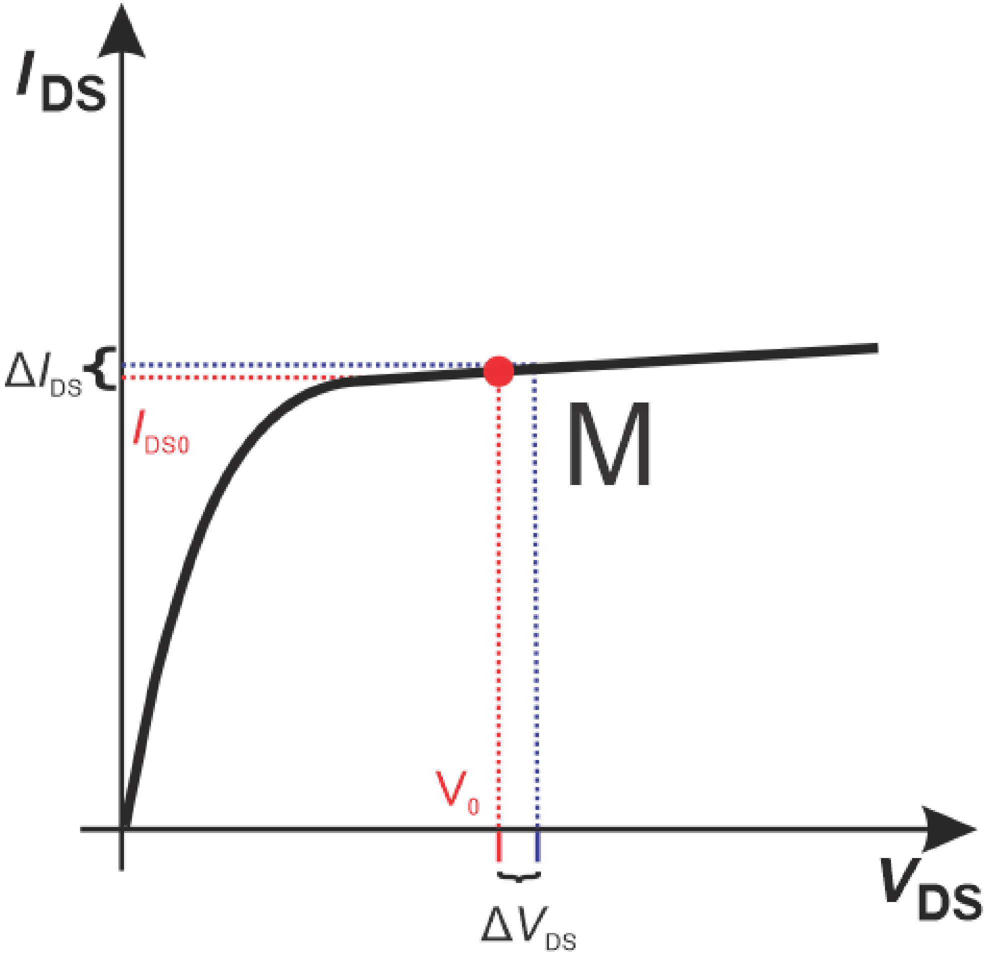
Model MOS tranzistora za male signale

$$I_{DS} = I_{DS0} + g_m \cdot V_m \sin \omega t = I_{DS0} + \underbrace{g_m \cdot v(t)}_{i_{DS}(t)}$$





Otpornost kanala MOS tranzistora



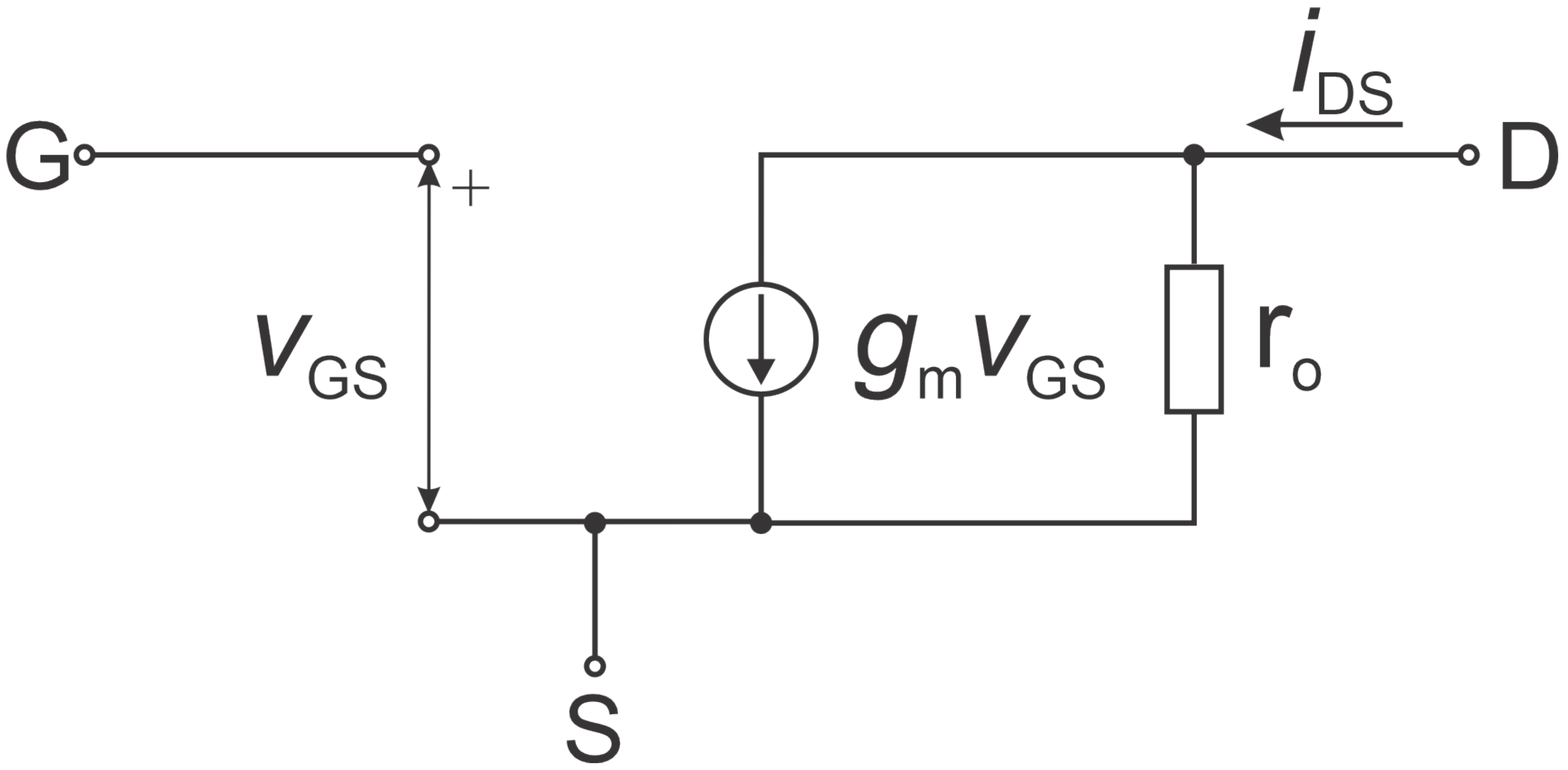
$$I_{DS} = I_{DSS} \cdot \left(\frac{V_{GS}}{V_{TH}} - 1 \right)^2 \left(1 + \lambda V_{DS} \right)$$

$$\frac{dI_{DS}}{dV_{DS}} = \lambda I_{DSS} \cdot \left(\frac{V_{GS}}{V_{TH}} - 1 \right)^2 \approx \lambda I_{DS0}$$

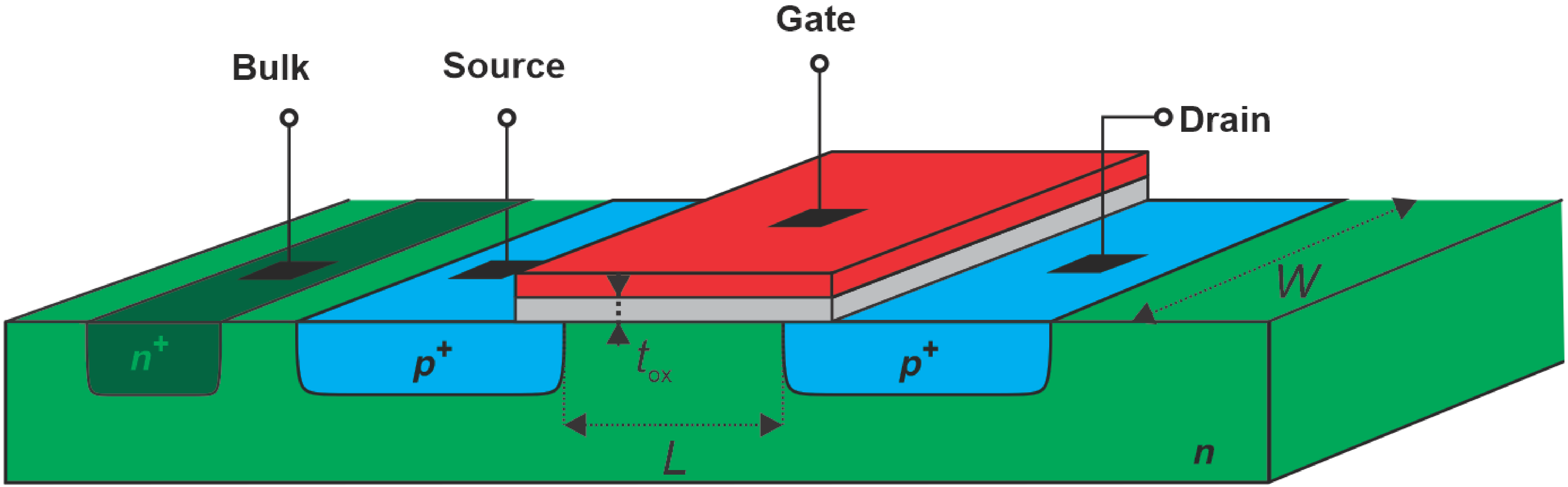
$$r_o = \frac{1}{\lambda I_{DS0}}$$

Model MOS tranzistora za male signale

$$g_m = \frac{2I_{DSS}}{V_{TH}} \cdot \left(\frac{V_{GS}}{V_{TH}} - 1 \right), \quad r_o = \frac{1}{\lambda I_{DS0}}$$



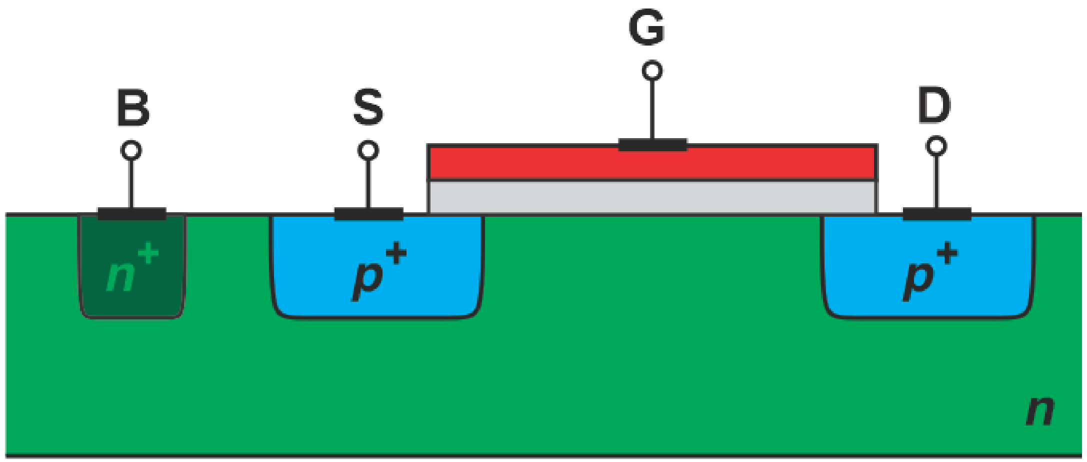
P-kanalni MOS tranzistor

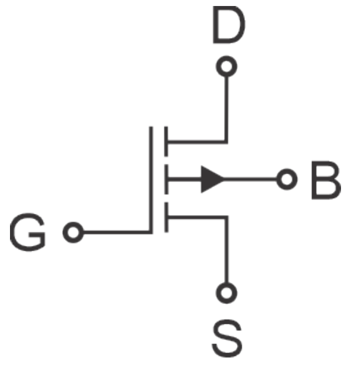


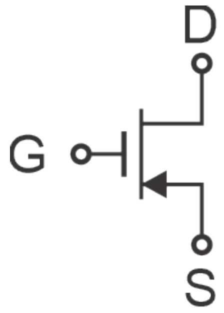
t_{ox}≈1.8nm, L≈90nm

$$C_{ox} = \varepsilon_{ox} \frac{L \cdot W}{t_{ox}}$$

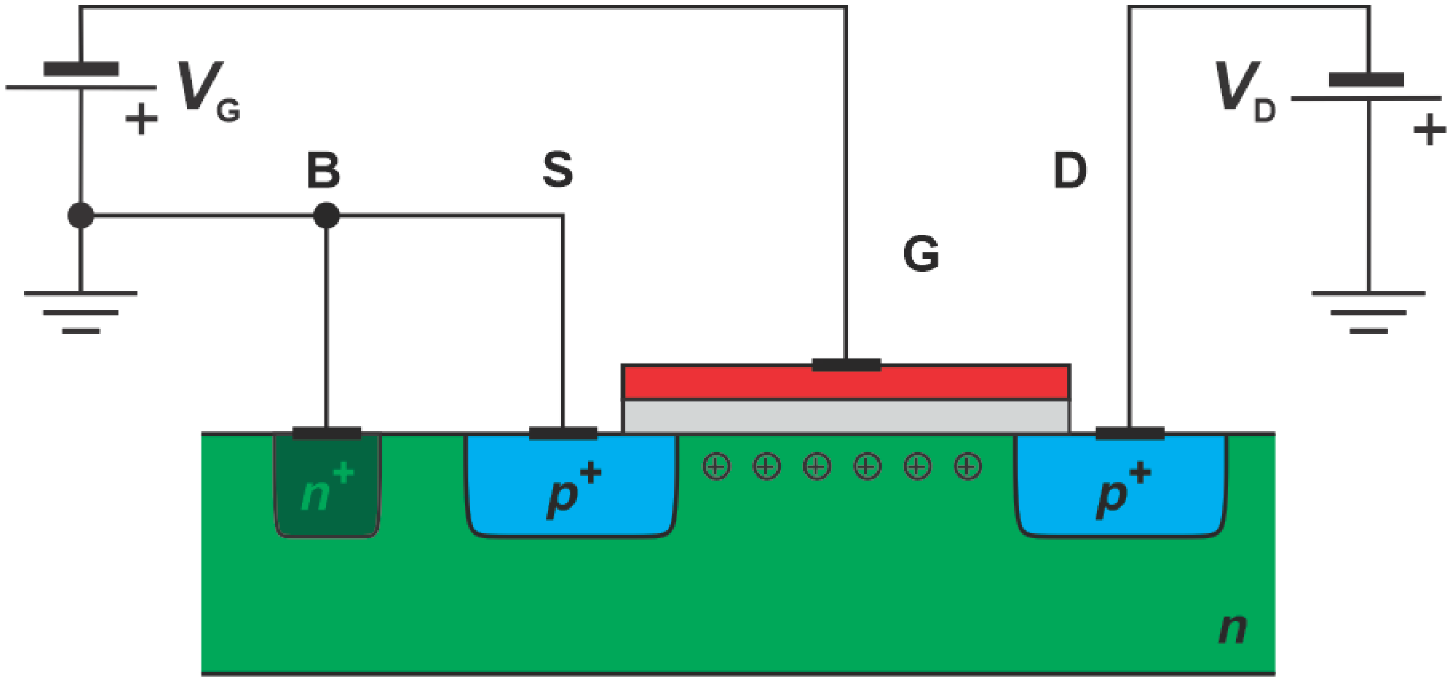
2D struktura MOS tranzistora i simboli (p-kanalni)

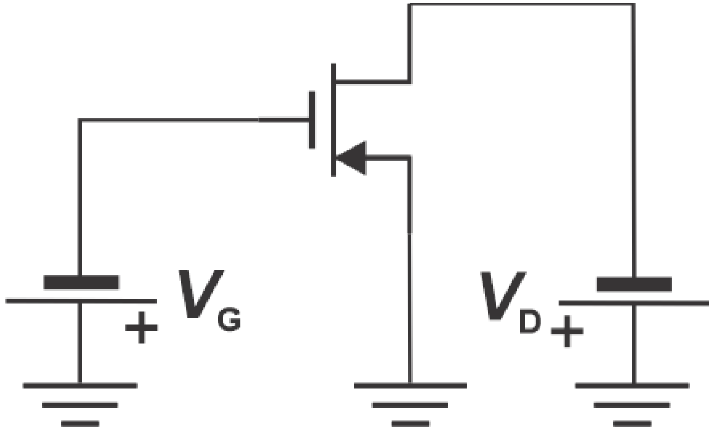






Tranzistorski efekat

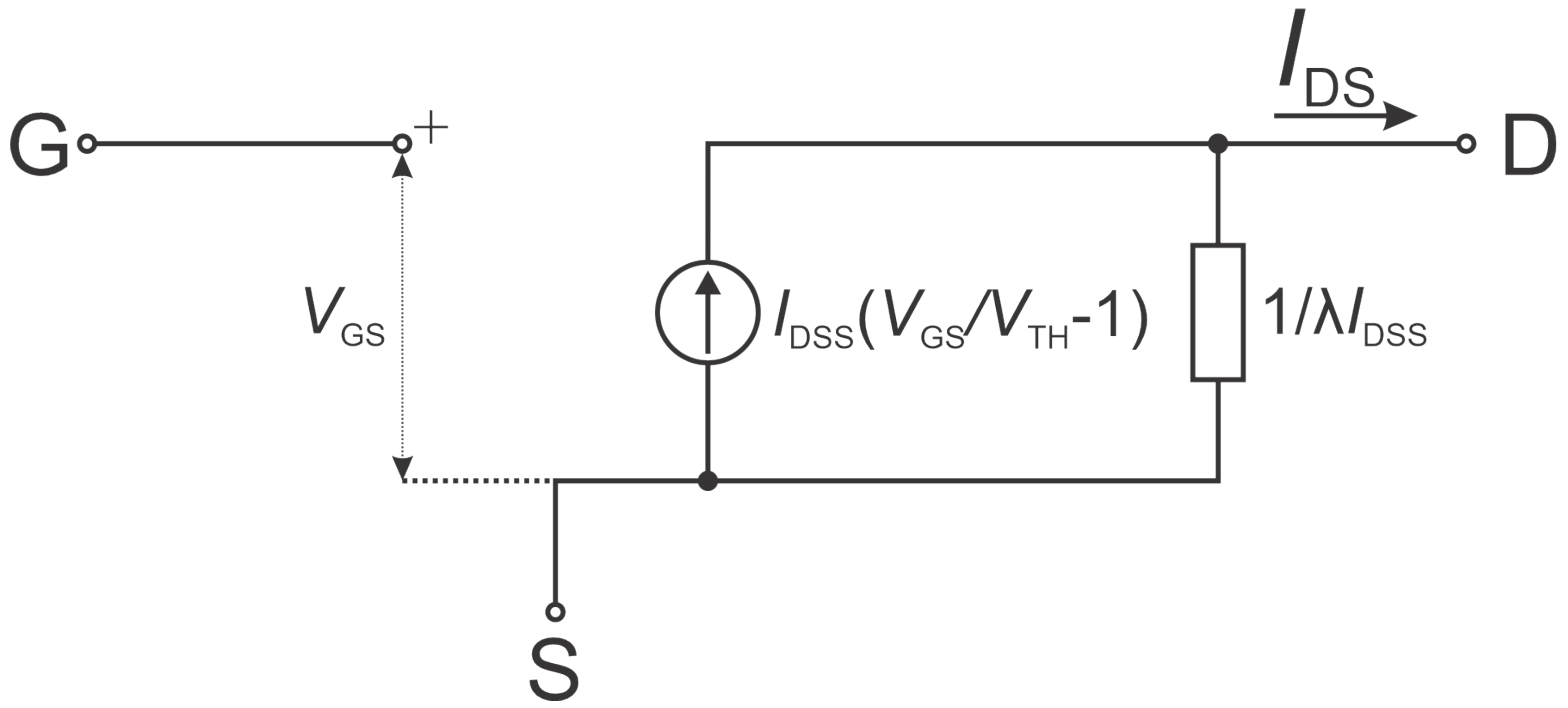




- Kada je $V_D < V_S$, protiče struja drejna koja zavisi od V_D i V_G.

Model za velike signale

- Parametri modela: I_{DSS}, V_{TH}, λ



Model MOS tranzistora za male signale

$$g_\mathrm{m} = \frac{2I_\mathrm{DSS}}{V_\mathrm{TH}} \cdot \left(\frac{V_\mathrm{GS}}{V_\mathrm{TH}} - 1 \right), \quad r_\mathrm{o} = \frac{1}{\lambda I_\mathrm{DS0}}$$