VREMENSKI ODZIV RC MREŽA

- prvo gledamo za $t=0^-$ i $t=0^+$ $\qquad \tau = R \cdot C$
- $0 \le t \le T$

$$u_C(t) = \underbrace{U_{C0}}_{\text{poč. vrijednost napona na kond.}} + \underbrace{(U_0 - U_{C0})}_{\text{razlika napona koja nabija kond.}}\left(1 - \exp\left(\frac{-t}{\tau}\right)\right)$$

- za nabijanje kondezatora je potrebno vrijeme jednako iznosu 5 vremenskih konstanti (5τ)

$$u_R(t) = u_{UL}(t) - u_C(t) = (U_0 - U_{C0})\exp\left(\frac{-t}{\tau}\right) \qquad 0<t<T$$

- u trenutku T^+ ulazni napon pada na 0V

- za $t \geq T$ $\qquad u_C(t) = u_C(T) \cdot \exp\left(\frac{-(t-T)}{\tau}\right)$

- $u_R(t) = -u_C(t) \qquad t > T$

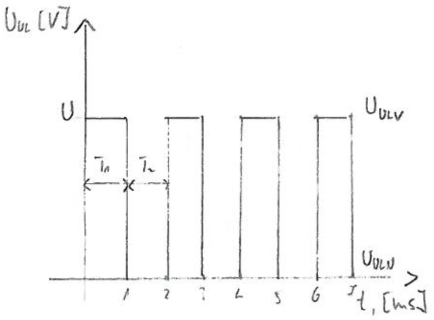
- CR - mreža:

$$u_{iz}(t) = \frac{R}{R+R_g}(U_0 - U_{C0})\exp\left(\frac{-t}{\tau}\right) \quad 0 \le t \le T$$

ako postoji unutarnji otpor (R_g) generatora

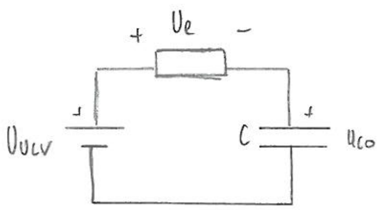
- u trenutku T^+ vrijedi: $u_{iz}(T^+) = -u_C(T^+) \cdot \frac{R}{R+R_g}$
- za $t > T$ $\qquad u_{iz}(t) = u_{iz}(T^+)\exp\left(\frac{-(t-T)}{\tau}\right)$

- analiza odziva na simetričan pravokutni napon

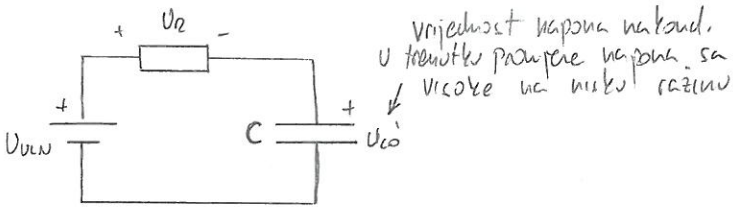


- oznake:
  - visoka razina ulaznog napona – U_{ULV}
  - trajanje visoke razine ulaznog napona – T_1
  - niska razina ulaznog napona – U_{ULN}
  - trajanje niske razine ulaznog napona – T_2
  - početni napon na kondezatoru – U_{C0}

- visoka razina:



- niska razina:



$$u_C(t) = U_{C0} + (U_{ULV} - U_{C0})\left(1 + \exp\left(-\frac{t}{\tau}\right)\right) \quad 0 \le t \le T_1$$

$$u_R(t) = U_{ULV} - u_C(t) = (U_{ULV} - U_{C0})\exp\left(-\frac{t}{\tau}\right) \quad 0<t<T_1$$

$$u_C(t') = U_{C0}' + (U_{ULN} - U_{C0}')\left(1 - \exp\left(\frac{-t'}{\tau}\right)\right) \quad 0 \le t' \le T_2$$

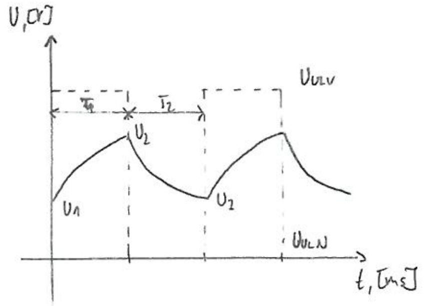
$$u_R(t') = U_{ULN} - u_C(t') = (U_{ULN} - U_{C0}')\exp\left(\frac{t'}{\tau}\right) \quad 0 < t' < T_2$$

$t' = 0 \Rightarrow$ trenutak promjene ulaznog napona sa visoke razine na nisku

- strmine izbijanja i nabijanja kond. nisu jednake: $|U_{ULV} - U_{C0}| > |U_{ULN} - U_{C0}'|$

- u stacionarnom stanju napon na kond. varira oko srednje vrijednosti ulaznog napona. Srednja vrijednost napona na kond. jednaka je srednjoj vrijednosti ulaznog napona, dok srednja vrijednost napona na otporniku iznosi 0V.

- odziv na kondenzatoru



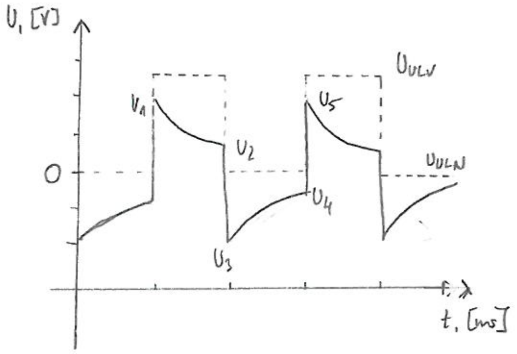
$$U_2 = U_1 + (U_{ULV} - U_1)\left(1-\exp\left(\frac{-T_1}{\tau}\right)\right) = U_{ULV} - (U_{ULV} - U_1)\exp\left(\frac{-T_1}{\tau}\right)$$

$$U_3 = U_2 + (U_{ULN} - U_2)\left(1-\exp\left(\frac{-T_2}{\tau}\right)\right) = U_{ULN} - (U_{ULN} - U_2)\exp\left(\frac{-T_2}{\tau}\right)$$

$$U_3 = U_1$$

- za simetričan signal vrijedi: $U_{ULV} - U_2 = U_1 - U_{ULN}$
- $u_R(t) = u_{UL}(t) - u_C(t)$

- odziv na naponu



$$U_0 = U_{ULV} - U_{ULN}$$
$$U_2 = U_1 \cdot \exp\left(\frac{-T_1}{\tau}\right)$$
$$U_3 = U_2 - U_0$$
$$U_4 = U_3 \cdot \exp\left(\frac{-T_2}{\tau}\right)$$
$$U_5 = U_4 + U_0 = U_1$$

- za simetričan signal: $U_3 = -U_1$ i $U_4 = -U_2$
- $U_C(t) = u_{UL}(t) - u_R(t)$

OSNOVNA SVOJSTVA POLUVODIČA

- $n_i = C \cdot T^{3/2} \exp\left[-\frac{E_G(T)}{2 \cdot E_T}\right] = C_1 \cdot T^{3/2} \cdot \exp\left(-\frac{E_{G0}}{2E_T}\right)$

$C = 7{,}07 \cdot 10^{15}$ $\quad E_{G0} = 1{,}196$

$C_1 = 3{,}07 \cdot 10^{16}$ $\quad E_T = k \cdot T = 8{,}62 \cdot 10^{-5} \cdot T$

- $n_i^2 = n \cdot p$
  - ako je $n \gg n_i$ ili $p \gg n_i$ onda je vodič EKSTRINZIČAN i možemo zaključiti:

$$n \cong N_D \quad \text{ili} \quad p \cong N_A$$

  - ako ne vrijedi $N_D \gg n_i$ ili $N_A \gg n_i$ vodič je INTRINZIČAN te koristimo:

$$n = \frac{1}{2}\left[N_D + \sqrt{N_D^2 + 4n_i^2}\right] \quad \text{ili} \quad p = \frac{1}{2}\left[N_A + \sqrt{N_A^2 + 4n_i^2}\right]$$

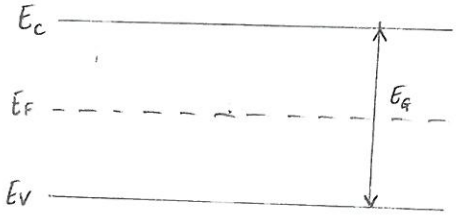
- Fermijeva energija

$$n_0 = N_C \exp\left(\frac{E_F - E_C}{E_T}\right) = n_i \exp\left(\frac{E_F - E_{Fi}}{E_T}\right)$$

$$p_0 = N_V \exp\left(\frac{E_V - E_F}{E_T}\right) = n_i \exp\left(\frac{E_{Fi} - E_F}{E_T}\right)$$

$$N_C = N_V = C T^{3/2}$$

$$E_{Fi} = \frac{E_V + E_C}{2}$$



E_C - vodljivi pojas

E_V - valentni pojas

- Vodljivost: $\sigma = q(\mu_n \cdot n + \mu_p \cdot p)$

- otpor silicijske pločice: $R = \rho \cdot \frac{l}{S} = \frac{1}{\sigma} \cdot \frac{l}{S} \Rightarrow \rho = \frac{1}{\sigma} \Rightarrow$ specifični otpor

pn - DIODA

- kontaktni potencijal: $U_K = U_T \cdot \ln\left(\frac{n_{on} \cdot p_{op}}{n_i^2}\right)$
- širina osiromašenog područja: $d_B = \sqrt{\frac{2\varepsilon_0 \cdot \varepsilon_r}{q} \cdot \left(\frac{1}{N_A} + \frac{1}{N_D}\right) \cdot (U_k - U)}$
- kapacitet osiromašenog područja: $C_B = \varepsilon_0 \cdot \varepsilon_r \cdot \frac{S}{d_B}$
- struja zasićenja za diodu:

$$I_s = q \cdot S \cdot \left(D_n \frac{n_{op}}{L_n} + D_p \frac{p_{op}}{L_p}\right) \quad \text{ili} \quad I_s = q \cdot S \cdot \left(D_n \frac{n_{op}}{W_p} + D_p \frac{p_{on}}{W_n}\right)$$

- ako je $L_p \gg W_n$ koristimo W_n inače L_p, ako je $L_n \gg W_p$ koristimo W_p inače L_n

- manjinski nosioci na p-strani:

$n_{op} = \frac{n_i^2}{N_A}$

$D_n = \mu_n \cdot U_T$

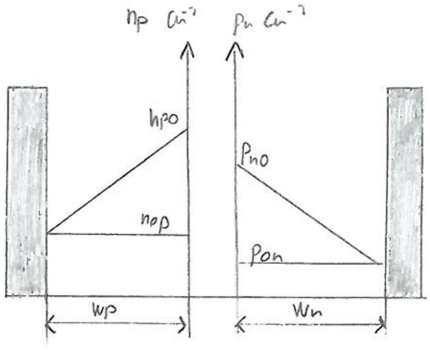
$L_n = \sqrt{D_n \cdot \tau_n}$

- manjinski nosioci na n-strani:

$p_{on} = \frac{n_i^2}{N_D}$

$D_p = \mu_p \cdot U_T$

$L_p = \sqrt{D_p \cdot \tau_p}$



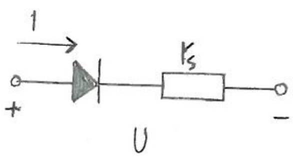
$n_{po} = n_{op} \exp\left(\frac{U}{U_T}\right)$

$p_{no} = p_{on} \exp\left(\frac{U}{U_T}\right)$

- struja kroz diodu:

$$I = I_s \cdot \left[\exp\left(\frac{U}{m \cdot U_T}\right) - 1\right]$$

- dinamički otpor: $r_d = \frac{U_T}{I + I_s}$

- 

$U = U_D + I \cdot R_s$

$U_D = U_T \cdot \ln\left(\frac{I}{I_s} + 1\right)$

- ako je priključena izmjenična struja:

$i_D = I + i_d \sin(\omega t)$

$U = U_D + I \cdot R_s$

$r_d = \frac{U_T}{I + I_s}$

$u_d = i_d (r_d + R_s)$

$\Big\} \; u_D = U + u_d \cdot \sin \omega t$

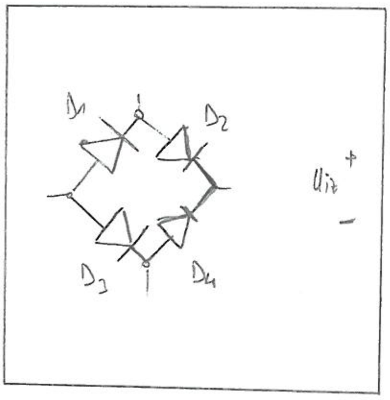
SKLOPOVI S DIODOM

- amplituda napona na sekundaru: $U_{sm} = \frac{\sqrt{2} \cdot U_{pef}}{n} = \frac{U_{pm}}{n} = U_{izm}$ → omjer transformacije transformatora

$\tau = R \cdot C$

$T = \frac{1}{f}$

- amplituda napona valovitosti na trošilu je:
  - poluvalni: $U_{izvm} = U_{izm} \frac{T}{2\tau}$
  - punovalni: $U_{izvm} = U_{izm} \frac{T}{4\tau}$



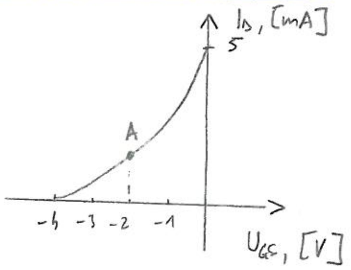
$U_{iz} = U_{izm} - U_{izvm}$

$U_{izef} = \frac{U_{izvm}}{\sqrt{3}}$

$r = \frac{U_{izef}}{U_{iz}}$

↑ faktor valovitosti

Unipolarni tranzistori – JFET



$\Rightarrow \quad U_p = -4V$

$I_{DSS} = 5mA$

- ako je:

$U_p < 0 \quad \rightarrow$ n-kanalni JFET ← I_D opada kada U_{GS} postaje negativniji

$U_p > 0 \quad \rightarrow$ p-kanalni JFET ← I_D raste kada U_{GS} postaje negativniji

- U zasićenju vrijedi:

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

$$g_m = \frac{\partial i_D}{\partial u_{GS}}\bigg|_{U_{DS}} = \frac{2 \cdot I_{DSS}}{-U_p}\left(1 - \frac{U_{GS}}{U_p}\right)$$

$$I_D = I_{DSS}\left(1 - \frac{U_{GS}}{U_p}\right)^2 (1 + \lambda U_{DS})$$

$$g_d = \frac{\partial i_D}{\partial u_{DS}}\bigg|_{U_{GS}} = \lambda \cdot I_{DSS}\left(1 - \frac{U_{GS}}{U_p}\right)^2 = \frac{\lambda \cdot I_D}{(1 + \lambda \cdot U_{DS})}$$

$$r_d = \frac{1}{g_d}$$

$$\mu = g_m \cdot r_d$$

Unipolarni tranzistori – MOSFET

- kad U_{GS} postaje pozitivniji a I_D raste → n-kanalni MOSFET
- kad U_{GS} postaje negativniji a I_D raste → p-kanalni MOSFET

- kad za $U_{GS} = 0V$ kanal nije formiran $(I_D = 0)$ → OBOGAĆENI TIP (radi samo s jednim predznakom napona upravljačke elektrode)
- kad za $U_{GS} = 0V$ kanal je formiran $(I_D \neq 0)$ → OSIROMAŠEN TIP (radi s dva predznaka napona upravljačke diode)

- za konstantan napon faktor λ nam nije potreban

- Ako je:

1) $|U_{DS}| < |U_{GS} - U_{GS0}|$ → MOSFET je u TRIODNOM području

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

- dinamički parametri:

$$g_m = \left.\frac{\partial i_D}{\partial U_{GS}}\right|_{U_{DS}} = K \cdot U_{DS}$$

$$g_d = \left.\frac{\partial i_D}{\partial U_{DS}}\right|_{U_{GS}} = K \cdot (U_{GS} - U_{GS0} - U_{DSQ})$$

$$r_d = \frac{1}{g_d}$$

$$\mu = g_m \cdot r_d$$

2) $|U_{DS}| > |U_{GS} - U_{GS0}|$ → MOSFET je u ZASIĆENOM području

$$I_D = \frac{K}{2}(U_{GS} - U_{GS0})^2(1 + \lambda U_{DS})$$

- dinamički parametri:

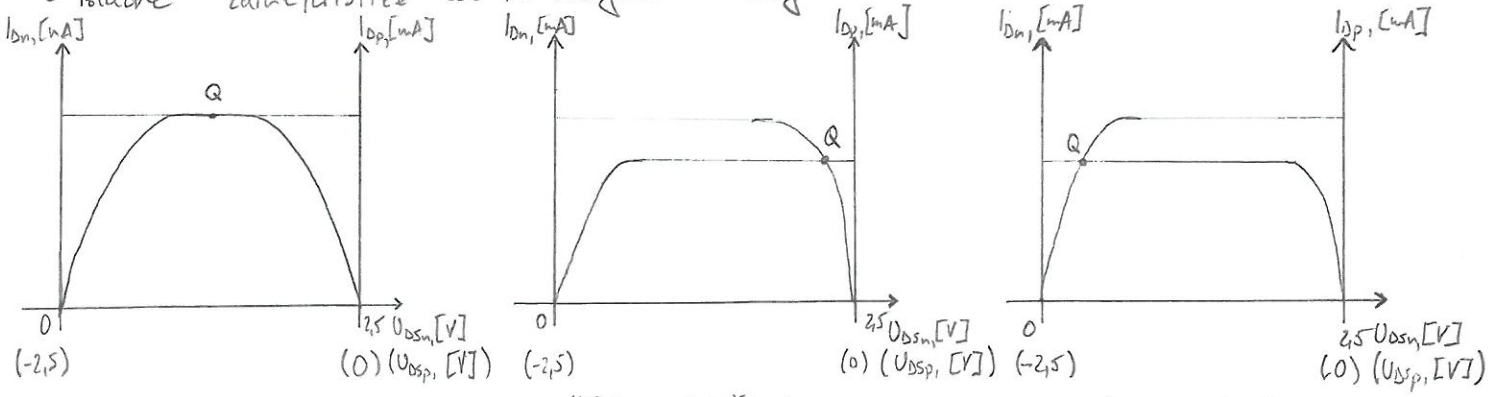
$$g_m = \left.\frac{\partial i_D}{\partial U_{GS}}\right|_{U_{DS}} = K(1 + \lambda U_{DS})(U_{GS} - U_{GS0})$$

$$g_d = \left.\frac{\partial i_D}{\partial U_{DS}}\right|_{U_{GS}} = \frac{K\lambda}{2}(U_{GS} - U_{GS0})^2 = \frac{K \cdot \lambda}{2}(U_{GS} - U_{GS0})^2\,\frac{1 + \lambda U_{DS}}{1 + \lambda U_{DS}} = \frac{I_D}{U_{DS} + \frac{1}{\lambda}}$$

- $$K = \mu_n \cdot \frac{\varepsilon_{ox}}{t_{ox}} \cdot \frac{W}{L}$$ → konstanta MOSFET-a

$$C_G = \frac{\varepsilon_{ox}}{t_{ox}} \cdot W \cdot L = \frac{\varepsilon_{ox}}{t_{ox}} \cdot \frac{W}{L} \cdot L^2 = \frac{K}{\mu_n} \cdot L^2$$ → kapacitet upravljačke elektrode

- izlazne karakteristike za tri moguća slučaja:



NMOS i PMOS u zasićenju

NMOS u zasićenju
PMOS u triodnom

NMOS u triodnom
PMOS u zasićenom

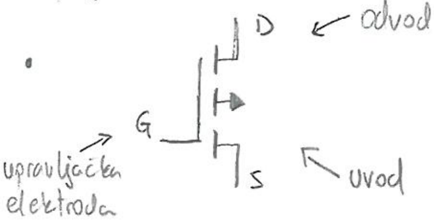
-  → PMOS  → NMOS

- $U_{GS} = U_G - U_S$

SKLOPOVI S MOSFET-om

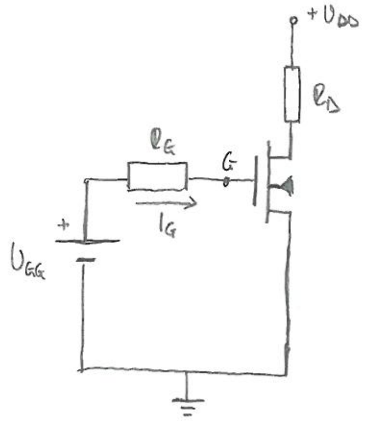
- spojevi pojačala: → spoj zajedničkog uvoda
  → spoj zajedničke upravljačke elektrode
  → spoj zajedničkog odvoda

- da bi odredili koji spoj imamo pogledamo na što su spojeni ulaz i izlaz pojačala, što nam ostane to je zajedničko

- 

- određivanje statičke radne točke:
  - pri statičkoj analizi kondezatori predstavljaju beskonačno velik otpor pa ih odspajamo
  - tri slučaja:

    1) bez otpora R_S u shemi



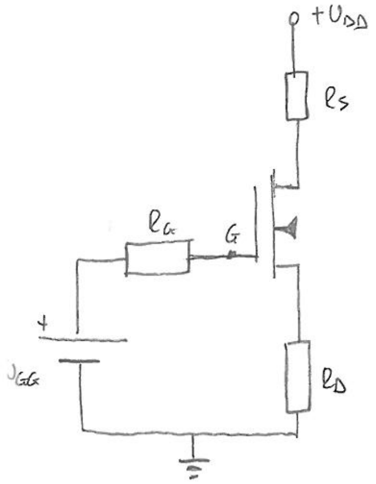
$$I_{DQ} = \frac{k}{2}\left(U_{GSQ} - U_{GS0}\right)^2$$

$$U_{GSQ} = \frac{R_2}{R_1+R_2} \cdot U_{DD}$$

$$R_G = R_1 \parallel R_2$$

$$U_{DSQ} = U_{DD} - R_D \cdot I_{DQ}$$

2) Uz otpor R_S u shemi



$$R_G = R_1 \| R_2$$

$$U_{GG} = \frac{R_2}{R_1 + R_2} U_{DD}$$

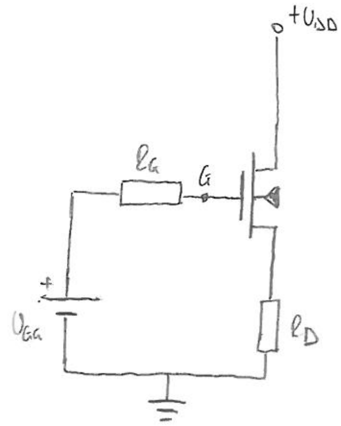
$$I_{DQ} = \frac{K}{2}(U_{GSQ} - U_{GS0})^2 = \frac{U_{GG} - U_{GSQ}}{R_S}$$

$$\Rightarrow \quad U_{GSQ}^2 + 2\left(\frac{1}{K \cdot R_S} - U_{GS0}\right) U_{GSQ} + U_{GS0}^2 - 2\frac{U_{GG}}{K \cdot R_S} = 0$$

- NMOS $\Rightarrow$ $U_{GSQ} > U_{GS0}$
- PMOS $\Rightarrow$ $U_{GSQ} < U_{GS0}$

$$U_{DSQ} = U_{DD} - I_{DQ}(R_S + R_D)$$

3) bez otpora R_D u shemi



$$R_G = R_1 \| R_2$$

$$U_{GG} = \frac{R_2}{R_1 + R_2} U_{DD}$$

$$I_{DQ} = \frac{K}{2}(U_{GSQ} - U_{GS0})^2 = \frac{U_{GG} - U_{GS0}}{R_S}$$

$$\Rightarrow \quad U_{GSQ}^2 + 2\left(\frac{1}{K R_S} - U_{GS0}\right) U_{GSQ} + U_{GS0}^2 - 2\frac{U_{GG}}{K \cdot R_S} = 0$$

- NMOS $\Rightarrow$ $U_{GSQ} > U_{GS0}$
- PMOS $\Rightarrow$ $U_{GSQ} < U_{GS0}$

$$U_{DSQ} = U_{DD} - I_{DQ} \cdot R_S$$

- određivanje dinamičkih parametara:
  - kako tranzistor radi kao pojačalo samo kada je u zasićenju konstrno struju:

$$I_D = \frac{K}{2}(U_{GSQ} - U_{GS0})^2 \cdot (1 + \lambda U_{DS})$$

$$g_m = \left.\frac{\partial i_D}{\partial U_{GS}}\right|_Q = (1 + \lambda U_{DS}) K (U_{GSQ} - U_{GS0})$$

$$g_d = \left.\frac{\partial i_D}{\partial U_{DS}}\right|_Q = \lambda \frac{K}{2}(U_{GSQ} - U_{GS0})^2 = \lambda \cdot I_{DQ}$$

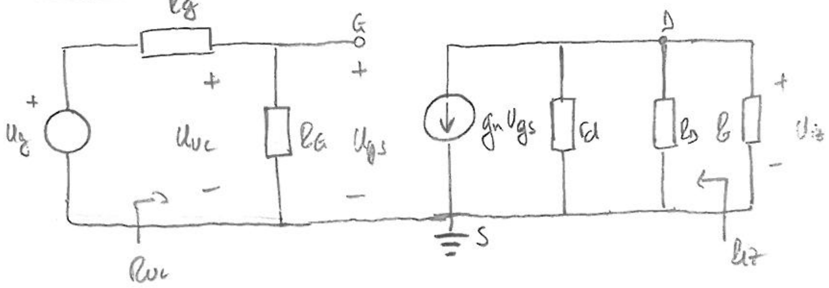
$$r_d = \frac{1}{g_d}$$

$$\mu = r_d \cdot g_m$$

- određivanje parametara tranzistora (A_v, A_{vg}, R_{ul}, R_{iz})

1) Spoj zajedničkog uvoda

a) bez R_S



$$\left.\begin{aligned} U_{iz} &= -g_m \cdot U_{gs} \cdot r_d \| R_D \| R_T \\ U_{ul} &= U_{gs} \end{aligned}\right\} \quad A_v = \frac{U_{iz}}{U_{ul}} = \frac{-g_m \cdot \cancel{U_{gs}} \cdot r_d \| R_D \| R_T}{\cancel{U_{gs}}} = -g_m \cdot r_d \| R_D \| R_T$$

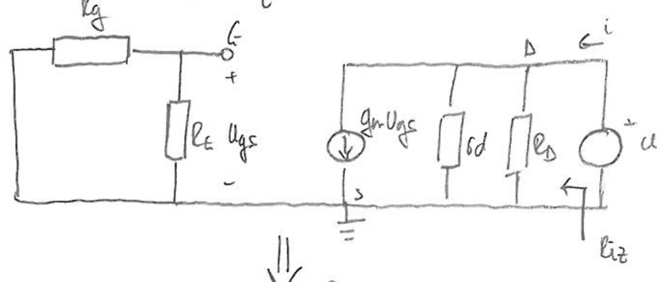
$$U_{ul} = \frac{R_G}{R_g + R_G} U_g$$

$$A_{vg} = \frac{U_{iz}}{U_g} = \frac{U_{iz}}{U_g} \cdot \frac{U_{ul}}{U_{ul}} = A_v \cdot \frac{U_{ul}}{U_g} = A_v \cdot \frac{\frac{R_G}{R_G + R_g} \cdot \cancel{U_g}}{\cancel{U_g}} = A_v \cdot \frac{R_G}{R_G + R_g}$$

$$R_{UL} = R_G$$

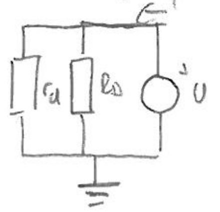
- Kod računanja izlaznog otpora sve nezavisne izvore ugasimo, tj. naponske izvore kratko spojimo, a strujne odspojimo. Zavisni izvori će postojati ako postoji napon ili struja o kojoj su ovisni. Trošilo zamijenimo naponskim izvorom u koji daje struju i. Izlazni otpor jednak je:

$$R_{iz} = \frac{u}{i}$$



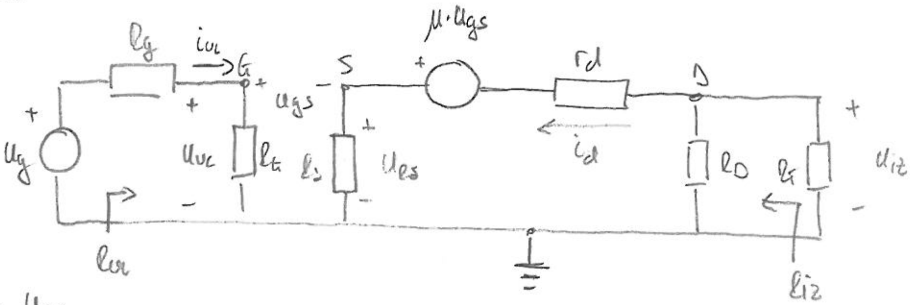
$$\Rightarrow U_{gs} = 0$$

$$\Downarrow$$



$$i = \frac{u}{r_d \| R_D} \quad \Rightarrow \quad R_{iz} = \frac{\cancel{u}}{\frac{\cancel{u}}{r_d \| R_D}} = r_d \| R_D$$

b) Sa R_S



$$i_d = \frac{\mu \cdot u_{gs}}{r_d + R_S + R_D \| R_T} \qquad u_{RS} = i_d \cdot R_S$$

$$u_{gs} = u_{ul} - u_{RS} = u_{ul} - R_S i_d = u_{ul} - R_S \frac{\mu \cdot u_{gs}}{R_S + r_d + R_D \| R_T}$$

$$\Rightarrow u_{ul} = u_{gs} + R_S \frac{\mu \cdot u_{gs}}{R_S + r_d + R_D \| R_T}$$

$$u_{iz} = -i_d \cdot R_D \| R_T = -\frac{R_D \| R_T \cdot \mu \cdot u_{gs}}{R_S + r_d + R_D \| R_T}$$

$$A_v = \frac{u_{iz}}{u_{ul}} = -\frac{\mu \cdot R_D \| R_T}{R_S(1+\mu) + r_d + R_D \| R_T}$$

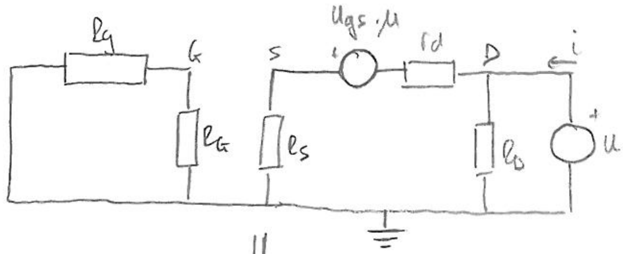
$$u_{ul} = u_g \cdot \frac{R_G}{R_G + R_g}$$

$$A_{vg} = \frac{u_{iz}}{u_g} = A_v \cdot \frac{u_{ul}}{u_g} = A_v \cdot \frac{R_G}{R_G + R_g}$$

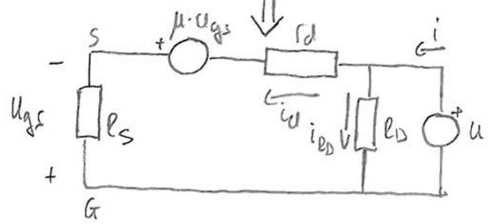
$$R_{ul} = R_G$$

- Kod računanja izlaznog otpora odspojimo sve nezavisne izvore, a zavisni će postojati samo ako postoje napon ili struja o kojoj su ovisni. Trošilo zamijenimo naponskim izvorom u koji daje struju i. Izlazni otpor jednak je:

$$R_{iz} = \frac{u}{i}$$



→ G spojen na masu



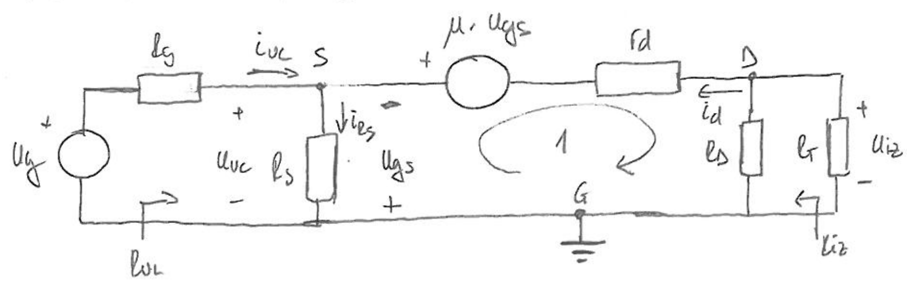
→ u_{gs} postoji

$$i = i_d + i_{RD}, \quad i_d = \frac{u + \mu \cdot u_{gs}}{r_d + R_S}, \quad u_{gs} = -i_d \cdot R_S$$

$$\Rightarrow i_d = \frac{u}{r_d + (1+\mu) R_S}, \quad i_{RD} = \frac{u}{R_S} \Rightarrow i = u \left(\frac{1}{R_S} + \frac{1}{r_d + (1+\mu) R_S} \right)$$

$$R_{iz} = \frac{u}{i} = \frac{u}{u \left(\frac{1}{R_S} + \frac{1}{r_d + (1+\mu) R_S} \right)} = R_S \| [r_d + (1+\mu) R_S]$$

2) Spoj zajedničke upravljačke elektrode



$u_{UL} = -u_{gs}$

• iz petlje "1": $u_{gs} + \mu \cdot u_{gs} - i_d \cdot r_d - i_d \cdot R_D \parallel R_T = 0$

$$(1+\mu)\, u_{gs} = i_d\,(r_d + R_D \parallel R_T)$$
$$-(1+\mu)\, u_{UL} = i_d\,(r_d + R_D \parallel R_T)$$
$$i_d = -\frac{(1+\mu)\cdot u_{UL}}{r_d + R_D \parallel R_T}$$

$$u_{iz} = -i_d \cdot R_D \parallel R_T = \frac{(1+\mu)\cdot u_{UL} \cdot R_D \parallel R_T}{r_d + R_D \parallel R_T}$$

$$A_V = \frac{u_{iz}}{u_{UL}} = \frac{g_m \cdot r_d \cdot R_D \parallel R_T}{r_d + R_D \parallel R_T}$$

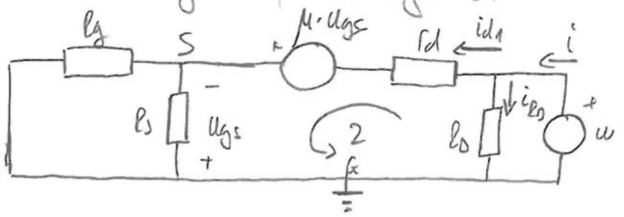
$\mu = g_m \cdot r_d$
ako je $\mu >> 1$
$(1+\mu) \approx \mu = g_m \cdot r_d$

$R_{UL} = \frac{u_{UL}}{i_{UL}}$, $i_{UL} = i_{R_S} - i_d$, $i_{R_S} = \frac{u_{UL}}{R_S}$, $\Rightarrow i_{UL} = u_{UL}\left(\frac{1}{R_S} + \frac{1+\mu}{r_d + R_D \parallel R_T}\right)$

$$R_{UL} = \frac{1}{\frac{1}{R_S} + \frac{g_m \cdot r_d}{r_d + R_D \parallel R_T}} = R_S \parallel \frac{r_d + R_D \parallel R_T}{g_m \cdot r_d}$$

• Kod računanja izlaznog otpora sve nezavisne izvore pogasimo, a zavisni će postojati samo ako postoje napon ili struja o kojoj su ovisni. Trošilo zamijenimo naponskim izvorom u koji daje struju i.

$R_{iz} = \frac{u}{i}$



→ dio struje i stvara pad napona na paraleli R_g i R_S → $u_{gs} \neq 0$

$i = i_{d1} + i_{R_D}$, $i_{R_D} = \frac{u}{R_D}$

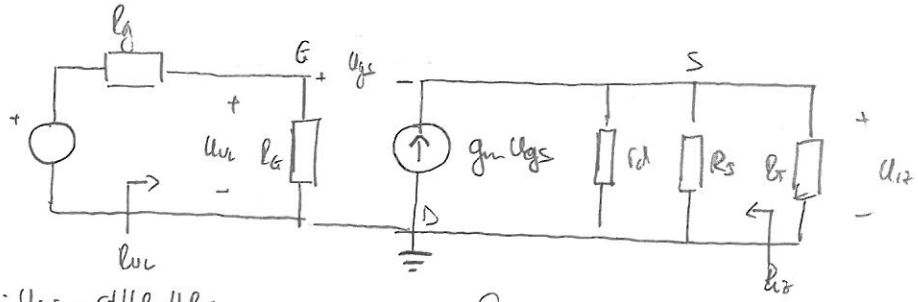
• iz petlje "2":

$$u = i_{d1} \cdot r_d - \mu \cdot u_{gs} + R_g \parallel R_S \cdot i_{d1} \Rightarrow i_{d1} = \frac{u}{r_d + (1+\mu)\, R_S \parallel R_g}$$
$$u_{gs} = -i_{d1} \cdot R_g \parallel R_S$$

$$i = u \cdot \left(\frac{1}{R_D} + \frac{1}{r_d + (1+\mu) R_S \parallel R_g}\right)$$

$$R_{iz} = \frac{u}{i} = \frac{1}{\frac{1}{R_D} + \frac{1}{r_d + (1+\mu) R_S \parallel R_g}} = R_D \parallel \left[r_d + (1+\mu) R_S \parallel R_g\right]$$

3) Spoj zajedničkog odvoda

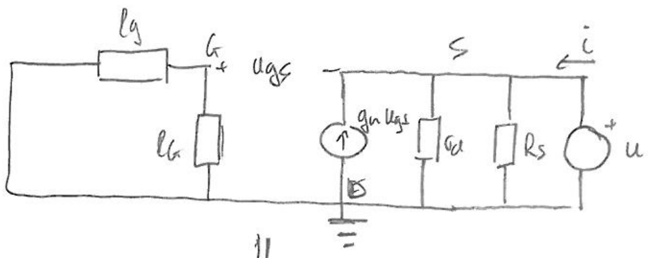


$u_{iz} = g_m \cdot u_{gs} \cdot r_d \| R_S \| R_T$

$u_{ul} = u_{gs} + u_{iz} = u_{gs} \left(1 + g_m \cdot r_d \| R_S \| R_T\right)$ $\Bigg\}$ $A_V = \frac{u_{ul}}{u_{iz}} = \frac{g_m \cdot r_d \| R_S \| R_T}{1 + g_m \cdot r_d \| R_S \| R_T}$

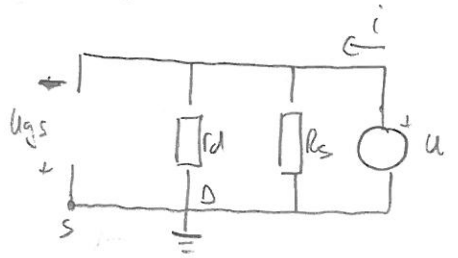
$R_{ul} = \frac{u_{ul}}{i_{ul}} = R_G$

- Kod računanja izlaznog otpora sve nezavisne izvore treba ugasiti, zavisni izvori će postojati ako postoji napon ili struja od koje zavise. Trošilo zamijenimo naponskim izvorom u koji daje struju i. $R_{iz} = \frac{u}{i}$



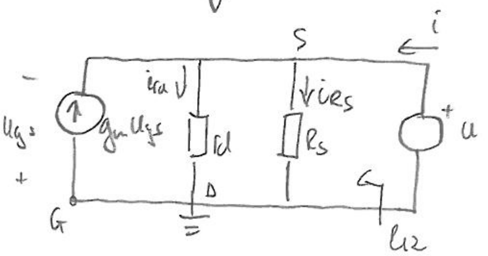
← prvo odspojimo izvor i pogledamo da li postoji napon U_{gs}

$\Downarrow$



← U_{gs} postoji

$\Downarrow$



$i + g_m u_{gs} = i_{rd} + i_{RS}$

$\Rightarrow i = i_{rd} + i_{RS} - g_m u_{gs} = i_{rd} + i_{RS} + g_m u$

$i = \frac{u}{r_d} + \frac{u}{R_S} + g_m u$

$R_{iz} = \frac{u}{i} = \frac{1}{\frac{1}{r_d} + \frac{1}{R_S} + g_m} = r_d \| R_S \| \frac{1}{g_m}$

BIPOLARNI TRANZISTOR

- NPN tranzistor

  - $I_E < 0 \qquad I_C, I_B > 0$

$$I_E + I_C + I_B = 0$$

$$-I_E = I_{nE} + I_{pE}$$

$$I_C = I_{nC} + I_{CBO} = -\overbrace{\gamma \beta^*}^{\alpha} I_E + I_{CBO}$$

$$I_B = I_{pE} + I_R - I_{CBO}$$

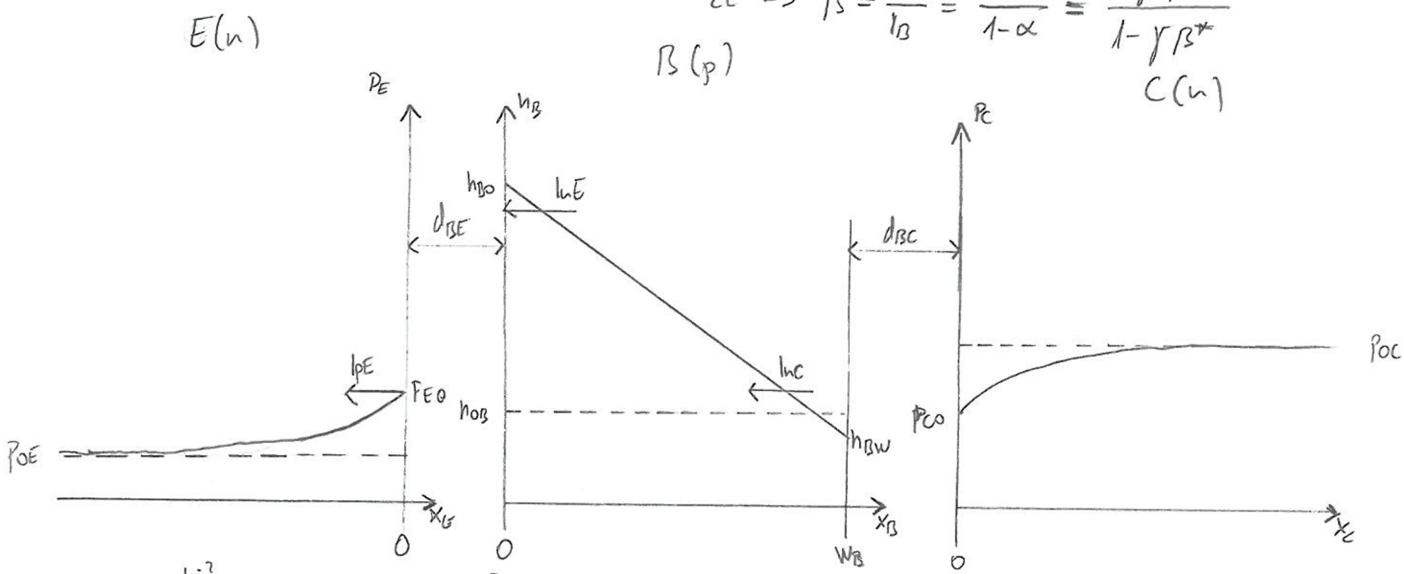
$$I_R = I_{nE} - I_{nC}$$

- Faktor injekcije / efikasnost emitera : $\gamma = \dfrac{I_{nE}}{I_{nE} + I_{pE}} = \dfrac{I_{nE}}{-I_E} = \dfrac{1}{1 + \frac{I_{pE}}{I_{nE}}}$

- transportni faktor : $\beta^* = \dfrac{I_{nC}}{I_{nE}} = 1 - \dfrac{I_R}{I_{nE}} = 1 - \dfrac{1}{2}\left(\dfrac{w_B}{L_{nB}}\right)^2$

- Faktor strujnog pojačanja : ZB $\rightarrow \alpha = \dfrac{I_C}{-I_E} = \dfrac{I_{nC}}{I_{nE} + I_{pE}} = \dfrac{\beta^* I_{nE}}{I_{nE} + I_{pE}} = \beta^* \cdot \gamma$

ZE $\rightarrow \beta = \dfrac{I_C}{I_B} = \dfrac{\alpha}{1-\alpha} = \dfrac{\gamma \cdot \beta^*}{1 - \gamma \beta^*}$



$n_{0B} = \dfrac{n_i^2}{N_{AB}} \qquad p_{0E} = \dfrac{n_i^2}{N_{DE}} \quad \leftarrow$ ravnotežne koncentracije

- rubne koncentracije :

$$n_{B0} = n_{0B} \cdot \exp\left(\frac{U_{BE}}{U_T}\right) \qquad p_{E0} = p_{0E} \cdot \exp\left(\frac{U_{BE}}{U_T}\right)$$

$$n_{BW} = n_{0B} \exp\left(\frac{U_{BC}}{U_T}\right) \qquad p_{C0} = p_{0C} \exp\left(\frac{U_{BC}}{U_T}\right)$$

- komponente struja:

$$I_{nE} = q S D_{nB} \cdot \frac{n_{B0}}{W_B} = \frac{Q_{nE}}{t_r}$$

$$I_{pE} = q S D_{pE} \cdot \frac{p_{E0}}{W_E}$$

$$\gamma = \frac{1}{1 + \frac{D_{pE} W_B N_{AB}}{D_{nE} W_E N_{DE}}}$$

- nakrani naboj:

$$Q_{nB} \approx q S \frac{n_{B0} W_B}{2}$$

$$\frac{Q_{nB}}{I_{nE}} = t_{tr} = \frac{W_B^2}{2D_{nB}}$$ ⇒ vrijeme proleta manjinskih nosilaca kroz bazu

$$I_R = q S D_{nB} \frac{n_{B0}}{W_B} \frac{W_B^2}{2L_{nB}^2} = q S \frac{n_{B0} \cdot W_B}{2 \tau_{nB}}$$

$$\tilde{\tau}_{nB} = \frac{Q_{nB}}{I_R}$$ → vrijeme života manjinskih elektrona u bazi

- PNP tranzistor
  - $I_E > 0 \qquad I_C, I_B < 0$

$$I_E = I_{pE} + I_{nE}$$

$$I_C = -I_{pC} + I_{CB0} = -\alpha I_E + I_{CB0}$$

$$I_R = I_{pE} - I_{pC}$$

$$I_B = -I_{nE} - I_R - I_{CB0}$$

- faktor injekcije: $\gamma = \frac{I_{pE}}{I_{pE} + I_{nE}} = \frac{I_{pE}}{I_E} = \frac{1}{1 + \frac{D_{nE} W_B N_{DB}}{D_{pB} L_{nE} N_{AE}}}$

- transportni faktor: $\beta^* = \frac{I_{pC}}{I_{pE}} = 1 - \frac{I_R}{I_E} = 1 - \frac{1}{2}\left(\frac{W_B}{L_{pB}}\right)^2$

- naboj: $Q_{pB} = q S \frac{p_{B0} \cdot W_B}{2}$

$$I_{pE} = q S D_{pB} \frac{p_{B0}}{W_B}$$

$$I_R = q S \frac{p_{B0} W_B}{2 \tau_{pB}}$$

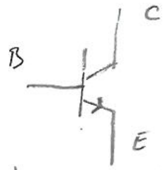
$$\frac{Q_{pB}}{I_{pE}} = \frac{W_B^2}{2D_{pB}} = t_{tr}$$

$$\frac{Q_{pB}}{I_R} = \tilde{\tau}_{pB}$$

SKLOPOVI S BIPOLARNIM TRANZISTORIMA

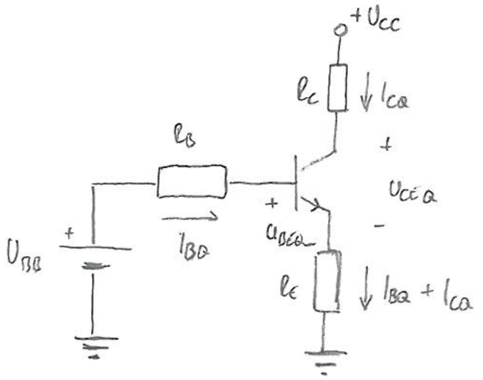
- spojevi pojačala : → spoj zajedničkog emitera
  → spoj zajedničke baze
  → spoj zajedničkog kolektora

- da bi odredili koji spoj imamo pogledamo na što su nam spojeni ulaz i izlaz pojačala, što nam ostane to je zajedničko



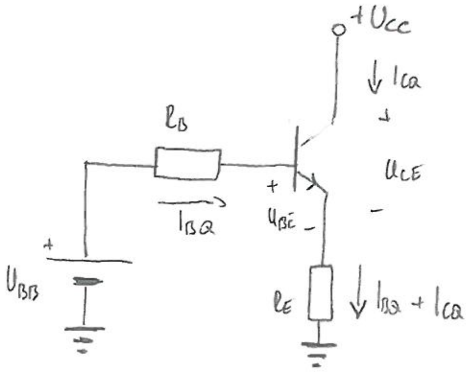
- NPN → strelica prema van
- PNP → strelica prema unutra

- određivanje statičke radne točke:
  - dva slučaja:
    1) sa otporom R_C u shemi



$$R_B = R_1 \| R_2$$
$$U_{BB} = \frac{R_2}{R_1 + R_2} U_{CC}$$
$$U_{BEQ} = U_\gamma$$
$$I_{BQ} = \frac{U_{BB} - U_{BEQ}}{R_B + (1+\beta) R_E}$$
$$I_{CQ} = \beta \cdot I_{BQ}$$
$$U_{CEQ} = U_{CC} - R_C \cdot I_{CQ} - R_E (I_{BQ} + I_{CQ})$$

2) bez otpora R_C u shemi



$$R_B = R_1 \| R_2$$
$$U_{BB} = \frac{R_2}{R_1 + R_2} U_{CC}$$
$$U_{BEQ} = U_\gamma$$
$$I_{BQ} = \frac{U_{BB} - U_{BEQ}}{R_B + (1+\beta) R_E}$$
$$I_{CQ} = \beta \cdot I_{BQ}$$
$$U_{CEQ} = U_{CC} - R_E (I_{BQ} + I_{CQ})$$

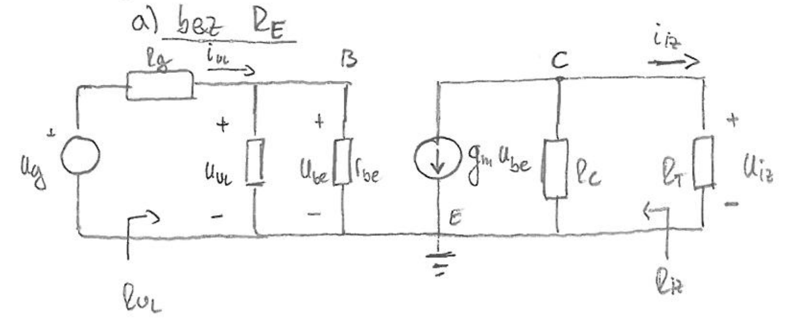
- određivanje dinamičkih parametara:

$$h_{fe} \approx \beta$$
$$r_{be} = \frac{U_T}{I_{BQ}}$$
$$r_{ce} = \frac{U_{CEQ} + U_A}{I_{CQ}}$$
$$g_m = \frac{h_{fe}}{r_{be}}$$

• određivanje parametara tranzistora:

1) zajednički emiter

a) bez R_E



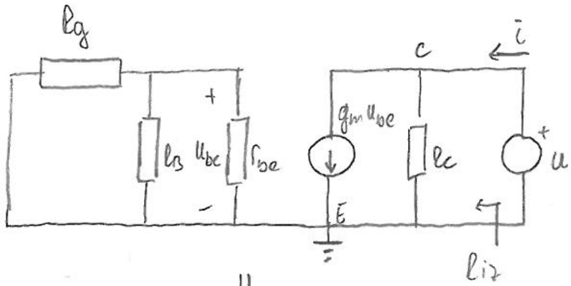
$$\left.\begin{aligned} u_{iz} &= -g_m \cdot u_{be} \, R_C \| R_T \\ u_{ul} &= u_{be} \end{aligned}\right\} \quad A_V = \frac{u_{iz}}{u_{ul}} = -g_m \cdot R_C \| R_T$$

$$\left.\begin{aligned} i_{iz} &= \frac{u_{iz}}{R_T} \\ i_{ul} &= \frac{u_{ul}}{R_B \| r_{be}} \end{aligned}\right\} \quad A_i = \frac{i_{iz}}{i_{ul}} = \frac{\frac{u_{iz}}{R_T}}{\frac{u_{ul}}{R_B \| r_{be}}} = A_V \cdot \frac{r_{be} \| R_B}{R_T}$$

$$u_{ul} = u_g \cdot \frac{R_B \| r_{be}}{R_B \| r_{be} + R_g} \Rightarrow A_{vg} = \frac{u_{iz}}{u_g} = \frac{u_{iz}}{u_g} \cdot \frac{u_{ul}}{u_{ul}} = A_V \cdot \frac{u_{ul}}{u_g} = A_V \cdot \frac{R_B \| r_{be}}{R_B \| r_{be} + R_B}$$

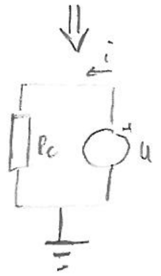
$$R_{ul} = R_B \| r_{be}$$

• za računanje izlaznog otpora sve nezavisne izvore ugasimo, a zavisni će postojati samo ako postoje napon ili struja o kojoj su ovisni. Trošilo zamijenimo naponskim izvorom u koji daje struju i: $R_{iz} = \frac{u}{i}$



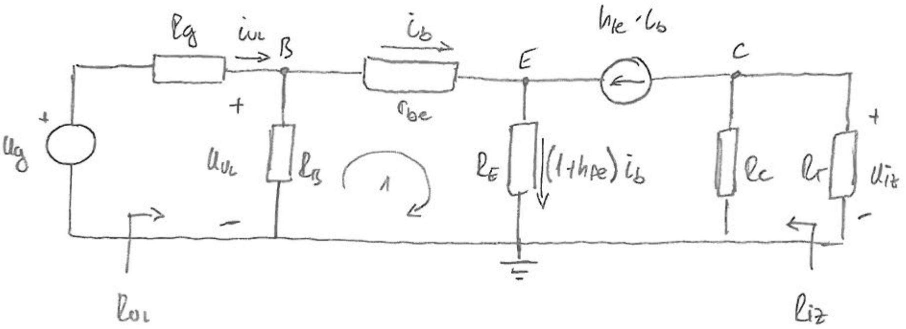
• iz slike vidimo da je $u_{be} = 0$

$\Downarrow$



$$i = \frac{u}{R_C} \Rightarrow R_{iz} = \frac{u}{\frac{u}{R_C}} = R_C$$

b) sa R_E



$u_{iz} = -h_{fe}\cdot i_b \cdot R_C||R_T$

• iz petlje "1":

$u_{ul} = i_{be}\cdot r_{be} + i_b(1+h_{fe})R_E$

$$A_V = \frac{u_{iz}}{u_{ul}} = -\frac{h_{fe}\cdot R_C||R_T}{r_{be}+(1+h_{fe})R_E}$$

$R_{ul} = \frac{u_{ul}}{i_{ul}}$, $i_{ul} = i_B + i_{RB}$, $i_{RB} = \frac{u_{ul}}{R_B}$, $i_b = \frac{u_{ul}}{r_{be}+(1+h_{fe})R_E}$

$$R_{ul} = \frac{\cancel{u_{ul}}}{\cancel{u_{ul}}\left(\frac{1}{R_B}+\frac{1}{r_{be}+(1+h_{fe})R_E}\right)} = R_B \,||\, \underbrace{\left[r_{be}+(1+h_{fe})R_E\right]}_{R'_{ul}}$$

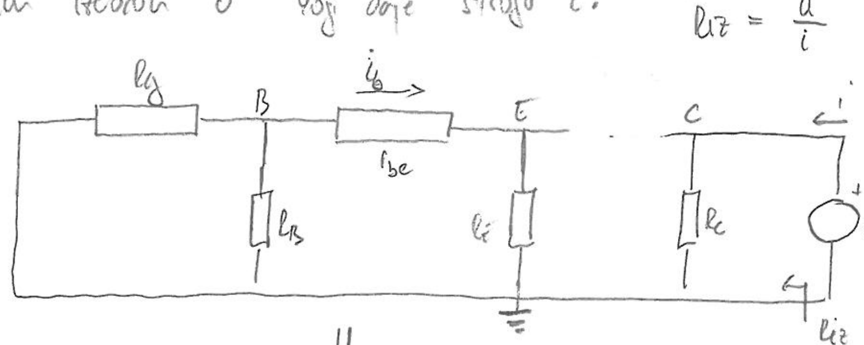
$i_{iz} = \frac{u_{iz}}{R_T}$

$i_{ul} = \frac{u_{ul}}{R_{ul}}$

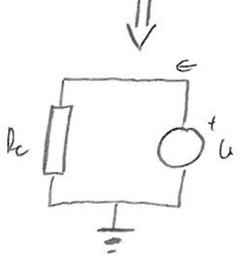
$$A_i = \frac{i_{iz}}{i_{ul}} = \frac{\frac{u_{iz}}{R_T}}{\frac{u_{ul}}{R_{ul}}} = A_V\cdot\frac{R_{ul}}{R_T}$$

$$u_{ul} = u_g\cdot\frac{R_{ul}}{R_{ul}+R_g} \Rightarrow A_{vg} = \frac{u_{iz}}{u_g} = \frac{u_{iz}}{u_g}\cdot\frac{u_{ul}}{u_{ul}} = A_V\cdot\frac{u_{ul}}{u_g} = A_V\cdot\frac{R_{ul}}{R_{ul}+R_T}$$

• za računanje izlaznog otpora odspojimo sve nezavisne izvore, a zavisni će postojati samo ako postoje napon ili struja o kojoj su ovisni. Trošilo zamijenimo naponskim izvorom u koji daje struju i: $R_{iz} = \frac{u}{i}$

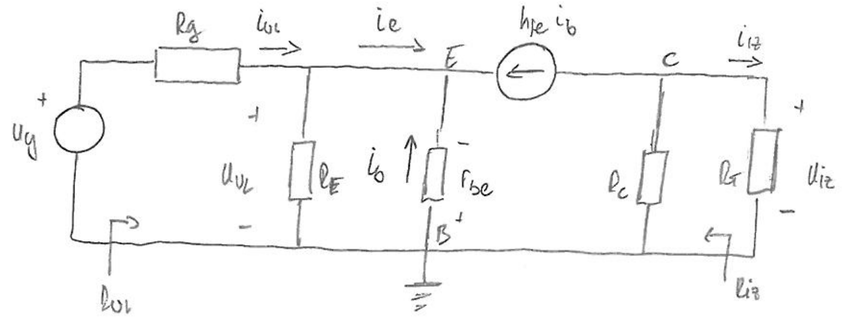


• vidimo da je $i_b = 0$



$$i = \frac{u}{R_C} \Rightarrow R_{iz} = \frac{u}{\frac{u}{R_C}} = R_C$$

2) Zajednička baza



$$\left.\begin{aligned} u_{iz} &= -h_{fe} \cdot i_b \cdot R_C \| R_T \\ u_{ul} &= -i_b \cdot r_{be} \end{aligned}\right\} \quad A_v = \frac{u_{iz}}{u_{ul}} = h_{fe} \cdot \frac{R_C \| R_T}{r_{be}}$$

$$R_{ul} = \frac{u_{ul}}{i_{ul}} \quad ; \quad i_{ul} = i_e + i_{RE} \quad , \quad i_{RE} = \frac{u_{ul}}{R_E} \quad , \quad i_b = -\frac{u_{ul}}{r_{be}}$$

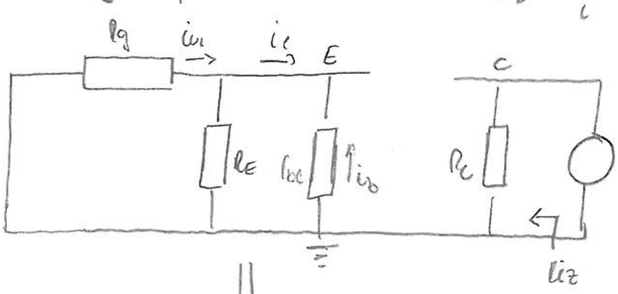
$$i_e + i_b + i_b h_{fe} = 0 \implies i_e = -i_b(1+h_{fe}) = \frac{u_{ul}}{r_{be}}(1+h_{fe})$$

$$i_{ul} = u_{ul}\left[\frac{1}{R_E} + \frac{1}{\frac{r_{be}}{1+h_{fe}}}\right] \implies R_{ul} = \frac{1}{\frac{1}{R_E} + \frac{1}{\frac{r_{be}}{1+h_{fe}}}} = R_E \| \frac{r_{be}}{1+h_{fe}}$$

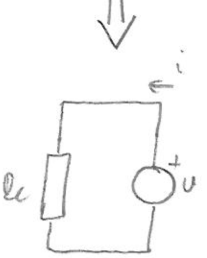
$$\left.\begin{aligned} i_{iz} &= \frac{u_{iz}}{R_T} \\ i_{ul} &= \frac{u_{ul}}{R_{ul}} \end{aligned}\right\} \quad A_i = \frac{i_{iz}}{i_{ul}} = \frac{u_{iz} \cdot R_{ul}}{u_{ul} \cdot R_T} = A_v \cdot \frac{R_{ul}}{R_T}$$

$$u_{ul} = u_g \frac{R_{ul}}{R_{ul} + R_g} \implies A_{vg} = \frac{u_{iz}}{u_g} = \frac{u_{iz}}{u_{ul}} \cdot \frac{u_{ul}}{u_g} = A_v \cdot \frac{R_{ul}}{R_{ul} + R_g}$$

- za računanje izlaznog otpora sve nezavisne izvore odspojimo, a zavisni će postojati ako postoje napon ili struja o kojoj su ovisni. Trošilo zamjenimo naponskim izvorom u koji daje struju i : $R_{iz} = \frac{u}{i}$

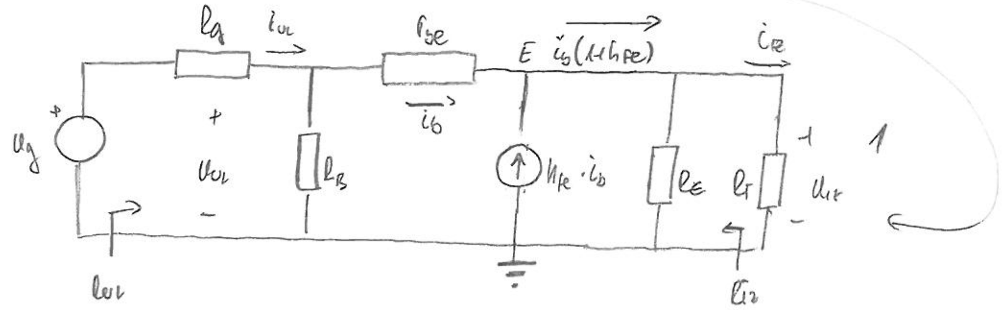


- vidimo da je $i_b = 0$



$$i = \frac{u}{R_C} \implies R_{iz} = \frac{u}{\frac{u}{R_C}} = R_C$$

3) zajednički kolektor



$$u_{iz} = i_b(1+h_{fe}) \cdot R_E \| R_T$$

• iz petlje "1":

$$u_{ul} = i_b\left[r_{be} + (1+h_{fe}) R_E \| R_T\right]$$

$$A_V = \frac{u_{iz}}{u_{ul}} = \frac{(1+h_{fe}) R_E \| R_T}{r_{be} + (1+h_{fe}) R_E \| R_T}$$

$$R_{ul} = \frac{u_{ul}}{i_{ul}}, \quad i_{ul} = i_b + i_{R_B}, \quad i_{R_B} = \frac{u_{ul}}{R_B}, \quad i_b = \frac{u_{ul}}{r_{be} + (1+h_{fe}) R_E \| R_T}$$

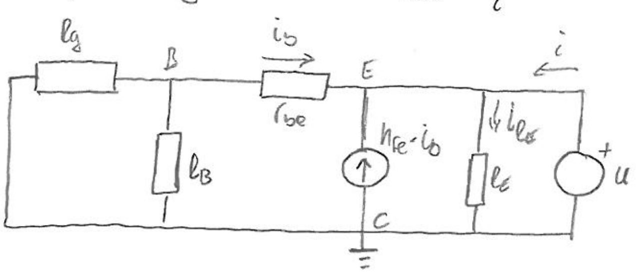
$$R_{ul} = \frac{u_{ul}}{u_{ul}\left[\frac{1}{R_B} + \frac{1}{r_{be} + (1+h_{fe}) R_E \| R_T}\right]} = R_B \| \left[r_{be} + (1+h_{fe}) R_E \| R_T\right]$$

$$i_{iz} = \frac{u_{iz}}{R_T}, \quad i_{ul} = \frac{u_{ul}}{R_{ul}}$$

$$A_I = \frac{i_{iz}}{i_{ul}} = \frac{u_{iz} \cdot R_{UL}}{u_{ul} \cdot R_T} = A_V \cdot \frac{R_{ul}}{R_T}$$

$$u_{ul} = u_g \cdot \frac{R_{UL}}{R_{ul} + R_g} \Rightarrow A_{Vg} = \frac{u_{iz}}{u_g} = \frac{u_{iz}}{u_{ul}} \cdot \frac{u_{ul}}{u_g} = A_V \cdot \frac{R_{ul}}{R_{ul} + R_g}$$

• Za računanje izlaznog otpora odspojimo sve nezavisne izvore, a zavisni će postojati ako postoje struja ili napon o kojem su ovisni. Trošilo zamijenimo naponskim izvorom u koji daje struju i: $R_{ul} = \frac{u}{i}$



• vidimo da je $i_b \neq 0$

$$i = i_{R_E} - i_b - i_b h_{fe} = i_{R_E} - i_b(1+h_{fe}), \quad i_{R_E} = \frac{u}{R_E}$$

$$u = -i_b(r_{be} + R_g \| R_B) \Rightarrow i_b = -\frac{u}{r_{be} + R_g \| R_B}$$

$$i = u\left(\frac{1}{R_E} + \frac{1+h_{fe}}{r_{be} + R_g \| R_B}\right)$$

$$R_{iz} = \frac{u}{i} = \frac{1}{\frac{1}{R_E} + \frac{1+h_{fe}}{r_{be} + R_g \| R_E}} = R_E \| \frac{r_{be} + R_g \| R_B}{1+h_{fe}}$$

- dodatno:
  - kod spoja zajedničkog emitera oba su pojačanja, naponsko i strujno, negativna, a kod preostala dva spoja pozitivna
  - po iznosu naponska pojačanja spoja ZE i ZB su velika i međusobno su jednaka
  - naponsko pojačanje spoja ZC samo je malo manje od 1
  - od sva tri spoja jedino pojačalo u spoju ZE ima oba pojačanja po iznosu veća od 1 (red iznosa tih pojačanja je tipično 100)
  - pojačalo u spoju ZB ima strujno pojačanje manje od 1, a pojačalo u spoju ZC naponsko pojačanje manje od 1
  - ulazni otpori u spoju ZB tipično su oko 10Ω, u spoju ZE oko $1k\Omega$, a u spoju ZC oko $100\,k\Omega$
  - u pojačalima u spoju ZE i ZB izlazni otpor je R_C (veličine kiloома), u pojačalu ZC izlazni otpor je mali (oko 10Ω)

DIFERENCIJSKO POJAČALO

- zajednički signal: $u_z = \dfrac{u_{g1} + u_{g2}}{2}$ (istofazni signal)
- diferencijski signal: $u_d = u_{g2} - u_{g1}$ (protufazni signal)

$$u_{g1} = u_z - \frac{u_d}{2}$$
$$u_{g2} = u_z + \frac{u_d}{2}$$

- za dobro pojačalo: $A_{vd} \gg A_{vz} \propto \dfrac{1}{R_E}$

$$A_{vz1} = \frac{u_{iz1}}{u_z} = \frac{-h_{fe} \cdot R_{C1}}{R_{g1} + r_{be1} + 2R_E(1+h_{fe})} \quad (-)$$

$$A_{vz2} = \frac{u_{iz2}}{u_z} = \frac{-h_{fe} \cdot R_{C2}}{R_{g2} + r_{be2} + 2R_E(1+h_{fe})} \quad (-)$$

$$A_{vz} = A_{vz2} - A_{vz1}$$

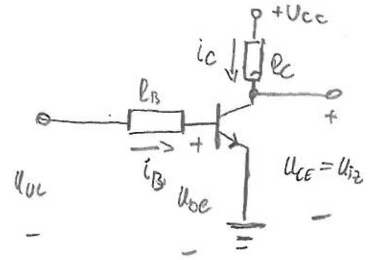
$$A_{vd1} = \frac{u_{iz1}}{u_d} = \frac{+h_{fe} R_{C1}}{2(R_{g1} + r_{be1})} \quad (+)$$

$$A_{vd2} = \frac{u_{iz2}}{u_d} = \frac{-h_{fe} \cdot R_{C2}}{2(R_{g2} + r_{be2})} \quad (-)$$

$$A_{vd} = A_{vD2} - A_{vD1}$$

BIPOLARNI TRANZISTOR KAO SKLOPKA

- koristi se spoj zajedničkog emitera



$$i_B = \frac{u_{UL} - u_{BE}}{R_B}$$

$$u_{IZ} = u_{CE} = U_{CC} - R_C \cdot i_C$$

- kada je u_{UL} negativniji od 0,5V radi sa zanemarivo malim strujama, tada je zanemariv i pad napona na R_C i izlazni napon $u_{IZ} = u_{CE} = U_{CC}$ (zapiranje)

  => ISKLJUČENA SKLOPKA

- porastom napona u_{UL} iznad 0,5V tranzistor počne voditi i ulazi u NAP; uz veće ulazne napone u_{UL} napon $u_{BE} \approx 0{,}7\,V$; porastom napona u_{UL} raste struja i_B, s njom raste i struja i_C a njenim porastom pada $u_{IZ} = u_{CE}$
- u_{CE} se može smanjiti do U_{CEzas}, kolektorska struja tada postiže maksimalnu vrijednost:

$$I_{Czas} = \frac{U_{CC} - U_{CEzas}}{R_C}$$

- U_{CEzas} je tipično između 0,1 i 0,3 V, u području zasićenja struja baze mora biti:

$$I_{Bzas} \geq \frac{I_{Czas}}{\beta}$$

pri čemu struju baze I_{Bzas} i dalje određuje ulazni krug sklopa

$$I_{Bzas} = \frac{U_{UL} - U_{BEzas}}{R_B} \quad \Rightarrow \quad U_{BEzas} \approx \text{od } 0{,}7 \text{ do } 0{,}8\,V$$

=> UKLJUČENA SKLOPKA

OPERACIJSKA POJAČALA

• IDEALNO pojačalo:

1) $R_{ul} = \infty \Rightarrow I_{op} = 0$

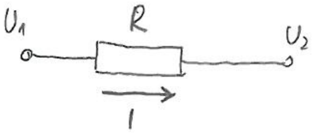
2) $A_{vop} = \infty \Rightarrow U_{iz} = A_{vop}(U_+ - U_-) \Rightarrow U_+ - U_- = \frac{U_{iz}}{A_{vop}}$

$\boxed{U_- = U_+}$ → prividni kratki spoj

3) $R_{iz} = 0$

NE PIŠEMO JEDNADŽBE ZA IZLAZNI ČVOR.

•

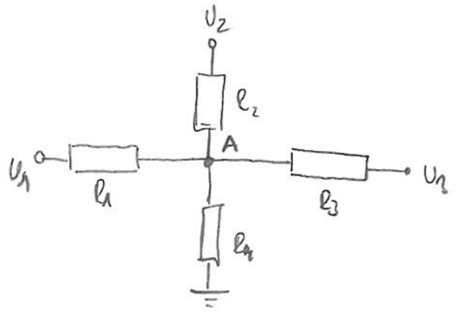


$I = \frac{U_1 - U_2}{R}$

• potencijal čvorova:

– napon čvora puta zbroj svih vodljivosti koje ulaze u taj čvor minus naponi susjednih čvorova puta vodljivost između ta dva čvora:

Pr



$U_A\left(\frac{1}{R_1} + \frac{1}{R_2} + \frac{1}{R_3} + \frac{1}{R_4}\right) - \frac{U_1}{R_1} - \frac{U_2}{R_2} - \frac{U_3}{R_3} - \frac{0}{R_4} = 0$

DODATAK:

- crtanje statičkog i dinamičkog radnog pravca:
  - x os -> U_{CE}
  - y os -> i_C
  - statički radni pravac određen je jednadžbom:

$$U_{CE} = U_{CC} - (R_C + R_E) I_C$$

=> za $i_C = 0$ i $U_{CE} = 0$ dobijemo presjecišta sa osima

=> na njemu označimo statičku radnu točku $Q(U_{CEQ}, I_{CQ})$

- dinamički radni pravac nacrtamo tako da nađemo udaljenost njegovih presjecišta od koordinata točke Q, te udaljenosti su ΔU_{CE} i Δi_C koje smo odredili iz nadomjesne sheme

- maksimalni hod napona je manji od dva raspona po kojima radna točka može šetati po DRP-u. Ti rasponi su U_{CEQ} i ΔU_{CE}, slično je i za struju