Osnovi elektronike, Popović

Predavanje 16.10.2024

Osnovi fizike poluprovodnika

Podjela materijala

1) metali / provodnici
2) dielektrici / izolatori
3) poluprovodnici

- Poluprovodnici - el / materijali kod kojih se u širokom opsegu može mijenjati σ $(10^{-2} \div 10^{5})(\Omega\, cm)^{-1}$ - spec. el. provodnost

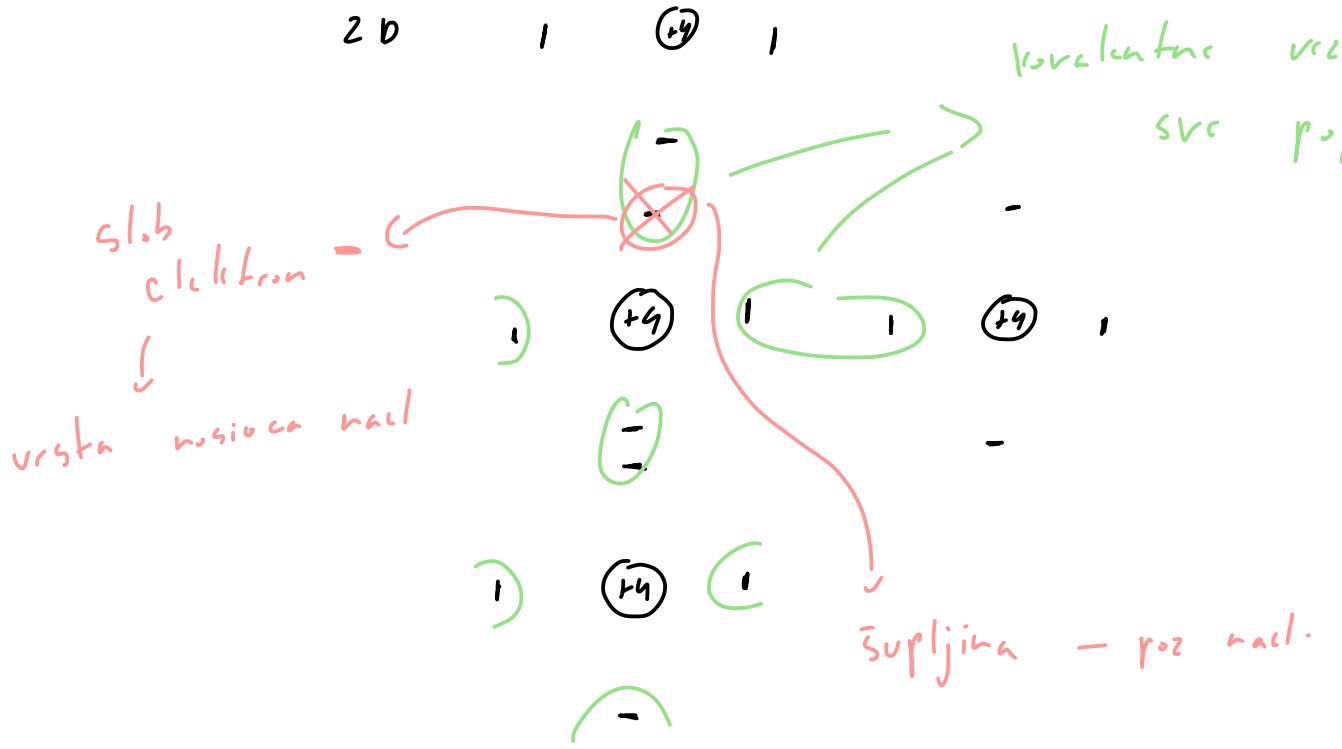
- Si, Ge (IV)
- B (III)
- As, P (V)

} elementarni

- (III - V) GaAs - poluprovodnička jedinjenja
- problem industrije - termička nestabilnost
- nulin. elementi
- Si IV grupa

14 $1s^2\ 2s^2\ 2p^6\ 3s^2\ 3p^2$

4 valentna elektrona ⟶ mogu postati sl.b. kada $T > 0K$



Termička energija ! može biti dovoljna da el. raskine kov. vezu; postane slobodni el

- na 0 K nijedan el nema dovoljnu energiju da postane slob el ⟶ veća T ⟶ više slob el. i šupljina

- osnovni nosioci nal. u $\overbrace{\text{poluprovodniku}}^{PP}$ su - slobodni elektron ; šupljina

- Slobodni elektron : n (konc. slobodnih elektrona) cm^{-3} — $-q$ — kol. nal.

- Šupljina : p (konc. šupljina) cm^{-3} — $q = 1.61 \cdot 10^{-19} C$

- Čist Si : $n = p = n_i$

n_i - koncentracija suprotnih nosilaca nal.

$n_i = f(T, \text{materijala})$

Si $T = 300K$ → sobna temp.

$n_i = 1.04 \cdot 10^{10} cm^{-3}$

$\approx 10^{10} cm^{-3}$ → ponaša se kao izolator

$$\boxed{n \cdot p = n_i^2}$$

n - tip pp

- V - grupa (P, As) → s valentnih el
  → 4 grade kov. veze
  1 može lako postati slob
- ubacuju se $10^{15} \div 10^{18}$ atoma fosfora
  ↳ svaki daje svoj s. valentni el kao slob el
  → $10^{15} \div 10^{18}$ slob el.

- $n = n_i + N_D$ - donorski el / primjesa
  n_i → od Si, N_D → od P

- $N_D = 10^{17} cm^{-3}$
  $n = 10^{10} + 10^{17} \approx 10^{17} cm^{-3}$ → povećali smo br. slob el u Si } većinski nosioci nal.

  $p = \frac{n_i^2}{n} = \frac{n_i^2}{N_D} = \frac{10^{20}}{10^{17}} = 10^3 cm^{-3}$ ↳ mali slob el su popunili } manjinski

- $\boxed{\sigma_n = q_n \mu_n}$

μ_n - pokretljivost el.

↳ koliko su el. sposobni da se kreću

$\mu_n \approx 1400 \ cm^2/Vs$

p - tip pp

- u Si III grupa - B → 3 valentna el

↳ 3 kov. veze sa susjednim atomima Si

4. veza Si će ostati neispunjena

↳ šupljina

- B - akceptorska primjesa N_A

↳ prima elektron → onoliko kolika ima at. B → toliko šupljina

- $p = n_i + N_A$ $\qquad N_A \gg n_i$

- $N_A = 10^{16} \ cm^{-3}$

$p = 10^{10} + 10^{16} \approx 10^{16} \ cm^{-3}$ } vrćinski

$n = \frac{n_i^2}{p} = \frac{n_i^2}{N_A} = \frac{10^{20}}{10^{16}} = 10^4 \ cm^{-3}$ → el su nestali

↳ manjinski

↳ nekoliko ne veliki br šupljina i popunili ih

$\boxed{\sigma_p = q_p \mu_p}$

↳ spec. provodnost

μ_p - pokretljivost šupljina

$\mu_p \approx 470 \ cm^2/Vs$

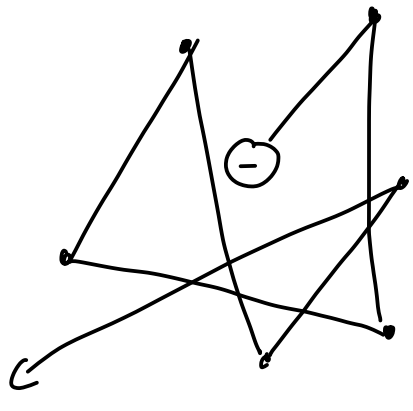
- cilj povećanja nosioca naboja → povećavanje struje

Transport nosioca naelektrisanja

- $T = 0K$ $\quad E_T = 0$ - termička energija
  ↳ nael. se ne kreću

- $T > 0K$ $\quad E_T > 0$
  ↳ el se kreću

šum (posljedica ovog kretanja)



termičko kretanje

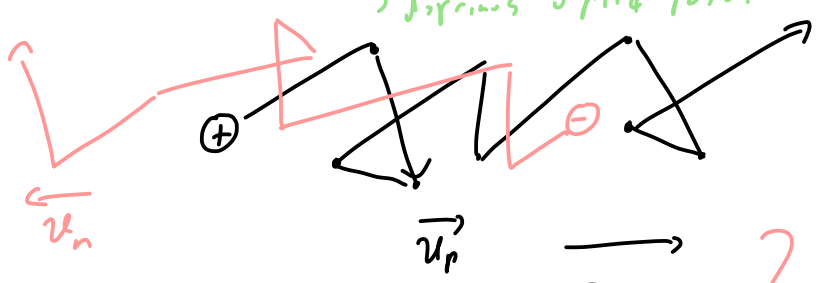
nema doprinosa u pređenom putu tj. $v_{sr} = 0$

Mehanizmi kretanja

1. Drift (pod dejstvom spolj. el. polja E)

$\longrightarrow E$, $T > 0K$ → hoće li

↳ doprinos u pređ. putu.



$\xrightarrow{I_p}$

$\xrightarrow{I_n}$

$I = I_n + I_p$

- $$\boxed{\begin{aligned} I_n &= A\, q\, n\, \mu_n \cdot E \\ I_p &= A \cdot q\, p\, \mu_p \cdot E \end{aligned}}$$

A → površ poprečnog presjeka kroz koji se nosioci nael. kreću

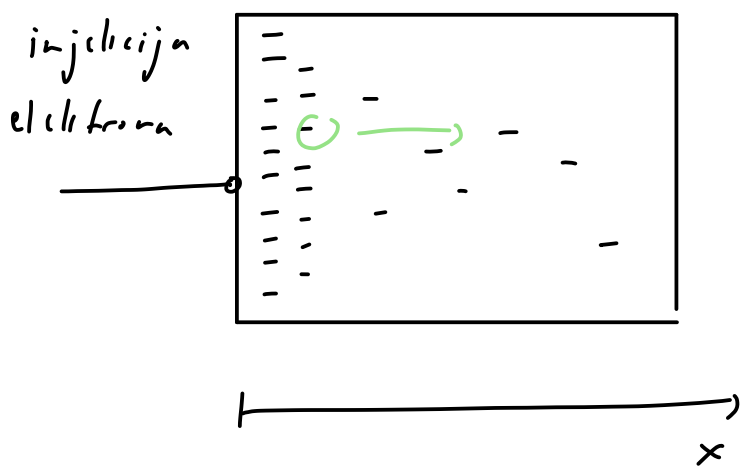
$$\left[I_{drift} = I_{ndr} + I_{pdr} = A \underbrace{q\,(n\mu_n + p\mu_p)}_{G} \cdot E \right]$$

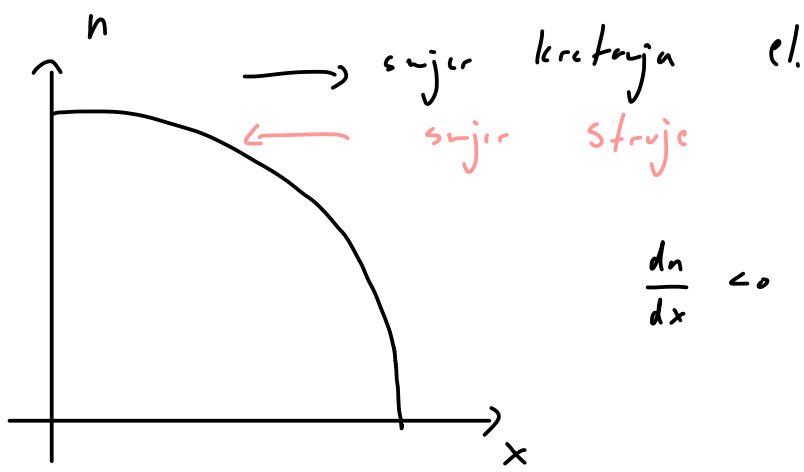
$G \cdot E = J$ → gustina struje

- dom. komp struje je ona od većinskog nosioca nael

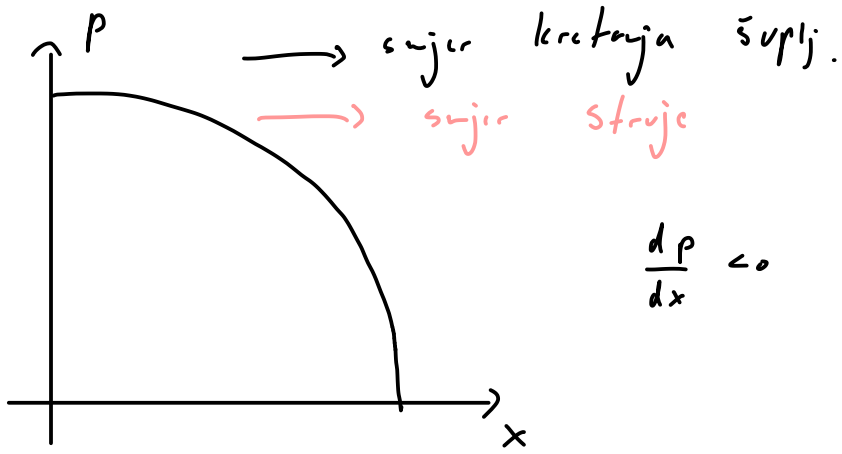
2. Difuzija

- kretanje nosilaca sa mjesta veće → manje koncentracije dok se ne izjednači tj. dok ne postane ravnomjerno





$$\frac{dn}{dx} < 0$$



$$\frac{dp}{dx} < 0$$

$$I_n = A \cdot q \cdot D_n \cdot \frac{dn}{dx}$$

$$I_{diff} = A\, q \left(D_n \frac{dn}{dx} - D_p \frac{dp}{dx} \right)$$

$$I_p = -A \cdot q \cdot D_p \cdot \frac{dp}{dx}$$

D_n - dif. konst. elektrona

$D_n \approx 39\ m^2/s$

D_p - dif. konst. šupljina

$D_p \approx 12\ m^2/s$

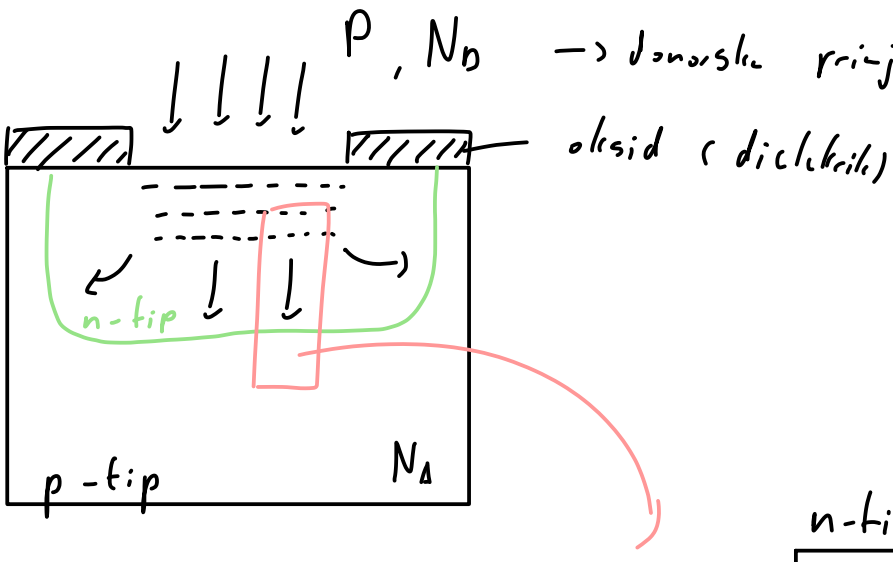
- dif. komponenta struje definišu manjinski nosioci nal

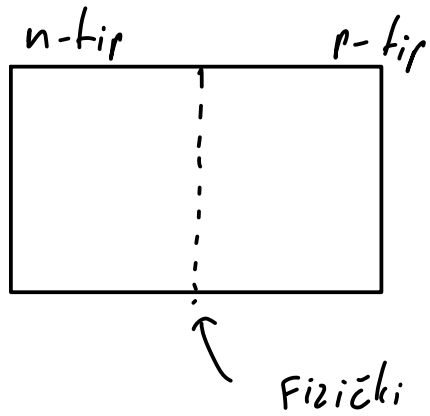
$$\left.\begin{aligned} I_{dr} &= A\, q\, (n \mu_n + p \mu_p)\, E \\ I_{diff} &= A\, q \left(D_n \frac{dn}{dx} - D_p \frac{dp}{dx} \right) \end{aligned}\right\} \text{Transportne jednačine}$$

$$I = I_{dr} + I_{diff}$$

PN spoj

pn spoj → osnovna struktura



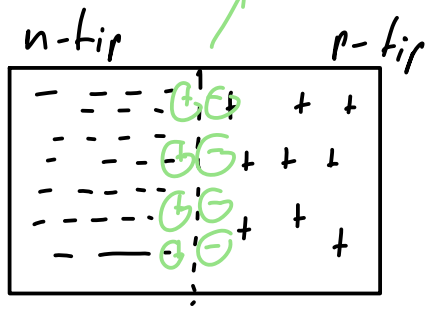


Fizički spoj (metalurški spoj)

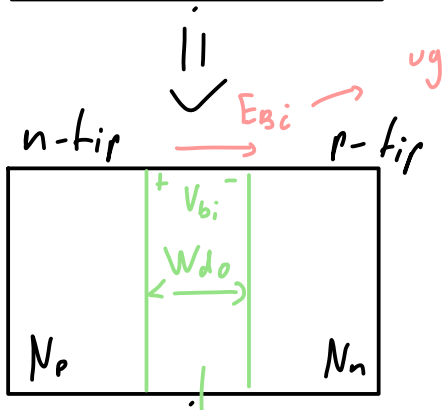
- Stanja:

1. Ravnotežno stanje PN-spoja

- nema spoljašnjeg napona, bez polarizacije



proces difuzije → učestvuju samo el blizu Fiz spoja



(nastal. zbog jona)

Osiromašena oblast → ponaša se kao izolator

(oblast prostornog naboja)

- Karakteristike:

1. Osiromašena oblast

Širina o. oblasti ← $W_{d0} = \sqrt{\frac{2\varepsilon_0 \varepsilon_{Si}}{q}\left(\frac{1}{N_A} + \frac{1}{N_D}\right)V_{bi}}$ ← ugrađen napon

$\varepsilon_0 = 8.85 \cdot 10^{-14}$ F/cm

$\varepsilon_{Si} = 11.7$

2. Ugrađen napon (potencijal) PN spoja

$$\boxed{V_{bi} = \frac{kT}{q} \cdot \ln \frac{N_A N_D}{n_i^2}}$$

V_t termički napon (potencijal)

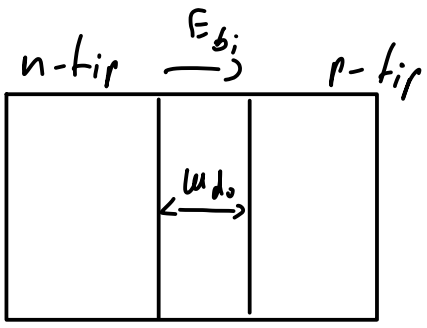
$V_t \ (T = 300\,K) = 25.6\ mV$

$$\boxed{V_{bi} = V_t \cdot \ln \frac{N_A N_D}{n_i^2}}$$

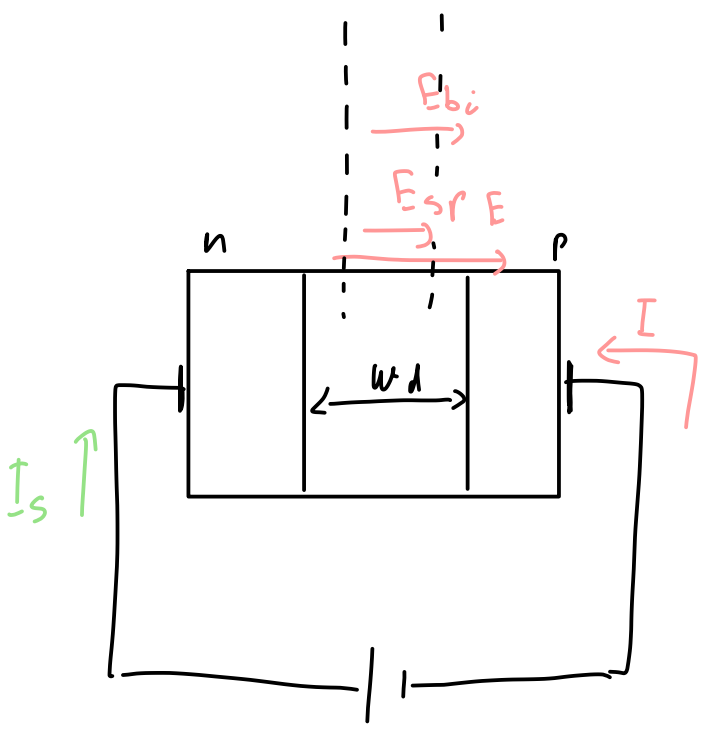
$W_{d_0} = (0.1 \div 1)\ \mu m$ – za standardne tehnologije

$V_{bi} = (0.6 \div 0.9)\ V$ → „napon barijere" kada hoćemo da dobijemo struju moramo dovesti napon koji je veći od napona barijere

2. Inverzna polarizacija PN-spoja



$W_d = f(V)$



$W_d > W_{d_0}$

I_s – inverzna struja zasićenja

$I = -I_s$

$I \approx 0$ – vrlo mala

- naponom kontrolisan kondenzator – debljina dielektrika (tj. kapacitivnost) se kontroliše naponom

$$\boxed{C = S\,\frac{\varepsilon_0 \varepsilon_{si}}{w_d}}$$

$$C = f(V)$$

Predavanje 23.10. 2024

U ravnotežnom stanju:

w_{d_0}

C_{j0} kapacitivnost po jed. površine

$$\boxed{C_{j0} = \frac{\varepsilon_0 \varepsilon_{si}}{w_{d_0}}}$$

Inverzna polarizacija:

$w_d = f_1(V)$

$$C_j = \frac{\varepsilon_0 \varepsilon_{si}}{w_d}$$

$$C_j = \frac{C_{j0}}{\sqrt{1 - \frac{V_R}{V_{bi}}}}$$

V_R – na pon inverzne polarizac.

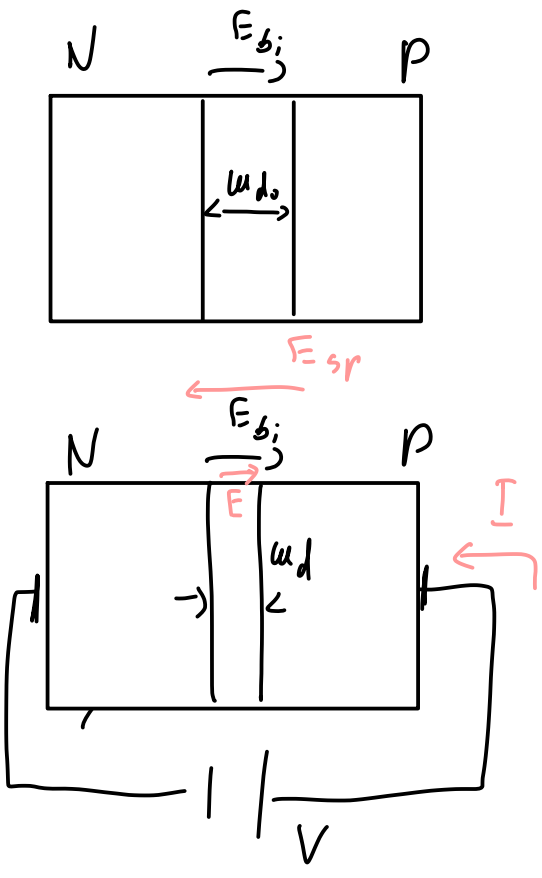
$V_R < 0$

$$C_j = \frac{C_{j0}}{\sqrt{1 - \frac{|V_R|}{V_{bi}}}}$$

3. Direktna polarizacija PN spoja

difuzioni struja velika (zbog velike razlike u koncentraciji)

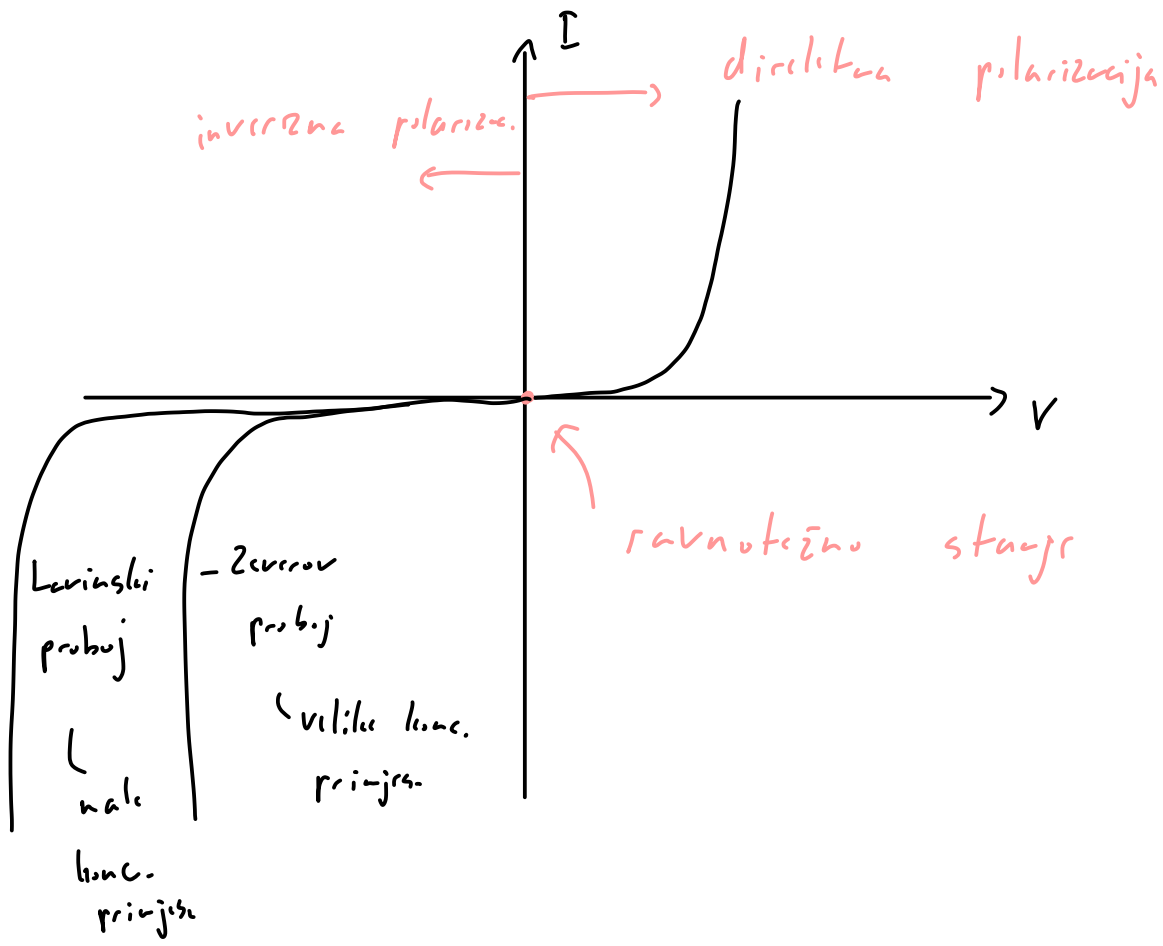
a drift. mala zbog malog polja



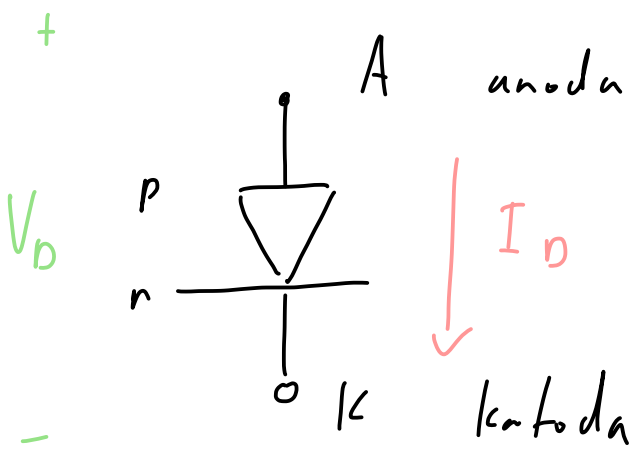
$$\boxed{I = I_S\left(e^{\frac{V}{V_t}} - 1\right)}$$

$V = V_F > 0$ – napon na PN spoju

I-V karakteristika



Diode

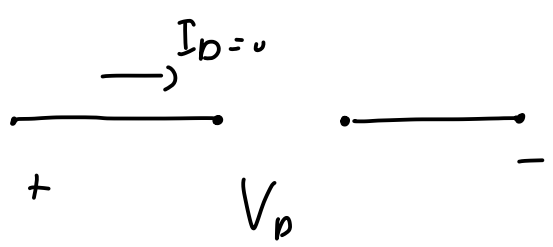


- nelinearni element

Model idealne diode

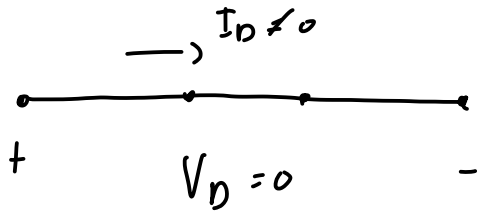
- idealni prekidač
- $V_D < 0$ D inverzno pol. ne vodi => $I_D = 0$

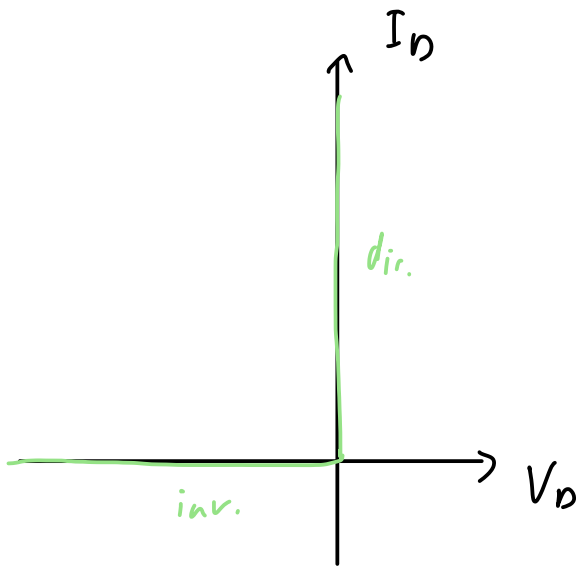
  D otvorena veza, prekidač



- $V_D \geq 0$, D dir. pol. => $I_D \neq 0$

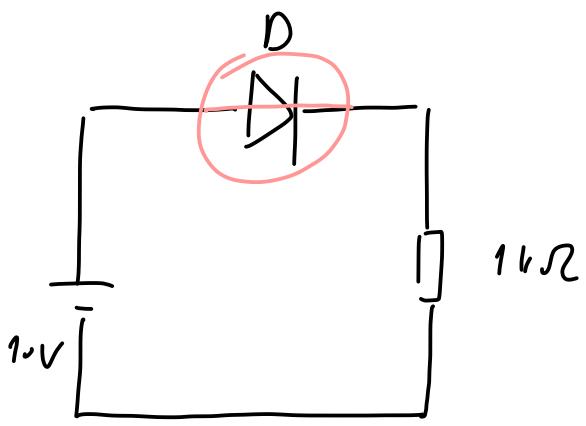
  D kratki spoj, idealni prekidač zatvoren

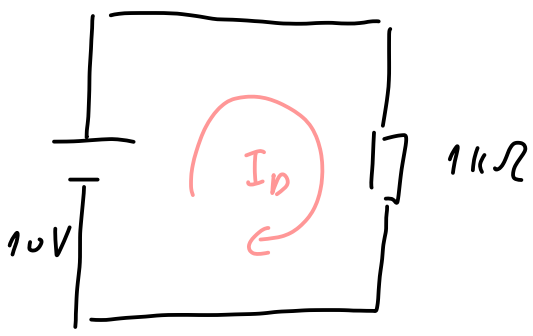




model idealne diode

Statička analiza, DC



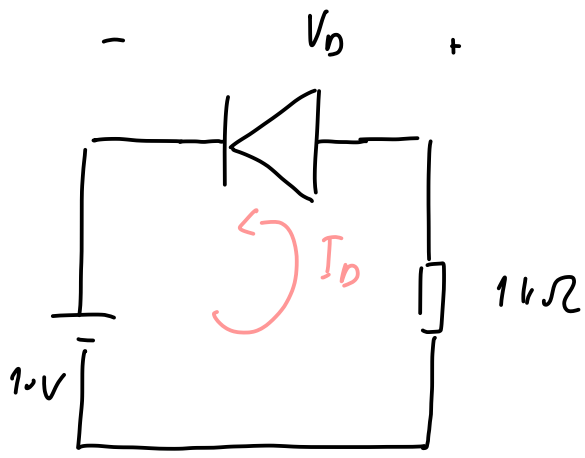


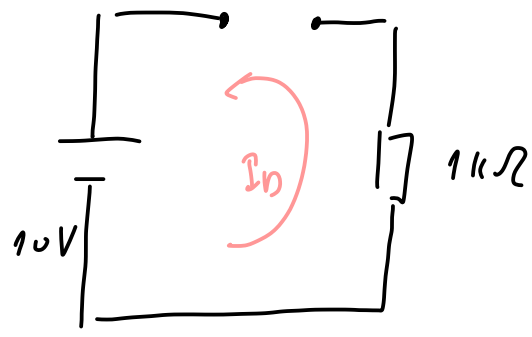
dir. polarizacija → zatvoren prekidač

D kratki spoj

$I_D = \frac{10V}{1k\Omega} = 10mA$

$V_D = 0V$



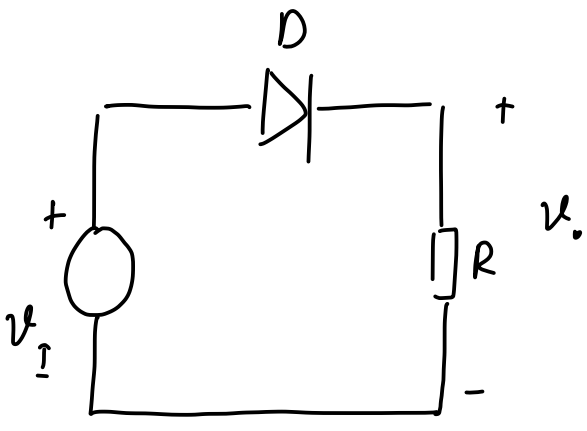


inv. polarizacija => D otvoren krug

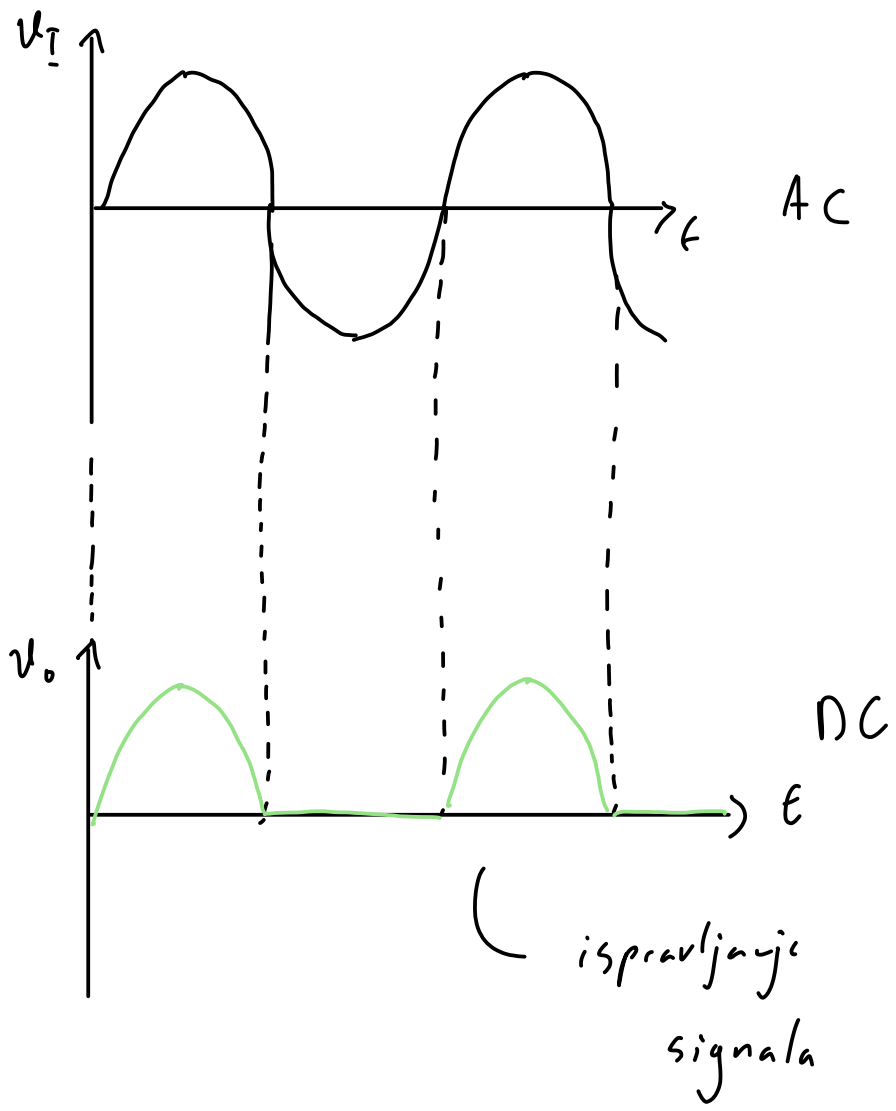
$I_D = 0A$

$V_D = -10V$

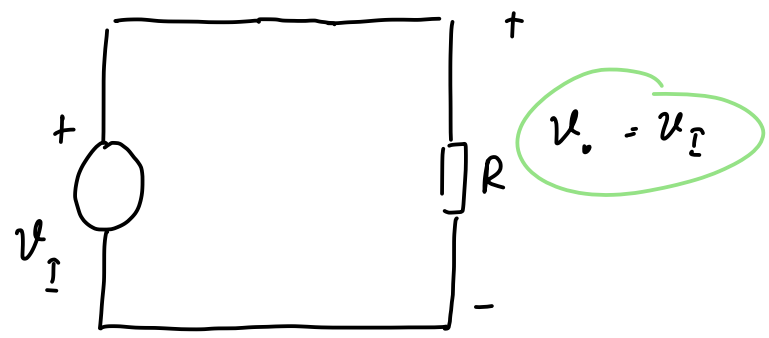
Dinamička analiza, AC



$v_I = V_{Im} \cdot \sin \omega t$

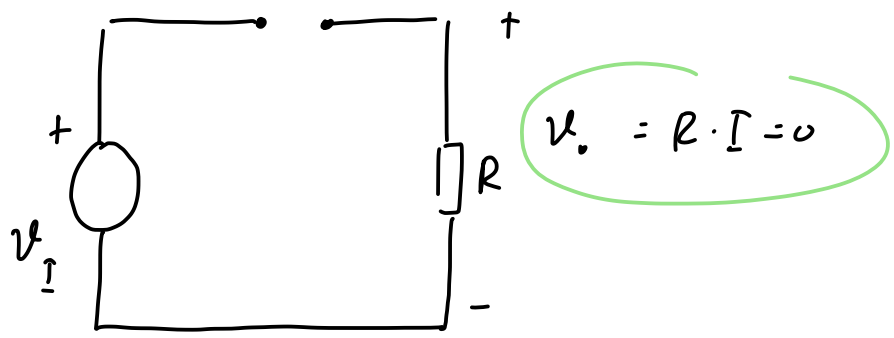


$v_I > 0$ D vodi



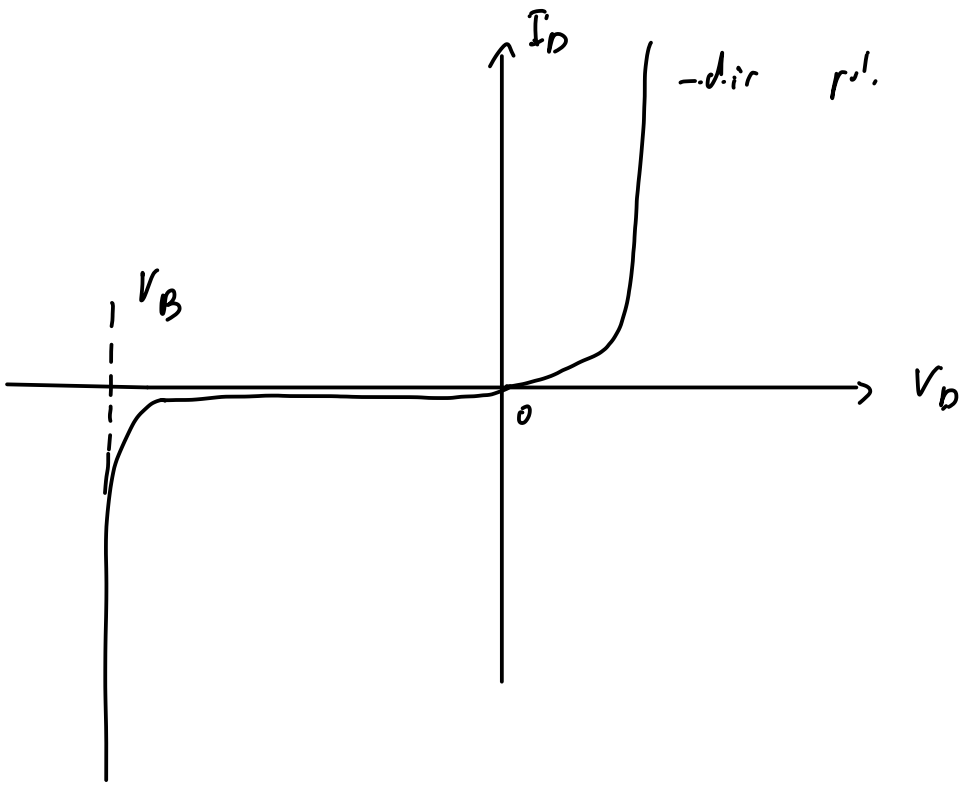
$v_o = v_I$

$v_I < 0$ D ne vodi



$v_o = R \cdot I = 0$

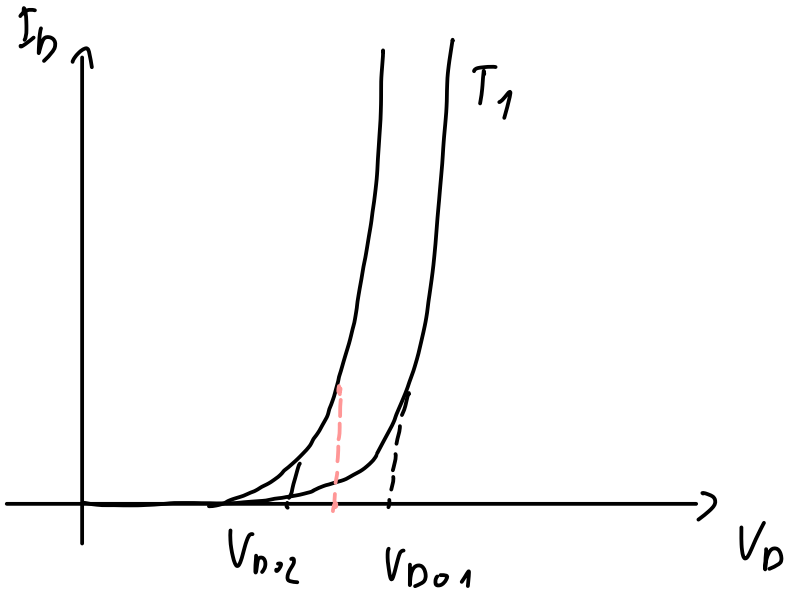
I - V karakteristika diode



dir pol: $I_D = I_S \left(e^{\frac{V_D}{nV_t}} - 1 \right)$ $n \in (1,2)$

inv pol: $I_D = -I_S \simeq 0$

V_B probojni napon



V_{D0} ugrađen potencijal PN spoja diode

$T_2 > T_1$

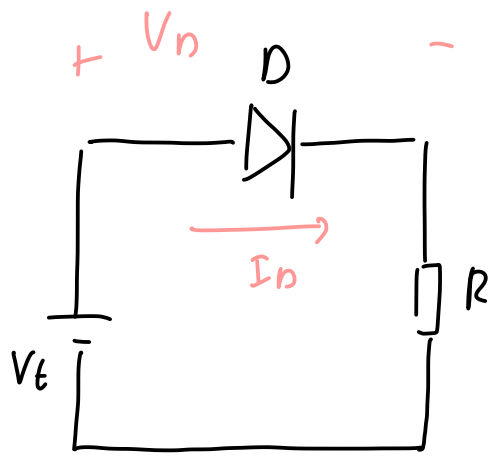
$T \nearrow$ $V_{D0} \searrow$

$\Downarrow$

$I_D \nearrow$

$\alpha_{V_{D0}} = (-2.5 \div (-2)) \frac{mV}{°C}$

Određivanje radne točke diode

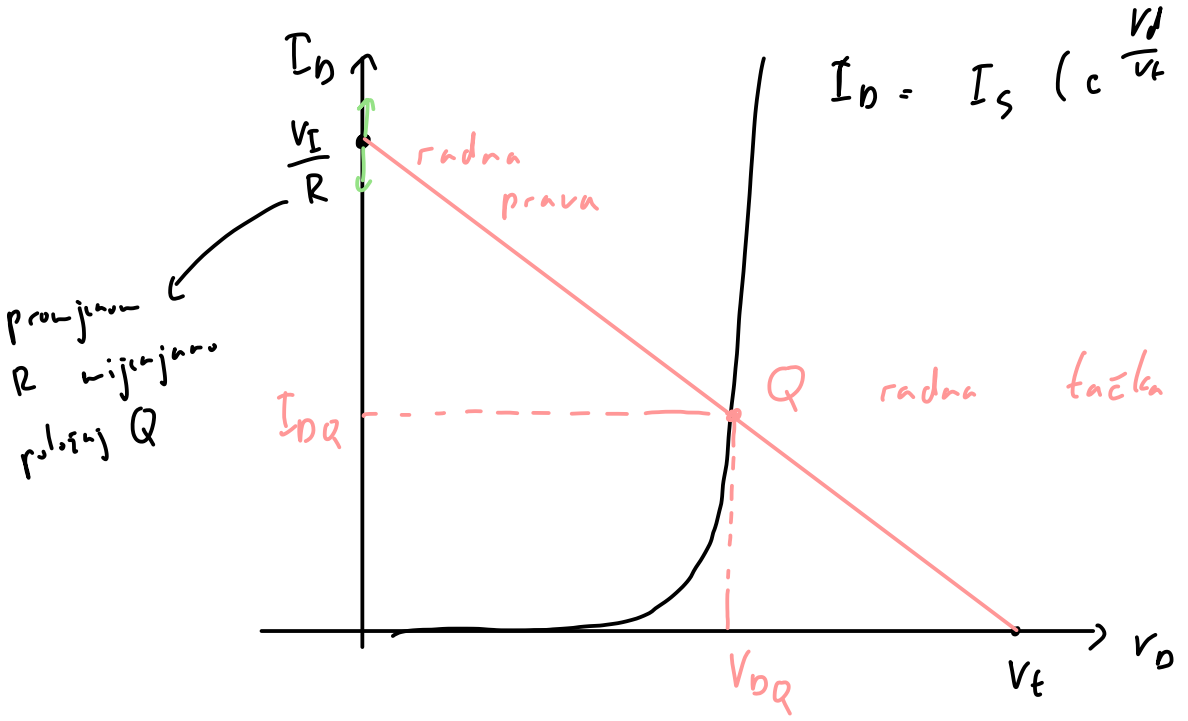


Q radna točka diode
(mirna radna točka)

$Q\ (V_{DQ}, I_{DQ})$

$$V_I = V_D + R\, I_D$$
$$I_D = I_S\left(e^{\frac{V_D}{V_t}} - 1\right)$$
V_D, I_D

Grafičko određivanje radne točke



$I_D = I_S\left(e^{\frac{V_d}{V_t}} - 1\right)$ (proizvođač)

$V_I = V_D + R\, I_D$ radna prava

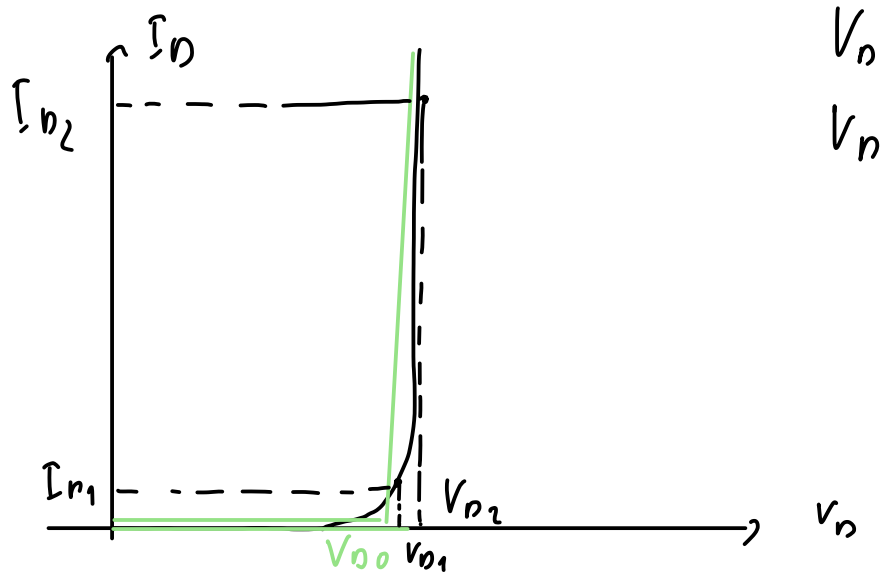
$V_D = 0 \Rightarrow I_D = \frac{V_I}{R}$

$I_D = 0 \Rightarrow V_D = V_I$

$V_R = R \cdot I_{DR}$

Model realne diode

1. Linearizirani model



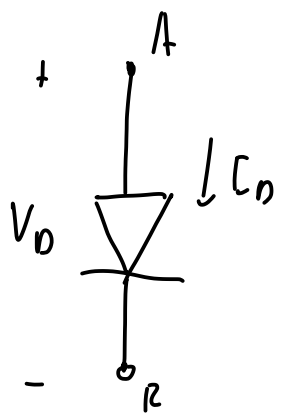
$V_D < V_{D0}$ D ne vodi, $I_D = 0$ otvorena veza

$V_D > V_{D0}$ D vodi $I_D = f(V_D)$

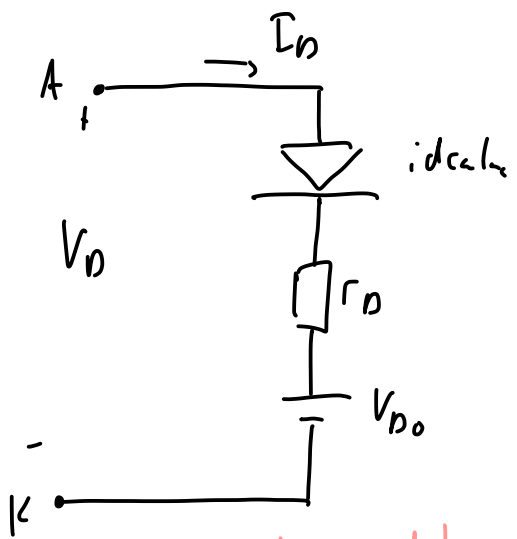
$$r_D = \frac{V_{D2} - V_{D1}}{I_{D2} - I_{D1}}$$

, r_D - inkrementalna otpornost

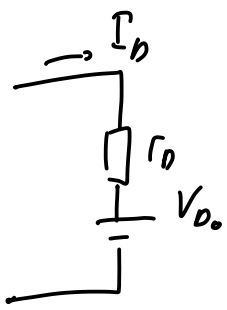
↳ napon vodenja



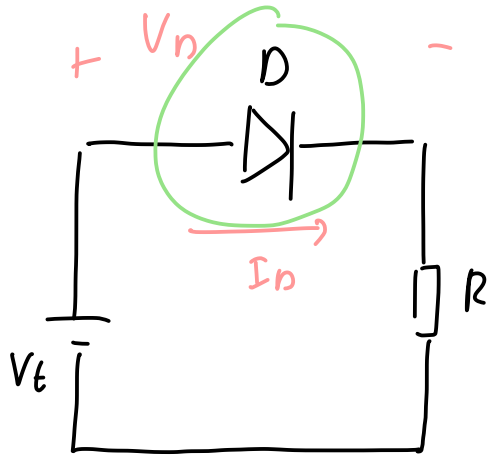
=>



Realni model



kad D vodi



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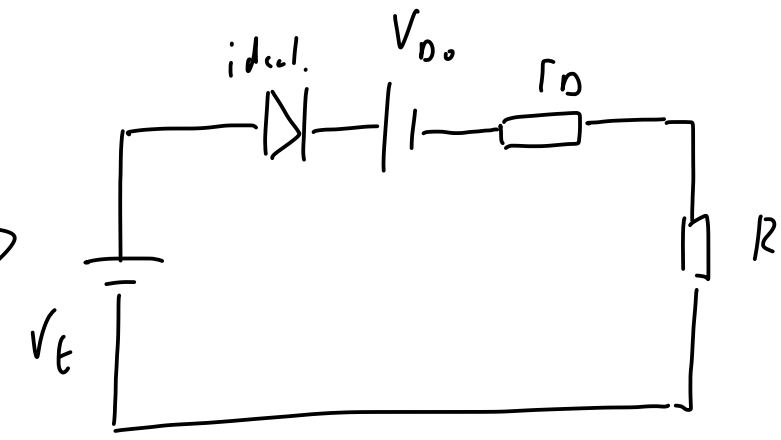
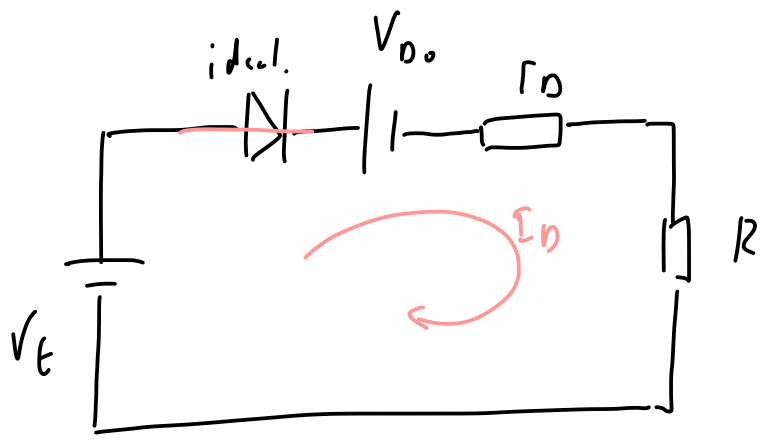


$V_I > V_{D0}$ idealna vodi

kratak spoj

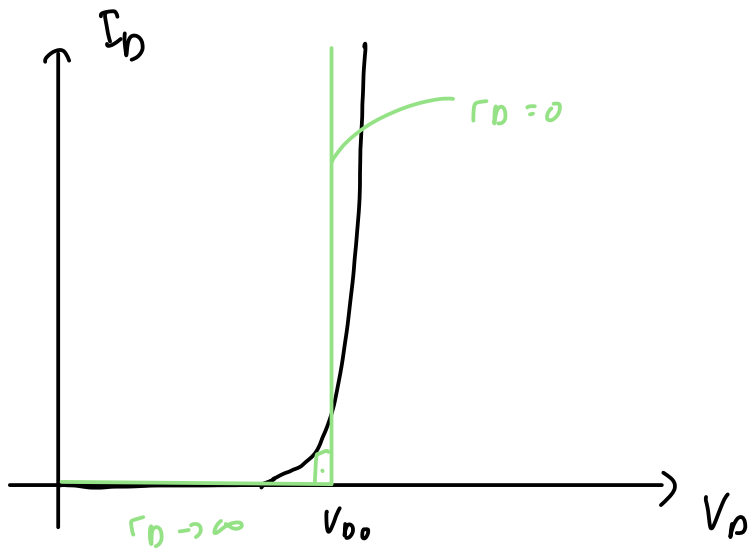
$V_I < V_{D0}$ dioda ne vodi

$I_D = 0$



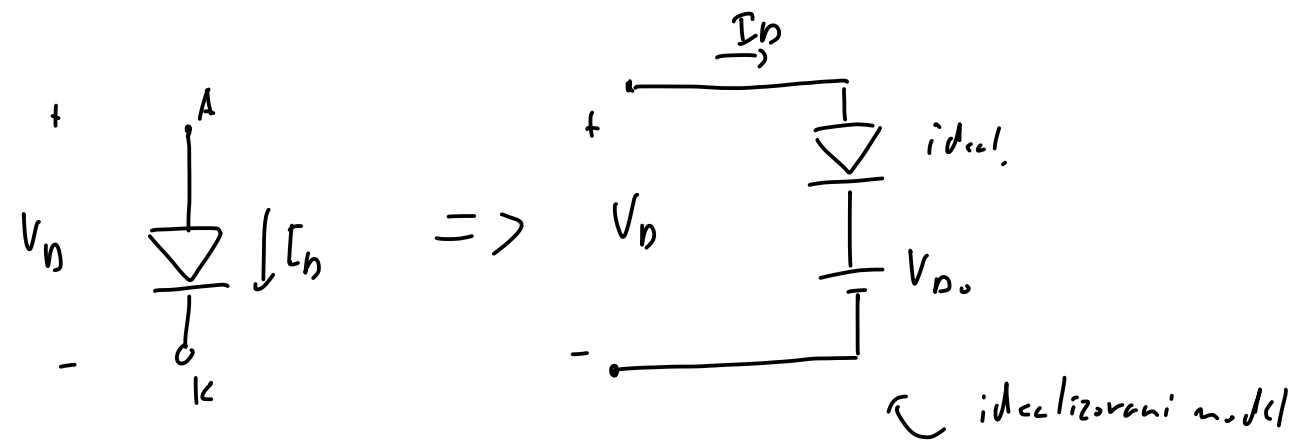
$$I_D = \frac{V_I - V_{D0}}{R + r_D}$$

2. Idealizirani model diode



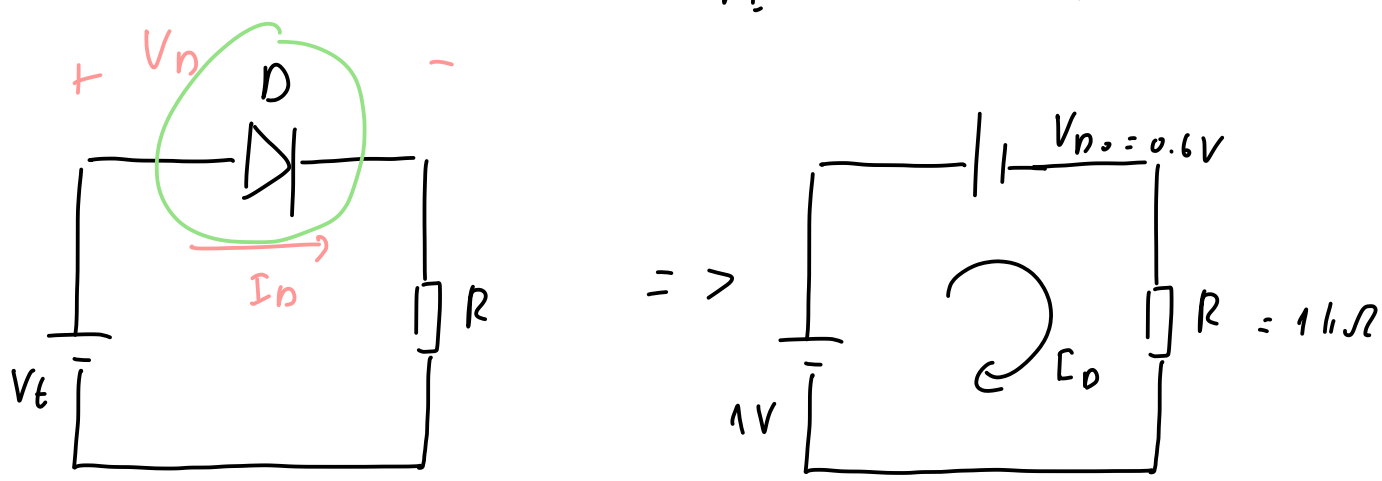
$V_D < V_{D0}$ D ne vodi, $I_D = 0$

$V_D \geq V_{D0}$ D vodi, $I_D \neq 0$



$V_I = 1\,V$ $V_{D0} = 0.6\,V$

$V_I > V_{D0}$, D vodi



$I_D = \frac{1V - 0.6V}{1k\Omega} = 0.4\,mA$

$V_{D0} = 0.6V$

$v_o = 10 - 3\,V_{D0} = 10V - 1.8V = 8.2V$

idealizirani model za brzu procjenu

Model za male signale

DC (statičke) I_{DQ}, V_{DQ}

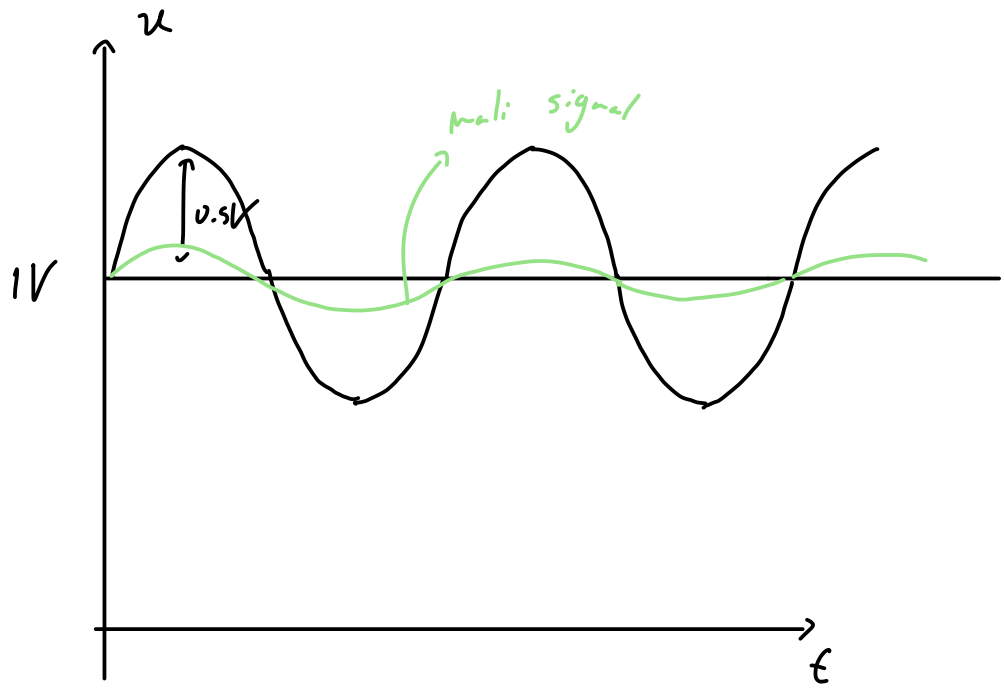
V_I statičke (DC)

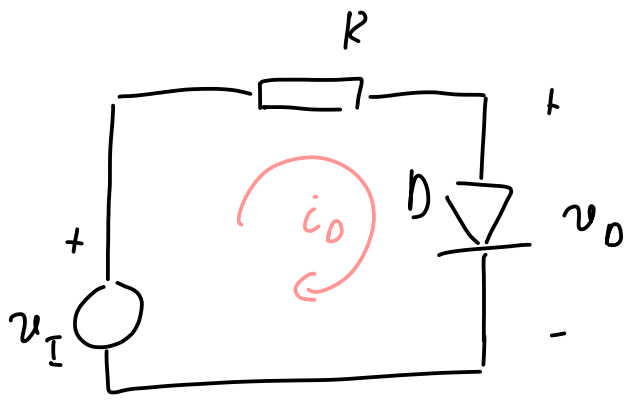
v_i mali signali

v_I ukupni napon

$$v_I = V_I + v_i$$

DC — mali signal





$$v_D = V_{DQ} + v_d$$

$$i_D = I_S e^{\frac{v_D}{V_t}} = I_S e^{\frac{V_{DQ}+v_d}{V_t}} = \underbrace{I_S \cdot e^{\frac{V_{DQ}}{V_t}}}_{I_{DQ}} \cdot e^{\frac{v_d}{V_t}}$$

$$e^{\frac{v_d}{V_t}} = 1 + \frac{v_d}{V_t} + \cancel{\frac{1}{2!}\left(\frac{v_d}{V_t}\right)^2 + \frac{1}{3!}\left(\frac{v_d}{V_t}\right)^3 + \dots} \to 0$$

$v_d < V_t$ $\quad v_d \approx 5mV$

$$e^{\frac{v_d}{V_t}} = 1 + \frac{v_d}{V_t}$$

$$i_D = I_{DQ} \cdot \left(1 + \frac{v_d}{V_t}\right)$$

$$= \underbrace{I_{DQ}}_{DC} + \underbrace{\frac{I_{DQ}}{V_t} \cdot v_d}_{\text{mali signal} = i_d} = \boxed{I_{DQ} + i_d}$$

superpozicija

prvo rješ. stat. analiz

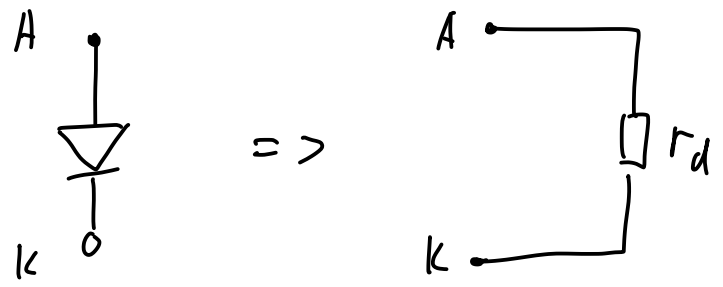
onda din. analiz

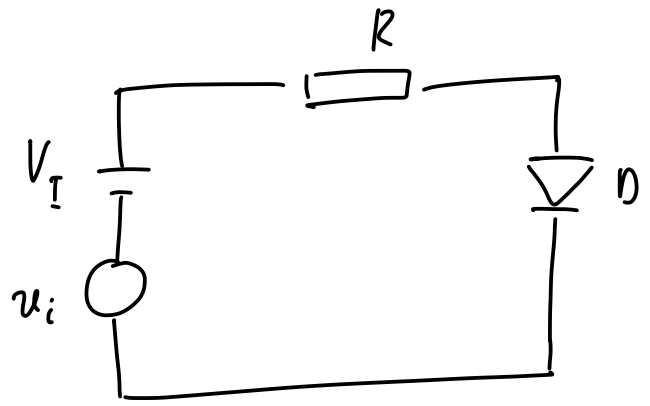
$$\boxed{i_D = \frac{I_{DQ}}{V_t} \cdot v_d = \frac{v_d}{r_d}}$$

r_d - dinamička otpornost diode

$$\boxed{r_d = \frac{V_t}{I_{DQ}}}$$

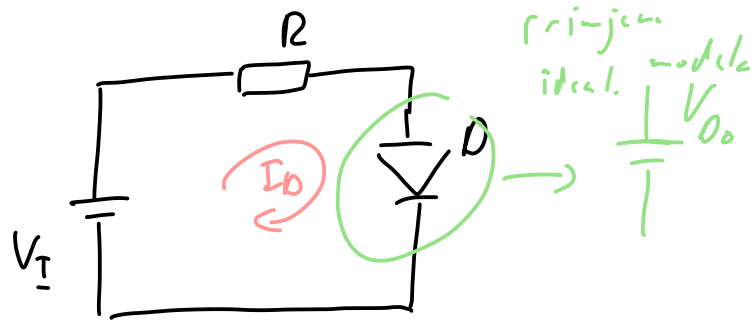
Analiza malih signala





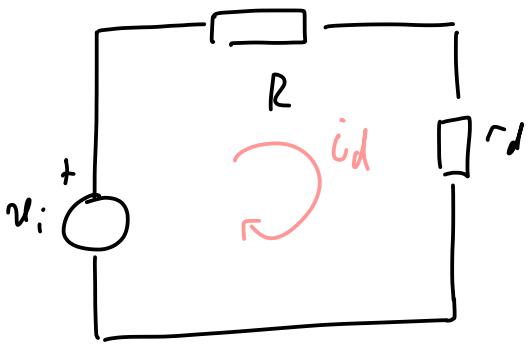
superpozicija

1° Statička analiza



$$I_{DQ} = \frac{V_I - V_{D0}}{R}$$

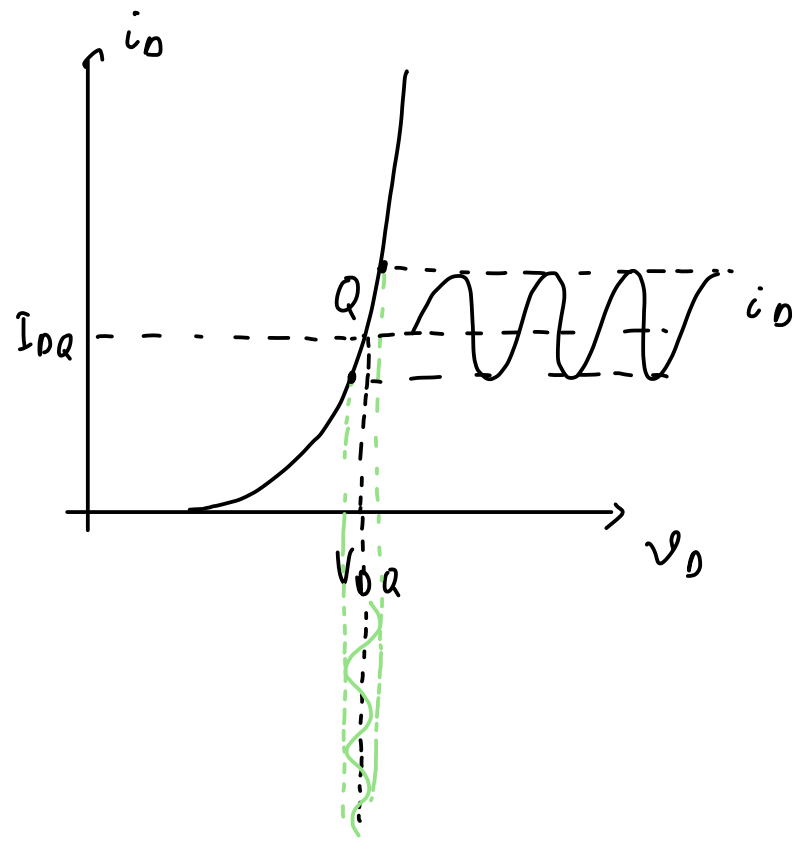
2° Analiza malih signala (dinamička)



$$r_d = \frac{V_t}{I_{DQ}}$$

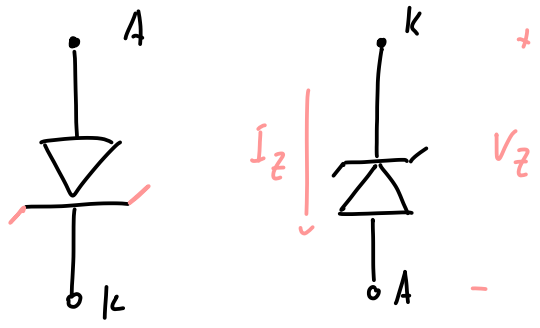
$$i_d = \frac{v_i}{R + r_d}$$

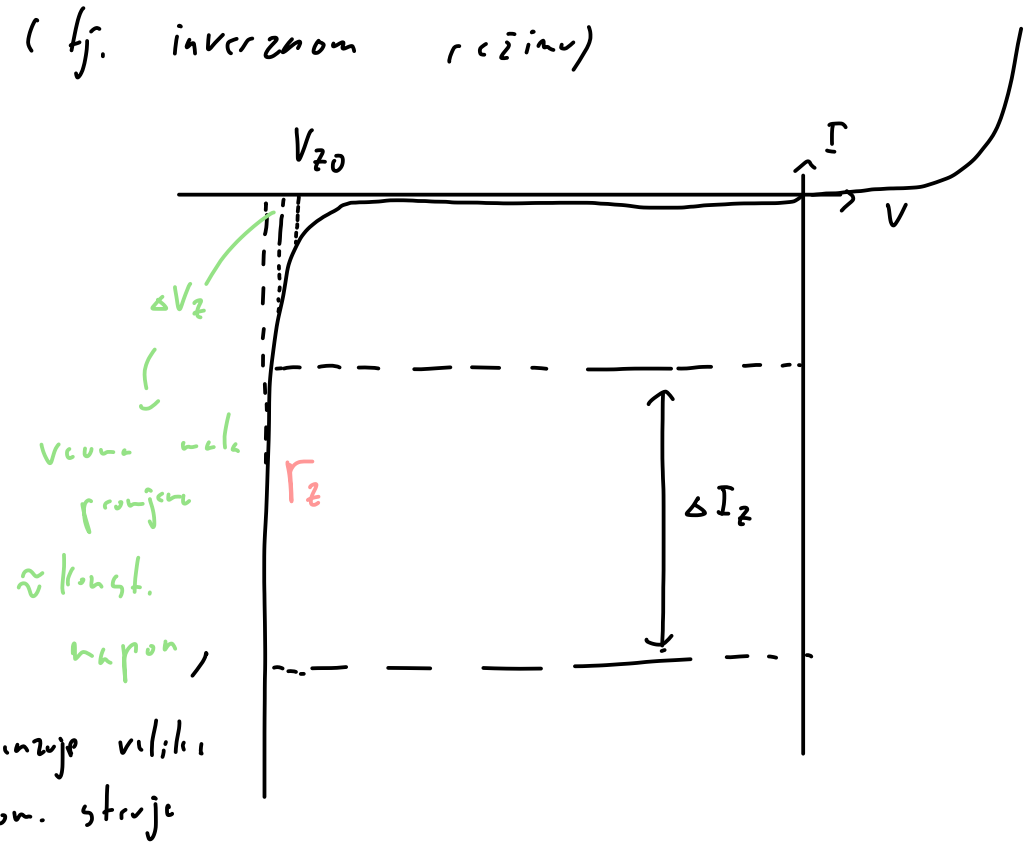
$$i_D = I_{DQ} + i_d$$



Zener dioda

- radi u oblasti proboja (tj. inverznom režimu)

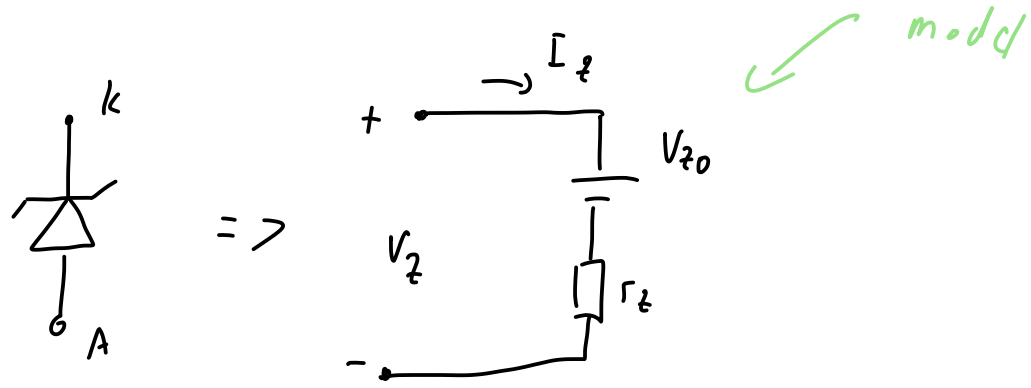




Uzima se: $V_Z > 0$

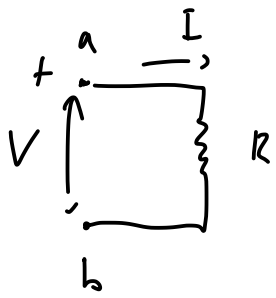
$I_Z > 0$

$$r_Z = \frac{\Delta V_Z}{\Delta I_Z}$$ par ohma (mala vrijednost)

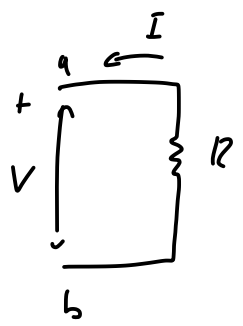


Vježbe 25.10.2024.

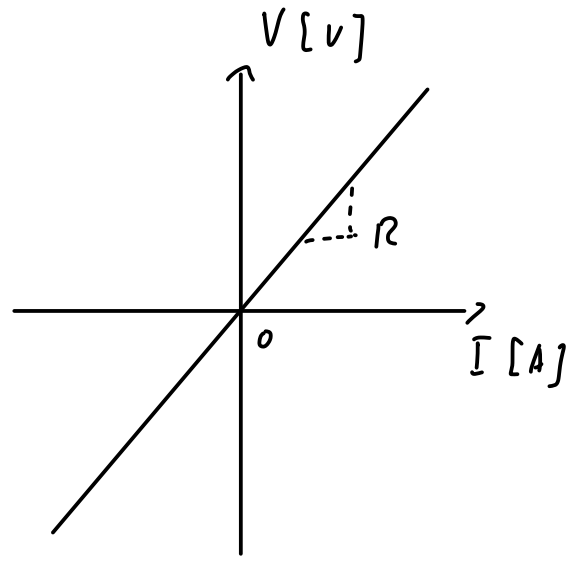
1. Ohmov zakon

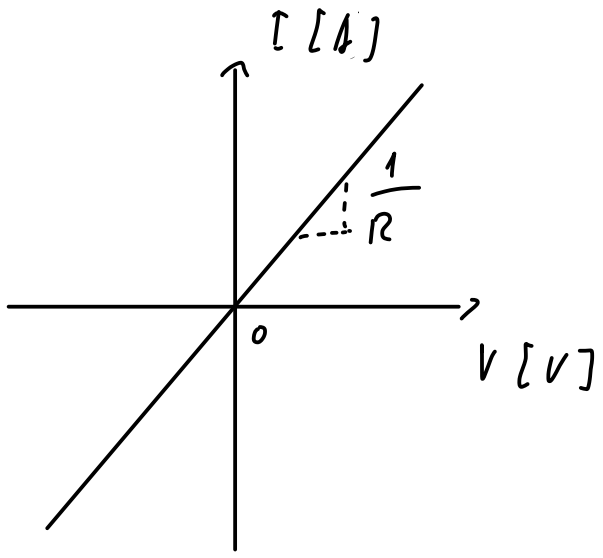


$V = RI$

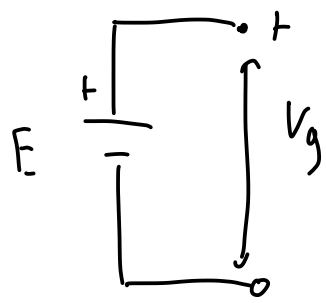


$V = -RI$

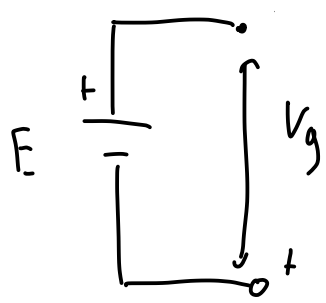




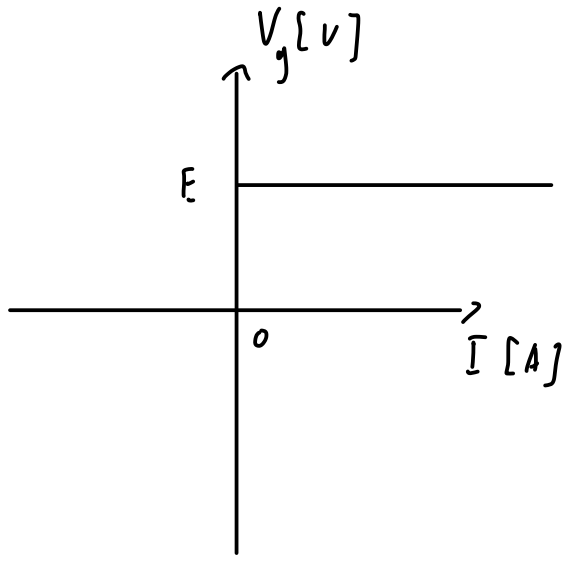
Idealni naponski izvor



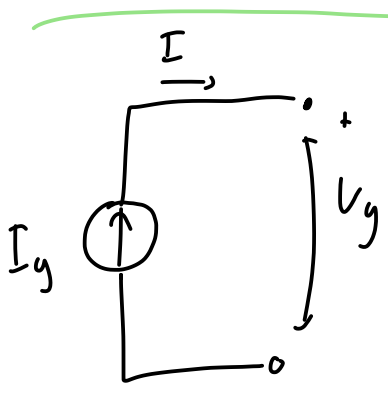
$V_g = E$



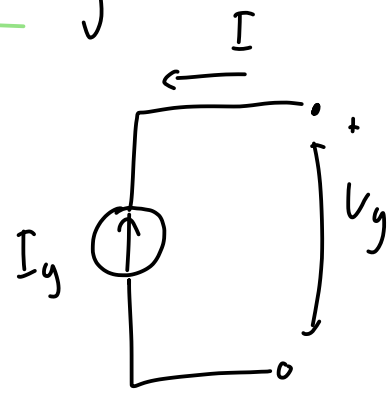
$V_g = -E$



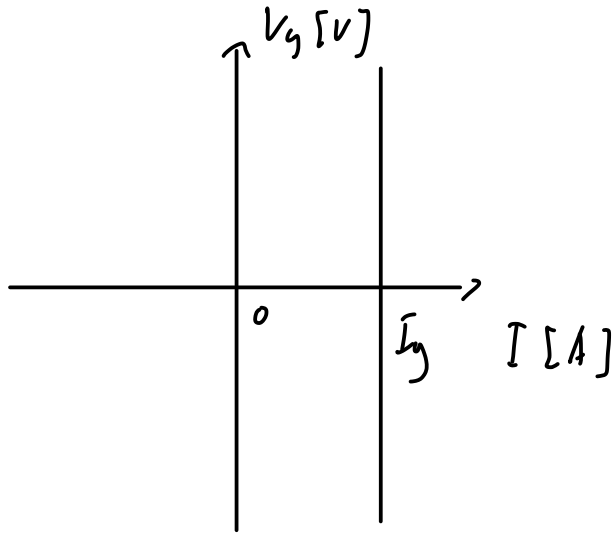
Idealni strujni izvor



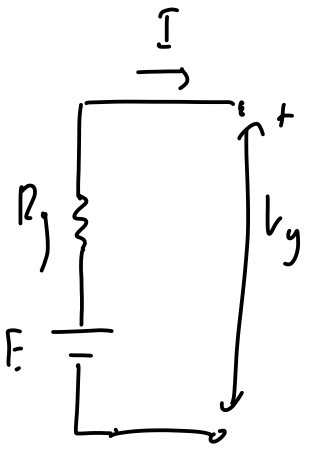
$I = I_g$



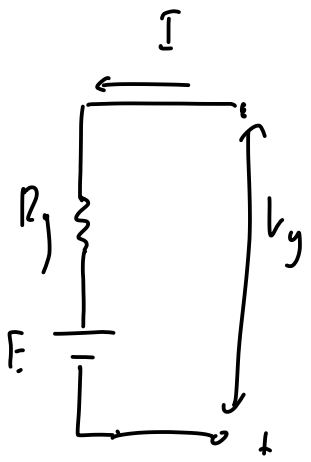
$I = -I_g$



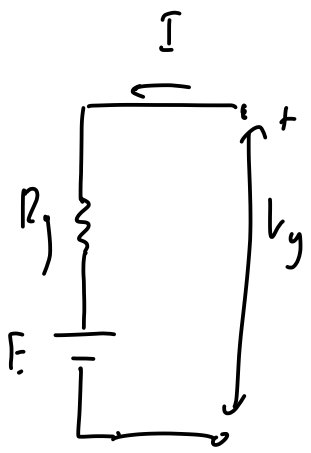
Realni naponski



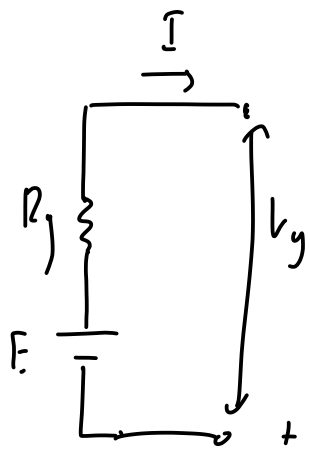
$V_g = E - R_g I$



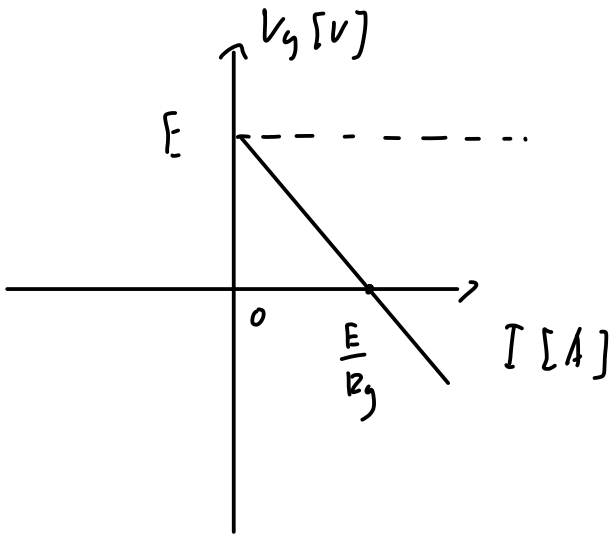
$V_g = -E - R_g I$



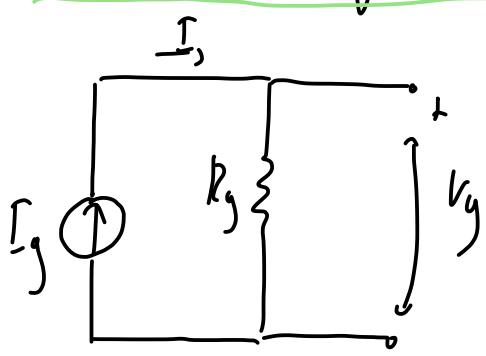
$V_g = E + R_g I$



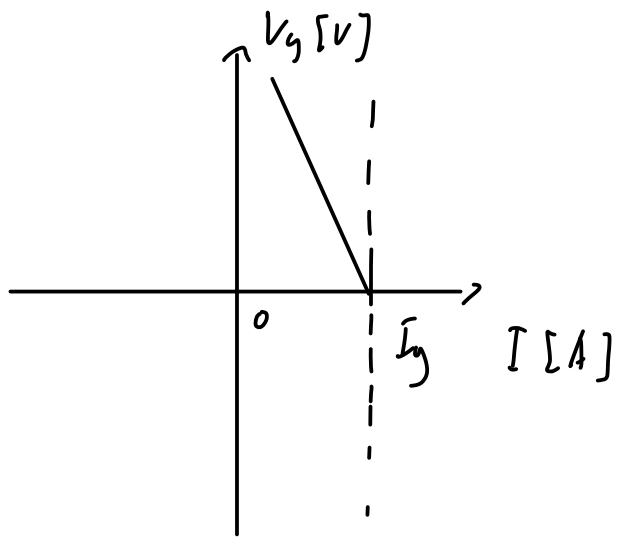
$V_g = -E + R_g I$



Realni strujni izvor

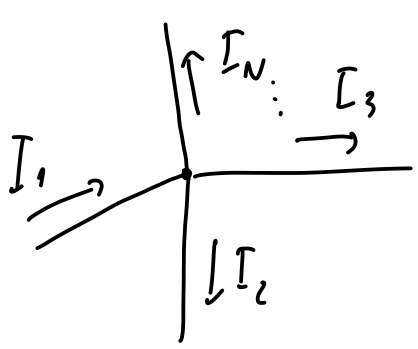


$V_g = R_g I$



2. Kirchofovi zakoni

Prvi Kirchofov zakon

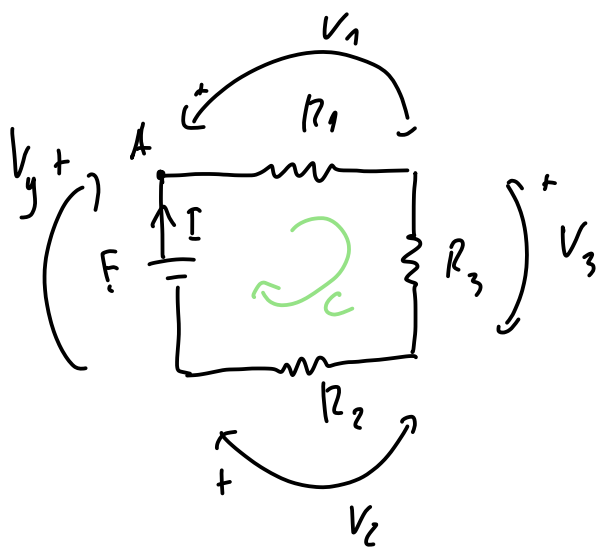


$$\sum_{i=1}^{N} I_i = 0$$

Drugi Kirhofov zakon

$$\sum_{i=1}^{N} V_i = 0$$

Primjer 1.



$$C: \quad -V_1 - V_3 + V_2 + V_g = 0$$

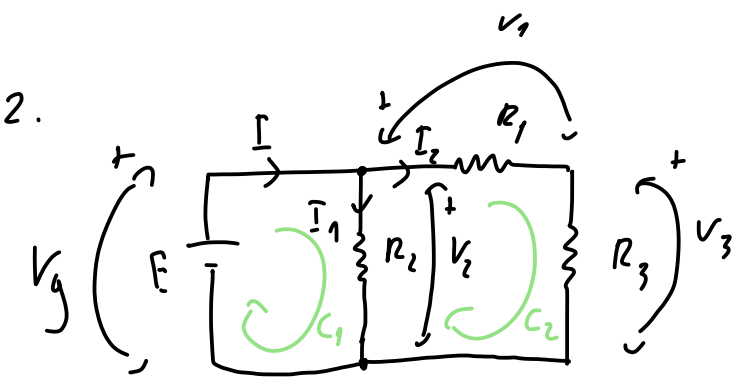
$$V_1 = R_1 I$$

$$V_3 = R_3 I$$

$$V_2 = -R_2 I$$

$$V_g = E$$

2.

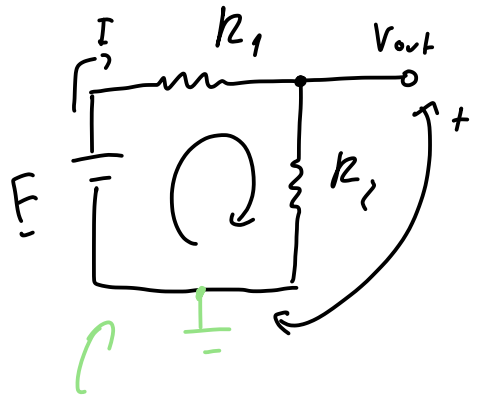


$$I = I_1 + I_2$$

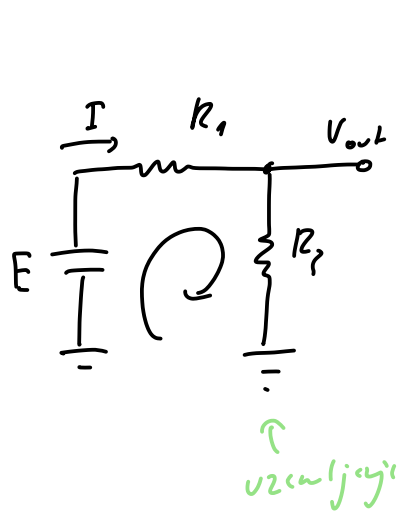
$$C_1: \quad -V_2 + V_g = 0$$

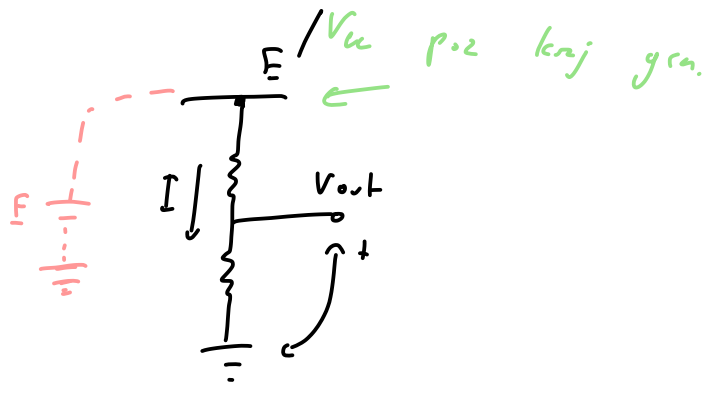
$$C_2: \quad -V_1 - V_3 + V_2 = 0$$

Naponski razdjelnik



obično vrijedno za neg kraj gen.





$$V_{cc} - R_1 I - R_2 I = 0 \quad (1)$$

$$V_{out} = R_2 I$$

$$I = \frac{V_{out}}{R_2} \quad (2)$$

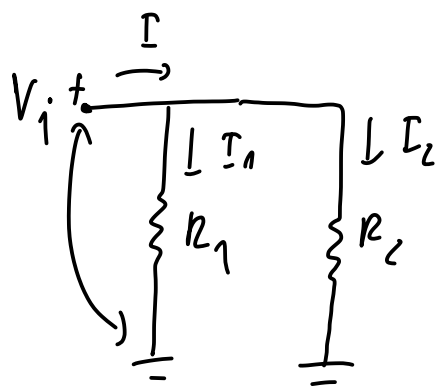
$$(2) \text{ u } (1): \quad V_{cc} - I(R_1 + R_2) = 0$$

$$V_{cc} - \frac{V_{out}}{R_2}(R_1 + R_2) = 0$$

$$\boxed{V_{out} = V_{cc} \frac{R_2}{R_1 + R_2}}$$

Strujni razdjelnik

$$V_1 = V_{CC} \frac{R_1}{R_1 + R_2}$$



$$I = I_1 + I_2$$

$$V_i = R_1 I_1 = R_2 I_2$$

$$R_1 I_1 = R_2 I_2$$

$$I_2 = I - I_1$$

$$R_1 I_1 = R_2 (I - I_1)$$

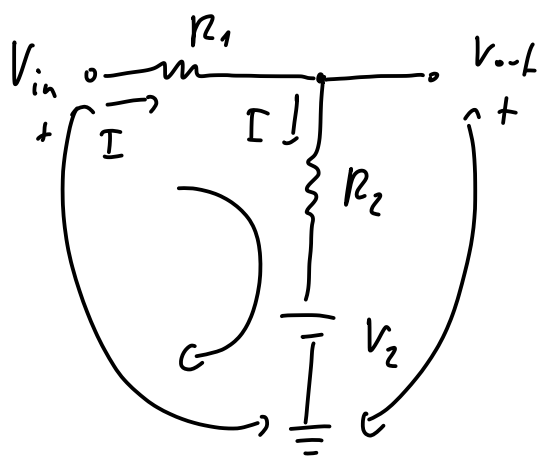
$$R_1 I_1 = R_2 I - R_2 I_1$$

$$I R_2 = I_1 (R_1 + R_2)$$

$$\boxed{I_1 = I \frac{R_2}{R_1 + R_2}} \qquad I_2 = I \frac{R_1}{R_1 + R_2}$$

3. Prenosna karakteristika

- funkcija zavisnosti izlazne karakteristike signala od ulaza



$$\boxed{V_{out} = f(V_{in})}$$ prenosna karakteristika

$$V_{in} - R_1 I - V_{out} = 0$$

$$V_{out} = R_2 I + V_R$$

$$R_2 I = V_{out} - V_R$$

$$I = \frac{1}{R_2}(V_{out} - V_R)$$

$$V_{in} - \frac{R_1}{R_2}(V_{out} - V_R) - V_{out} = 0$$

$$V_{in} - \frac{R_1}{R_2} V_{out} + \frac{R_1}{R_2} V_R - V_{out} = 0$$

$$V_{in} - V_{out}\left(\frac{R_1}{R_2} + 1\right) + \frac{R_1}{R_2} V_R = 0$$

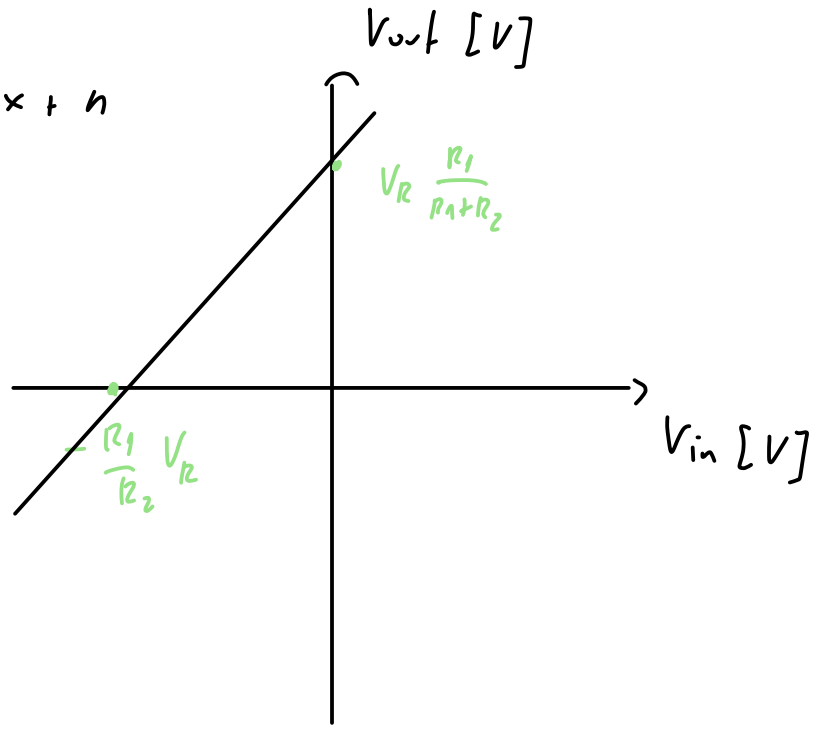
$$V_{out}\left(\frac{R_1 + R_2}{R_2}\right) = V_{in} + \frac{R_1}{R_2} V_R$$

$$\boxed{V_{out} = V_{in} \frac{R_2}{R_1 + R_2} + V_R \frac{R_1}{R_1 + R_2}}$$

jedina promjenljiva

Crtanje:

$y = kx + n$



$V_{in} = 0 \Rightarrow V_{out} = V_R \frac{R_1}{R_1+R_2}$

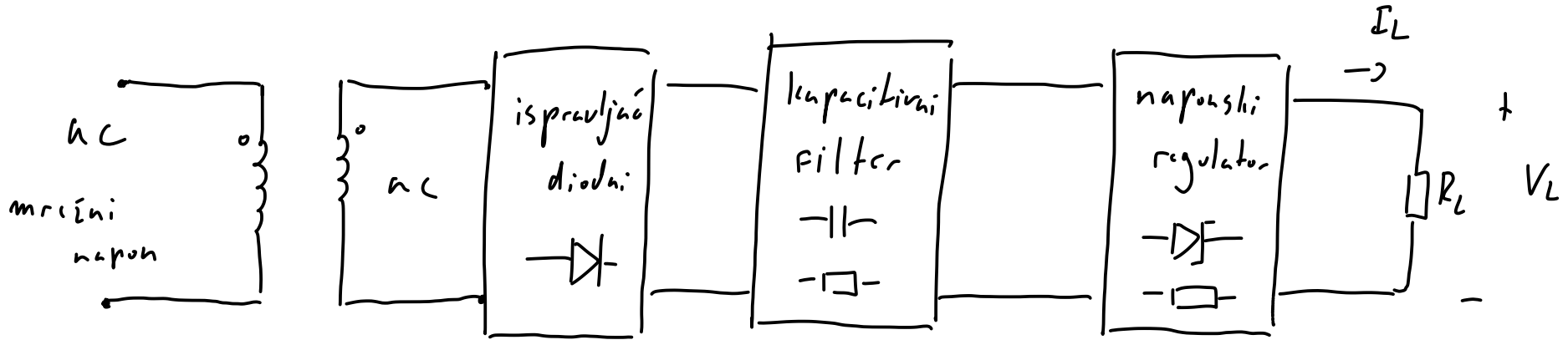
$V_{out} = 0 \Rightarrow V_{in} = -\frac{R_1}{R_2} V_R$

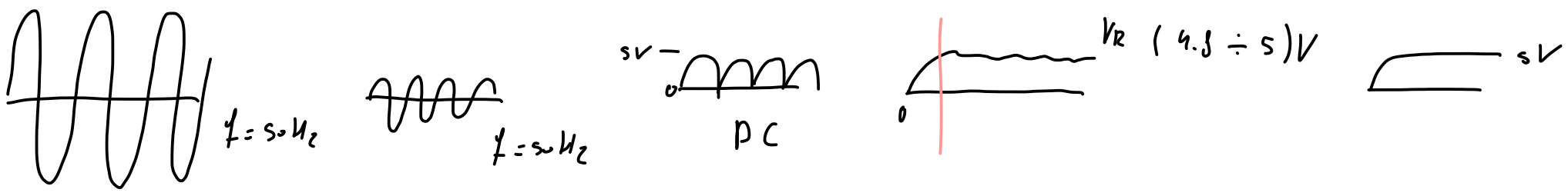
Predavanje 30.10.2024

Kola sa diodama

opterećenje
!
L - load

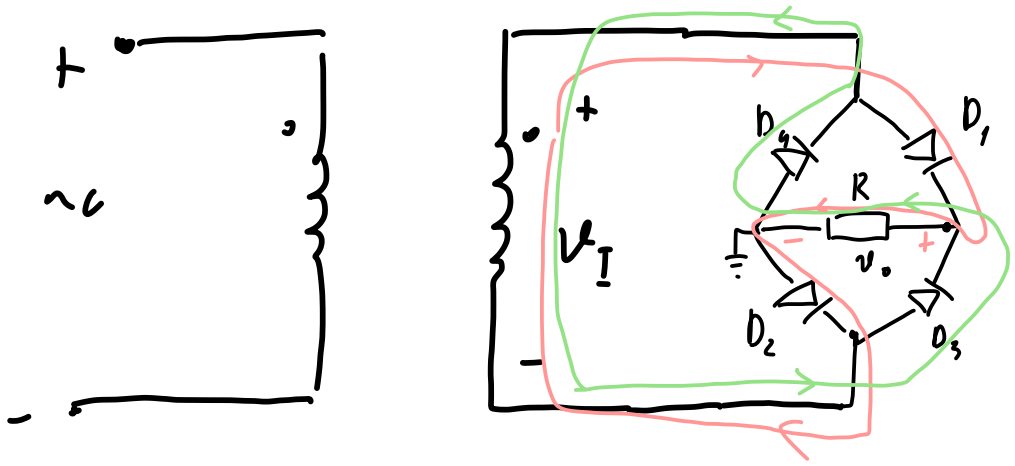
Ispravljači (usmerači)





* pitanje na usmeravanje

1. Mosni ispravljač (Graecov spoj)

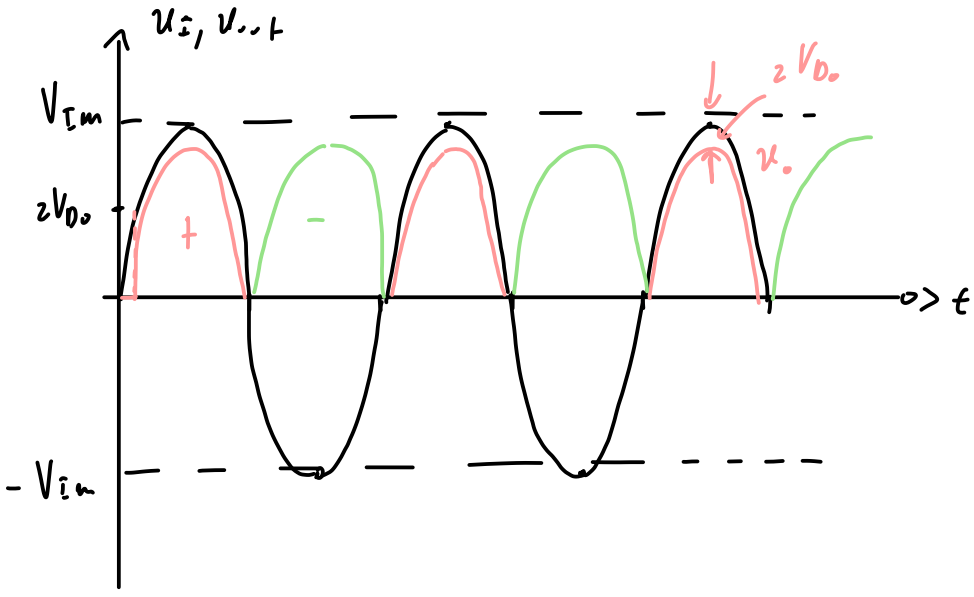


$v_I = V_{Im} \sin \omega t$

$v_I > 0$ idealizovani model diode (kad vodi V_{D0})

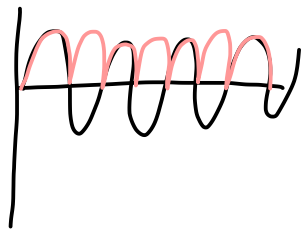
izlazni napon $v_I \geq 2V_{D0}$ (da bi obe diode vodile)

$v_o = v_I - 2V_{D0}$



$u_I < 0$ $\quad u_I \leq -2V_{D0}$

$u_o = -u_I - 2V_{D0}$



idealna dioda (nema pada napona)

+ vode D_1 i D_2, ne vode D_3 i D_4

− vode D_3 i D_4, ne vode D_1 i D_2

$V_{Im} = 5V$

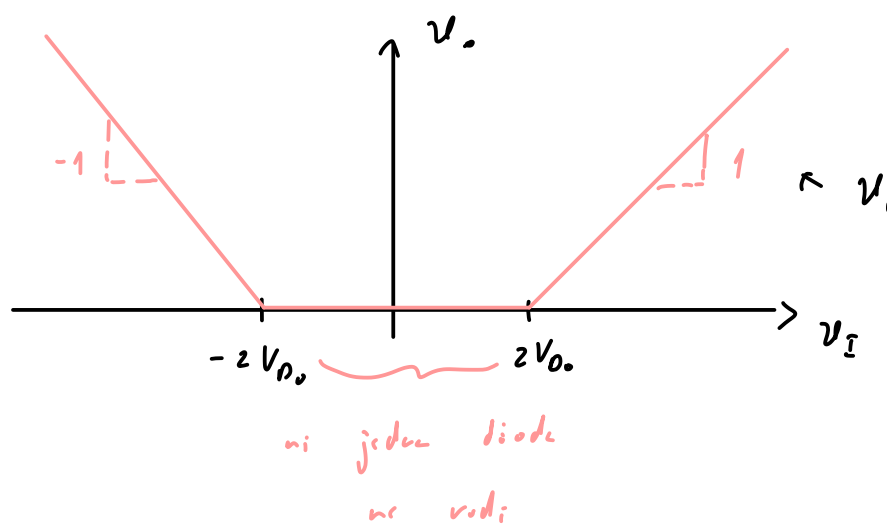
$V_{D0} = 0.6V$

izlazni napon

$5 - 2 \cdot 0.6 = 3.8V$

Prenosna karakteristika – zavisnost nekog izlaznog od nekog ulaznog veličine

$v_o = f(v_I)$ – naponska prenosna karakteristika

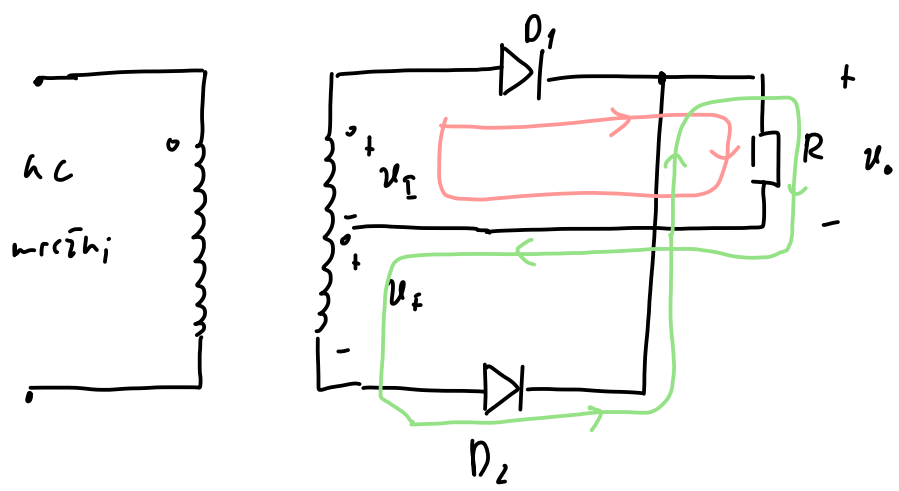


kat. pravac

$v_o = v_I - 2V_{D0}$

biće uvijek poz. jer je usaglašen smjer napona i struje na R

2. Sa transformatorom sa srednjim izvodom



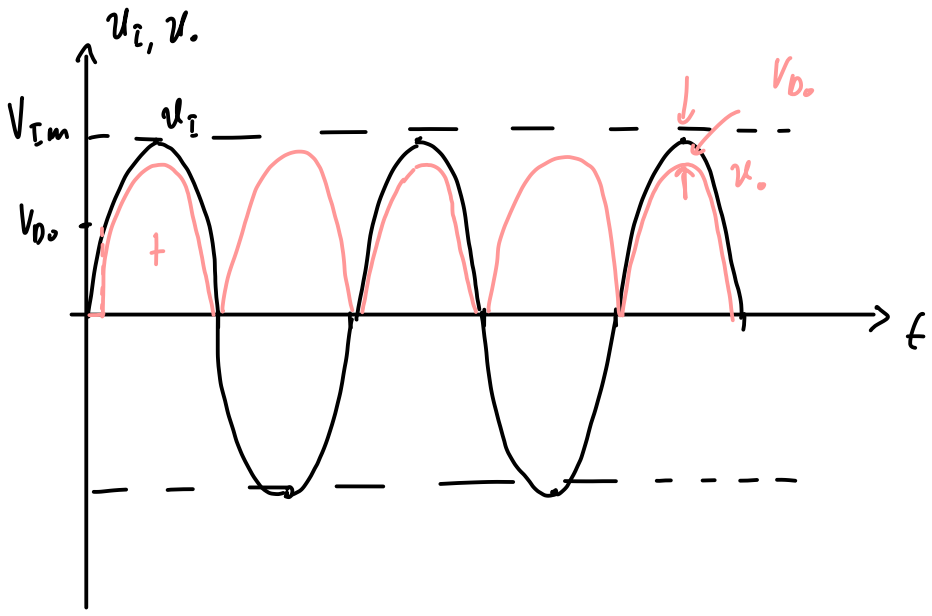
Idealizirani model diode (kad vodi $-|\overset{V_{D0}}{|}-$)

$v_I > 0$ $\quad v_I \geq V_{D0}$ $\quad$ vod. D_1, ne vodi D_2

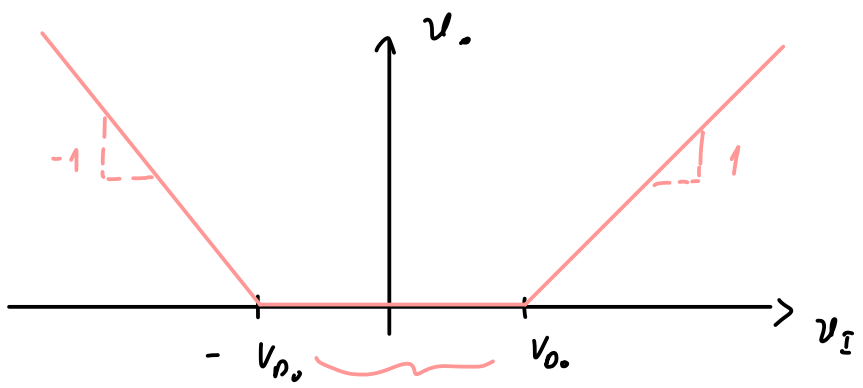
$v_o = v_I - V_{D0}$

$v_I < 0$ $\quad v_I \leq -V_{D0}$ $\quad$ vodi D_2, ne vodi D_1

$v_o = -v_I - V_{D0}$



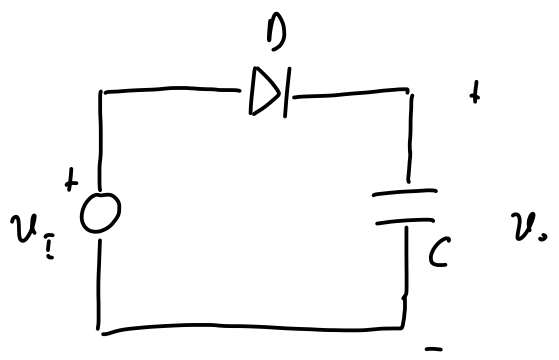
Prenosna:



ni jedna dioda ne vodi → manji nego kod Greacovog spoja (bolje)

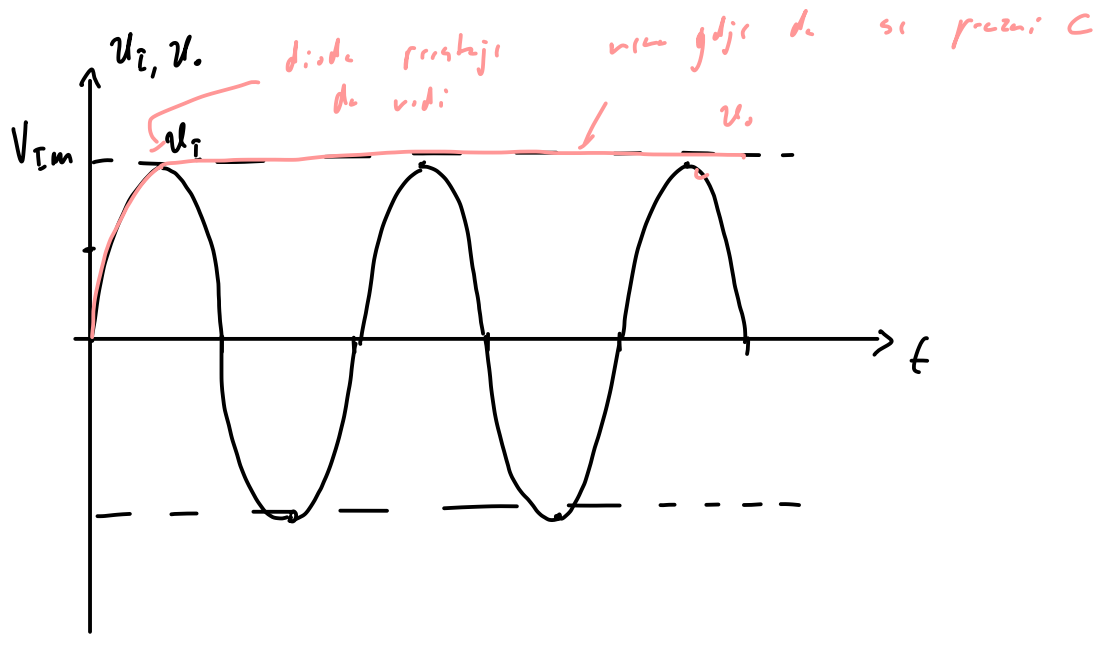
Kapacitivni filtar

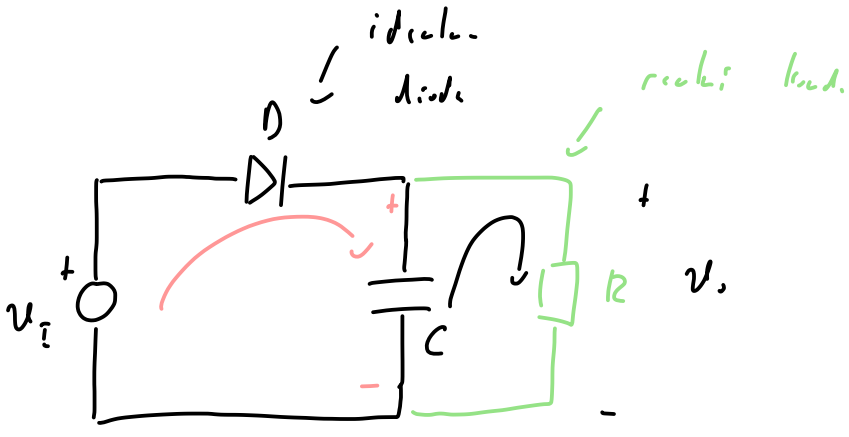
Idealni

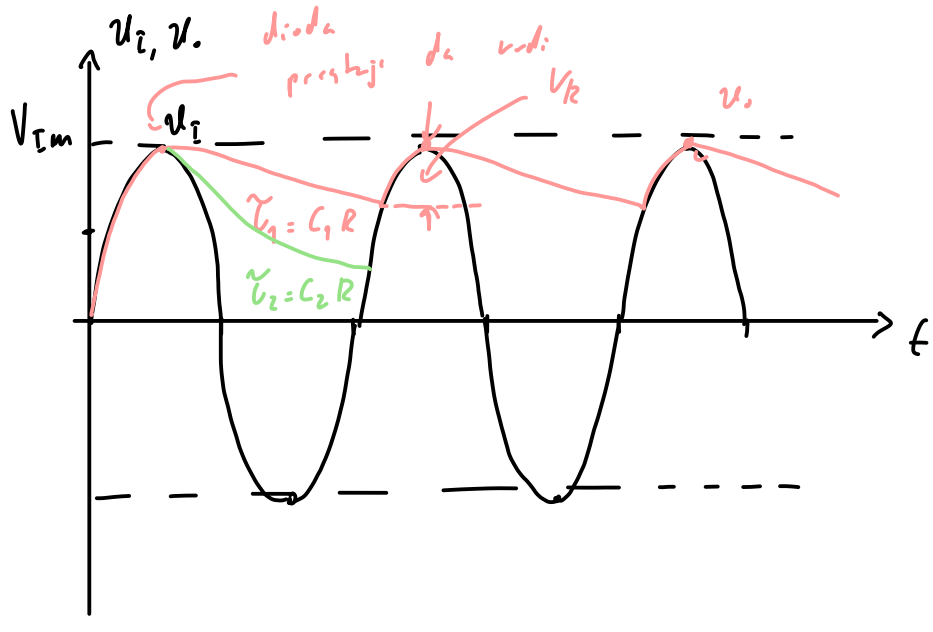


pretpostavke: - dioda idealna
- kond. nije napunjen ($t=0$)

$v_I \geq 0$ D vod. $v_o = v_I$





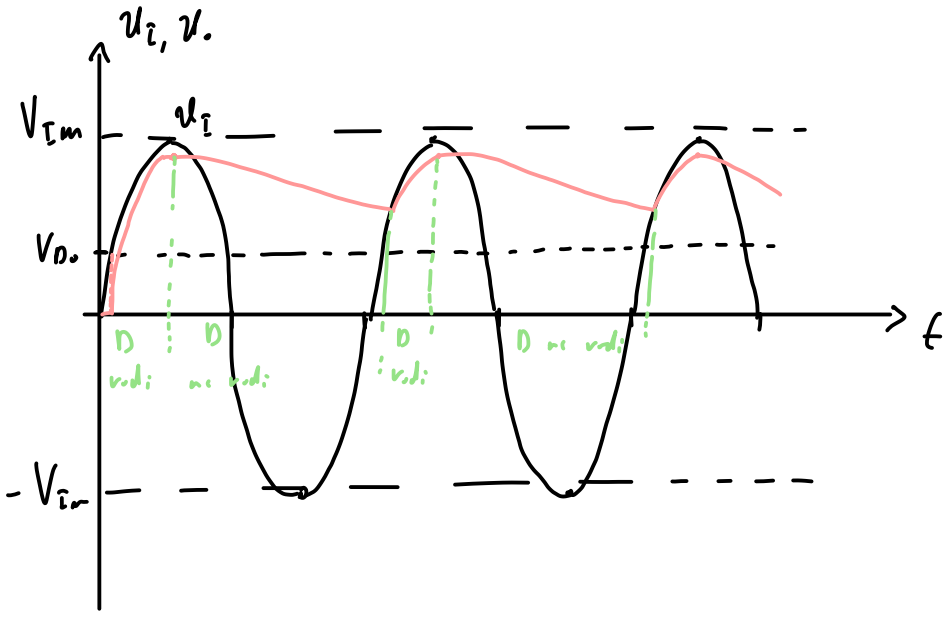


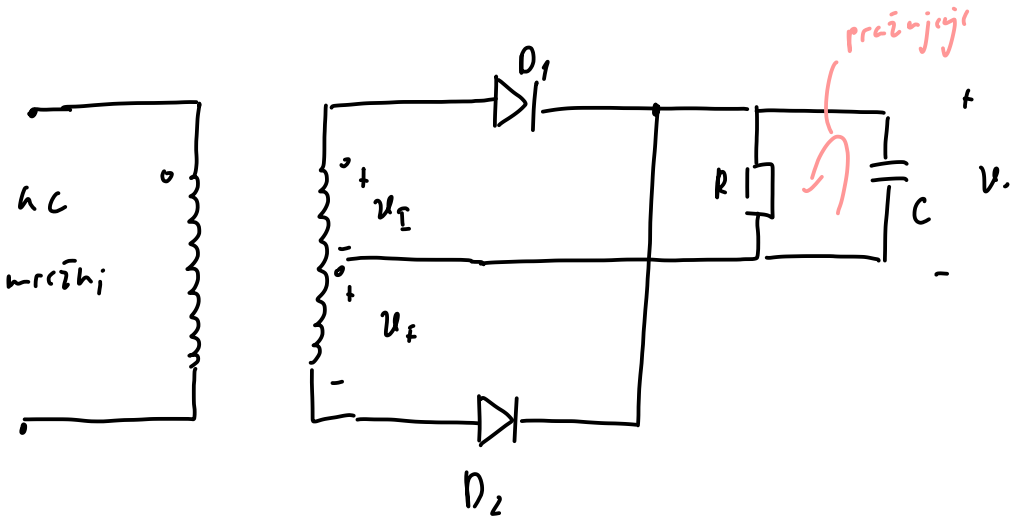
τ - vremenska konst. praznjenja

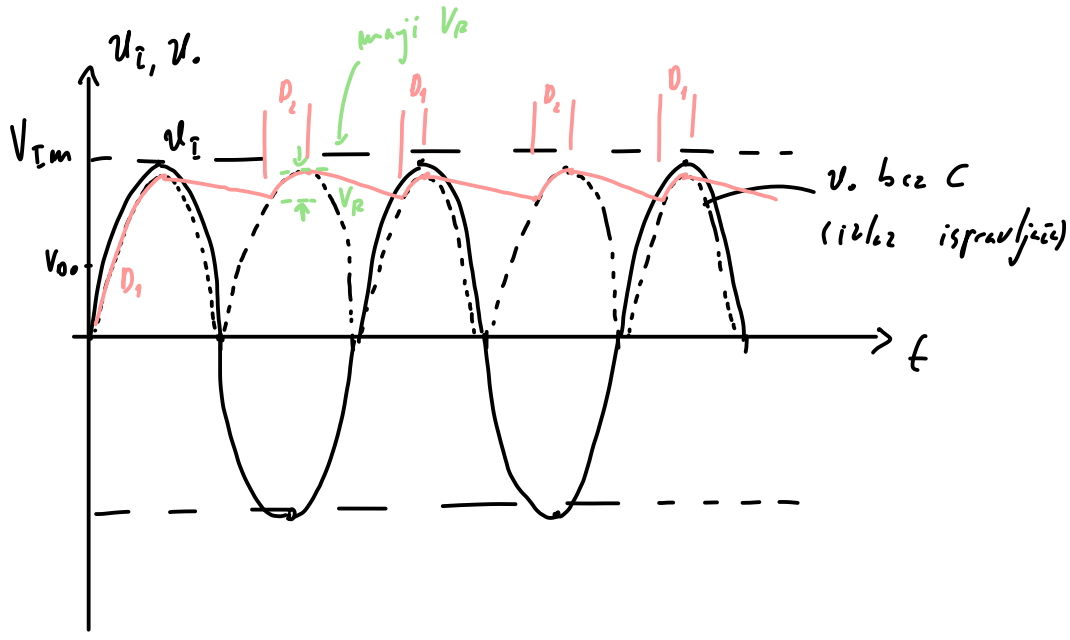
$\tau = RC$

→ želimo da bude velika

Realna diode, idealizirani model (V_{D0})







Tranzistori

Bipolarni tranzistori

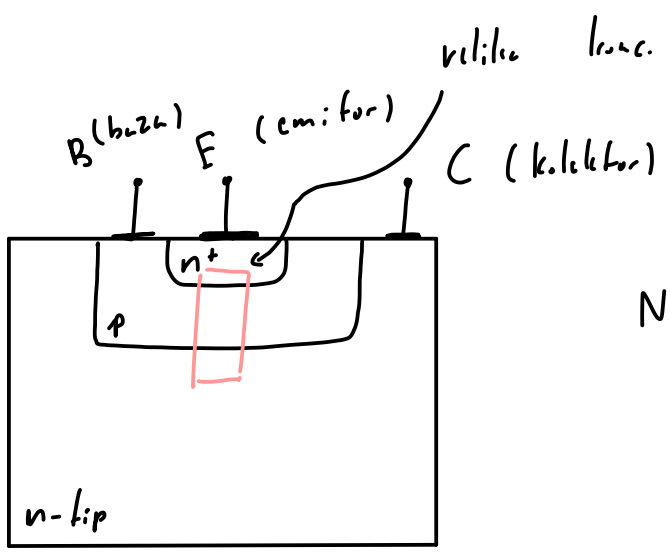
obe vrste nosilaca (i elektroni i šupljine)

transfer + resistor

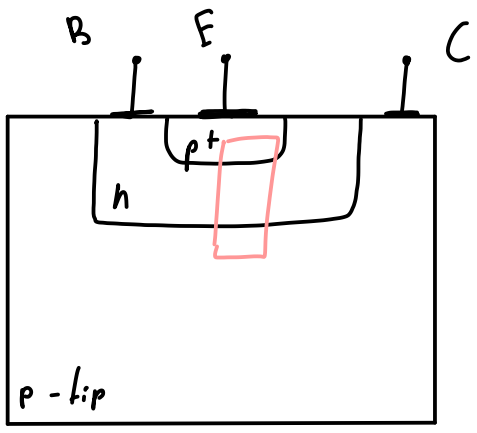
prenosni otpornik

BJT : 2 PN spoja

junction (spoj)

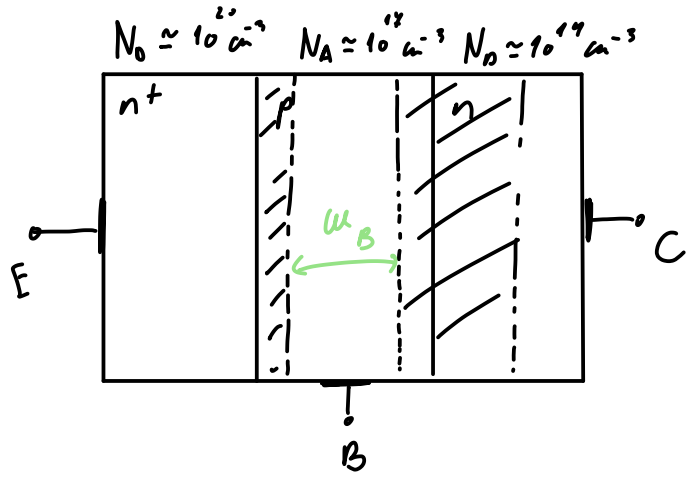


NPN tranzistor



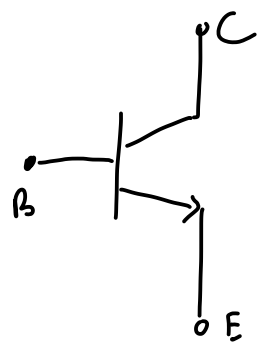
PNP tranzistor

NPN

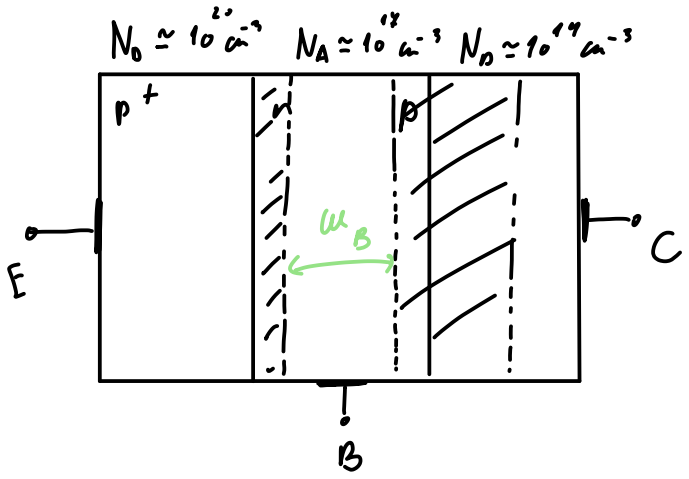


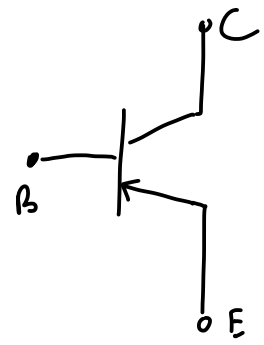
BE bazno emiterski spoj

BC bazno kolektorski spoj



PNP





NPN:

BE spoj	BC spoj	Režim rada	
direktno	inverzno	aktivni režim	} pojačavač
direktno	direktno	zasićenje (saturaciju)	} prekidač
inverzno	inverzno	zakočenje (isključen)	} prekidač
inverzno	direktno	inverzni režim	– ne koristi se (daje malo struju)

BJT u aktivnom režimu

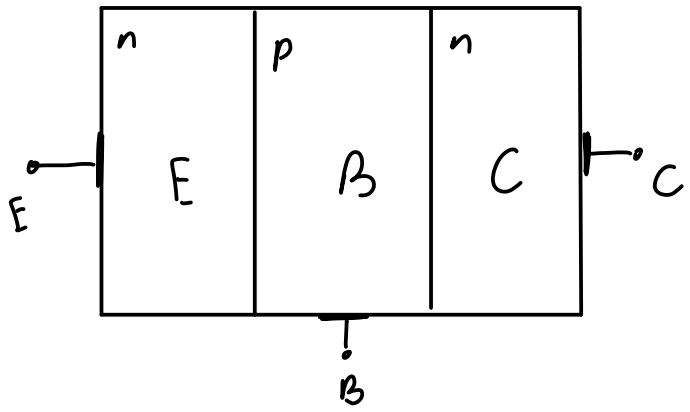
napon barijere

BE spoj direktna polarizacija $V_{BE} > 0$, $V_{BE} > V_{BE0} \simeq 0.5V$

$V_B > V_E$

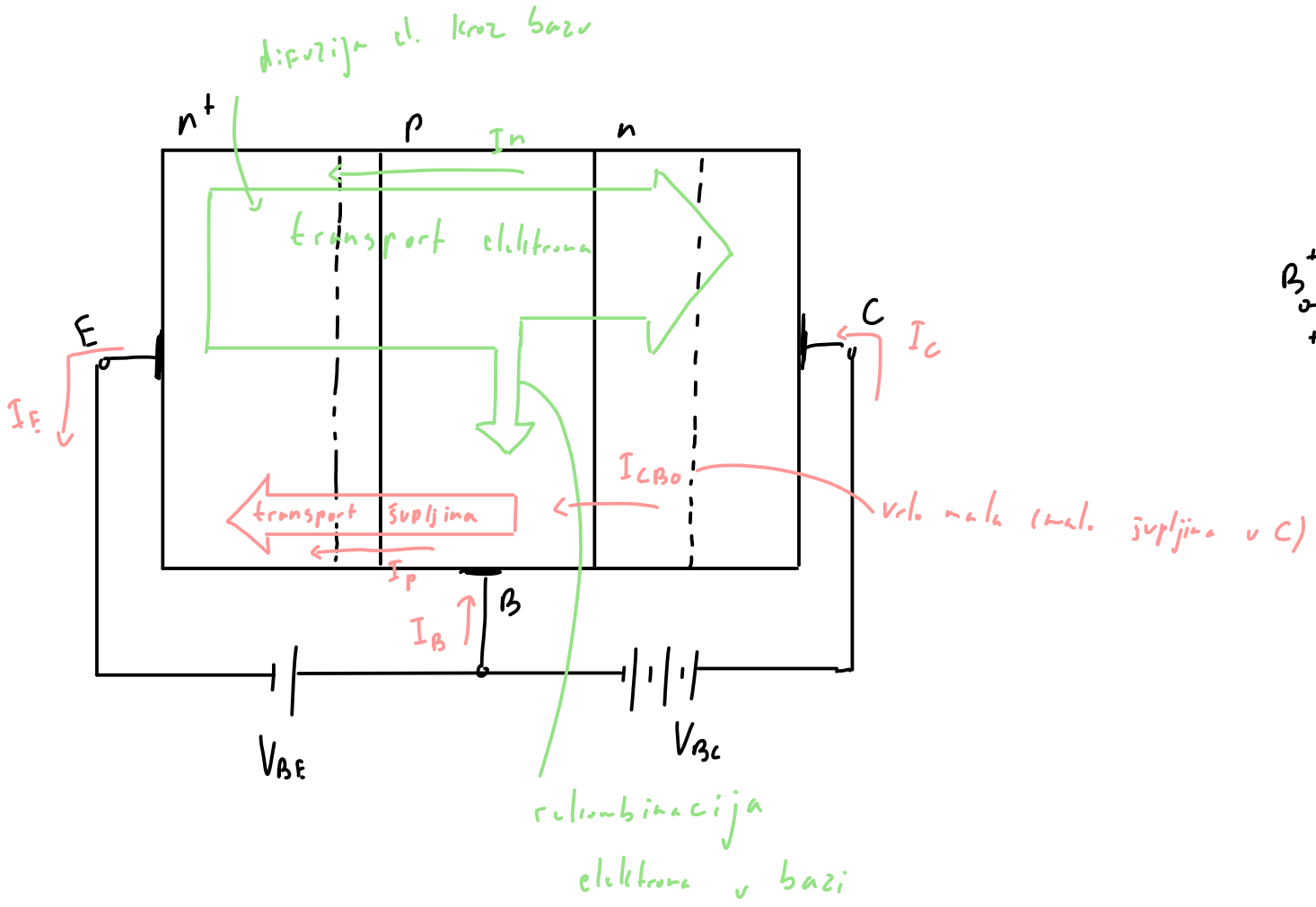
BC spoj inverzna polarizacija $V_{BC} < 0$ $V_{BC} < -(0.3 \div 0.4)\,V$

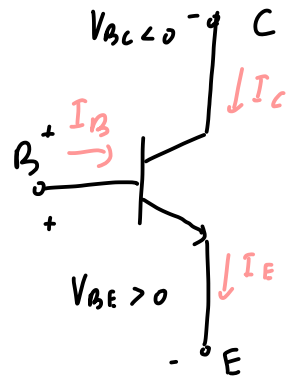
$V_B < V_C$



aktivni režim

$$\boxed{V_C > V_B > V_E}$$





$I_E, I_B, I_C > 0$

$I_E > I_C > I_B$

$I_{nE} > I_{nC}$ poželjno $I_{nE} \simeq I_{nC}$

$I_E = I_{nE} + I_{pE}$ poželjno $I_E \simeq I_{nE}$

$I_C \simeq I_{nC} \simeq I_{nE}$

$$\boxed{I_C \simeq I_S \cdot e^{\frac{V_{BE}}{V_t}}}$$

ulaz

izlaz

– prenosna funkc

Efikasnost emitera

$$\boxed{\gamma = \frac{I_{nE}}{I_{nE} + I_{pE}} < 1}$$

I_B

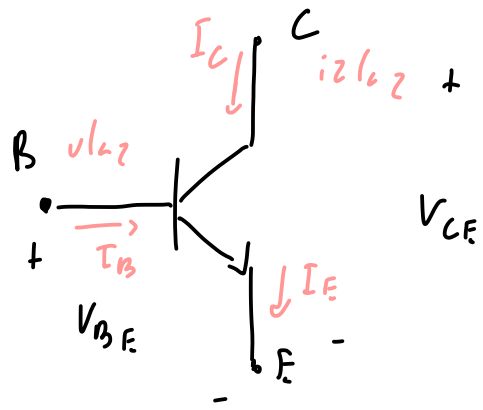
$I_E = I_C + I_B$

Predavanje 6.11.2024.

Zajednički emitor (ZE konfiguracija)

ulaz : baza (V_{BE}, I_B)

izlaz : kolektor (V_{CE}, I_C)



$V_{CE} = V_{BE} - V_{BC}$

aktivni režim : $V_{BE} > 0.5\,V$ (direktna polarizacija)

$V_{BC} < 0\,V$ (inv. pol.)

$V_C > V_B > V_E$

V_E obično uzemljen $V_E \simeq 0\,V$

} naponski uslovi

Strujno pojačanje (sa ZE)

$$\boxed{\beta = \frac{\text{izlazna struja}}{\text{ulazna struja}} = \frac{I_C}{I_B}}$$

, obično β (50 ÷ 200)

I_B

$I_C = \beta I_B$

$I_E = I_B + I_C$

$= (1+\beta) I_B$

$I_C = I_S e^{\frac{V_B}{V_T}}$

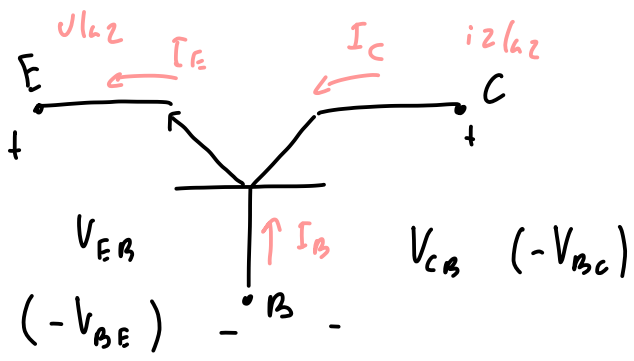
$I_B = \frac{I_C}{\beta} = \frac{I_S}{\beta} \cdot e^{\frac{V_B}{V_T}}$

$I_E = \frac{(1+\beta)}{\beta} I_C = \frac{1+\beta}{\beta} e^{\frac{V_{BE}}{V_T}}$

$I_C, I_B, I_E = f(V_{BE})$

} sve struje

Zajednička baza (ZB konfiguracija)



ulaz : emitor (V_{EB}, I_E)

izlaz : kolektor (V_{CB}, I_C)

$V_C > V_B > V_E$ } nap. uslovi

Strujno pojačanje za ZB

$$\boxed{\alpha = \frac{\text{izlaz } I}{\text{ulazna } I} = \frac{I_C}{I_E}}$$

$$I_E = I_B + I_C$$

$$\alpha = \frac{I_C}{I_B + I_C} < 1$$, strujno pojačanje ~ faktor pojačanja

$$\boxed{\alpha = \frac{I_C}{I_E}} < 1$$

α $(0.98 \div 0.99)$

I_E

$$\boxed{I_C = \alpha I_E}$$

$$I_B = I_E - I_C = I_E - \alpha I_E$$

$$\boxed{I_B = (1-\alpha) I_E}$$

$$I_C = I_S \cdot e^{\frac{V_{BE}}{V_t}} = I_S e^{-\frac{V_{EB}}{V_t}}$$

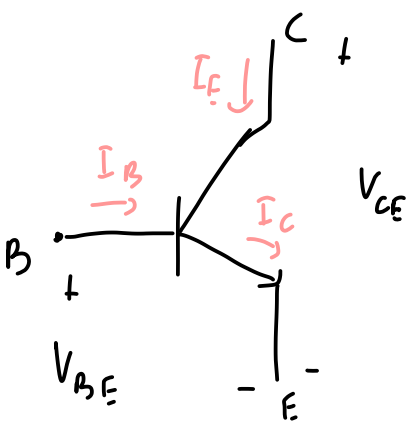
$$I_E = \frac{I_C}{\alpha} = \boxed{\frac{I_S}{\alpha} e^{\frac{V_{BE}}{V_t}}}$$

$$\boxed{I_B = \frac{1-\alpha}{\alpha} I_C = \frac{1-\alpha}{\alpha} I_S e^{\frac{V_{BE}}{V_t}}}$$

$$\boxed{\alpha = \frac{\beta}{1+\beta}} \qquad \boxed{\beta = \frac{\alpha}{1-\alpha}}$$

} relacije između strujnih pojačanja

Strujno-naponske karakteristike (sa ZE)



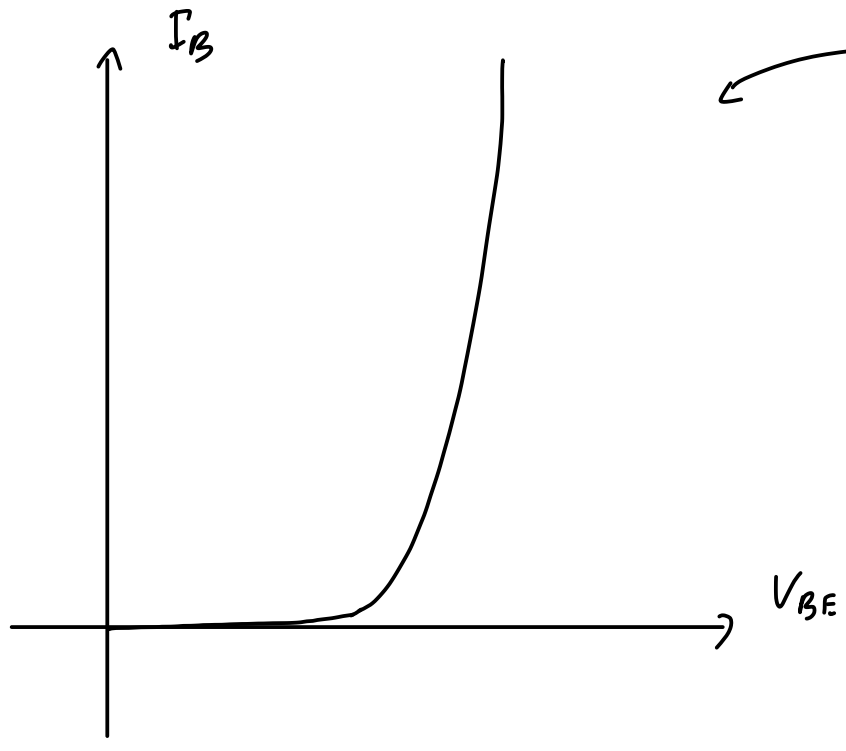
ulaz: V_{BE}, I_B

izlaz: V_{CE}, I_C

1. Ulazna

- $I_B = f(V_{BE})$, zavisnost ulazne str. od ulaznog napona

$$I_B = \frac{I_C}{\beta} = \frac{I_S}{\beta} e^{\frac{V_{BE}}{V_t}} \Rightarrow \boxed{I_B = \frac{I_S}{\beta} e^{\frac{V_{BE}}{V_t}}}$$

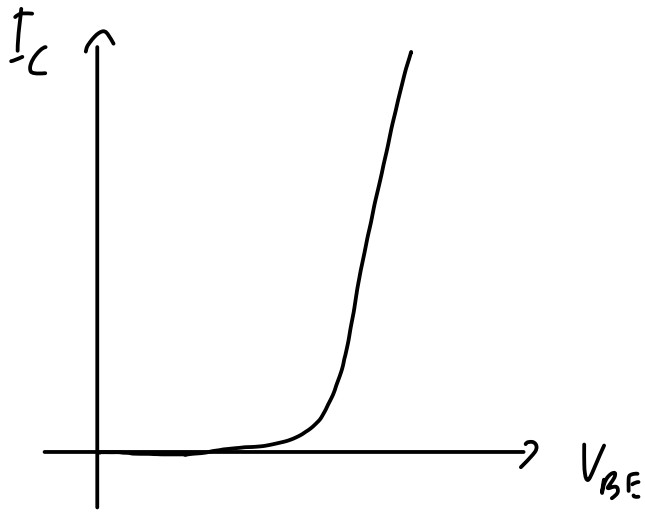


eksponencijalna karakteristika

2. Prenosna:

$I_C = f(V_{BE})$, zavisnost izlazne I od ulazne V

$$\boxed{I_C = I_S \cdot e^{\frac{V_{BE}}{V_t}}}$$



I_B je β puta manja od I_C

$I_B = \frac{I_C}{\beta}$, $\beta \in (50 \div 200)$

) pa nema smisla crtati na istom graf.

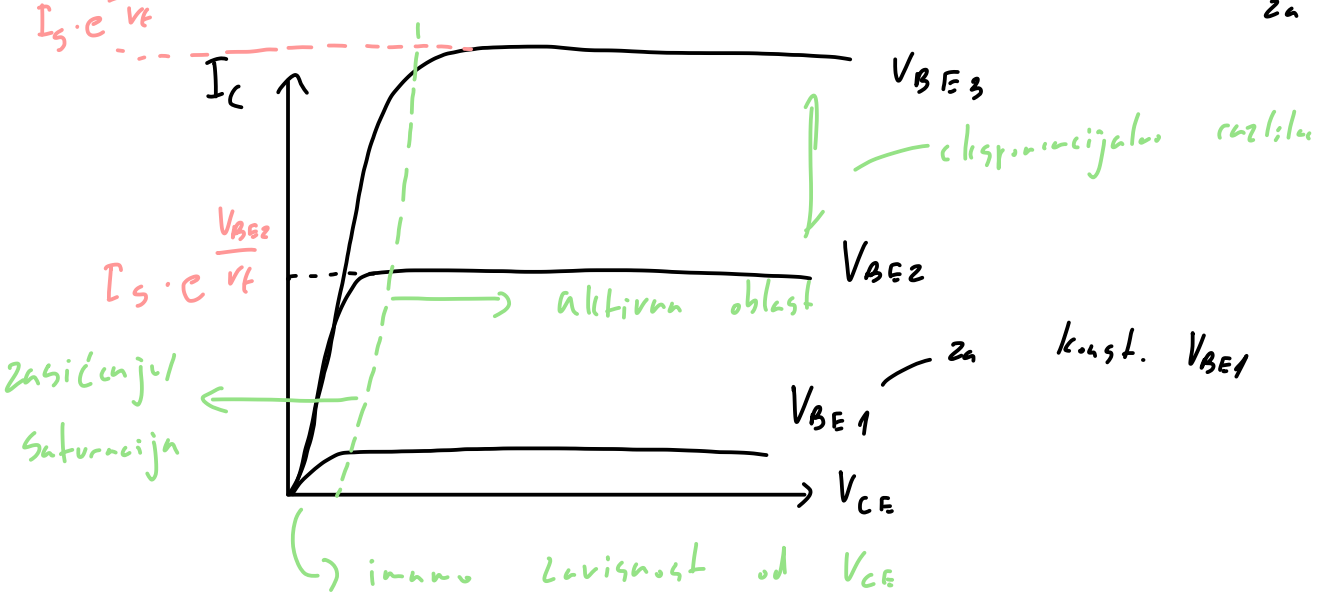
3. Izlazne karakteristike:

- $I_C = f(V_{CE})\big|_{V_{BE},\, I_B}$, zav. izlazni I od izlazne V

↳ moramo imati i neki ulaz

U odnosu na napon V_{BE}:

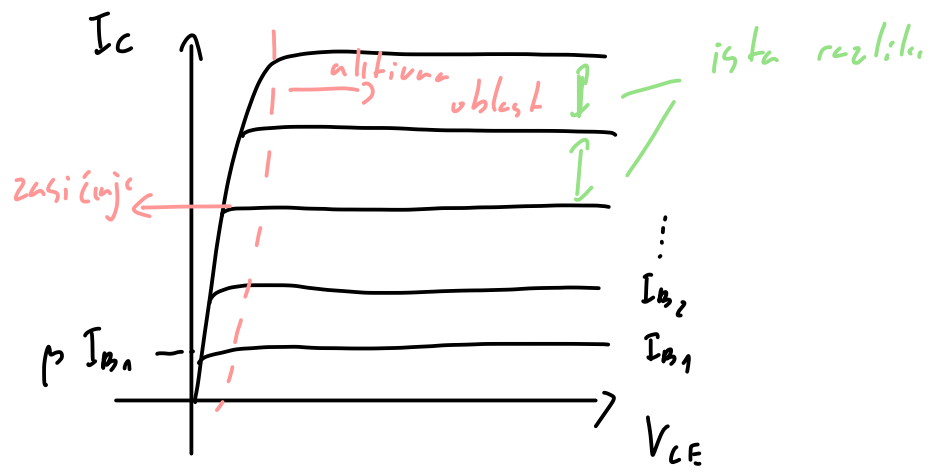
$I_C = I_S \cdot e^{\frac{V_{BE}}{V_t}}$, ne zavisi od V_{CE} osim za male vrijednosti V_{CE}



kad rad: kao pojačavač → treba biti u aktivnoj oblasti

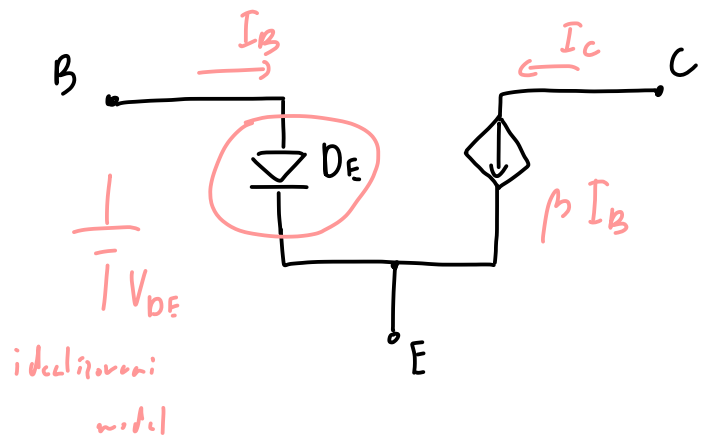
$I_C = f(V_{CE})|_{I_B}$

$\boxed{I_C = \beta I_B}$ — lin. funkc

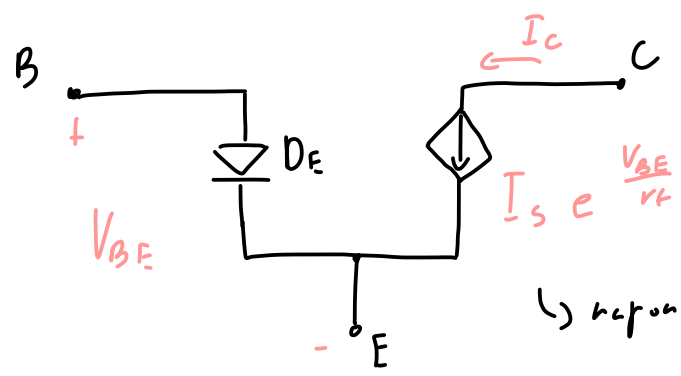


Model BJT-a za velike signale (statički model) ZE

strujom upravljan model



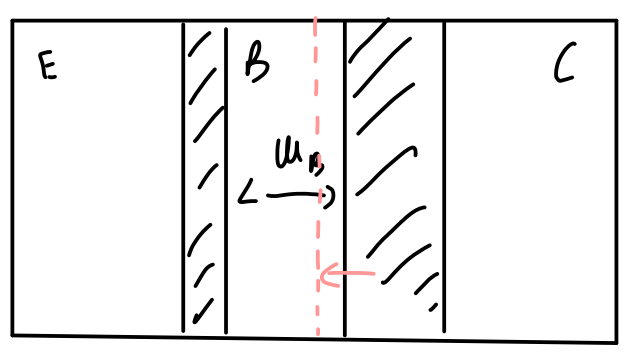
naponom upravljan model



↳ naponom kontrolisan strujni generator

Erlijev efekat

$I_C \neq f(V_{CE})$ u aktivnoj oblasti



$V_C \nearrow$

BC spoj je sve više inverzno pol.

→ širi se osiromašena oblast

→ W_B se smanjuje ↓

→ sve manja rekombinacija (više e^- će stići do C)

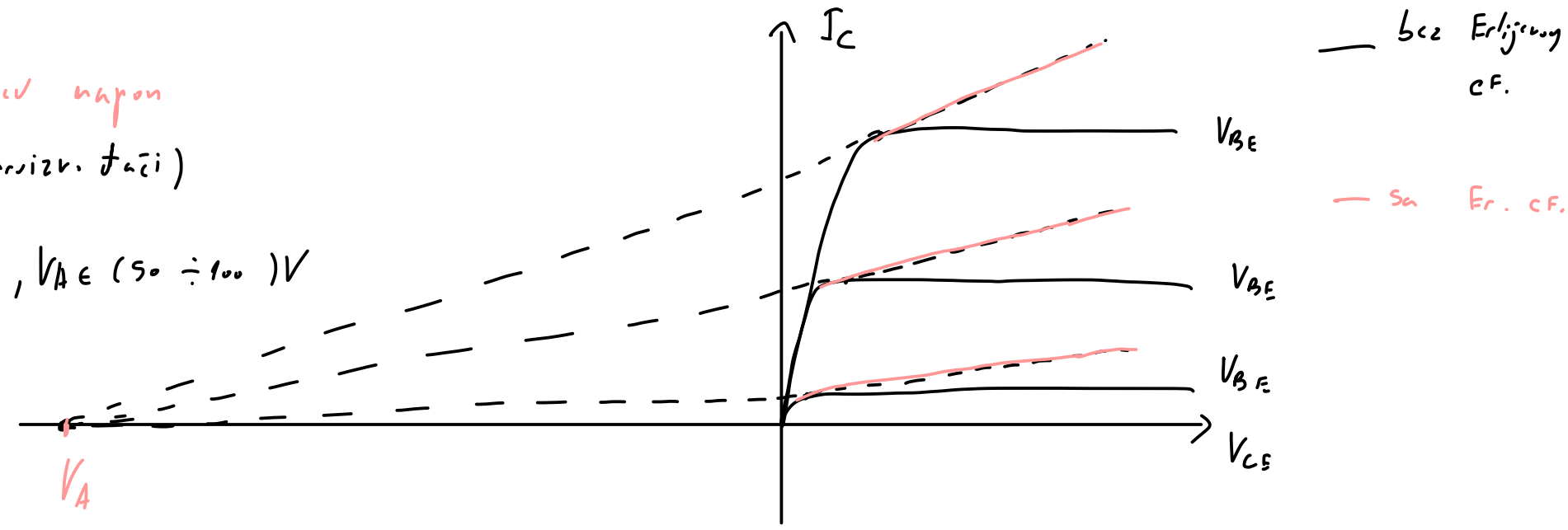
→ $I_C \nearrow$

- porast I_C uslijed smanjenja bazne oblasti tj. povećanja V_C (Erlijev efekat)

V_A Erlijev napon

(daju proizv. tači)

$V_A > 0$, $V_A \in (50 \div 100)\,V$



$$I_C = I_S \cdot e^{\frac{V_B}{V_t}} \left(1 + \frac{V_{CE}}{V_A}\right)$$

$\frac{V_{CE}}{V_A}$ → može se zanemariti

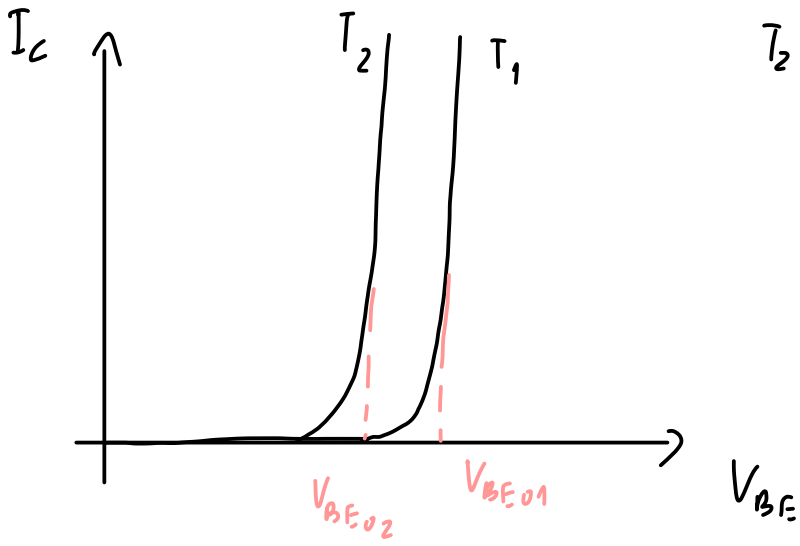
Dinamička otpornost (izlazna otpornost)

$$\boxed{r_o = \frac{V_A}{I_C}}$$

Ograničenja u radu tranzistora

Termičke karakteristike:

$T \uparrow$



$T_2 > T_1$ $\quad T \uparrow$ $\quad$ napon rotacija $\downarrow$

$V_{BE02} < V_{BE01}$ $\quad V_{BEG} \downarrow$

$-2.5\ \frac{mV}{°C}$

$I_{C2} > I_{C1}$ $\quad I_C \uparrow$

$$I_C = I_S\, e^{\frac{V_{BE}}{V_t}}$$

$I_S = f(T)$

$T \uparrow$ $\quad I_S \uparrow$

inverzna struja zasićenja

$\beta = f(T)$

$T \uparrow$ $\quad \beta \uparrow$

I_C, I_S, β, V_{BEo} – Funkcije temperature

$$\boxed{T \uparrow : \quad I_C \uparrow,\ I_S \uparrow,\ \beta \uparrow,\ V_{BEo} \downarrow}$$

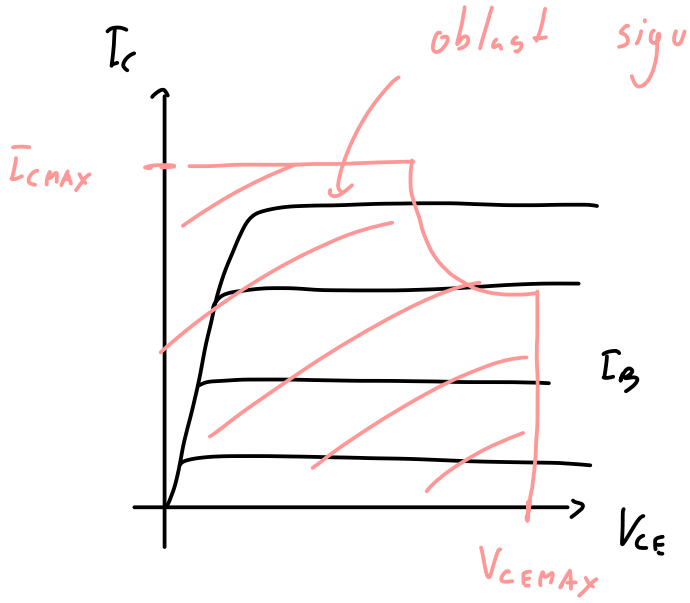
Proizvođači:

- I_{CMAX}
- V_{CEMAX}
- $P_{D\,MAX}$ - maks. snaga disipacije
  → ono što tranzistor troši

izlazne veličine

$$\boxed{P_D = I_C \cdot V_{CE}}$$

$$P_D < P_{DMAX}$$



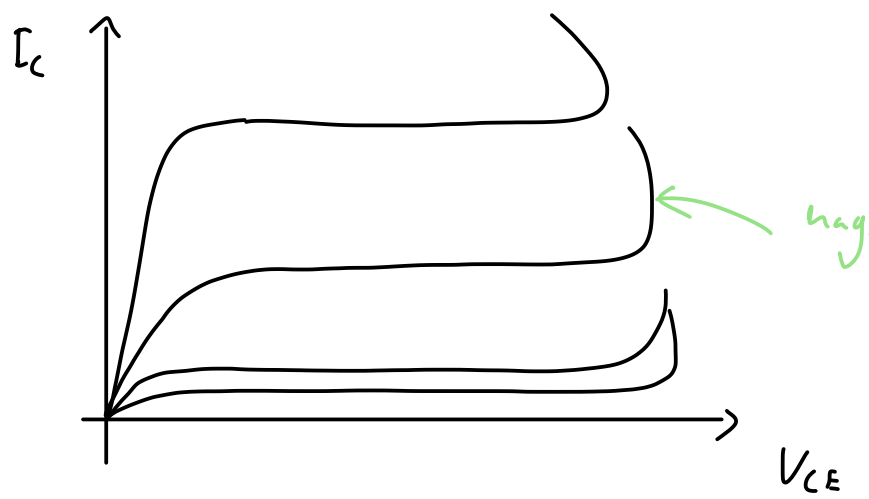
oblast sigurnog rada

ne smiju se pojaviti u isto vrijeme oba

$$P_{D\,MAX} < I_{CMAX} \cdot V_{CEMAX}$$

Proboj tranzistora

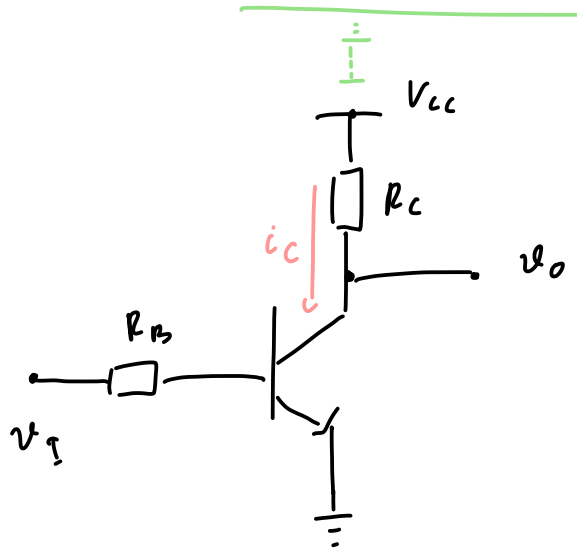
- proboj se događa kad inv. pol → znači BC probija



BV_{BCO}

nagli porast struje → trajno će oštetiti tranzistor

Analiza za male signale i BJT za male signale



V_{CC} napajanje

$$v_I = V_I + v_i$$

V_I – DC napon

v_i – napon malih signala

$$v_i = V_{Im} \sin \omega t$$

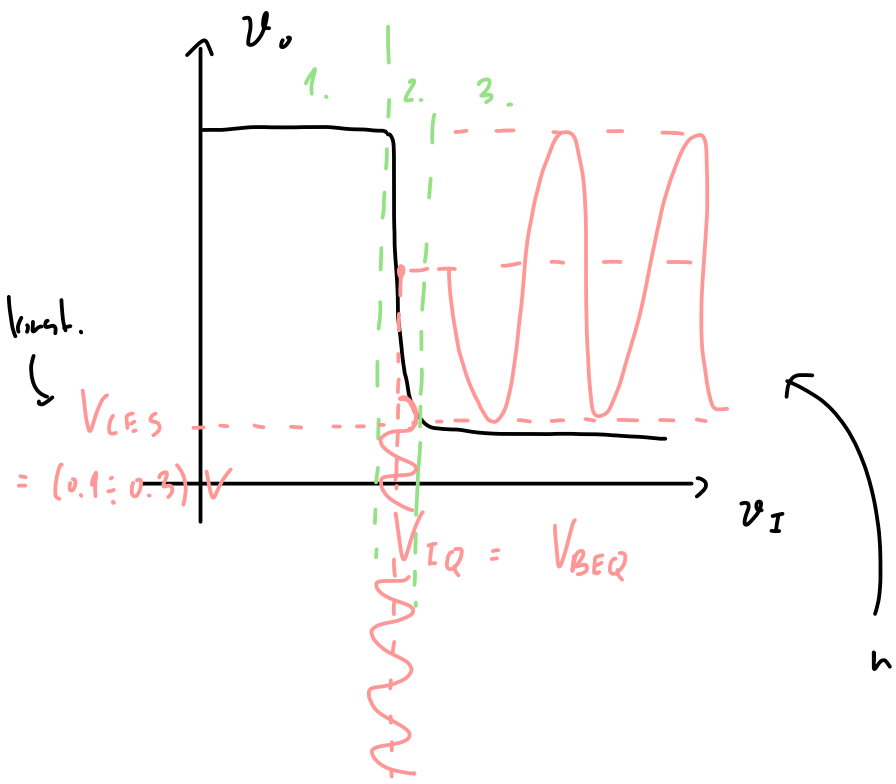
$$i_C = I_S \cdot e^{\frac{v_{BE}}{V_t}} \qquad v_O = V_O + v_o$$

$$v_O = V_{CC} - R_C \cdot i_C = V_{CC} - R_C \cdot I_S \cdot e^{\frac{v_{BE}}{V_t}}$$

$$v_{BE} \simeq v_I$$

$$v_O = V_{CC} - R_C \cdot e^{\frac{v_I}{V_t}}$$

$v_O = f(v_I)$ - naponska prenosna karakteristika



1. tranzistor isključen
2. tranzistor u aktivnoj oblasti
3. tranzistor je u zasićenju

radna tačka treba da bude u 2.

naponski pojačivač

uvedemo:

$$v_{BE} = V_{BE} + v_{be}$$

$$i_C = I_S e^{\frac{v_{BE}}{V_t}} = I_S e^{\frac{V_{BE} + v_{be}}{V_t}}$$

$$i_C = \underbrace{I_S e^{\frac{V_{BE}}{V_t}}}_{I_C = I_{CQ}} \cdot e^{\frac{v_{be}}{V_t}}$$

$$e^{\frac{v_{be}}{V_t}} \quad (v_{be} \simeq 5\,mV) \simeq 1 + \frac{v_{be}}{V_t}$$

$$i_C = I_C \left(1 + \frac{v_{be}}{V_t}\right)$$

$$i_C = I_C + \underbrace{\frac{I_C}{V_t} \cdot v_{be}}_{i_c}$$

i_c — kolektorska struja malih signala

$$i_c = \boxed{\frac{I_C}{V_t}}\, v_{be}$$

↳ provodnost

tj.

$$\boxed{g_m = \frac{I_C}{V_t}}$$

transkonduktansa (strmina)

$$i_B = \frac{i_C}{\beta} = \frac{I_C + i_x}{\beta} = \underbrace{\frac{I_C}{\beta}}_{I_B = I_{BQ}} + \underbrace{\frac{i_x}{\beta}}_{i_b} = I_B + i_b$$

$$i_b = \frac{i_x}{\beta} = \frac{\overset{g_m}{I_C}}{\beta V_t} \cdot v_{be}$$

$$i_b = \frac{g_m}{\beta} v_{be}$$

r_π - ulazna otpornost gledana u bazu

$$\boxed{r_\pi = \frac{v_{be}}{i_b} = \frac{\beta}{g_m}}$$

$$i_E = \frac{i_C}{\alpha} = \frac{I_C + i_x}{\alpha} = \underbrace{\frac{I_C}{\alpha}}_{I_E = I_{EQ}} + \underbrace{\frac{i_x}{\alpha}}_{i_e}$$

$$i_e = \frac{i_x}{\alpha} = \frac{g_m}{\alpha} \cdot v_{be}$$

struja lin. zavisi od napona baza-emiter

$$\boxed{r_e = \frac{v_{be}}{i_e} = \frac{\alpha}{g_m}}$$ gledano u emiter

$$r_e \simeq \frac{1}{g_m}, \text{ jer } \alpha \simeq 1$$

r_e i r_π iste otpornosti - samo se jedna pojavljuje, npr. ako je ZE onda gledamo u bazu, a za ZB u r_e

$\downarrow$

i vidimo samo r_π

$$\left.\begin{aligned} v_{be} &= i_e r_e \\ v_{be} &= i_b r_\pi \end{aligned}\right\} \quad r_e \cdot i_e = i_b \cdot r_\pi$$

$$r_e (1+\beta) i_b = i_b \cdot r_\pi$$

$$\boxed{r_\pi = (1+\beta) r_e}$$

$$\boxed{\begin{aligned} g_m &= \frac{I_C}{V_t} \\ r_\pi &= \frac{\beta}{g_m} \\ r_o &= \frac{V_A}{I_C} \end{aligned}}$$

$$v_o = V_{CC} - R_C \cdot i_C$$

$$v_o = v_{CE}$$

u dinamičkoj analizi (analiza malih sig.):

$$v_{CE} = V_{CC} - R_C (I_C + i_x)$$

$$= V_{CC} - R_C I_C - R_C i_x$$

V_{CEQ} $\quad$ $v_{ce} = v_o$

Naponsko pojačanje malih signala

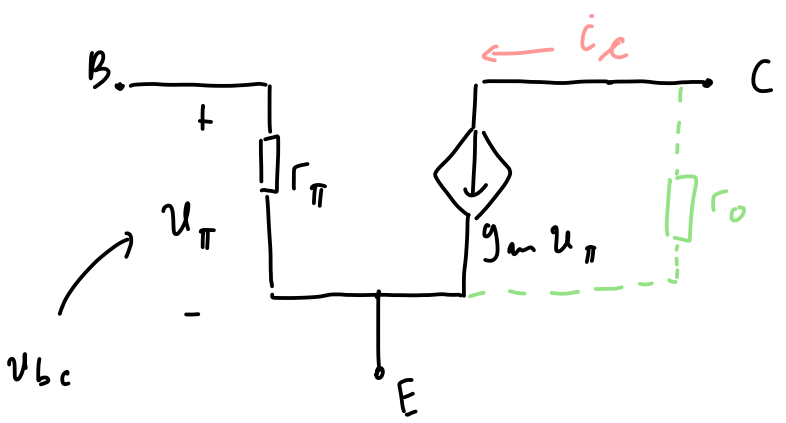
$$A_v = \frac{v_o}{v_i} = \frac{v_{ce}}{v_{be}}$$

$$A_v = \frac{-R_c \cdot i_c}{i_c / g_m}$$

$$\boxed{A_v = -g_m R_c}$$

→ ulazni i izlazni signali su u protifazi (fazno pomjereni za π)

Model BJT za male signale:



Su Erlijevim efektom ima r_o, ako nema Erlijevog efekta $r_o \nearrow \infty$

1. iz statičke analize: radna tačka I_C (I_{CQ})

2. dinamička analiza (model za male signale)

parametri modela:

$$g_m = \frac{I_C}{V_t}$$

$$r_\pi = \frac{\beta}{g_m} = \frac{V_t \cdot \beta}{I_C}$$

$$r_o = \frac{V_A}{I_C}$$

svi zavise od radne tačke, tj od kolektorske struje I_{CQ}

3. naponsko pojačanje: $A_v = -g_m R_c$

Vježbe 15.11.2024.

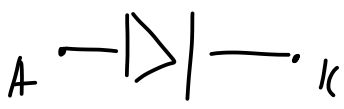
1. Diode (15.11)
2. BJT i MOS (22.11)
3. OP-AMP (29.11)

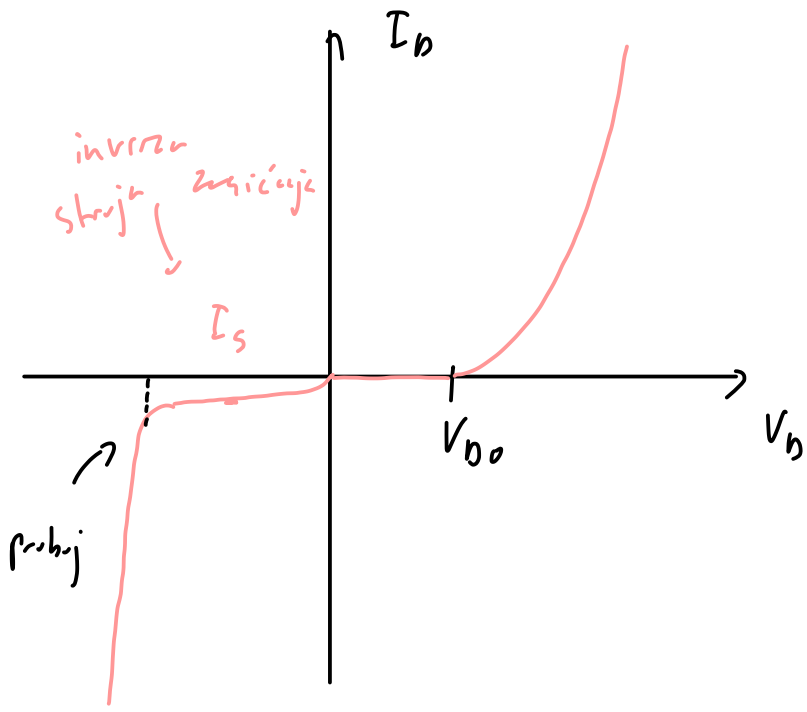
} I kolokvijum (12-27.12.)

4. Logička kola (6.12)
5. CMOS ; TTL (13.12)
6. A/D, D/A ; RAM (20.12)

} II kolokvijum (13.1 ili ispitni rok, 1 termin)

Diode i diodna kola





napon na krajevima diode

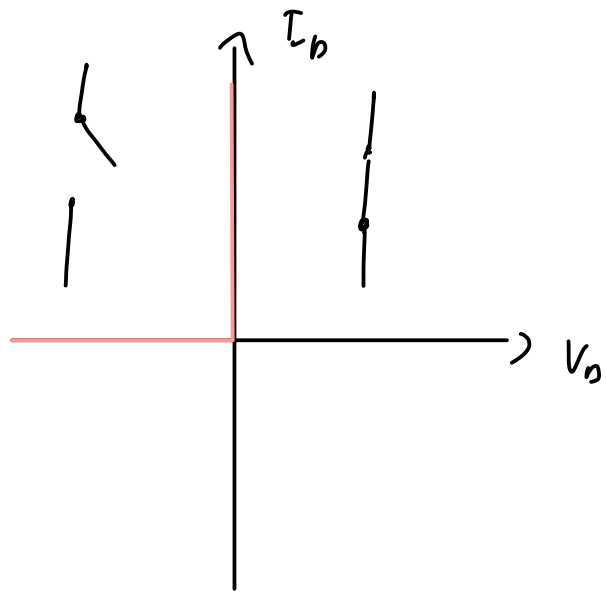
$$I_D = I_S \left(e^{\frac{V_D}{nV_t}} - 1\right) \cong I_S \cdot e^{\frac{V_D}{V_t}}$$

V_t - termički potencijal $\hat{=}$ 25mV

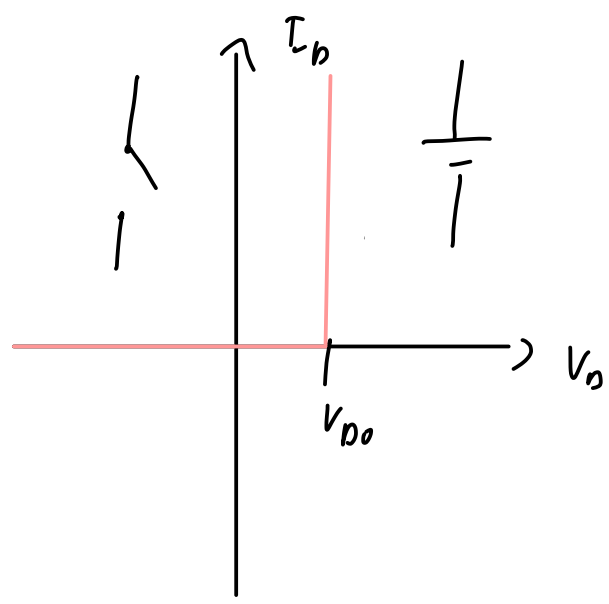
$n \sim 1$

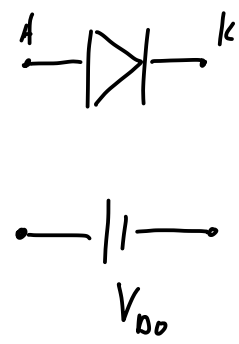
Modeli diode:

1. Model idealne diode

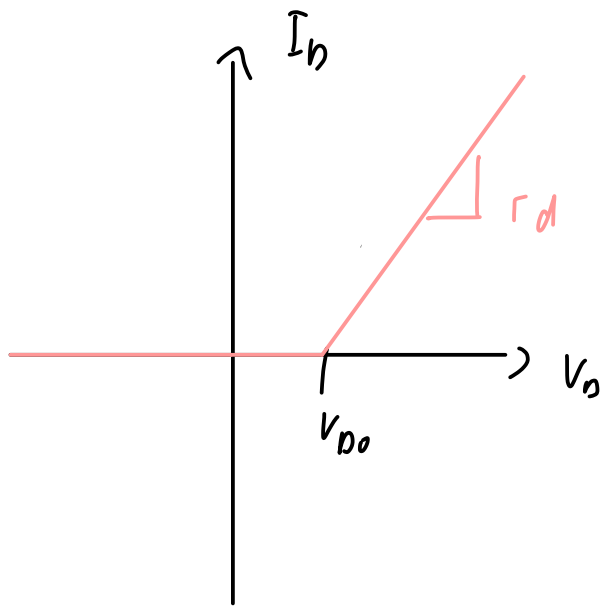


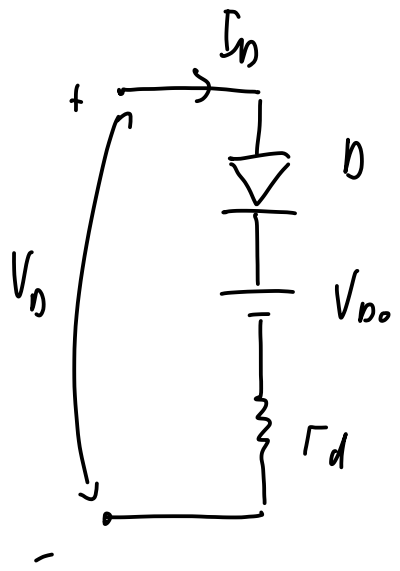
• Idealizovani model





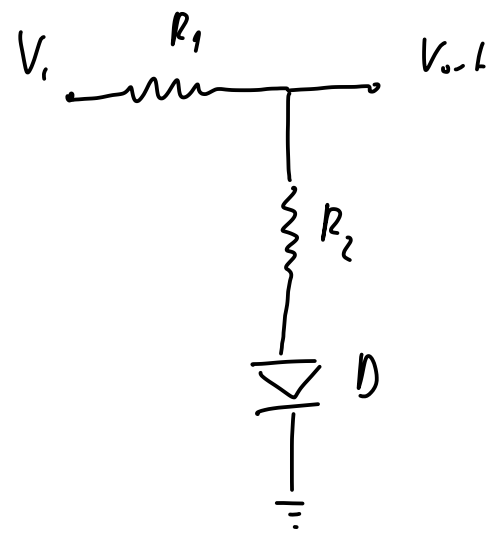
- Linearizovani





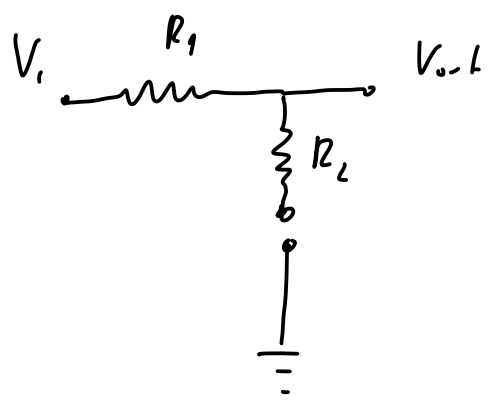
idealna dioda

1. Nacrtati prenosnu karakteristiku kola sa slike
   a) koristeći model idealne diode
   b) kor. model idealizovane diode

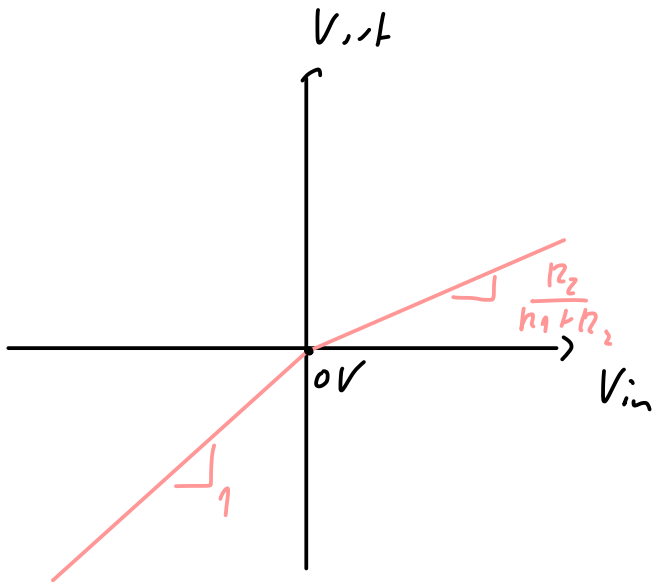


$V_{out} = f(V_{in})$

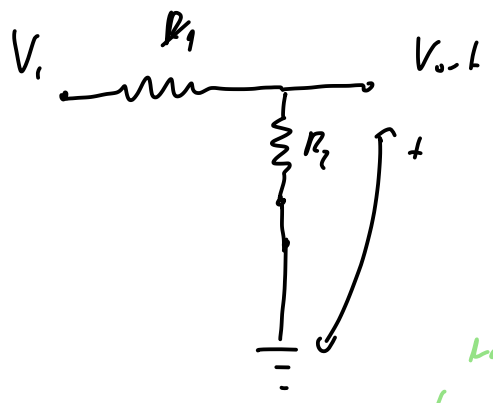
a) $V_i < 0\ V$ — dioda ne vodi



$V_{out} = V_{in}$



$V_i > 0\ V$

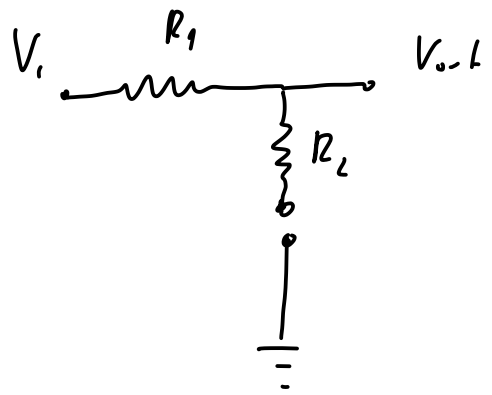


kar. razdjelnik

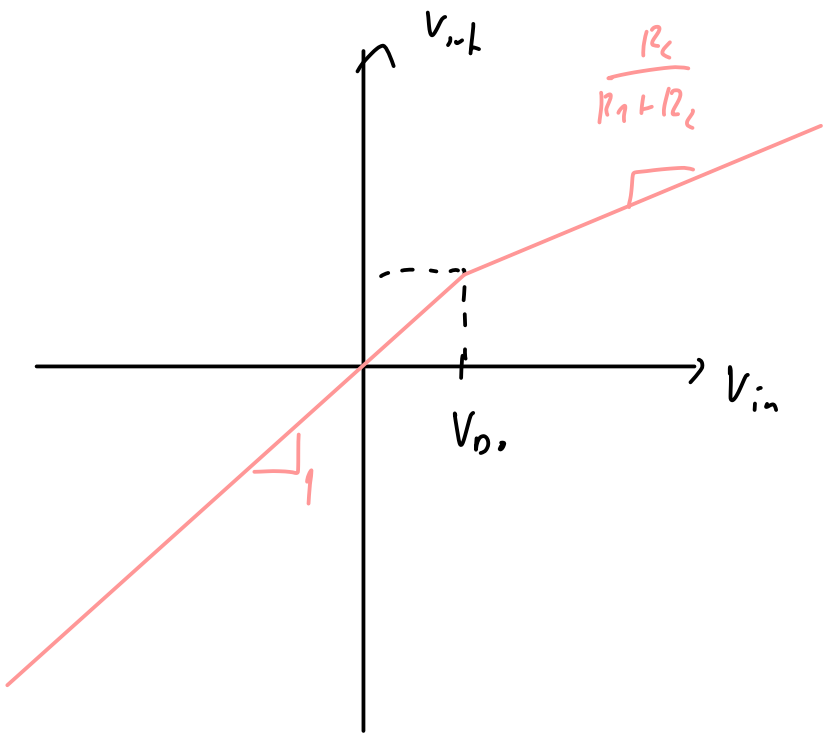
$$V_{out} = V_{in} \frac{R_2}{R_1+R_2}$$

$y = k\,x$

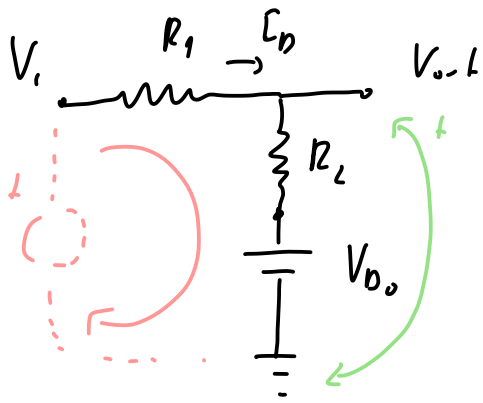
b) $V_{in} < V_{D0}$



$V_{out} = V_{in}$



$V_{in} \geq V_{D0}$ – vod:



$$V_i - R_1 I_D - R_2 I_D - V_{D0} = 0$$

(1) $V_i - I_D (R_1 + R_2) - V_{D0} = 0$

$$V_{out} = V_{D0} + R_2 I_D$$

(2) $I_D = \frac{V_{out} - V_{D0}}{R_2}$

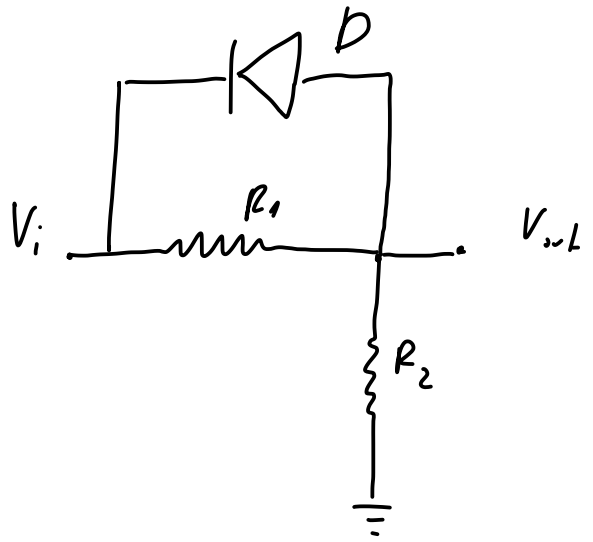
(2) u (1): $V_i - \frac{1}{R_2}(V_{out} - V_{D0})(R_1 + R_2) - V_{D0} = 0$

$$\overset{y}{V_{out}} = \overset{x}{V_i} \overset{k}{\frac{R_2}{R_1+R_2}} + \overbrace{V_{D0} \frac{R_1}{R_1+R_2}}^{n}$$

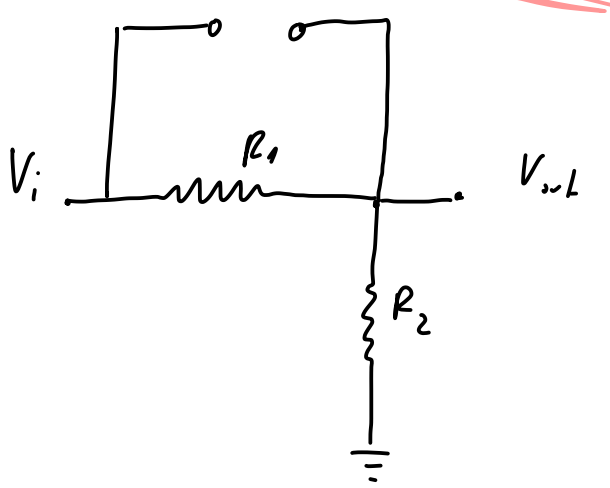
$$y = kx + n$$

2. Nacrtati prenosnu karakteristiku kola (idealizovani model):

1° ne vodi:



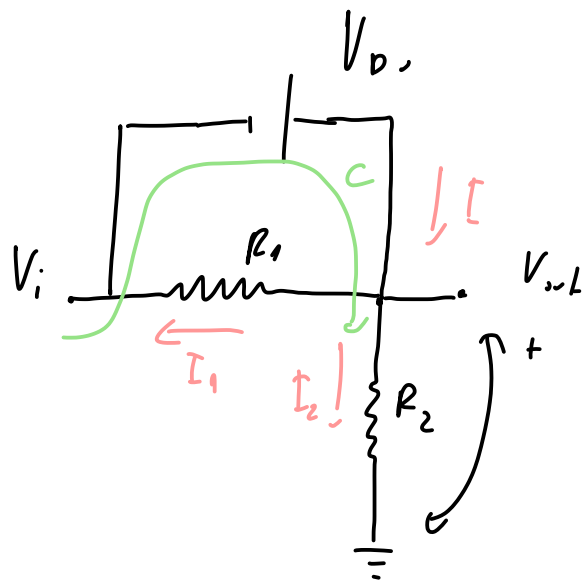
nova strana 1a



nar. razdjelnik:

$$V_{out} = V_{in} \cdot \frac{R_2}{R_1 + R_2}$$

2° vodi:



I. KZ:

$I = I_1 + I_2$

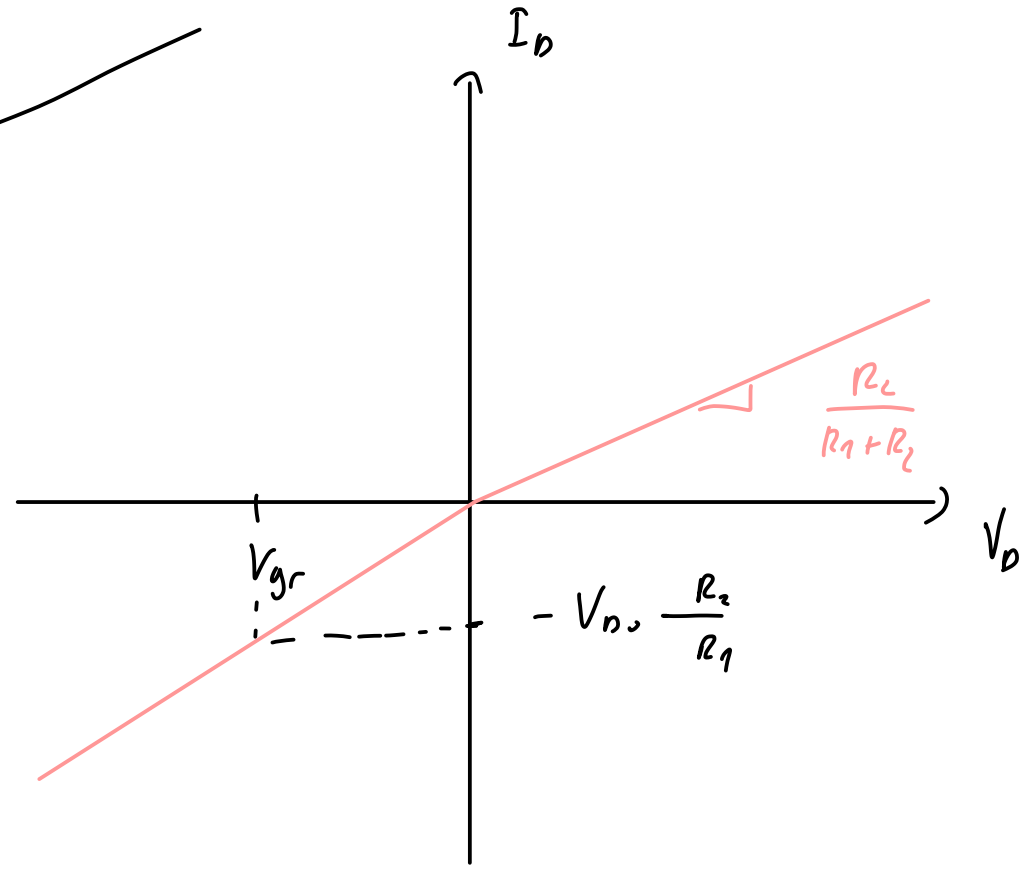
$I_1 = -I_2$, $I = 0A$ – usko kad se dioda isključuje

$I_1 = \frac{V_{D0}}{R_1}$ (1) $\quad I_2 = \frac{V_{out}}{R_2}$

II 1,2 (c):

$$V_{out} = V_{in} + V_{D0}$$

$$I_2 = \frac{V_{in} + V_{D0}}{R_2} \quad (2)$$



$$(1) \,;\, (2): \quad \frac{V_{D0}}{R_1} = -\frac{V_{in} + V_{D0}}{R_2}$$

$$V_{gr} = V_i = -V_{D0}\left(1 + \frac{R_2}{R_1}\right)$$

mejna napetost za

kaji dioda prestaja da vodi:

$$V_{out} = V_i + V_{D0}$$

$$\downarrow$$

$$V_{out} = V_{gr} + V_{D0}$$

3. Ali je dioda dir. pol. kolikšna je potrebna povečati napetost, da bi se stroja povečala 10 puta?

predpostavljam, ker model je nije rečeno:

$$I_D = I_S \cdot \left(e^{\frac{V_D}{nV_t}} - 1\right)$$

$$I_D = I_S \, e^{\frac{V_D}{V_t}} \quad , n=1$$

$$\Delta V = V_2 - V_1$$

$$\frac{I_D}{I_S} = e^{\frac{V_D}{V_t}} \quad / \ln$$

$$V_D = V_t \cdot \ln \frac{I_D}{I_S}$$

$$V_1 = V_t \ln \frac{I_{D1}}{I_S}$$

$$V_2 = V_t \ln \frac{I_{D2}}{I_S}$$

$$\Delta V = V_t\left(\ln \frac{I_{D2}}{I_S} - \ln \frac{I_{D1}}{I_S}\right)$$

$$\Delta V = V_t \left(\ln \frac{\frac{I_{D2}}{\cancel{I_S}}}{\frac{I_{D1}}{\cancel{I_S}}}\right)$$

$$= V_t \left(\ln \frac{I_{D2}}{I_{D1}}\right)$$

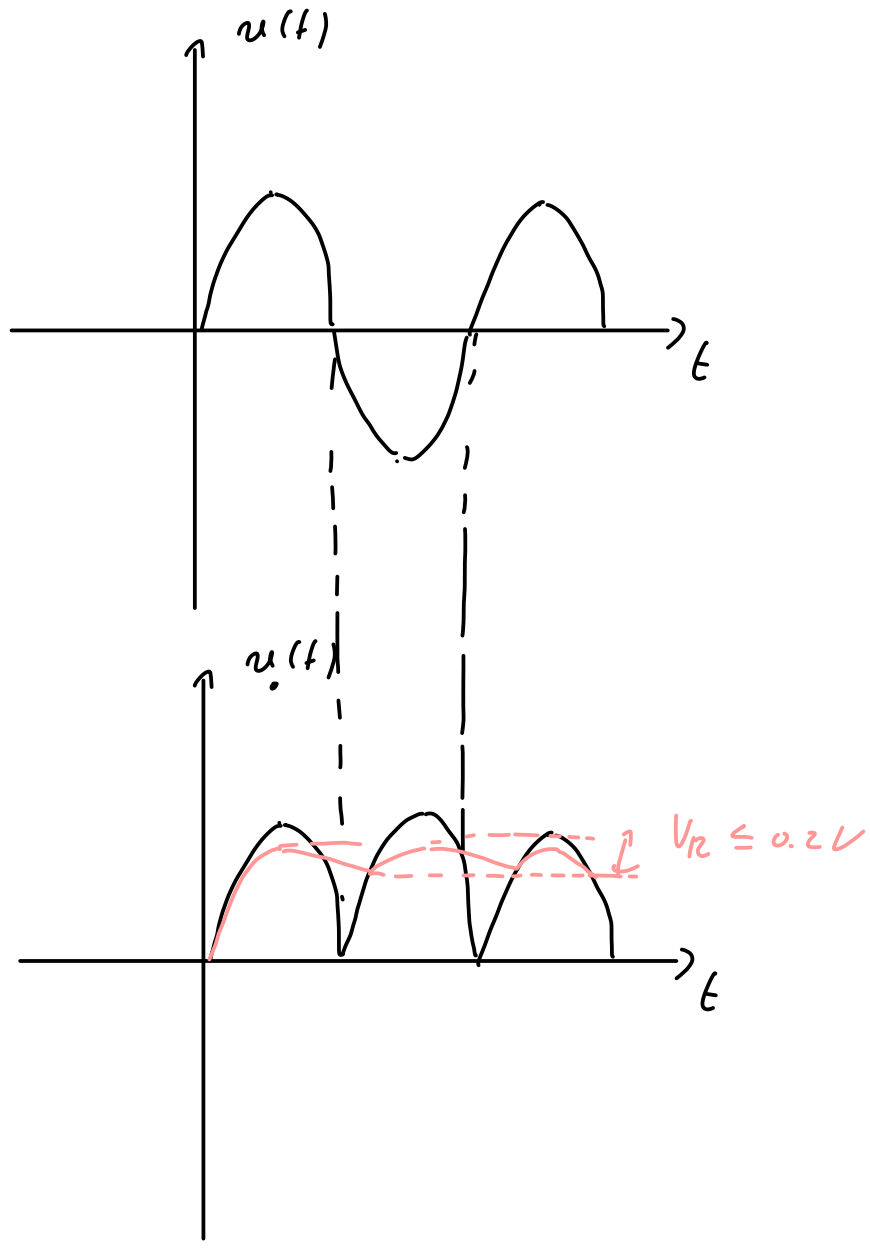
$$I_{D2} = 10 \, I_{D1}$$

$$\Delta V = V_t \left(\ln \frac{10 \cancel{I_{D1}}}{\cancel{I_{D1}}}\right)$$

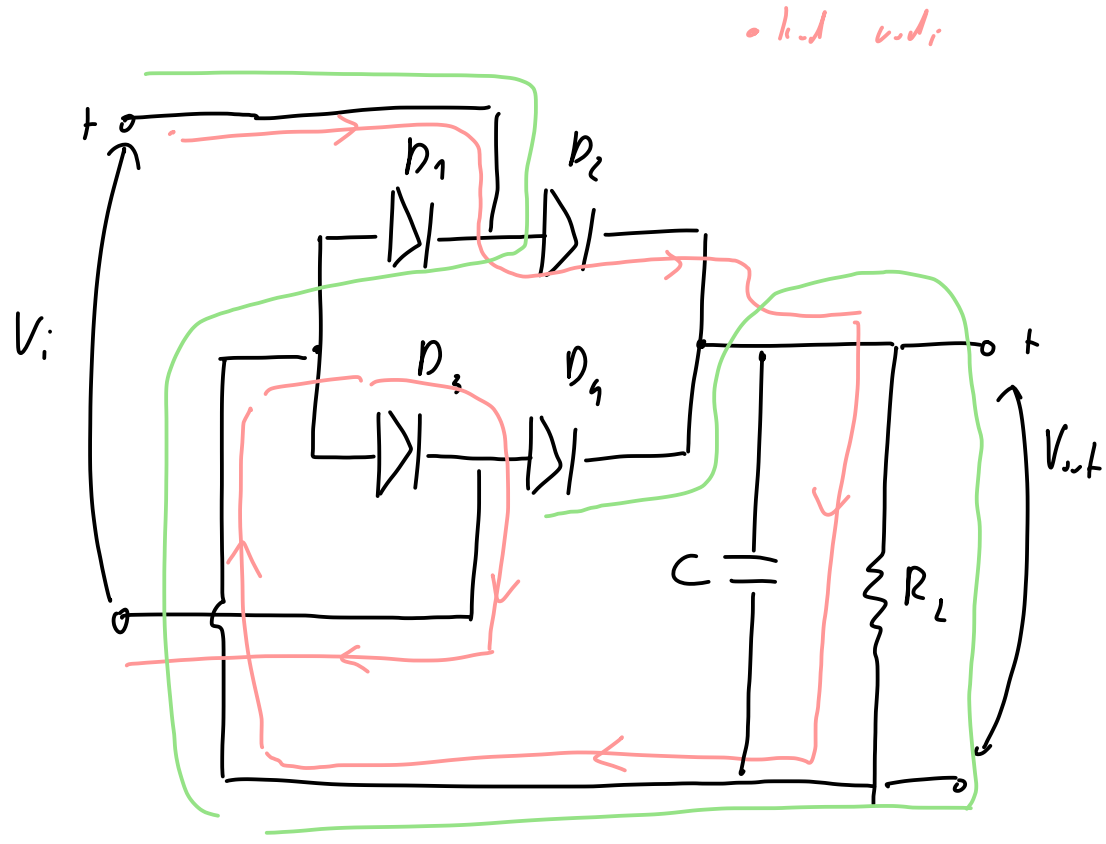
$$\Delta V = V_t \ln 10 \quad , V_t = 25 \, mV$$

$$\Delta V = 57.51 \, mV$$

4. Projektirati dvostrani ispravljač napona snage na izlazu 2 W i izlaznog napona 3.6 V, tako da ripple napona na izlazu bude < 0.2 V.



Klasični Graecov spoj



$$V_R = \frac{I_L}{2fC}$$ – dvostrani

$$V_R = \frac{I_L}{fC}$$ – jednostrani

$f = 50\,Hz$ – frekv. gradske mreže

$V_R = 0.2\,V$

$C = ?$

$I_L = ?$

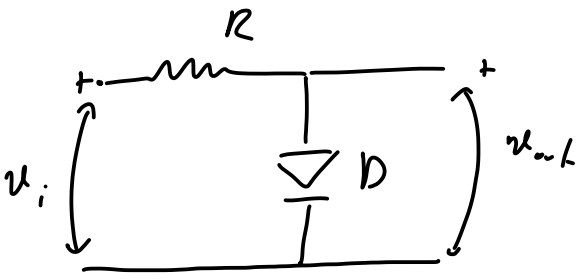
$$C = \frac{I_L}{2fV_R} = 28\,mF$$

$$P_{out} = V_{out} \cdot I_L$$

$$I_L = \frac{2W}{3.6V} = 0.56\,A$$

5. Projektirati dvostrani ograničavač koji ograničava napon na izlazu na ± 100 mV. Napon praga vođenja diode je 0.8 V.

Najjednostavniji slučaj:

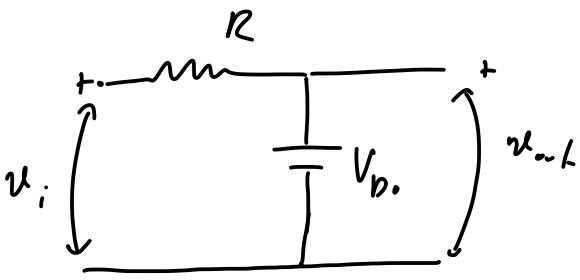


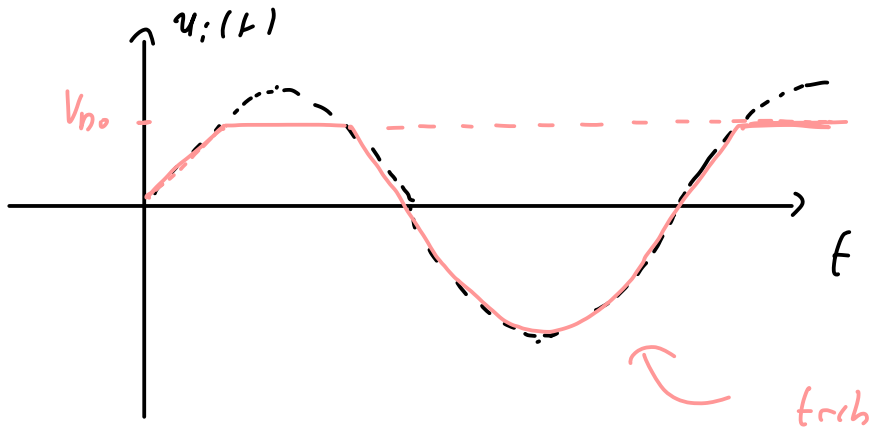
$V_{D0} = 0.8\,V$ (idealizirani model)

$u_i(t) = V_m \sin(\omega t)$

$V_m > V_{D0}$

↓ kada sinusoida dostigne napon V_{D0} → dioda provodi

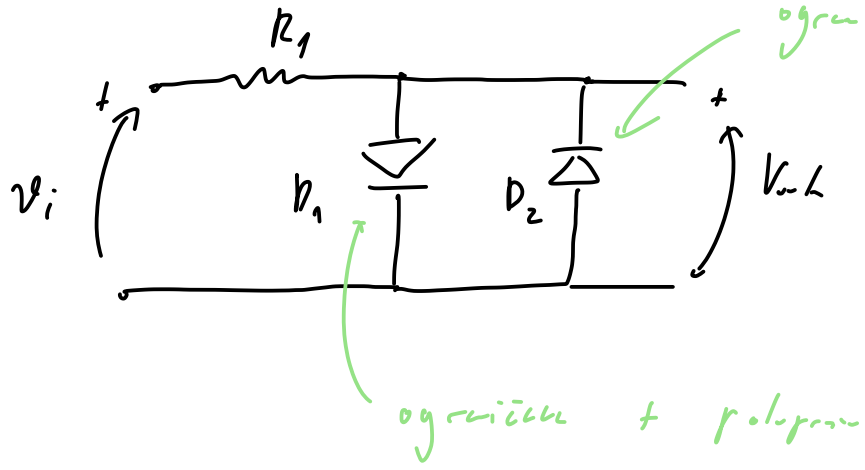




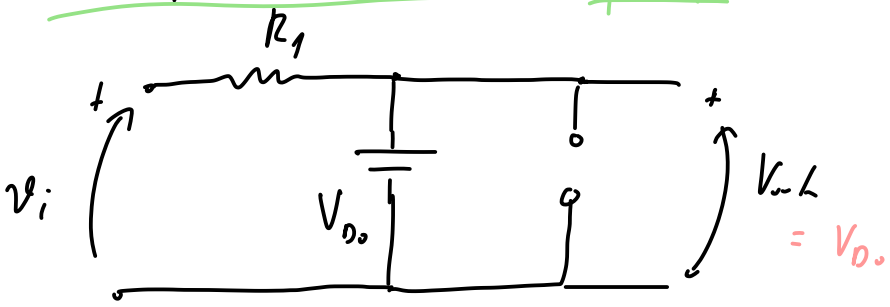
trebamo ograničiti i drugu poluperiodu

↓

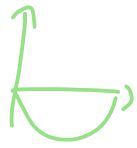
kada je prva dioda dir pol → druga mora biti inverzno → mora je okrenuti

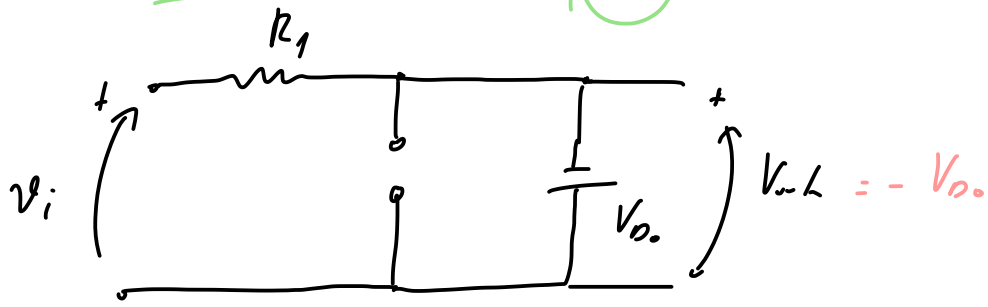


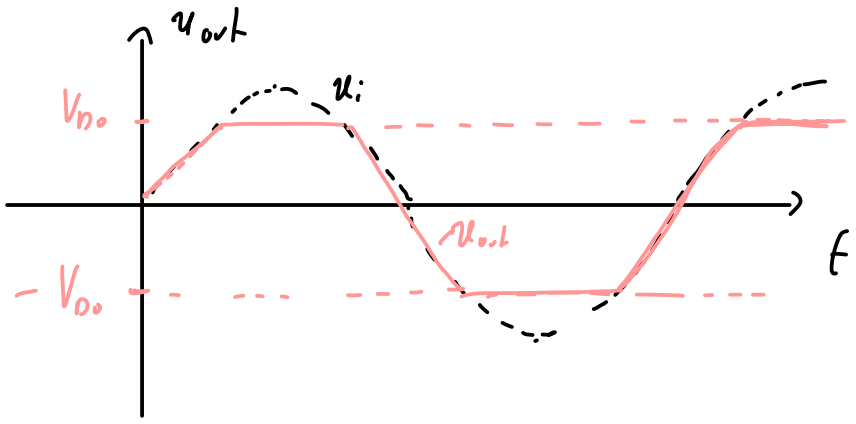
1° D_1 vodi:



2° D_2 vodi:







traži se

$\pm 100\,mV$

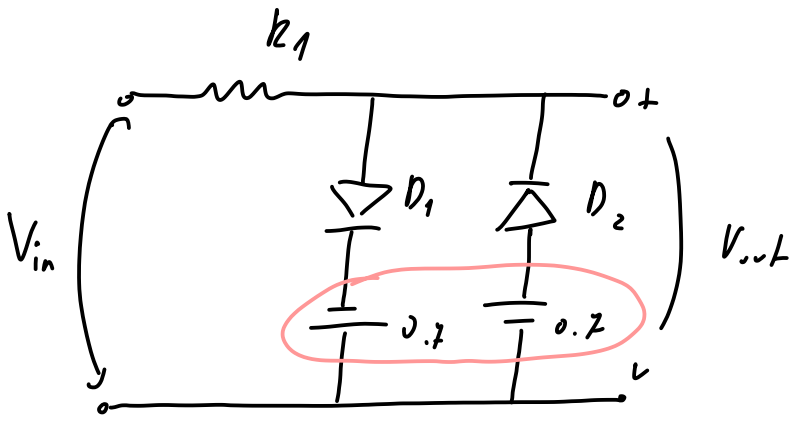
$V_{D0} = 0.8\,V$

↑ trebamo spustiti napon

↓

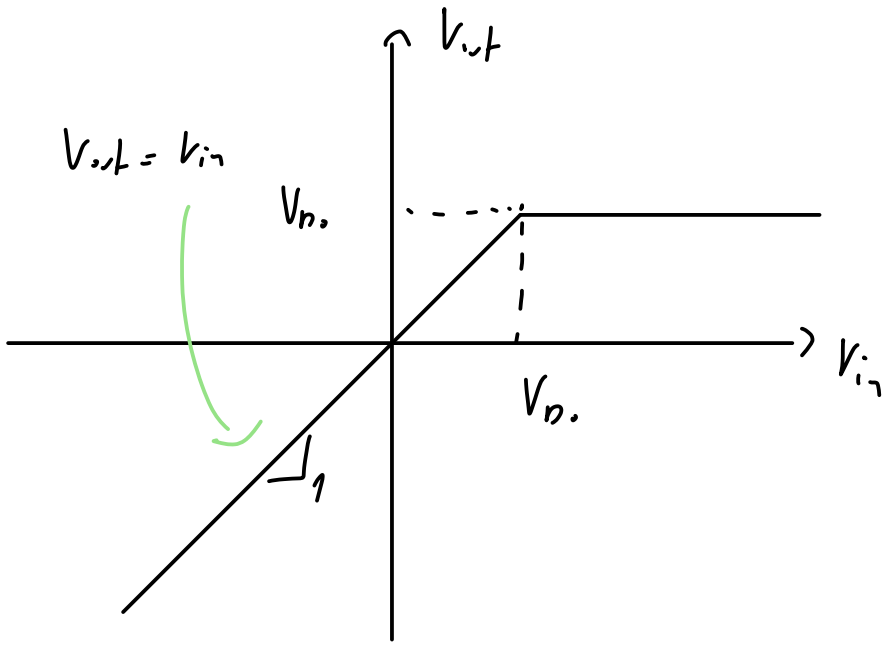
dodajem još 1 bateriju u seriji

tranzistor ograničen

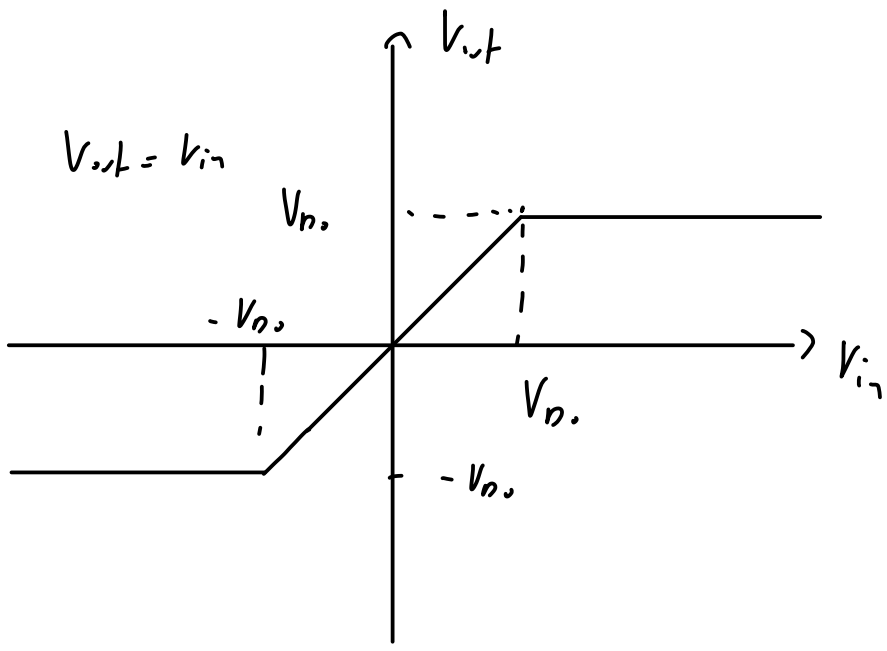


Prijenosna karakteristika

(jednostrani ispravljač)



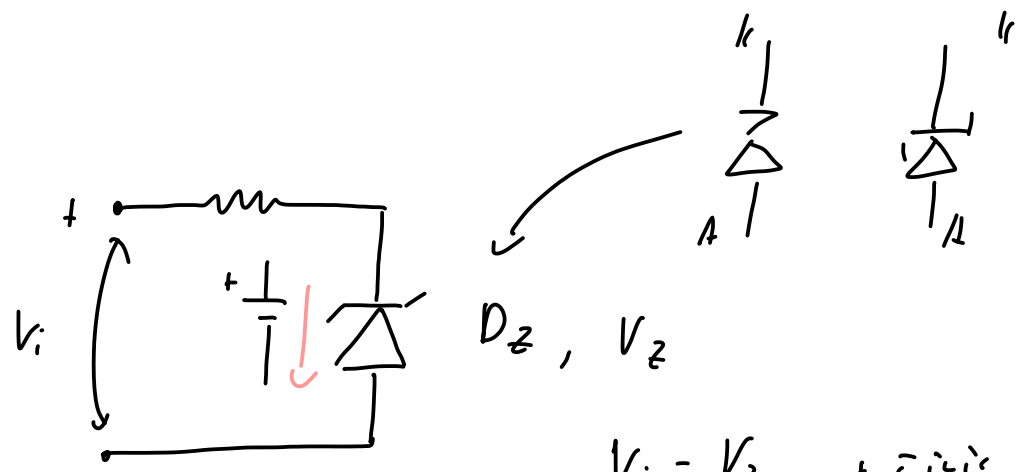
dvostrani ispravljač



6. Nacrtati sinu ograničavača ako se

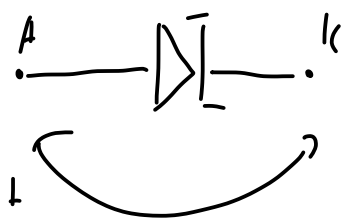
a) koristi 1 obična i 1 zener diode

2) 2 zener diode

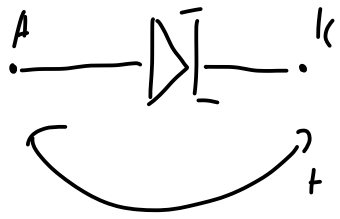


$V_i = V_z$ počinje da vodi u kontra smjeru

i nastavlja se sa: V_z

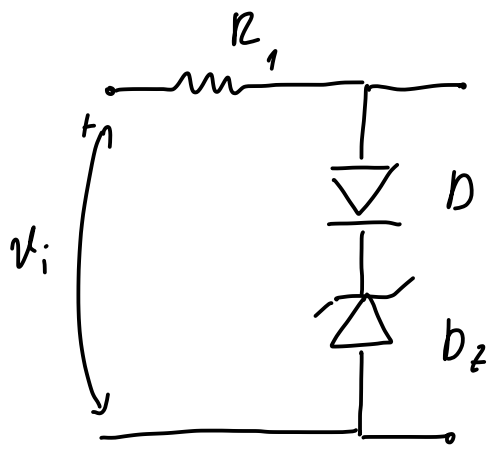


V_γ – ponaša se kao obična dioda



– radi u lavu smjeru

$V_D = V_Z$

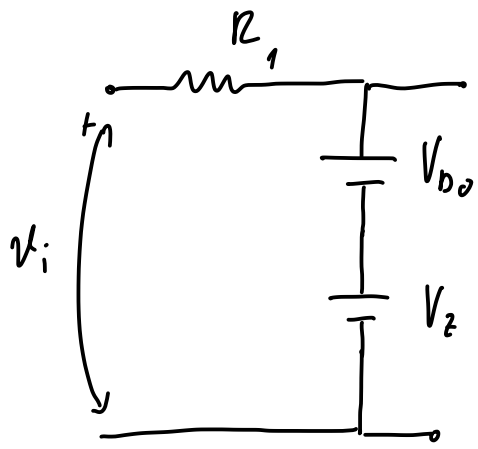


1° $V_i < V_{D0} + V_Z$ obe isključene

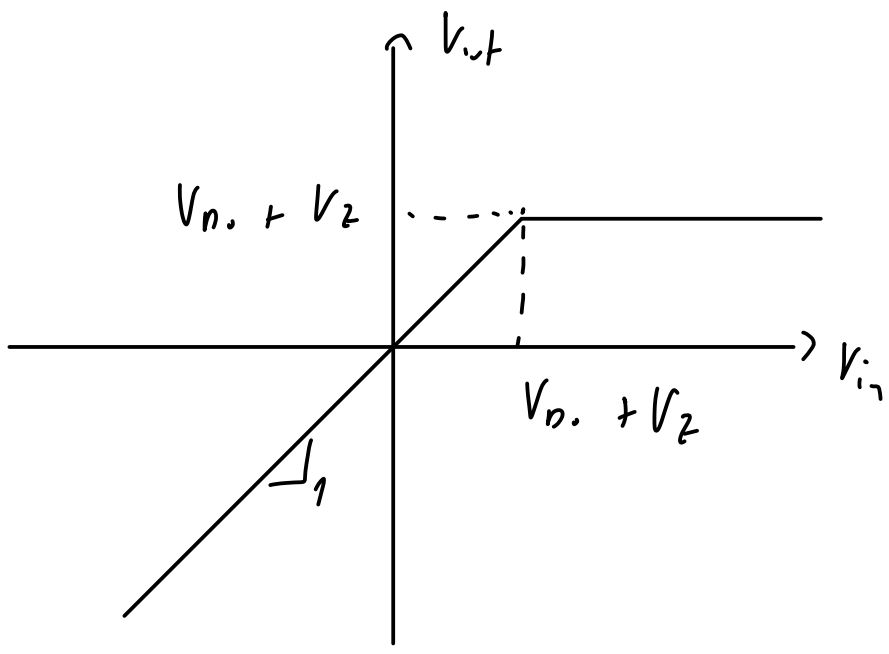
$V_{out} = V_{in}$

2° $V_i \geq V_{D0} + V_Z$

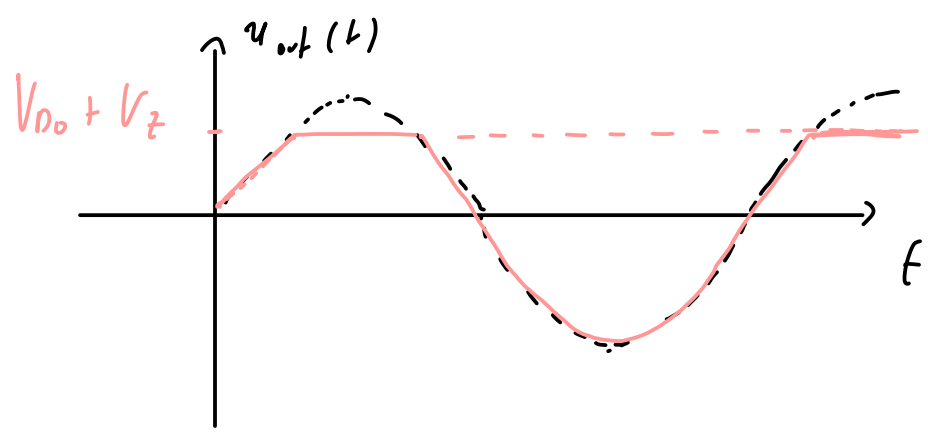
$V_{out} = V_{D0} + V_Z$



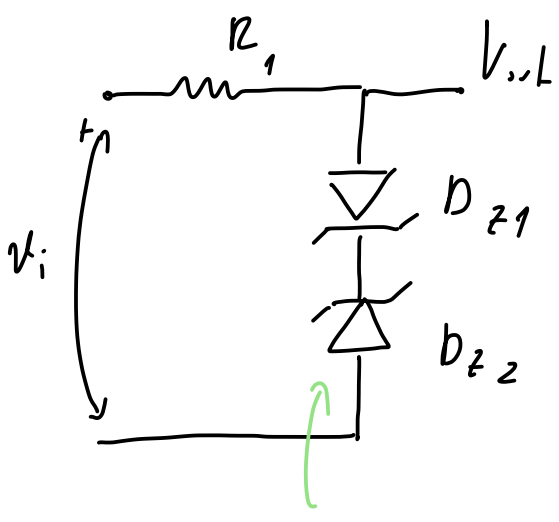
Prenosna karakteristika



Valni oblici:



b)



okrenuta je kontra

→ ponaša se kao obična dioda

$V_{in} = V_{D0} + V_Z$

ova kao zener

1° $V_{in} < V_{D0} + V_Z$

$V_{out} = V_{in}$ – nijedna od ved.

2° $-(V_{D0} + V_Z) > V_i$

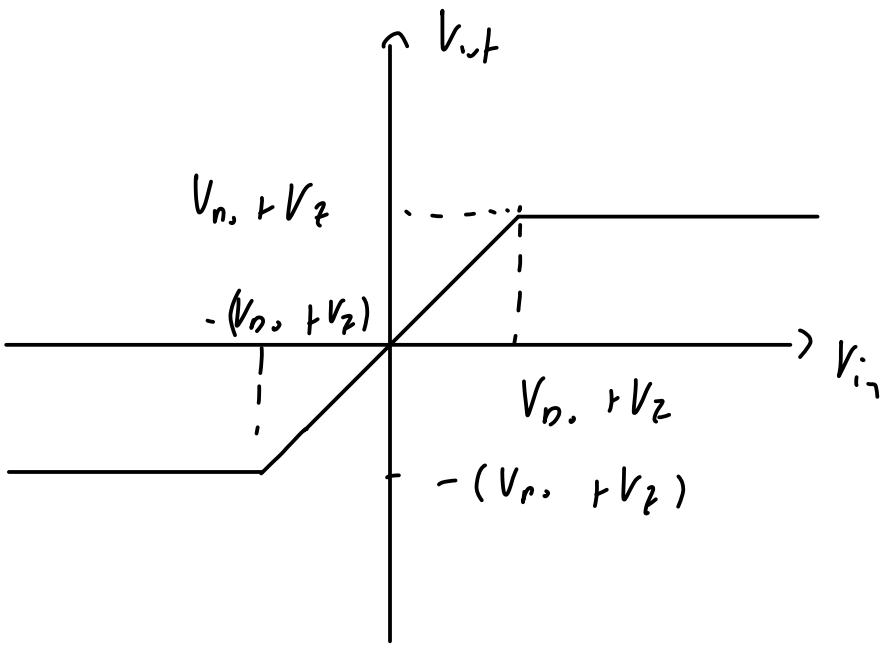
$V_{out} = V_{in}$ – nijedna od ved.

3° $V_{in} > V_{D0} + V_Z$; $V_{in} < -(V_{D0} + V_Z)$

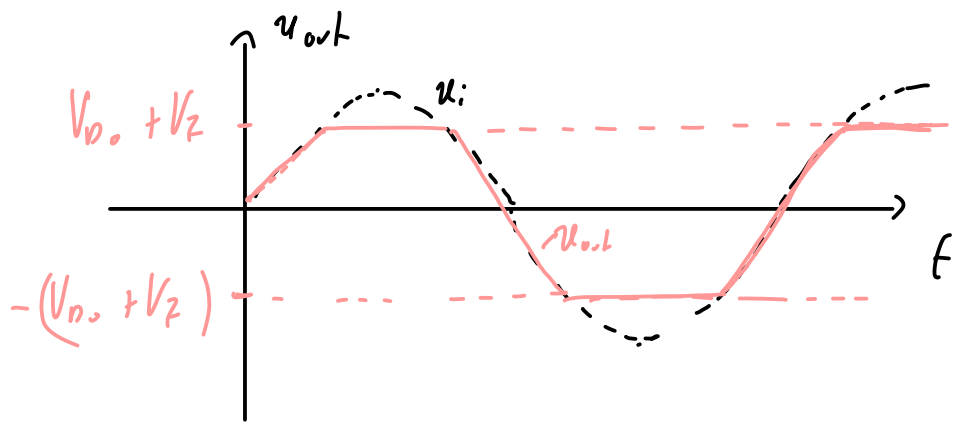
$\downarrow$ $\qquad\qquad$ $\downarrow$

$V_{out} = V_{D0} + V_Z$ $\qquad$ $V_{out} = -V_{D0} + V_Z$

Prenosna karakteristika



Talasni oblik



Predavanje 16.11.2024.

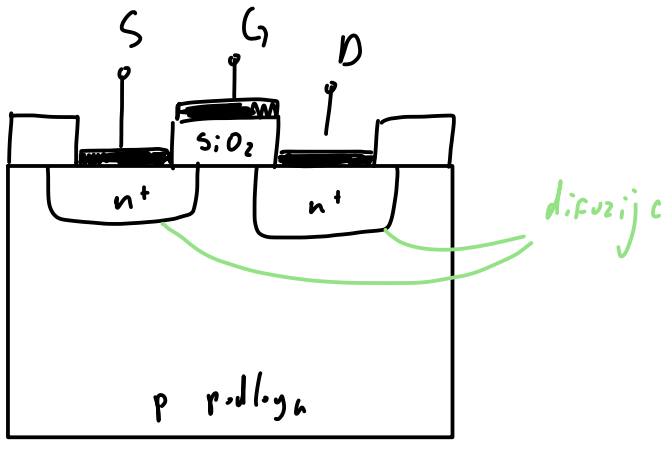
Tranzistori sa efektom polja

(JFET i MOSFET)

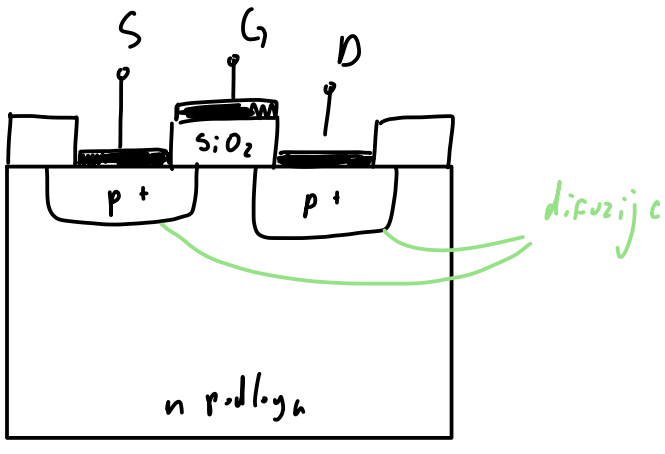
MOSFET

- MOS tranzistor
  - poluprovodničke komponente
  - 4 elektrode: source, drejn, gejt, supstrat /bulk → isti potencijal
  - 2 vrste: NMOS (e^-), PMOS
    - šupljine odgovorne za uspostavljanje struje
  - u zavisnosti od postojanja kanala: 1. tranzistori sa ugrađenim kanalom
    2. tranz. sa indukovanim kanalom
    - spoljašnjim poljem se formira kanal

Struktura MOS tranz.



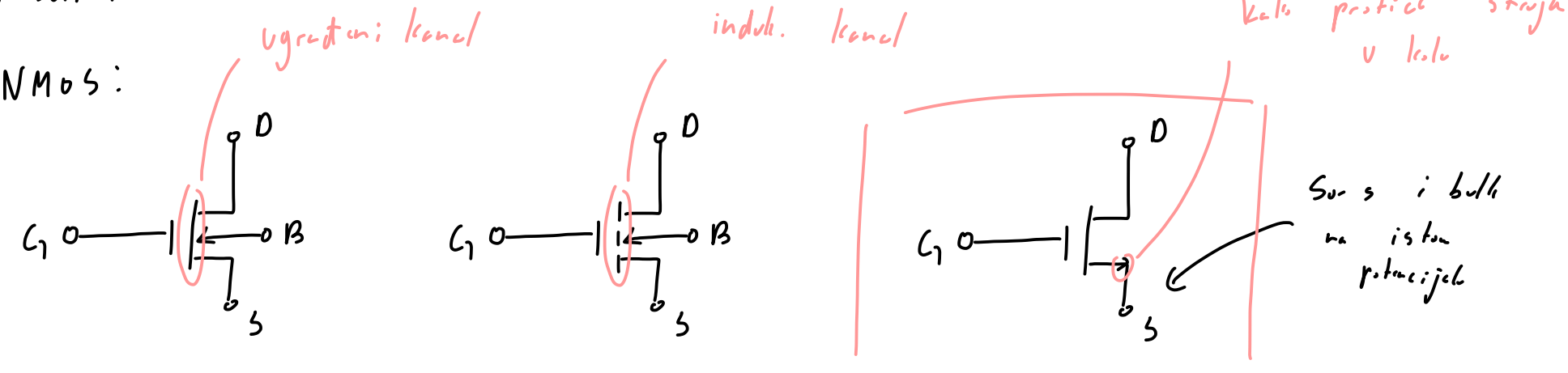
NMOS



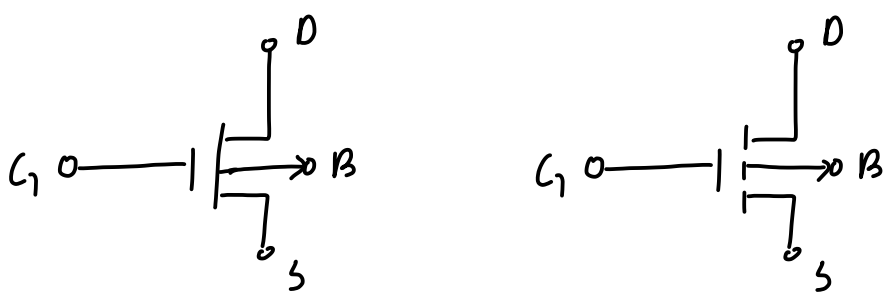
PMOS

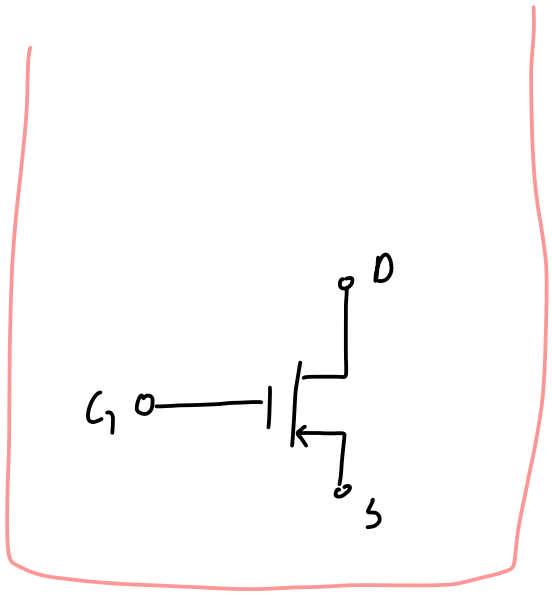
Simboli:

NMOS:



PMOS:





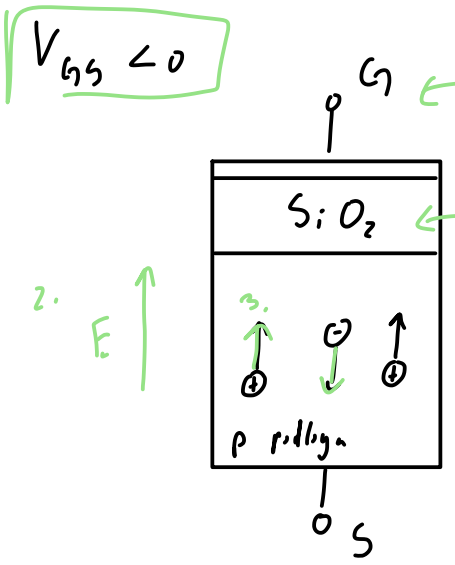
Kapacitivnost MOS kondenzatora

- $V_D = V_S = 0$
- V_{GS} se može mijenjati
- Gejt - oksid - supstrat → pločasti kondenzator (1 elektroda gejt, druga supstrat)
  - oksid ~ dielektrik
- mijenjanje napona → mijenjanje kapacitivnosti

C-V kriva

- realizacija integrisanih kondenzatora

$V_{GS} < 0$



1. dovedim neg napon
4. velika koncentracija šupljina → akumulacija

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

- kapacitivnost po jed površine

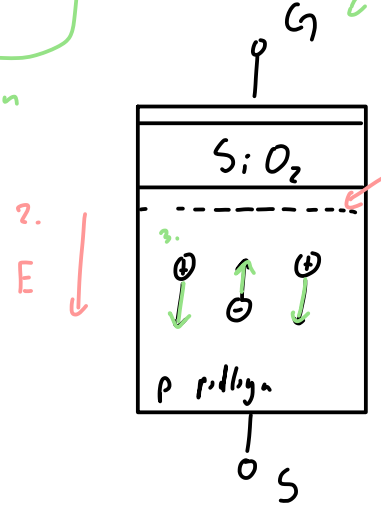
debljina oksida

$$\varepsilon_{ox} = \varepsilon_0 \cdot \varepsilon_{rox}$$

3.9

$V_{GS} \geq 0$

mali napon



1. dovedim napon veći od nule

osiromašena oblast ~ dielektrik

e^- se kreću na međupovršinu oksid - poluprovodnik

→ formiranje osiromašenja

$$C = \frac{C_{ox} \cdot C_{si}}{C_{ox} + C_{si}}$$

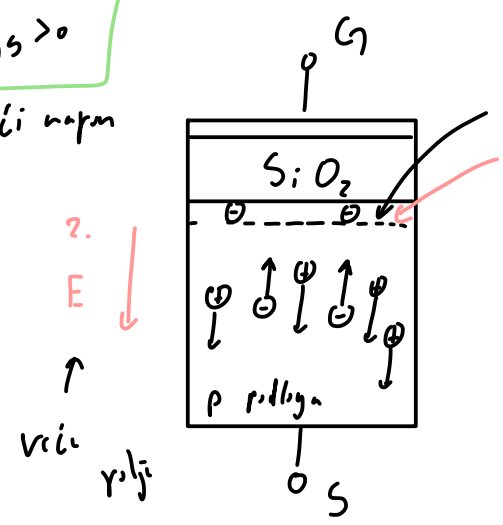
→ kao dva redno vezana kond.

konst

zavisi od dubine / debljine osiromašene oblasti

$V_{GS} > 0$

veći napon



osiromašena oblast

elektroni imali dovoljno energije da se uvuku u osiromašenu oblast

→ slobodni elektroni → slaba inverzija

(jer su elektroni sada nosioci naboja, a ne šupljine)

veći polje

$$C = \frac{C_{ox} C_{Si}}{C_{ox} + C_{Si}}$$

← povećava se

$V_{GS} > 0, V_{tn}$

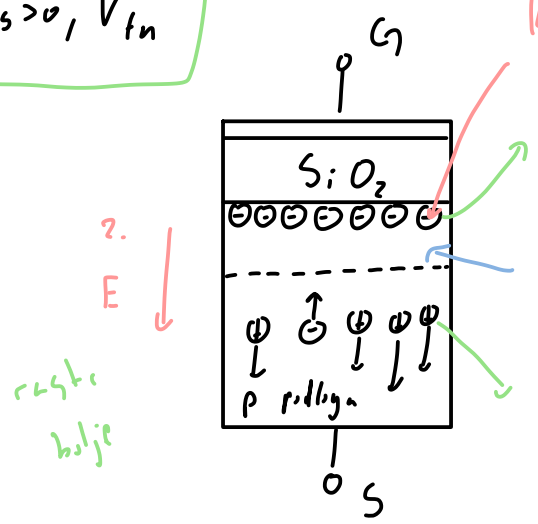
kanal (jer imamo slob nosioce naboja)

veći br e^- koji se izvlače uz metaloxid → veliki br slob. e^-

→ mogu se kretati

– ispod oksida pojavljuje se o blast n-tipa

→ jaka inverzija



osiromašena oblast

rastu polje

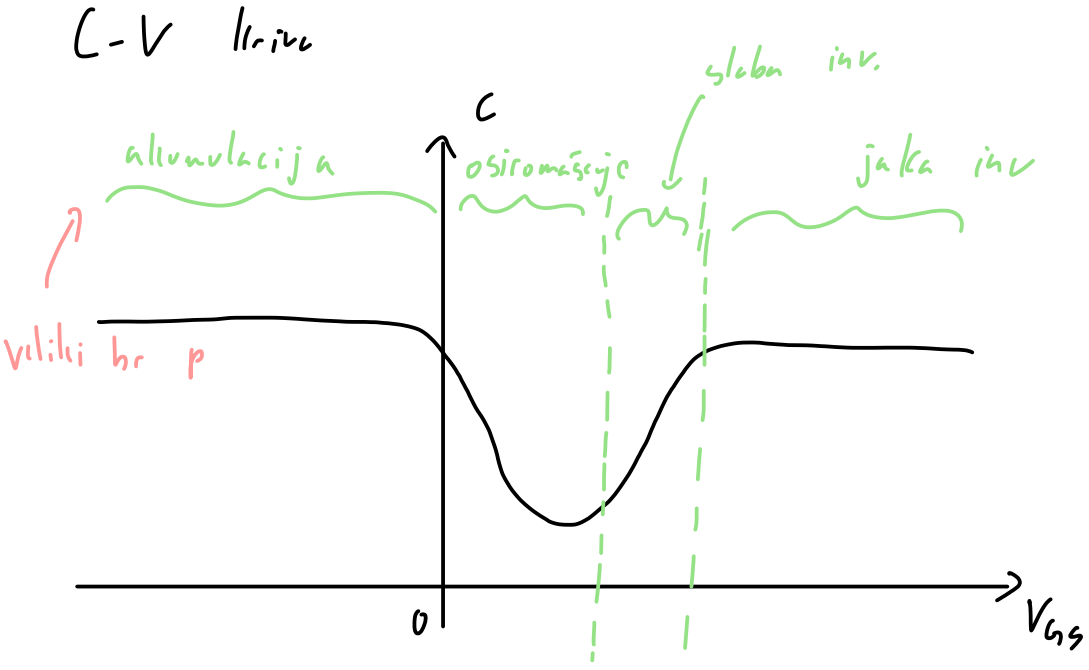
veći br šupljina koje se guraju ka unutrašnjosti supstrata

$$\boxed{C = C_{ox} = \frac{\varphi_{ox}}{t_{ox}}}$$

← zavisi samo od oksida

– sa daljim povećanjem napona → C konst

C-V kriva



Napon praga

- napon između G i S pri kojem dolazi do inverzije tipa podloge
- osnovni el parametar MOS tranzistora
- za tranz. sa induk. kanalom:

- $\boxed{\text{NMOS - pozitivan}, V_{tn} > 0}$
- PMOS - neg, $V_{tp} < 0$

- ugrađenim kanalu
  - NMOS - neg, $V_{tn} < 0$
  - PMOS - poz, $V_{tp} > 0$

} sors i supstrat na jed naponu

- sors i supstrat na različitim potenc.:

$$\boxed{V_{tn} = V_{tn0} + \gamma \left(\sqrt{2|\psi_F| + |V_{SB}|} - \sqrt{2|\psi_F|} \right)}$$

za $V_{SB} = 0$

Fermijev potencijal $(-0.4\,V \div -0.3\,V)$

$$\boxed{\gamma = \frac{\sqrt{2 q \varepsilon_{Si} N_A}}{C_{ox}}}$$

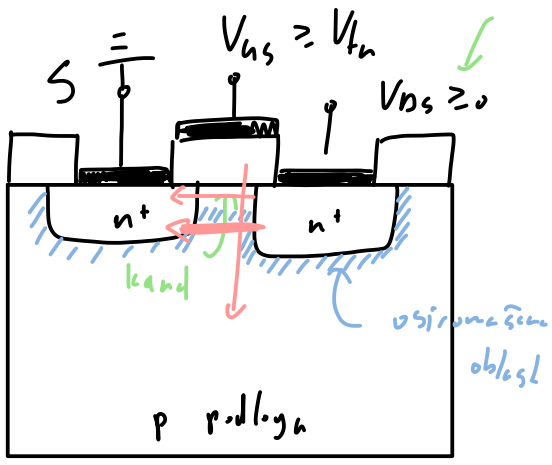
- konst. polarizacije supstrata (efekt tijela)

Uspostavljanje struje drejna

- predpost. da je formiran kanal, $\boxed{V_{GS} \geq V_{tn}}$.

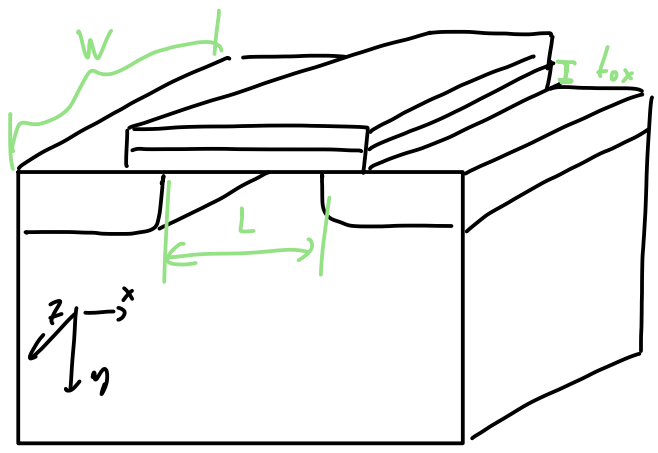
-

drejn i sors na različitim potenc → da bi protekla struja $V_{DS} \geq 0$



- omogućava formiranje kanala.

- e^- se kreću od S ka D
  ↳ uspostavlja se struja drejna



t_{ox} - debljina oksida

W - širina kanala

L - dužina kanala

V_{DS} - mali

- kanal → otpornik
- lin zav. izmedu V i I → linearna oblast rada:

$$I_D = \underbrace{\frac{\mu_n \varepsilon_{ox} W}{t_{ox} L}}_{\text{tehnološki parametri}} (V_{GS} - V_{tn}) V_{DS} = \boxed{\frac{V_{DS}}{R_{on}}}$$

V_{GS} – kojim se formira kanal

V_{DS} – primjenjujemo napon

$V_{DS} \nearrow$

- kanal se sužava na strani D
- struja ne zavisi lin od napona
- ova oblast + lin. oblast → triodna oblast / nezasićena oblast

$$\boxed{I_D = \frac{\mu_n \varepsilon_{ox} W}{2 t_{ox} \cdot L} \left[2 (V_{GS} - V_{tn}) V_{DS} - V_{DS}^2 \right]}$$

→ važi i za lin oblast za male V_{DS}

$\boxed{V_{GS} - V_{tn} > V_{DS}}$ – nap. uslov za triodnu oblast

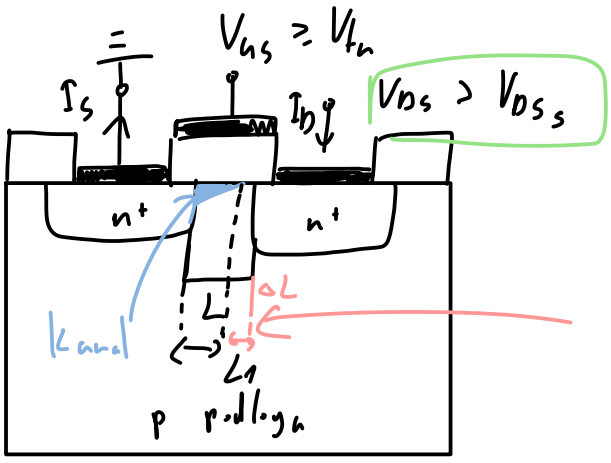
$$\boxed{k_n = \frac{\mu_n \varepsilon_{ox}}{2 t_{ox}} \frac{W}{L} = \mu_n C_{ox} \frac{W}{2L}}$$

→ transkonduktansni parametar

$$I_D = k_n \left[2 (V_{GS} - V_{tn}) V_{DS} - V_{DS}^2 \right]$$

$V_{DS} \nearrow\nearrow$ $\quad (V_{GS} - V_{tn} = V_{DS})$

- prekid kanala (jer se tu suzi)
- napon zasićenja $\boxed{V_{DSs} = V_{GS} - V_{tn}}$ – razdvaja triodnu oblast i oblast zasićenja



I_D - konst - tranzistor se može koristiti kao izvor konst struje

kanal se skraćuje

$L \to L_1$

- oblast zasićenja : ($V_{DS} > V_{DSs}$)

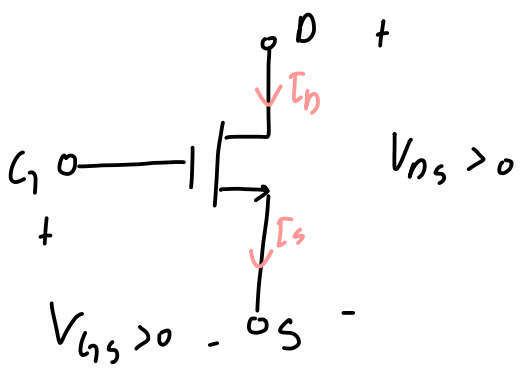
$$\boxed{I_D = \frac{\mu_n \varepsilon_{ox} W}{2 t_{ox} L} (V_{GS} - V_{tn})^2 = k_n (V_{GS} - V_{tn})^2}$$

↑ ne zavisi od V_{DS}

Statičke karakteristike

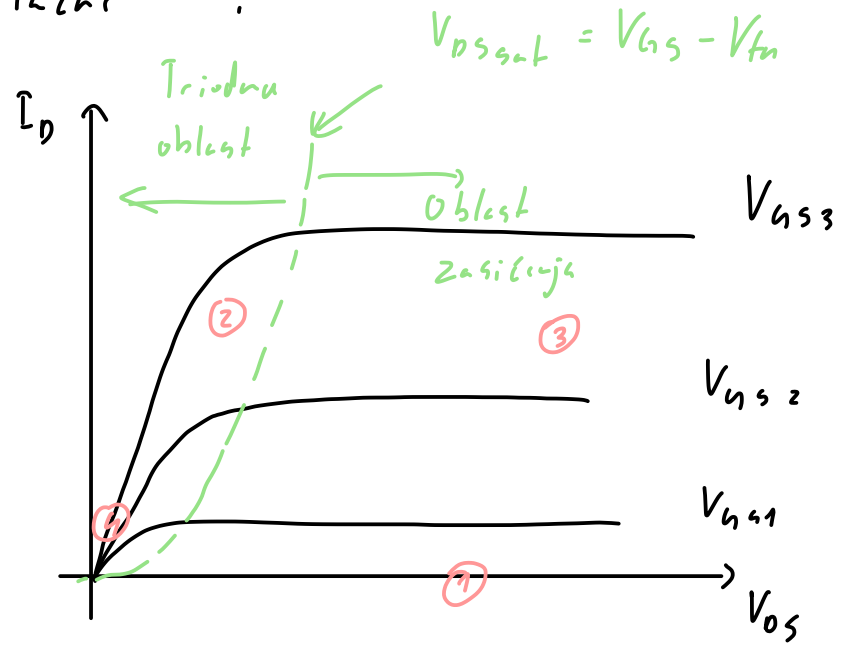
- Strujno-naponske karakteristike

  - izlazne karakteristike $I_D = f(V_{DS})$, V_{GS} - parametar
  - prenosne $I_D = f(V_{GS})$, V_{DS} - parametar



$I_D = I_S$ (ne postoji ulazna struja) iz G

Izlazne :



1. Oblast zaključenja - napon na gejtu < napona praga
   ↓
   nema struje

2. Triodna oblast - nap gejta > nap. praga
   nap na drejnu < $V_{ov} = V_{GS} - V_{tn}$
   ↑ overdrive napon
   ↳ ima struju

3. Oblast zasićenja - nap gejta > nap praga,
   nap na drejnu > V_{ov}

4. Lin oblast – nap gate > nap praga, a nap na drainu mali

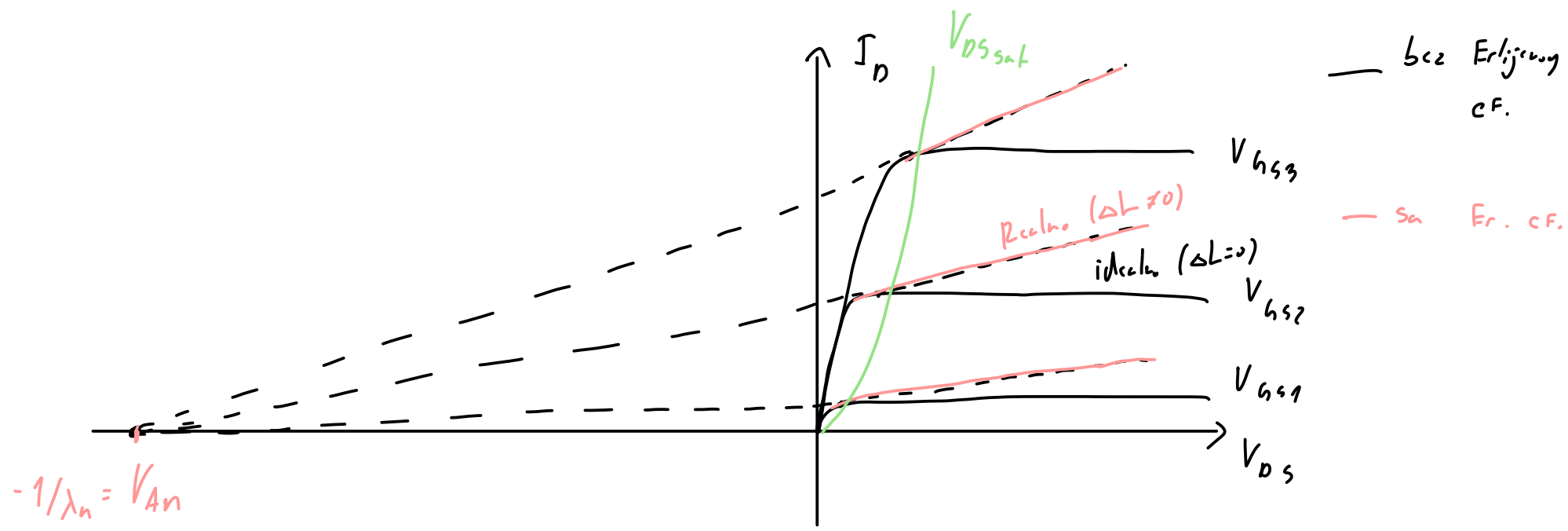
Efekat modulacije dužine kanala

– skraćivanje kanala usljed mijenjanja V_{DS} ↗

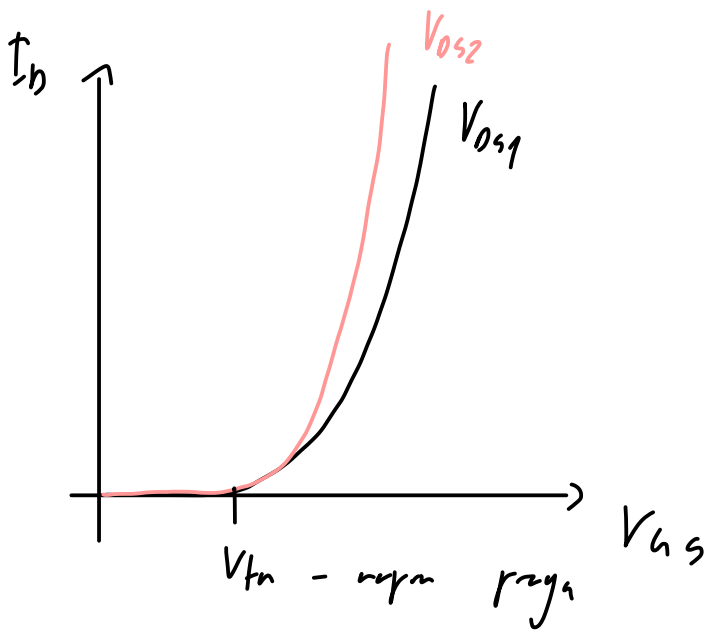
$$I_D = k_n (V_{GS} - V_{tn})^2 (1 + \lambda_n V_{DS}), \qquad V_{DS} > V_{GS} - V_{tn}$$

$\lambda_n = \frac{1}{V_{An}}$ → analogno efektivnom naponu

↑ ovaj član uzima u obzir efekat



Prenosne karakteristike



V_{DS} ↗ I_D ↗ (ako je uključen efekat)

$V_{DS1} < V_{DS2}$

Ograničenja u radu

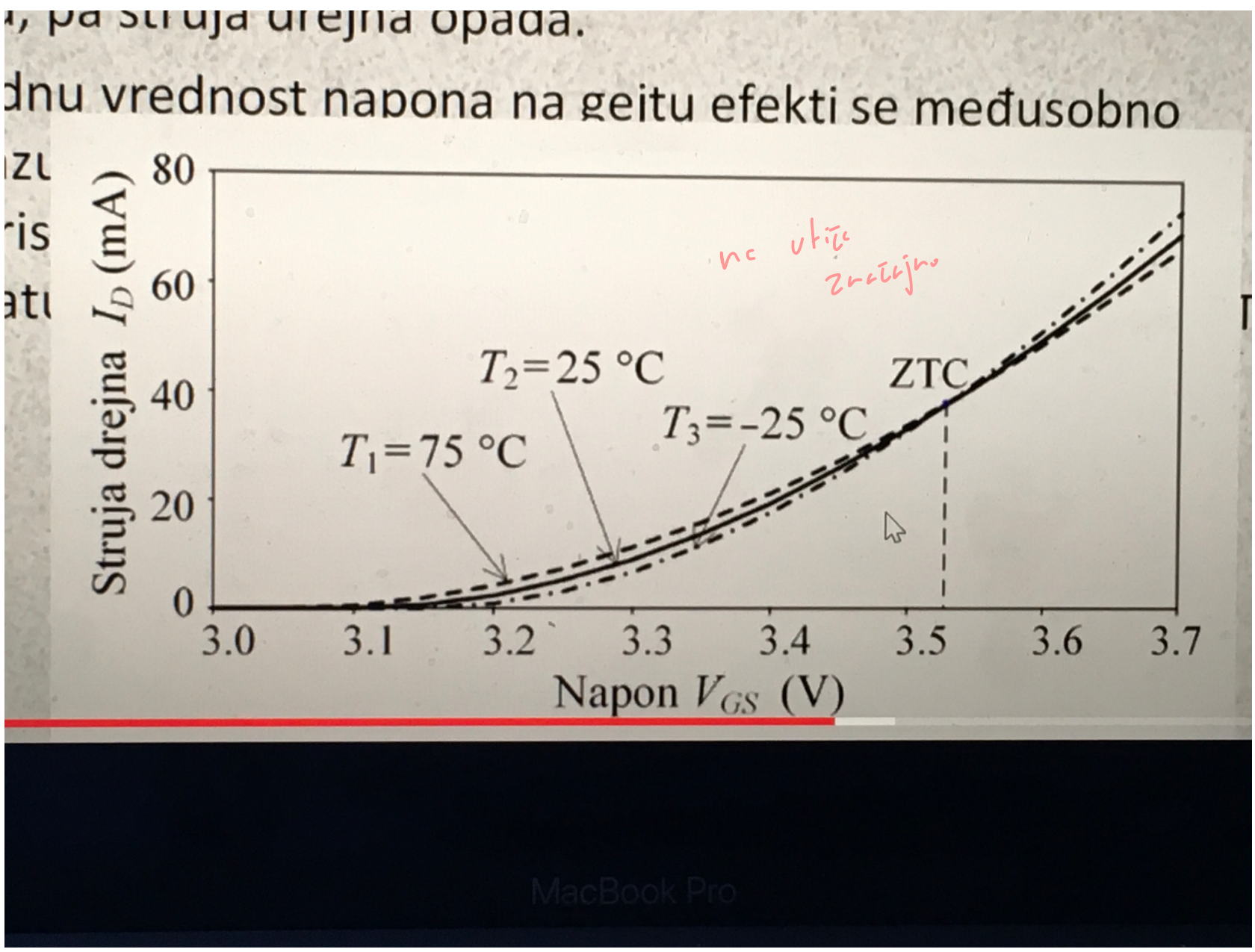
1. Term. karakteristike

- $T \uparrow$ $V_{tn} \downarrow$ i μ_n u kanalu $\downarrow$
- za nulu V_{GS} – dominira $V_{tn} \downarrow$ pa struja drejna $\uparrow I_D$
- za veće V_{GS} – dominira $\mu_n \downarrow$ pa $I_D \downarrow$
- za jednu vrijednost nap V_{GS} ovi efekti se međusobno kompenzuju
  → prenosne karakteristike se presijecaju u toj tački

↓

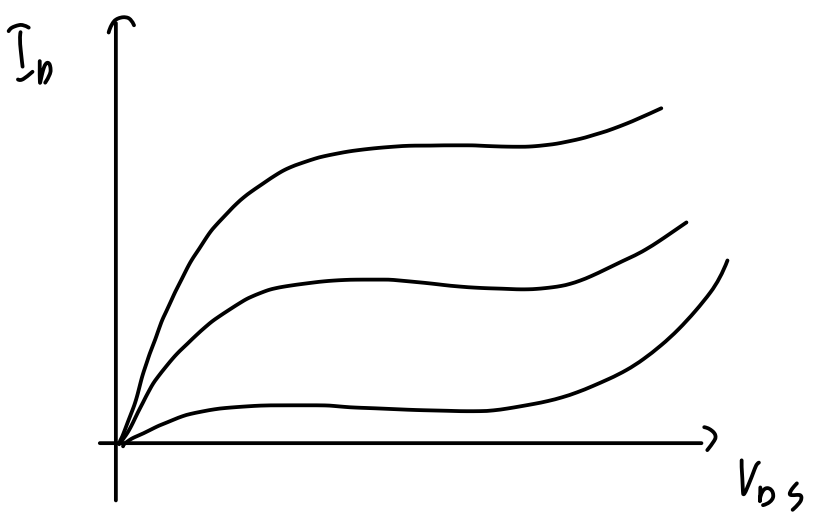
tačka nultog temp. koef.

ZTC – zero temp. coeff.



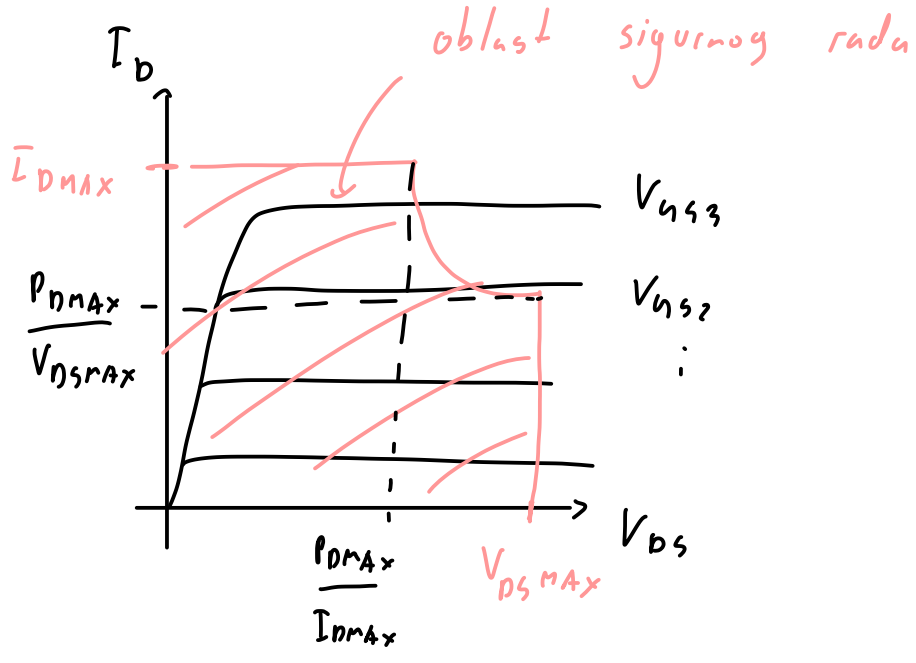
2. Proboj

- PN spoj DS kritičan

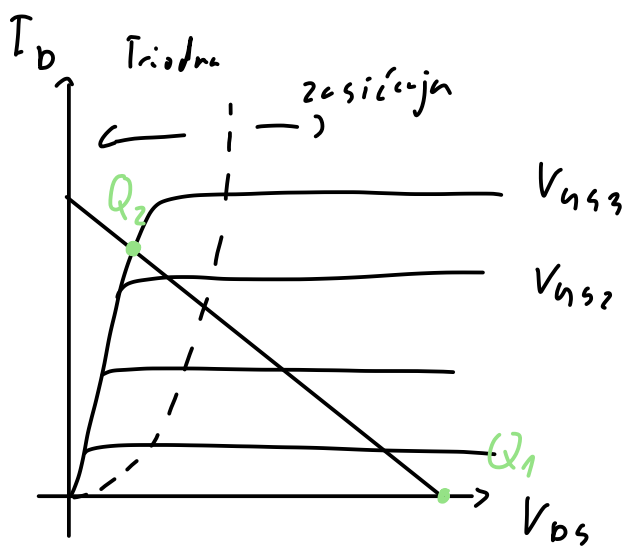


3 Disipacija snage

P_{DMAX}



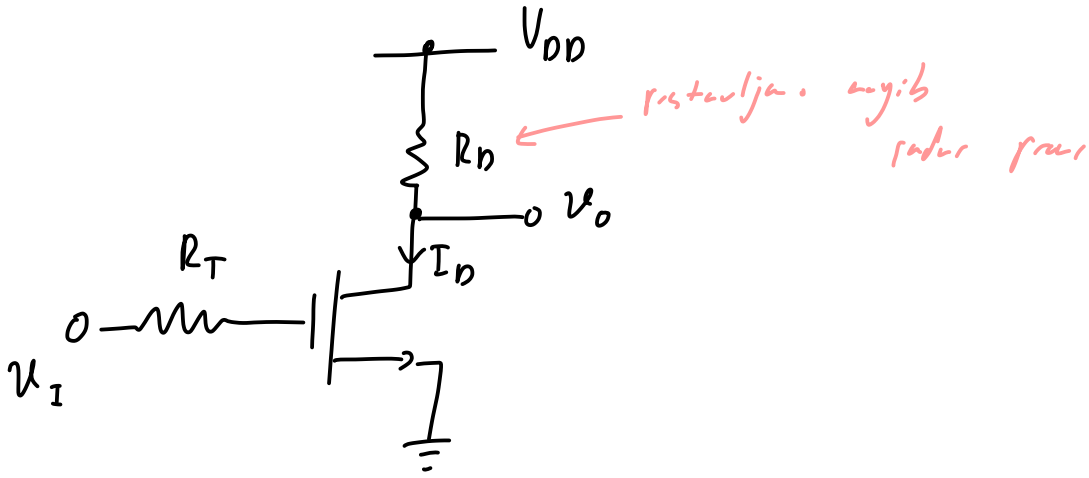
MOS tranzistor kao prekidač

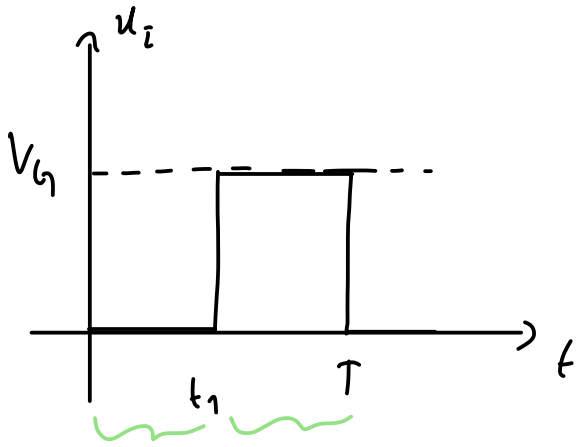


- ili u Q_1 ili Q_2

Q_1 → isključenje

Q_2 → triodna oblast





$V_{GS} < V_{tn}$

→ tranzistor ne vodi

→ $V_o = V_{DD}$

→ tranzistor → prekidač

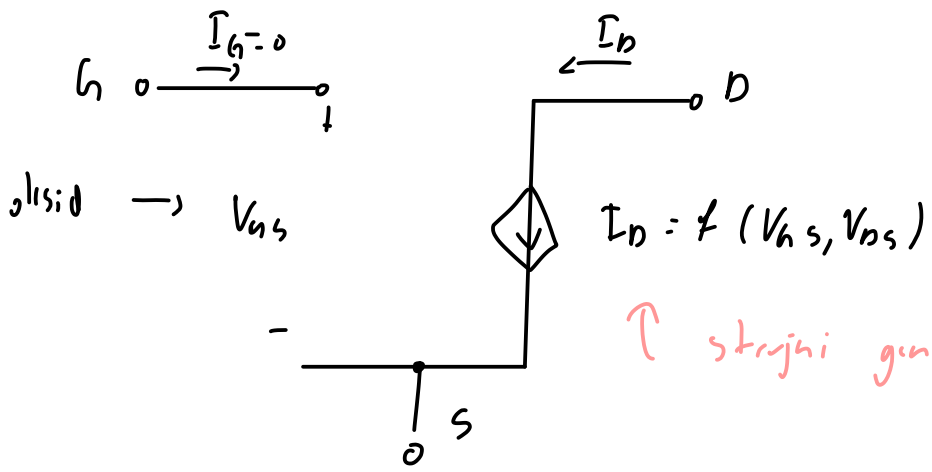
$V_{GS} > V_{tn}$

→ tranzistor vodi (trioda oblast)

→ $V_o = 0$

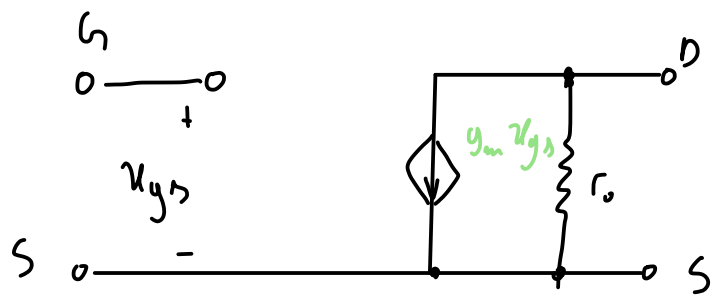
→ zatvoren prekidač

Model za male signale



strujni izvor kontrolisan naponom

Model MOS tranzistora za male signale



$$g_m = \left.\frac{di_D}{dv_{GS}}\right|_Q = 2\sqrt{k_n I_D}$$

transkonduktansa

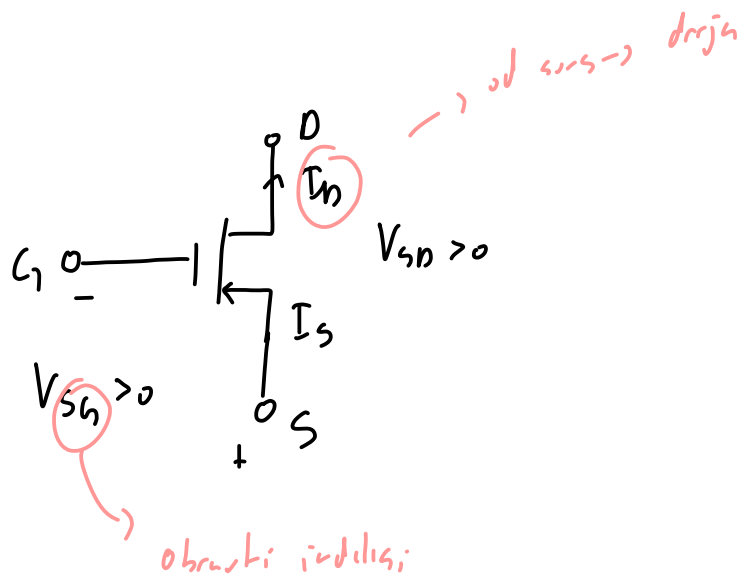
$$r_o = \frac{1}{\lambda_n I_D} = \frac{V_A}{I_D}$$

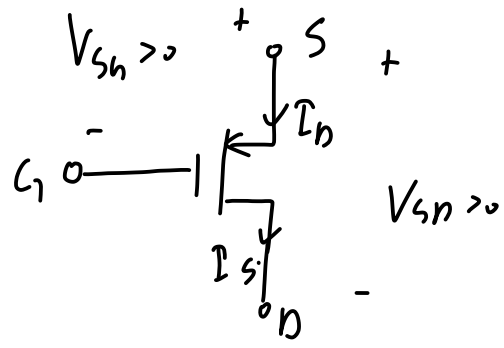
– dinamička otpornost

PMOS tranzistor

- u kanalu šupljine nosioci nael. slob.
- I_D << nego kod NMOS
- $k_p = \frac{\mu_p \varepsilon_{ox}}{2 t_{ox}} \frac{W}{L} = \mu_p C_{ox} \frac{W}{2L}$

razlika - pokretljivost šupljina





Triodna oblast:

$$I_D = \frac{\mu_p C_{ox} W}{2 t_{ox} L} \left[2 (V_{SG} - |V_{tp}|) V_{SD} - V_{SD}^2 \right]$$

$$I_D = k_p \left[2 (V_{SG} - |V_{tp}|) V_{SD} - V_{SD}^2 \right]$$

$V_{SG} > 0$ i $V_{SD} > 0$

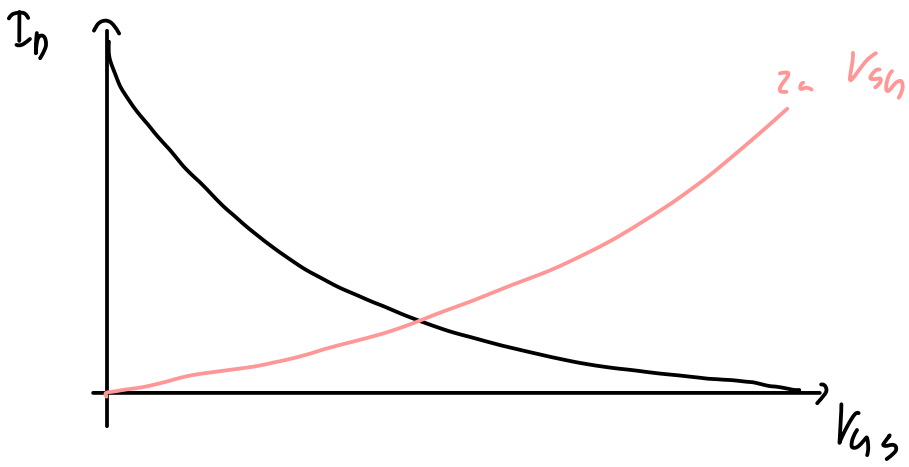
Oblast zasićenja:

$$I_D = k_p (V_{SG} - |V_{tp}|)^2 \left(1 + \frac{V_{SD}}{|V_{Ap}|}\right)$$

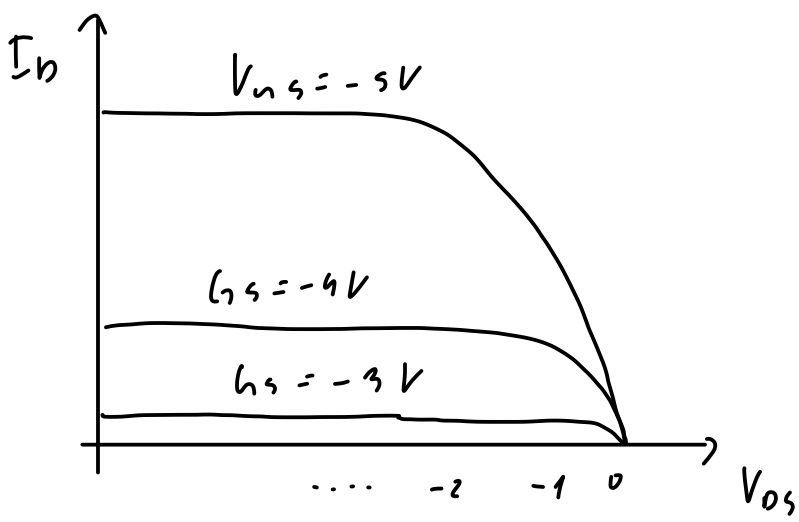
λ_p i V_p - konstantne vrijednosti

$$I_D = k_p (V_{SG} - |V_{tp}|)^2 (1 + |\lambda_p| V_{SD})$$

Prenosna karakteristika



Izlazna karakteristika



MOS tranzistori sa ugrađenim kanalom

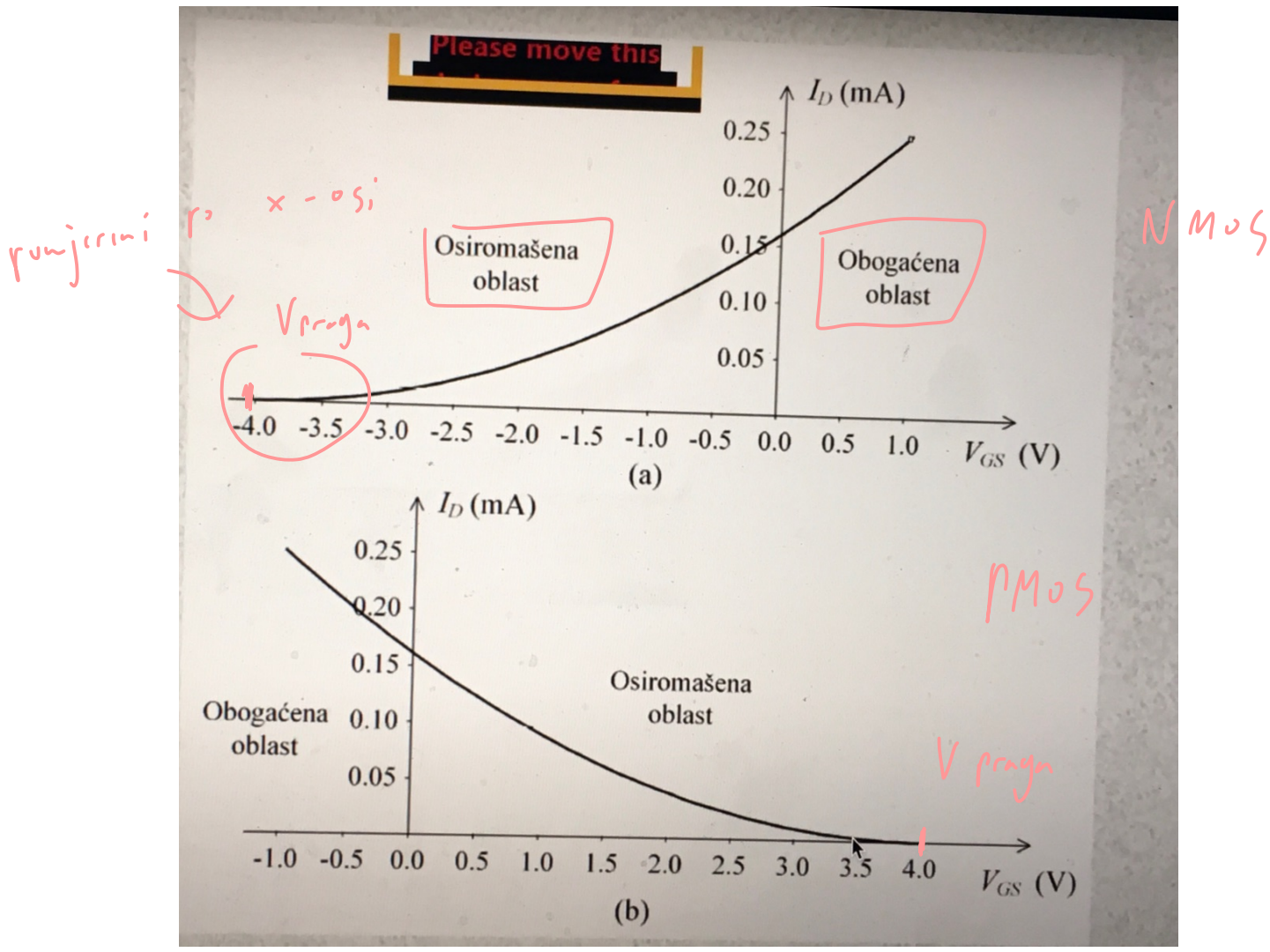
- postoji kanal pri naponu $V_{GS} = 0$
- $V_{GS} < 0$ - osiromašena oblast
- $V_{GS} > 0$ - obogaćena oblast

} NMOS

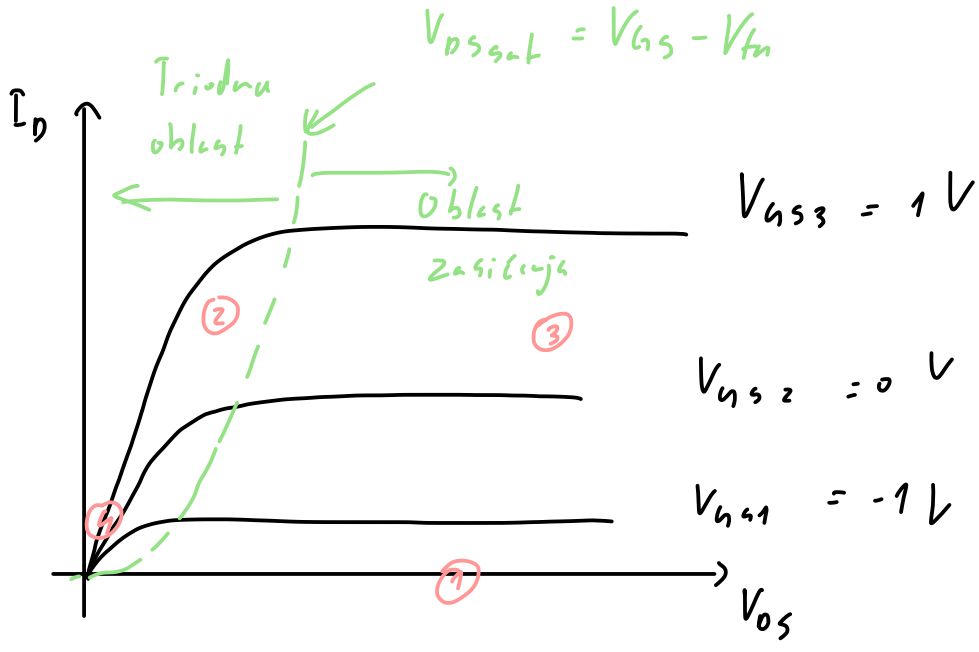
- $V_{GS} > 0$ - osiromašena
- $V_{GS} < 0$ - obogaćena

} PMOS

Prenosna karakteristika



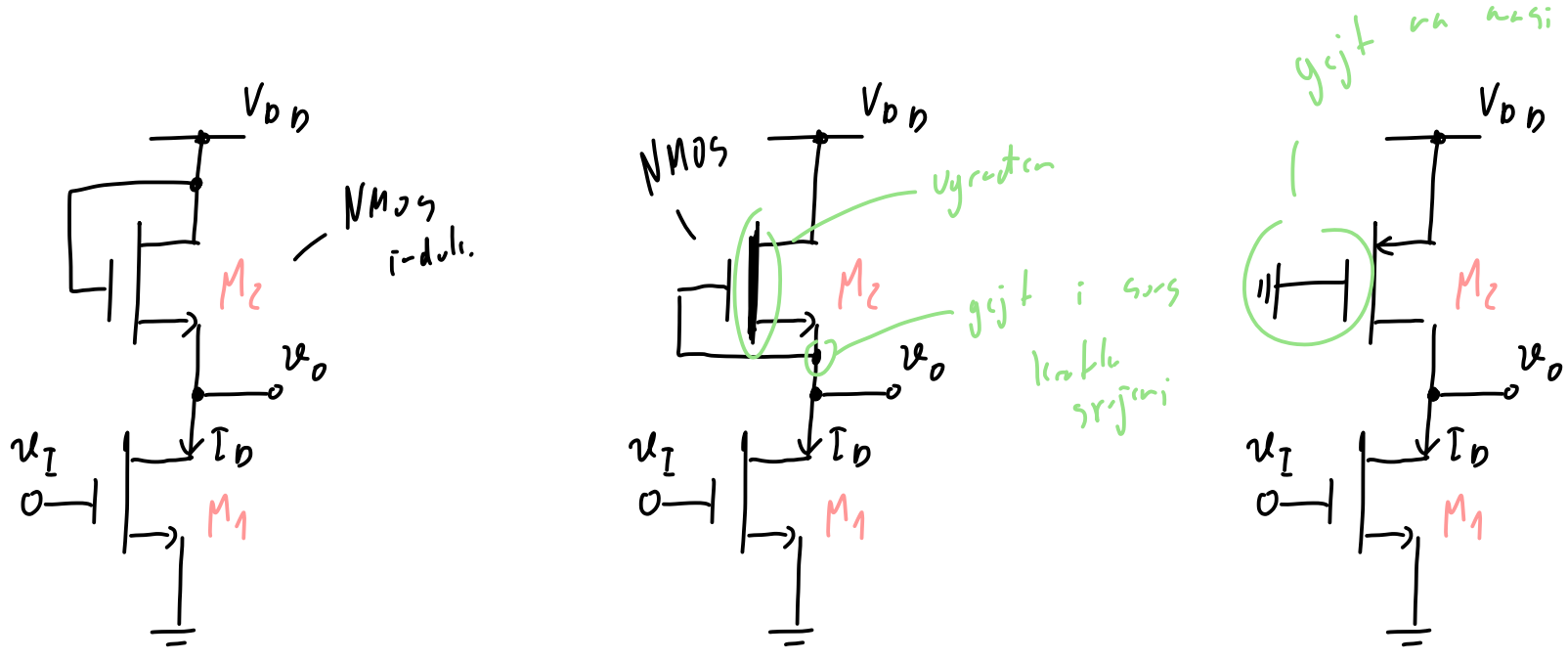
Izlazne karakteristike



mogu imati i pozitivne vrijednosti

MOS tranzistori u integrisanim kolima

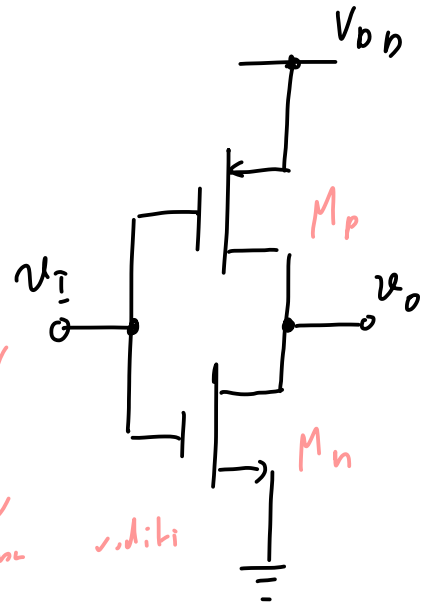
- dominantno su indukt. kanala
  - ↳ V_{GS} i V_{DS} istog polariteta
    (kada imamo serijske veze)
    izlaz jednog stepena se može direktno povezati na ulaz drugog (V_{GS} na V_{DS})
- za realizaciju otpornika → NMOS tranzistor
  (sa indukt. ili ugrađenim)
  aktivno opterećenje
  → PMO sa indukt.



M_1 - aktivni tranzistor

M_2 - aktivno opterećenje

CMOS invertor



ne mogu oba voditi istovremeno

- komplementarni par tranzistora M_p i M_n gdje su gejtovi kratko spojeni
  - M_p → PMOS
  - M_n → NMOS

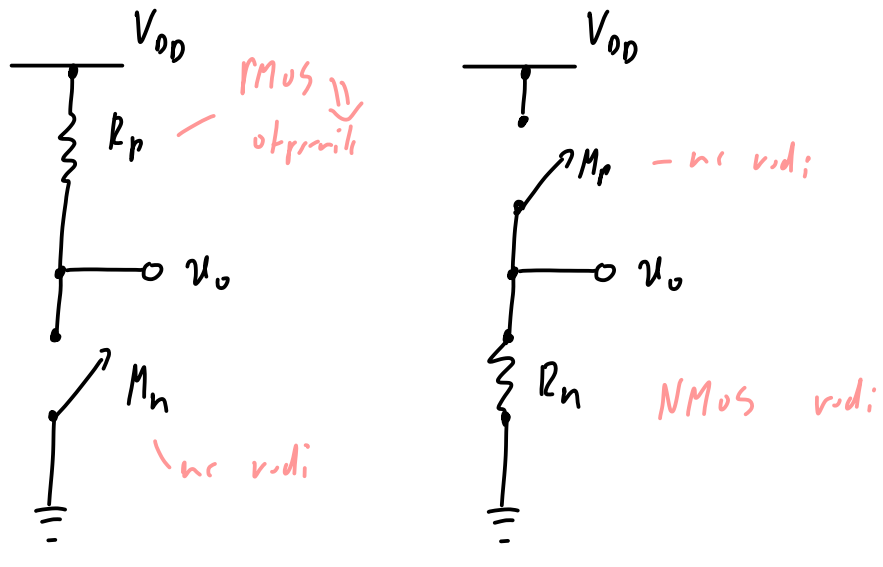
$$\boxed{V_{tn} = |V_{tp}|}$$

širina PMOS > NMOS

jer je pokretljivost $\mu_p < \mu_n$

↳ da bi bila ista I_D

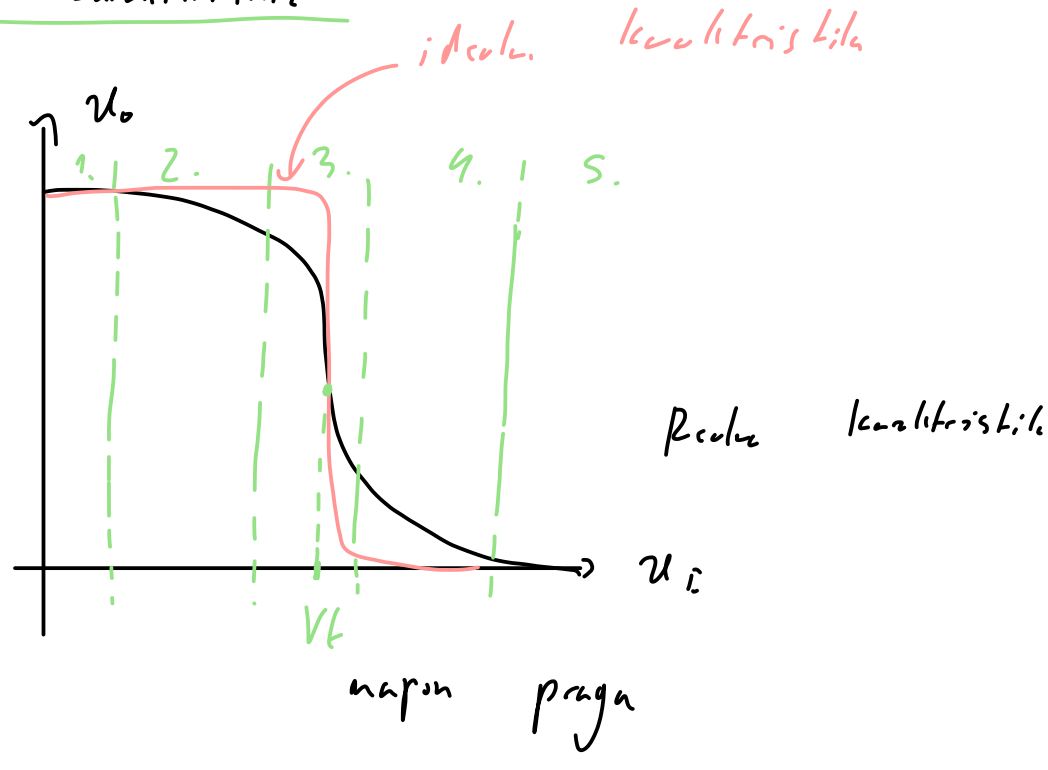
idealni : statička struja = 0



$v_I = 0$ $\qquad$ $v_I = V_{DD}$

$v_O < V_{DD}$ $\qquad$ $v_O \approx 0$

Prenosna karakteristika

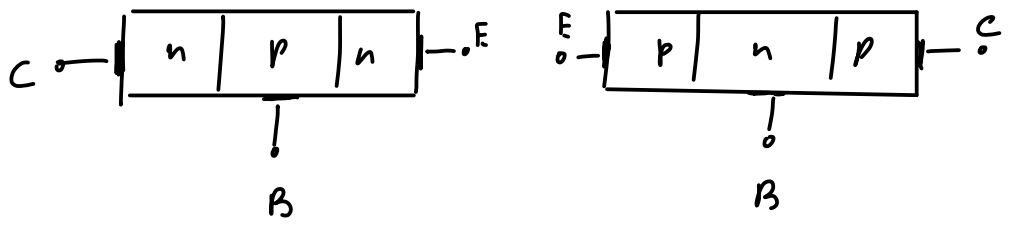


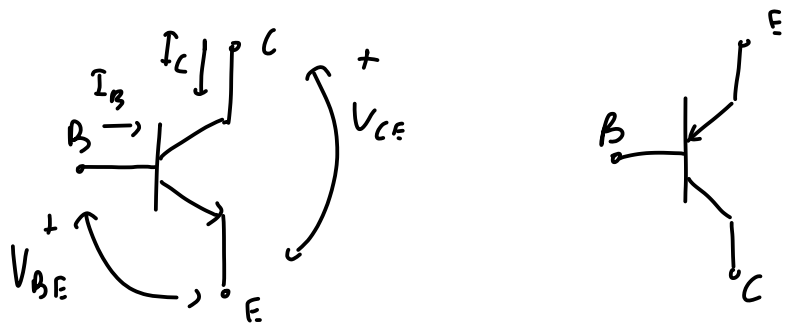
Realna karakteristika

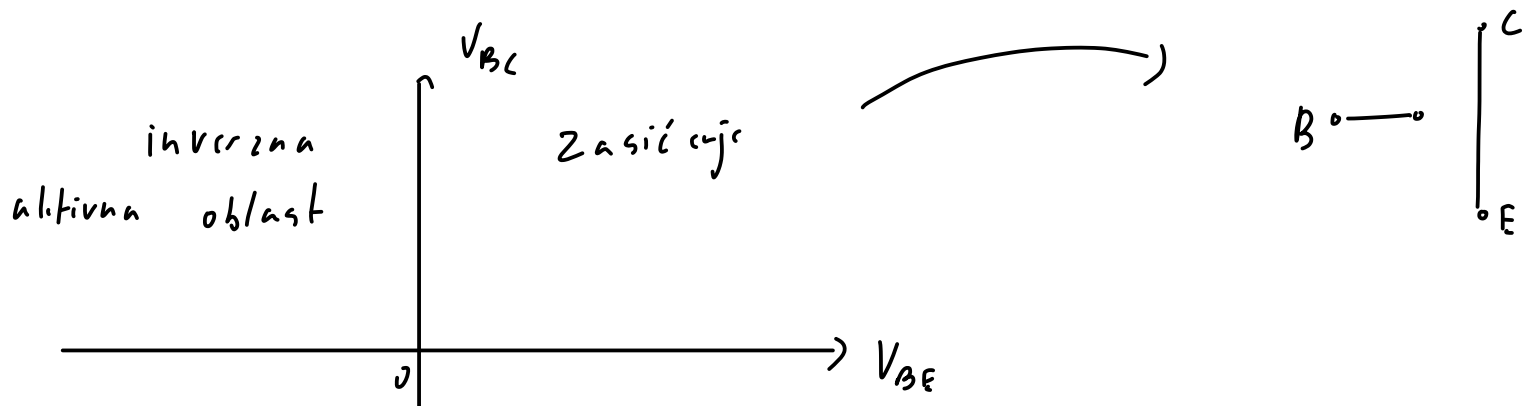
Vježba 11.11.

Bipolarni tranzistori

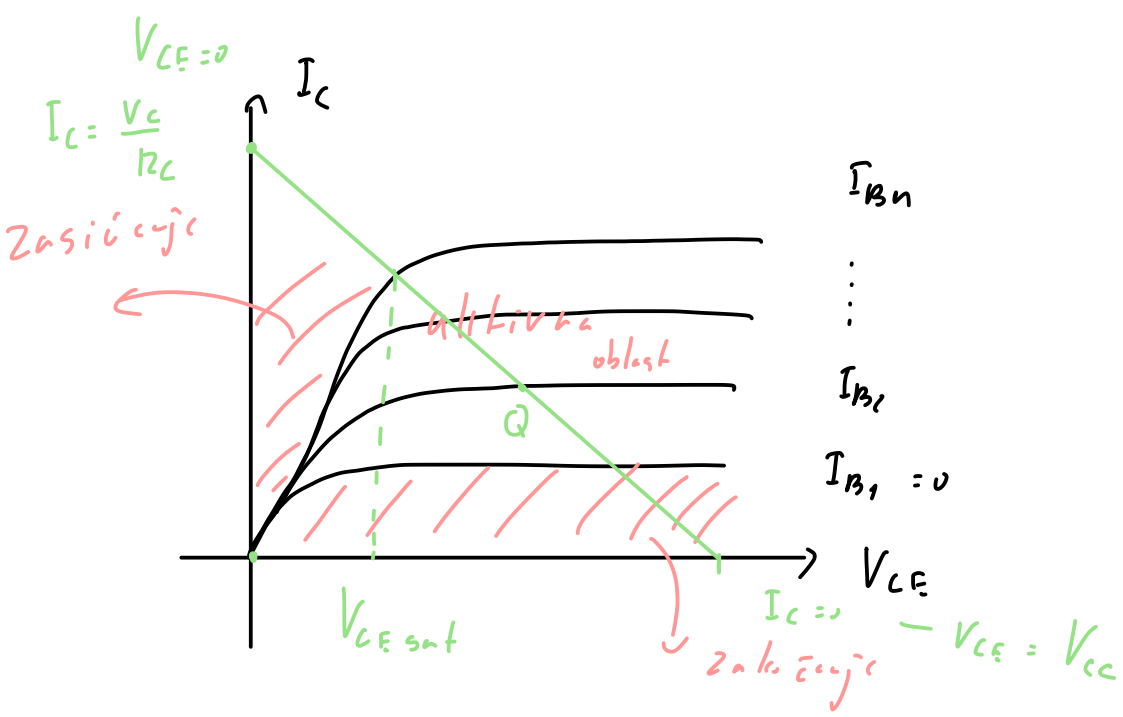
Teorija







Izlazne karakteristike



Jednadžbe

$$I_C = I_S e^{\frac{V_{BE}}{V_t}}$$

$$I_C = \beta I_B$$

$$I_C = \alpha I_E \quad , I_C \approx I_E$$

$$\beta = \frac{\alpha}{1-\alpha}$$

$$\alpha = \frac{\beta}{1+\beta}$$

1. Za kol. sa slike odrediti

a) napone i struje na priključcima tranzistora i provjeriti radi li tranzistor u aktivnom režimu

b) odrediti $R_{C\,max}$ tako da bipolarni tranzistor i dalje radi u aktivnom rež.

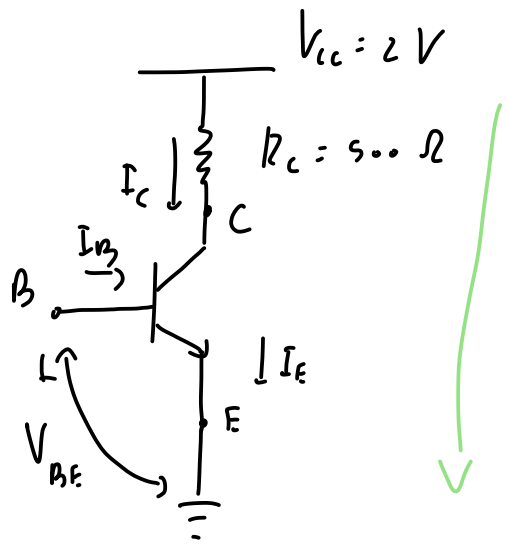
Poznato je:

$I_S = 5 \cdot 10^{-12}\ A$

$V_{BE} = 0.8\ V$

$\beta = 100$

$R_C = 500\ \Omega$



a)

$$I_C = I_S e^{\frac{V_{BE}}{V_t}} \quad , V_t = 26\ mV$$

$$I_C = 1.153\ mA$$

$$I_C = \beta I_B \rightarrow I_B = \frac{I_C}{\beta} = 11.53\ \mu A$$

$$I_C = \alpha I_E \rightarrow I_E = \frac{1+\beta}{\beta} I_C = 1.165\ mA$$

$$\alpha = \frac{\beta}{1+\beta}$$

$V_{BE} = 0.8\ V \rightarrow$ dir. pol

$V_E = 0\ V$

$V_C = V_{CC} - R_C I_C = 1.424\ V$

$V_{BC} = V_B - V_C = 0.5 - 1.929 = \underline{-0.624\,V}$ → inv. r.l

aktivni režim

b) $V_{BC} = 0\,V$

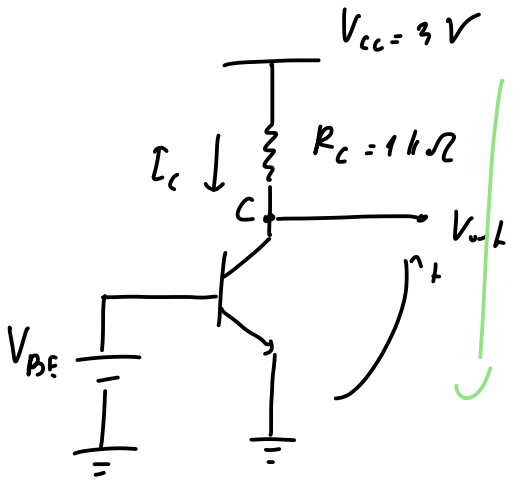
$V_{CC} = R_C I_C + V_C$

$V_{CC} - V_C = R_C I_C$

$R_{C\,max} = \dfrac{V_{CC} - V_C}{I_C}$

$R_{C\,max} = \dfrac{2\,V - 0.5\,V}{1.155\,mA} = 1.041\,k\Omega$

2. Odrediti izlazni napon za k.l. na slici



$I_S = 5 \cdot 10^{-16}\,A$

$V_{BE} = 0.75\,V$

$V_t = 26\,mV$

$I_C = I_S \cdot e^{\frac{V_{BE}}{V_t}} = 1.69\,mA$

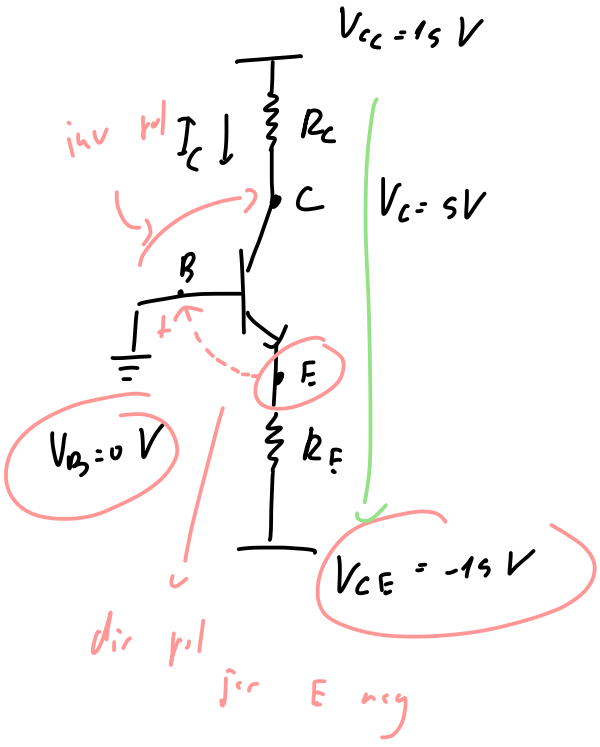
$V_{CC} - R_C I_C - V_{out} = 0$

$V_{out} = V_{CC} - R_C I_C = \underline{1.31\,V}$

analizirati → odrediti sve I i V

odrediti vrijednost 1 el u k.l.

3. Tranzistor sa slike ima $\beta = 100$ i $I_{C1} = 1\,mA$ za $V_{BE1} = 0.7\,V$. Projektirati k.l. tak. da struja kolektora bude $I_{C2} = 2\,mA$ i potencijal C da bude 5V



$I_{C1} = 1\,mA$, $V_{BE1} = 0.7\,V$, $\beta = 100$

$I_{C2} = 2\,mA$, $V_C = 5\,V$

$V_{CC} - R_C I_{C2} - V_C = 0$

$-R_C I_{C2} = -V_{CC} + V_C$

$R_C = \dfrac{V_{CC} - V_C}{I_{C2}} = \dfrac{15 - 5}{2\,mA} = \underline{5\,k\Omega}$

Aktivni režim

$$\frac{I_{C1}}{I_{C2}} = \frac{\cancel{I_S}\, e^{\frac{V_{BE1}}{V_t}}}{\cancel{I_S}\, e^{\frac{V_{BE2}}{V_t}}} \quad ? \longrightarrow V_{BE2} = V_{BE1} - V_t \ln \frac{I_{C1}}{I_{C2}}$$

$$V_{BE2} = 0.718\,V$$

$$V_{BE} = V_B - V_E$$

$$V_E = V_B - V_{BE} = -0.718\,V$$

$$I_E = \frac{\beta + 1}{\beta} I_{C2}$$

$$I_E = 2.02\ mA$$

$$R_E = \frac{V_E - V_{EE}}{I_E} = \underline{7.02\ k\Omega}$$

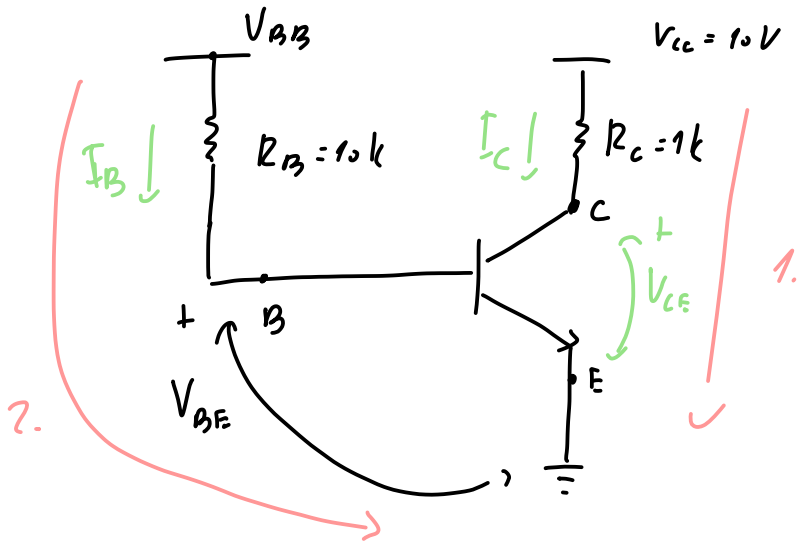
4. Za kol. sa slike odrediti V_{BB} tak da tranzistor radi u

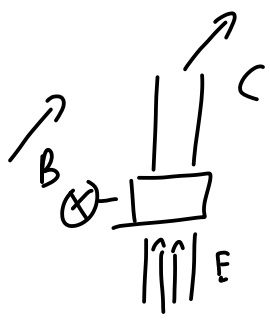
a) aktivnom režimu za $V_{CE} = 5V$

b) na granici zasićenja

c) dubok u zasićenju pri čemu je $\beta_s = 10$ — β u zasićenju

Poznato je $V_{BE} = 0.7V$ (const) i $\beta = 50$





a) $V_{CE} = 5V$

1. $V_{CC} - R_C I_C - V_{CE} = 0$

$$I_C = \frac{V_{CC} - V_{CE}}{R_C} = 5\ mA$$

$$I_C = \beta I_B \Rightarrow I_B = \frac{I_C}{\beta} = 0.1\,\mu A$$

2. $V_{BB} - R_B I_B - V_{BE} = 0$

$$V_{BB} = R_B I_B + V_{BE}$$

$$V_{BB} = 1.7\,V$$

b) $V_{CE\,sat} = 0.3\ V$

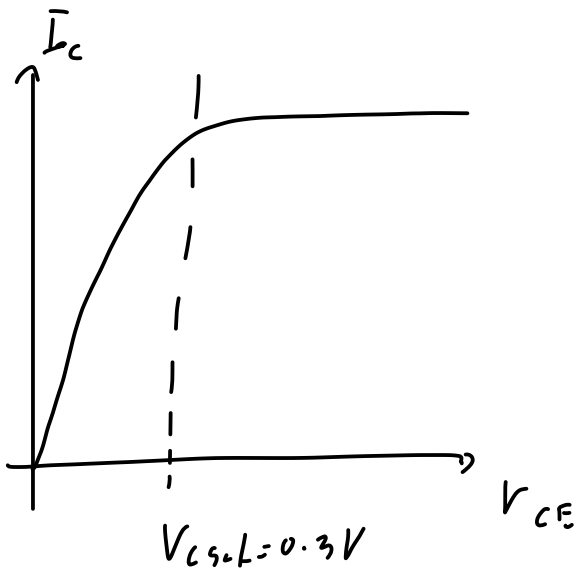
$$I_C = \frac{V_{CC} - V_{CE}}{R_C} = 9.7\ mA$$

$$I_B = \frac{I_C}{\boxed{\beta}}$$ na granici zasićenja $\beta = 50$

$$I_B = 0.194\ mA$$

$$V_{BB} = R_B I_B + V_{BE} = 2.64\ V$$

c)



$V_{CE} = 0.2\ V$

$$I_C = \frac{V_{CC} - V_{CE}}{R_C} = \frac{10 - 0.2}{1k} = 9.8\ mA$$

$$I_{BS} = \frac{I_C}{\beta_S} = 0.98\ mA$$

„strujom upravljani prekidač"

$$V_{BB} = R_B I_B + V_{BE} = 10.5\ V$$

Predavanje 20.11.2024.

metal oxide semiconductor

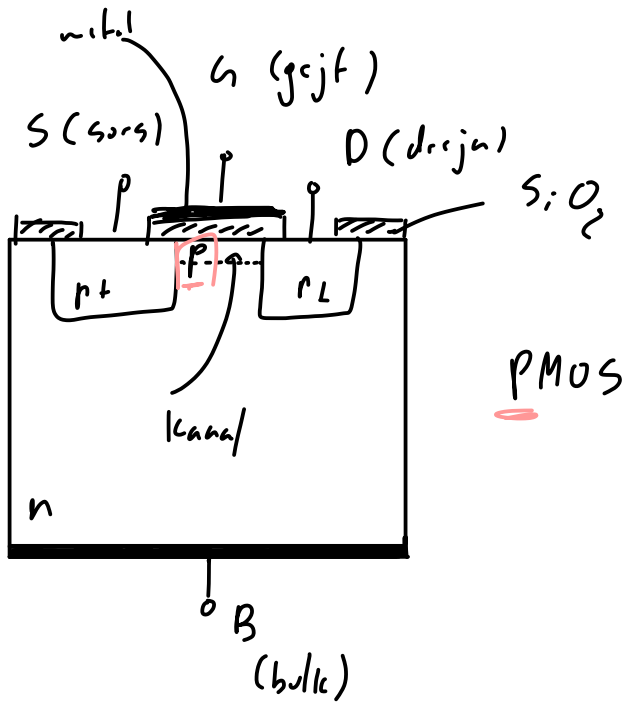
MOSFET

↳ drift dominantan mehanizam za uspostavljanje struje

- unipolarni - samo 1 nositelj naboja

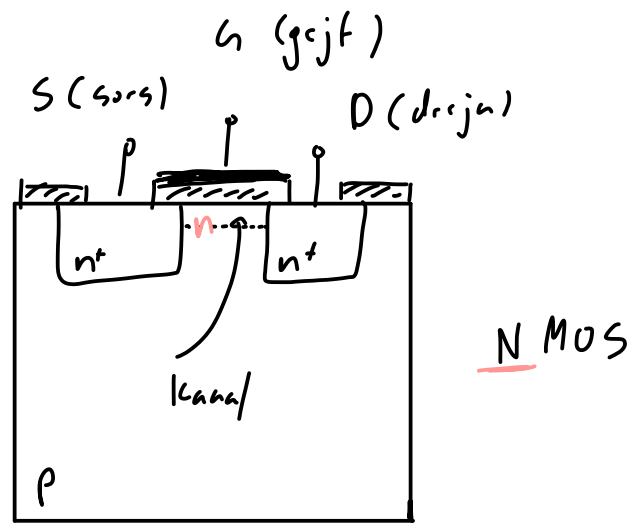
NMOS - elektroni

PMOS - šupljine



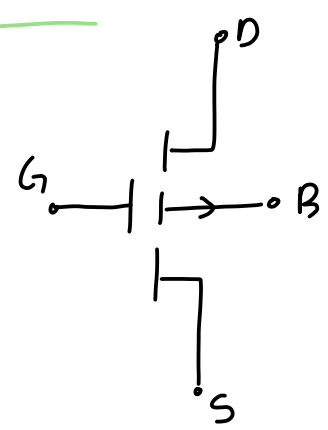
PMOS

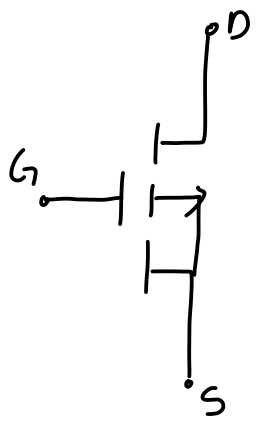
↳ obično na istom potencijalu kao S



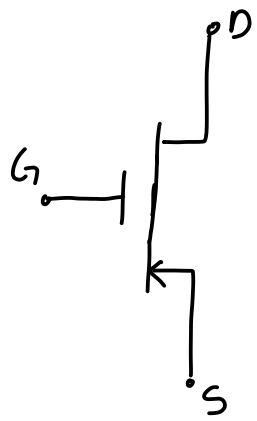
NMOS

Simboli

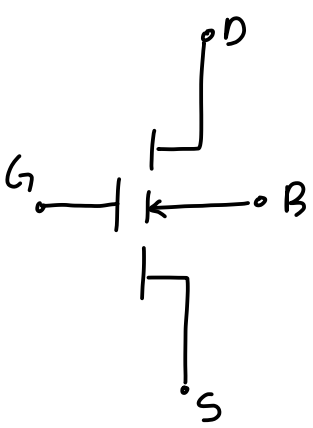


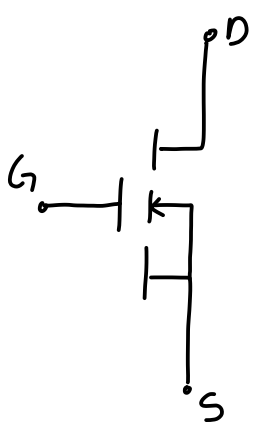


PMOS (stari)

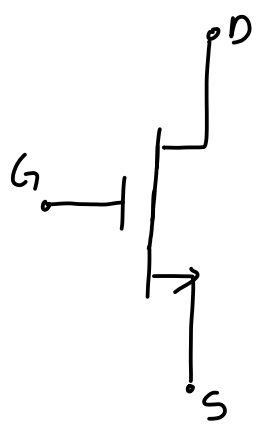


PMOS (novi)





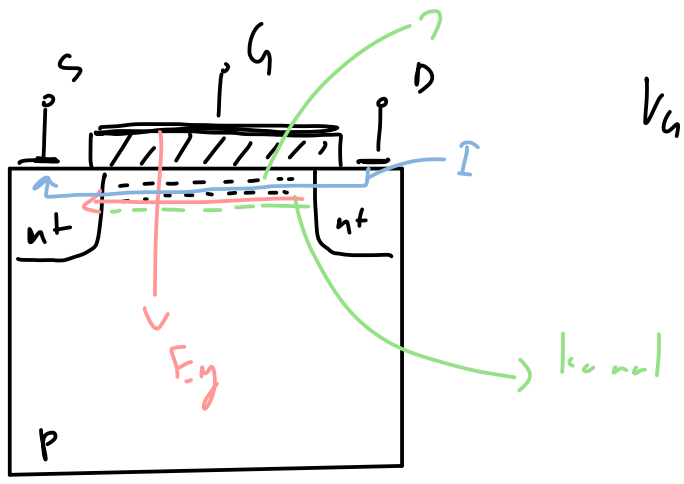
NMOS (stari)



NMOS (novi)

NMOS

el. izvučeni iz supstrata



$V_{GS} > 0$ $\quad V_S = V_B = 0$

V_{tn} - napon praga $(0.3 \div 1)\,V$

n-tip

↳ napon pri kome se mijenja tip

$V_{GS} \geq V_{tn}$ - Formiran kanal

$V_{DS} > 0$ - za uspostavljanje struje

↓ dobijamo lateralno el. polje

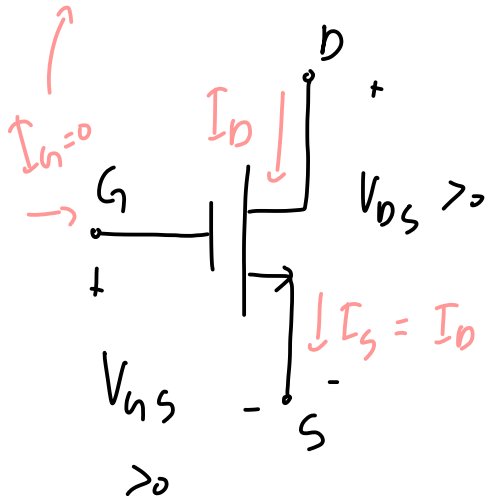
el se kreću od S -> D

↓

dobija se struja D -> S

kroz oksid nema struje

jer $I_G = 0$



I-V karakteristika NMOS

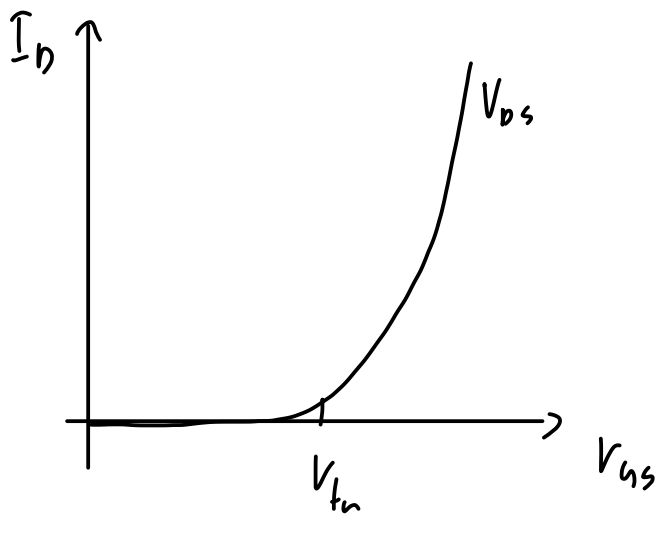
$I_D = 0$ -> nema ulazaka karakteristike

Ulaz : gejt (V_{GS})

Izlaz : drejn (V_{DS}, I_D)

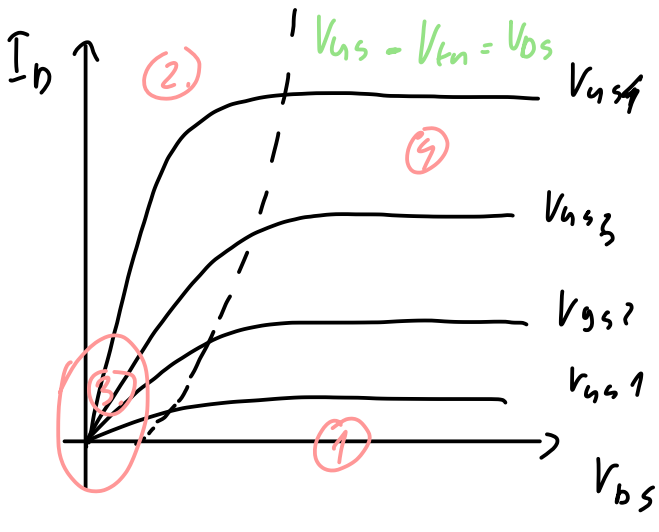
Prenosna:

$I_D = f(V_{GS})$



Izlazna:

$I_D = f(V_{DS})\big|_{V_{GS}}$



kod bipolarnog

① Nije formiran kanal (tr. isključen) → nije formiran kanal

$V_{GS} < V_{tn} \Rightarrow I_D = 0$

② Triodna (nezasićena) oblast

$V_{GS} > V_{tn}$ – formiran je kanal

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

$$\boxed{I_D = \frac{\mu_n C_{ox}}{2} \frac{W}{L} \left[2 (V_{GS} - V_{tn}) \cdot V_{DS} - V_{DS}^2 \right]}$$

pokretljivost el

k_n – transkondukcijski parametar

$\boxed{C_{ox} = \frac{\varepsilon_{ox}}{t_{ox}}}$ – kapac. oksida po jed. površini

$$k_n = \underbrace{\frac{\mu \cdot C_{ox}}{2}}_{k_n'} \cdot \frac{W}{L}$$

W – širina kanala

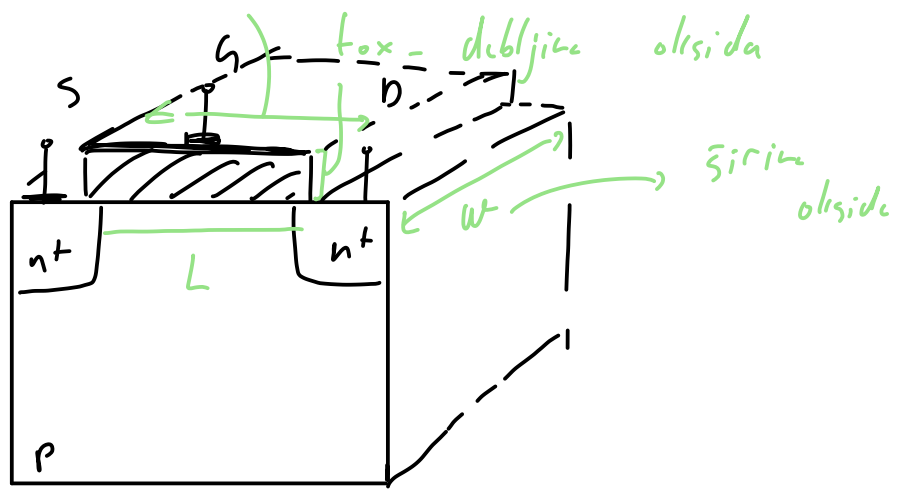
L – dužina kanala

dužina gejta

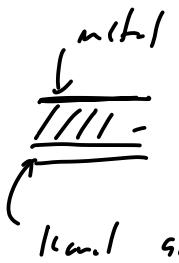
L_G

t_{ox} – debljina oksida

$t_{ox} \nearrow \quad V_{tn} \nearrow$



kondenzator



kanal se pravi

$e^- \rightarrow$ kao metal

③ Linearna oblast

- lin zavisnost struje od napona
  - ↳ tranzistor kao otpornik

- naponski uslovi:
  - $V_{GS} > V_{tn}$ – formiran kanal
  - $V_{GS} - V_{tn} \gg V_{DS}$

$$\boxed{I_D = 2 k_n (V_{GS} - V_{tn}) V_{DS}}$$

$V_{DS} \downarrow\downarrow \quad V_{DS}^2 \rightarrow 0$

$$R_{DS} = \frac{V_{DS}}{I_D} = \frac{1}{2k_n (V_{GS} - V_{tn})}$$

④. Zasićenje / Saturacija

$V_{GS} > V_{tn}$ → formiran kanal

$V_{GS} - V_{tn} \leq V_{DS}$

$$\boxed{I_D = k_n (V_{GS} - V_{tn})^2}$$

$I_D \approx$ const

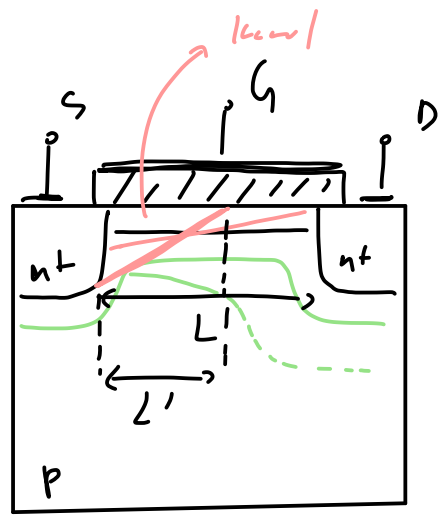
$I_D \not\sim f(V_{DS})$

- red: kao pojačavač

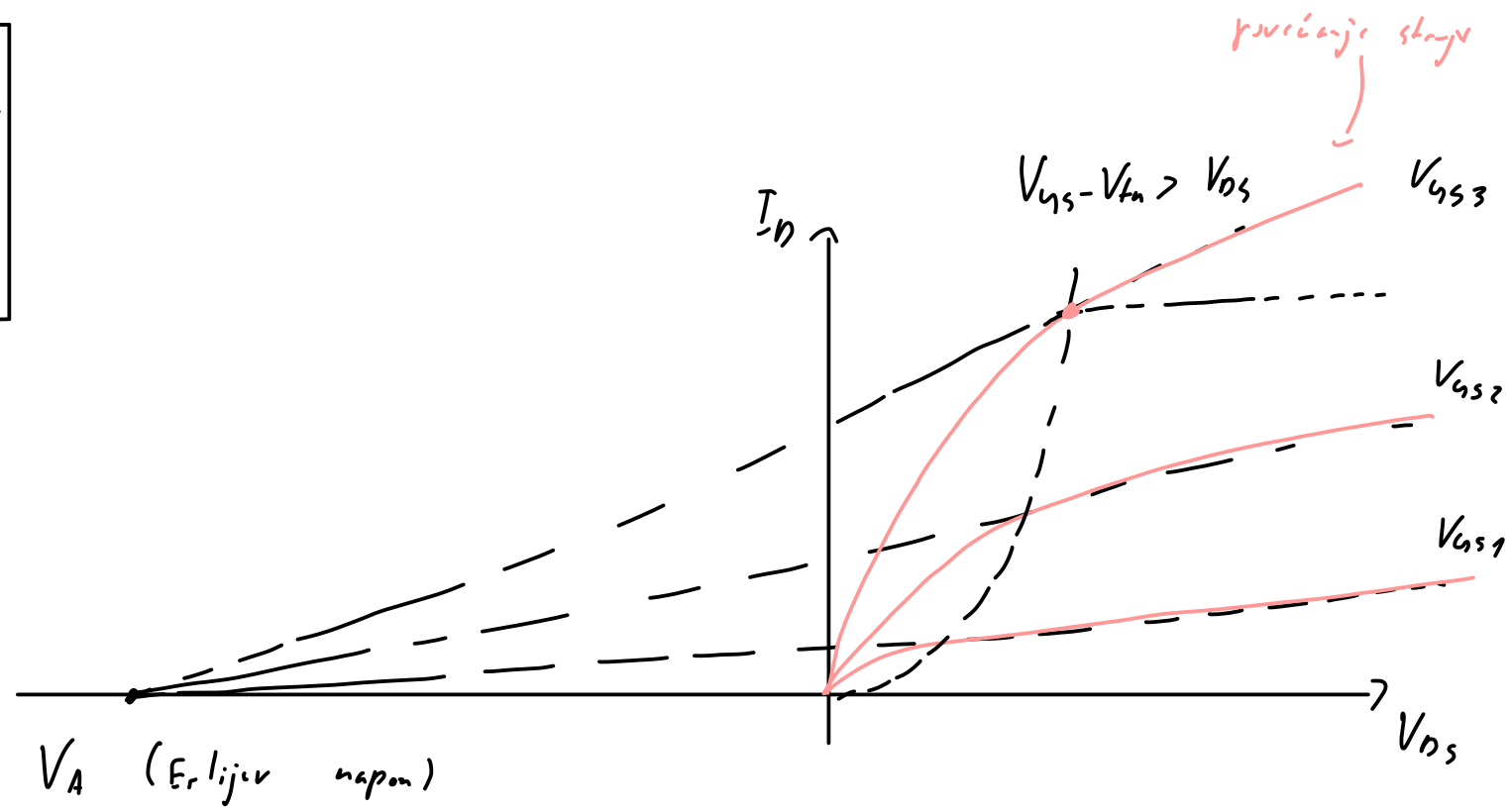
kao prekidač → između isključenja i triode naizmjenično

Efekat modulacije dužine kanala

- $V_{DS} > V_{GS} - V_{tn}$ → samo u oblasti zasićenja



– izračun kad kraćih kanala



$V_A > 0$

$$I_D = k_n (V_{GS} - V_{tn})^2 \left(1 + \frac{V_{DS}}{V_A}\right)$$

$$\boxed{\lambda_n = \frac{1}{V_A}}$$, $\lambda_n > 0$

$$\boxed{I_D = k_n (V_{GS} - V_{tn})^2 (1 + \lambda_n V_{DS})}$$

Dinamička (izlazna) otpornost tranzistora

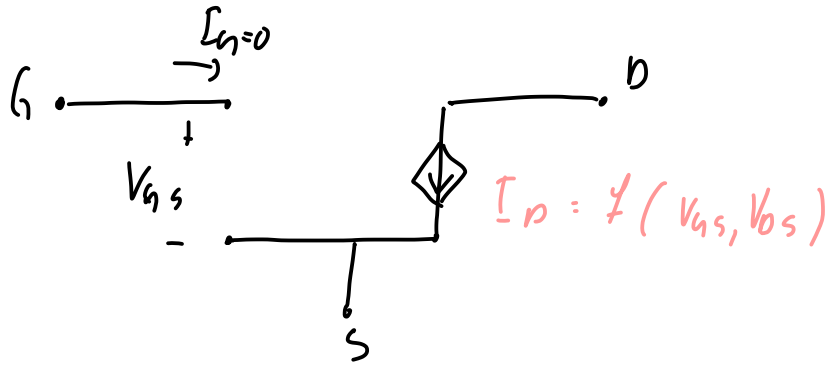
$$\boxed{r_D = \frac{V_A}{I_D} = \frac{1}{\lambda_n I_D}}$$

$$P_D = I_D \cdot V_{DS}$$

$$P_D < P_{DMAX}$$

Model za velike signale (statički model)

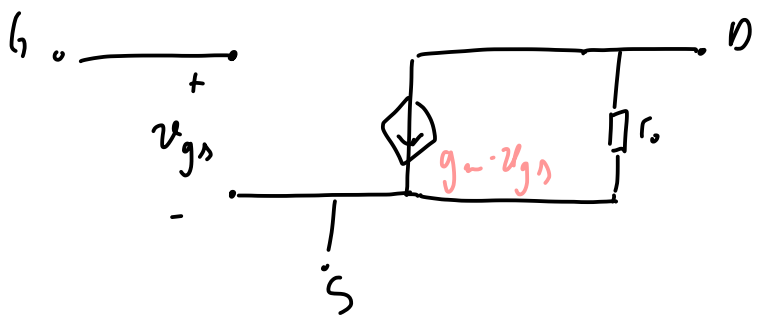
- samo naponom upravljan model, jer $I_G = 0$



$$I_D = k_n (V_{GS} - V_{tn})^2$$

$$V_{GS} - V_{tn} = \sqrt{\frac{I_D}{k_n}}$$

Model za male signale (dinamički model)



Parametri:

$$g_m = \frac{\partial I_D}{\partial V_{GS}} \quad \frac{\partial (k_n (V_{GS} - V_{tn})^2)}{\partial V_{GS}}$$

$$\boxed{r_o = \frac{1}{\lambda_n I_D}}$$

$$\boxed{\begin{aligned} g_m &= 2 k_n (V_{GS} - V_{tn}) \\ g_m &= 2 \sqrt{k_n I_D} \end{aligned}}$$

Strmina/ transkonduktanca

Naponski (jednostepeni) pojačavači

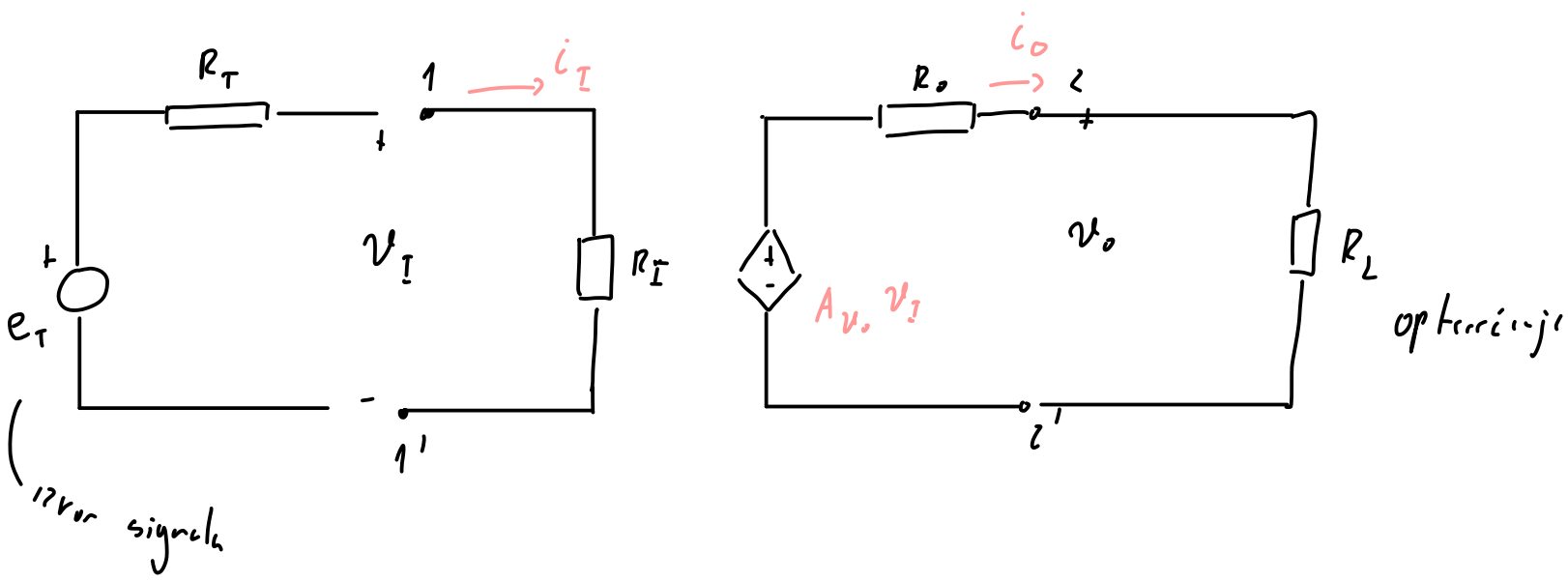
v_I ulazni signal

v_o izlazni signal

$$v_o = A \cdot v_I$$

$A = \text{const.}$

Model nap. pojačavača



Parametri modela nap. pojač.

1. R_I - ulazna otpornost

$$R_I = \frac{v_I}{i_I}$$

- idealno $R_I \to \infty$

2. R_o - izlazna otpornost

$$R_o = \left.\frac{v_o}{i_o}\right|_{v_I = 0}$$

→ za kratko spojene ulazne priključke

- idealno $R_o = 0$

3. A_{v_o} - naponsko pojačanje otvorenog kruga

v nula

$$A_{v_o} = \left.\frac{v_o}{v_I}\right|_{R_L \to \infty}$$

- idealno $A_{v_o} \nearrow\nearrow$

4. A_v - ukupno nap. pojačanje

$$A_v = \left.\frac{v_o}{e_T}\right|_{R_L \neq \infty}$$

$$v_o = \frac{R_L}{R_L + R_o} \cdot A_{vo} \cdot v_I$$

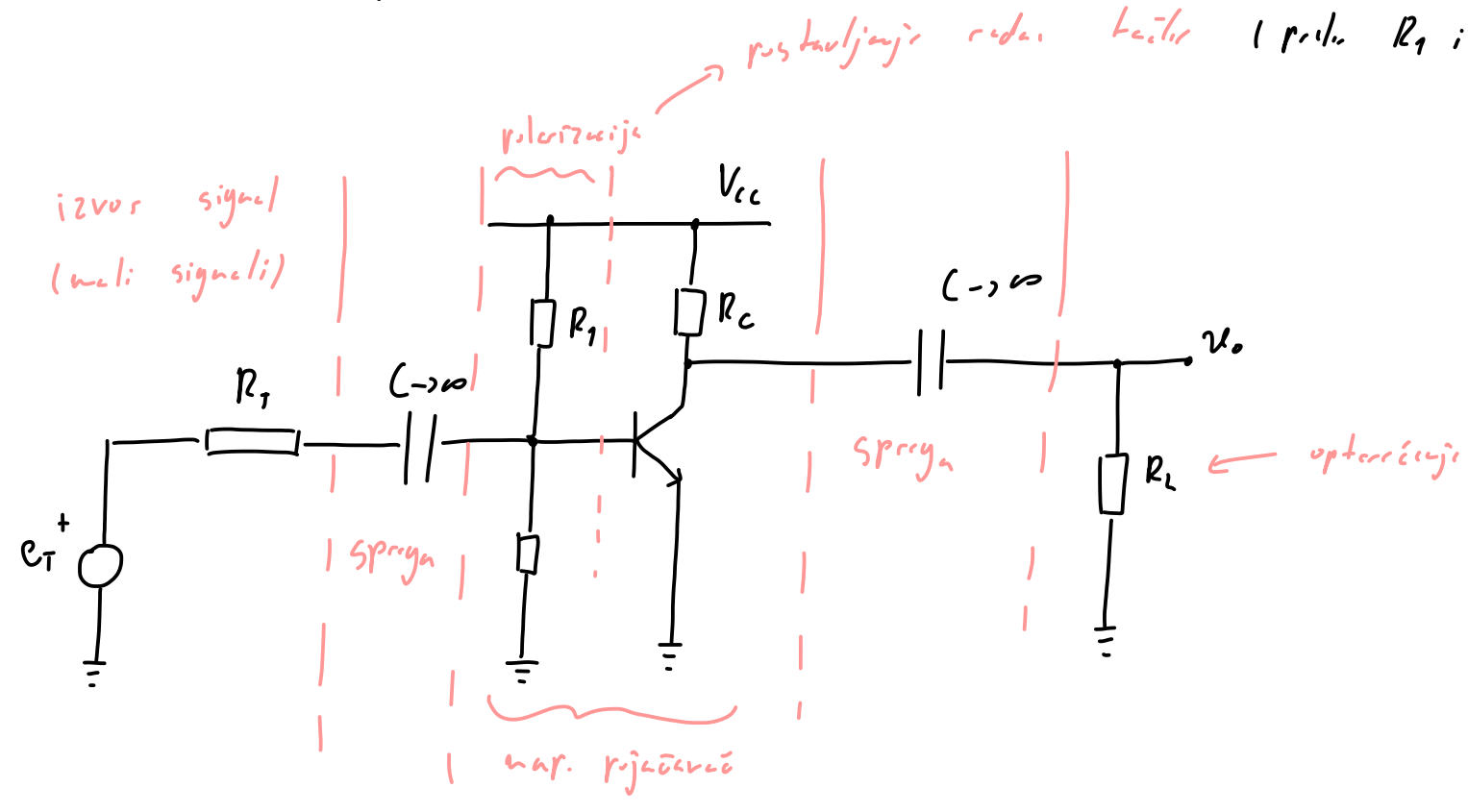
/ nap razdjelnik

$$v_I = \frac{R_I}{R_I + R_T} e_T$$

$$v_o = \frac{R_L}{R_L + R_o} A_{vo} \cdot \frac{R_I}{R_I + R_T} e_T$$

$$\boxed{A_v = A_{vo} \cdot \frac{R_L}{R_L + R_o} \cdot \frac{R_I}{R_I + R_T}}$$

Pojačavač sa zaj. emiterom (ZE pojačavač)

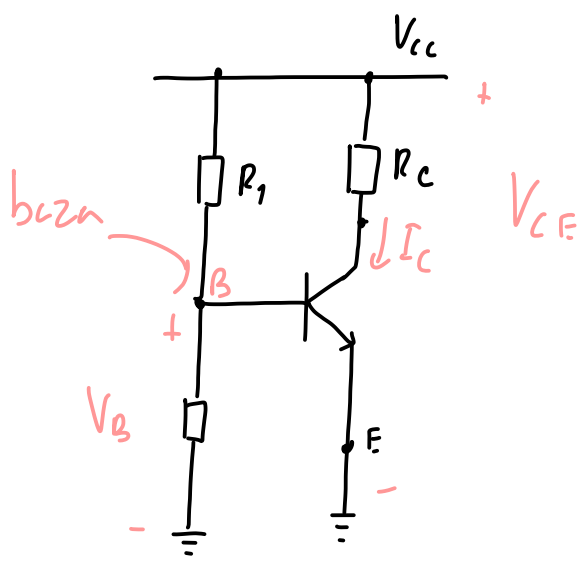


* $C \to \infty$

DC : otvorena veza

AC (dinamička) : kratki spoj

1. Statička analiza (određivanje radne točke $\to I_C$)



$$V_B = \frac{R_2}{R_1 + R_2} \cdot V_{CC}$$ (iz nap razdjelnika)

$$V_E = 0$$

V_{BE} postavlja radnu R_2 i R_1

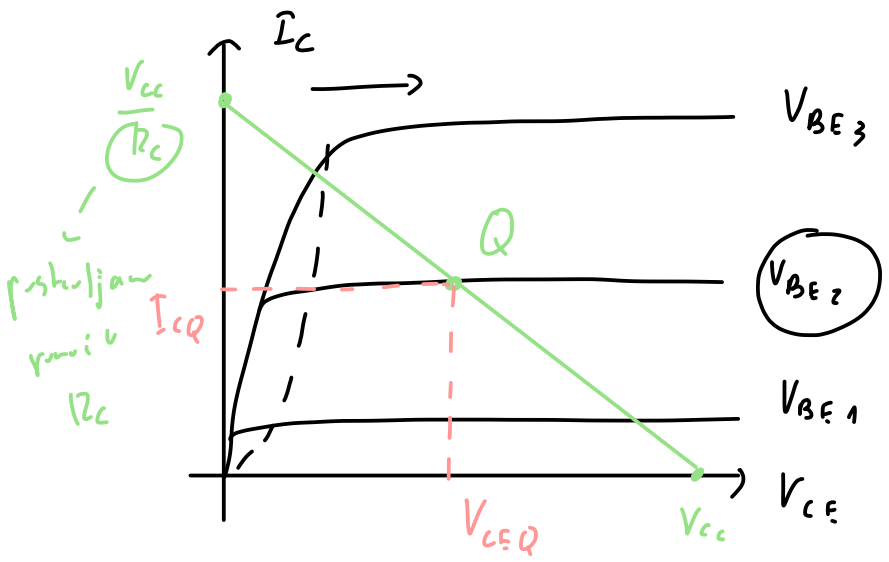
1. $$V_{BE} = V_B = \frac{R_2}{R_1 + R_2} V_{CC}$$

2. Određujemo I_C

$$I_C = I_S \, e^{\frac{V_{BE}}{V_t}}$$

$$V_{CE} = V_{CC} - R_C I_C$$

I-V karakteristika



Q u aktivnoj oblasti

$$\boxed{V_{CE} = V_{CC} - R_C I_C}$$

radna prava

$I_C = 0 \Rightarrow V_{CE} = V_{CC}$

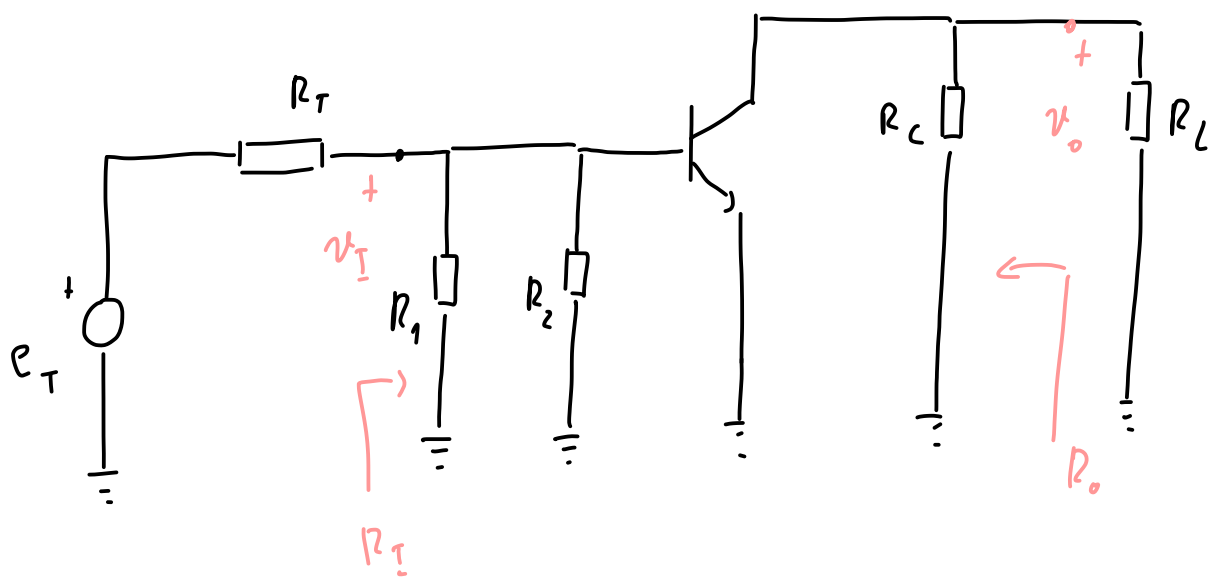
$V_{CE} = 0 \Rightarrow I_C = \frac{V_{CC}}{R_C}$

2. Dinamička analiza (analiza malih signala)

1° C → kratki spoj

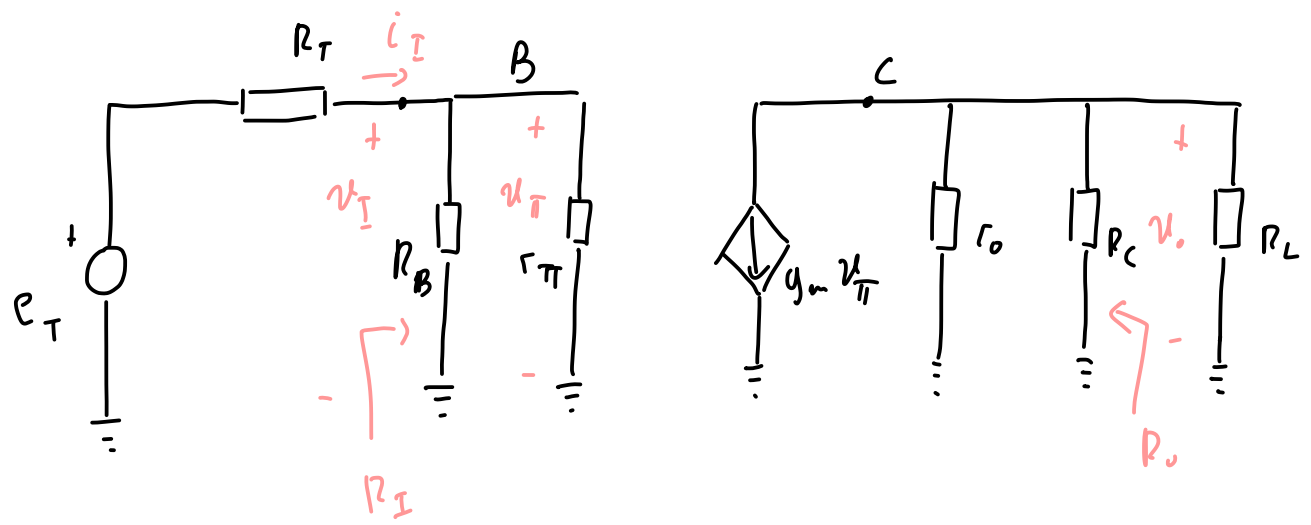
2° DC izvori napajanja → Unutrašnja otpornost
(od V_{CC} unutrašnja otpornost = 0)

$V_{CC} \to 0\,V$ (masa)



3° Tranzistori mijenjamo modelom za male signale

$$g_m = \frac{I_{CQ}}{V_t} \qquad r_o = \frac{\beta}{g_m} \qquad r_o = \frac{V_A}{I_{CQ}}$$

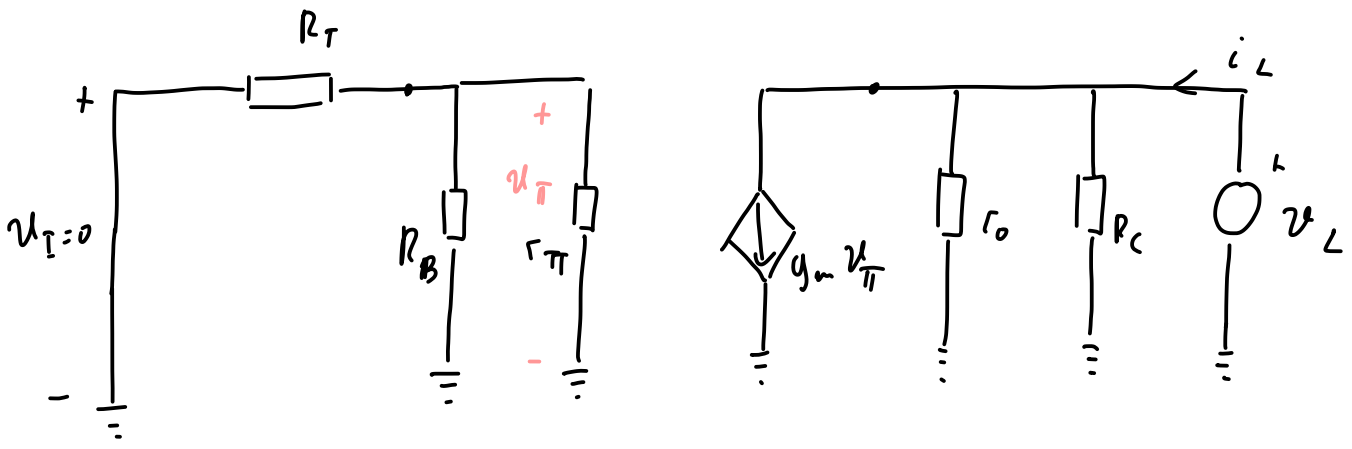


4. Odrediti R_I, R_o, A_{vo}, A_v

Ulazna otpornost R_I:

$$R_I = \frac{v_I}{i_I} = R_B \parallel r_\pi$$

Izlazna otpornost R_o: (za kratko spojene ulazne priključke):



$$\boxed{R_o = \frac{v_L}{i_L}\Big|_{v_I=0}}$$

$v_I = 0 \Rightarrow v_\pi = 0 \Rightarrow g_m v_\pi = 0$

$$\boxed{R_o = r_o \parallel R_C}$$

$r_o \gg R_C$

$$\boxed{R_o \simeq R_C}$$

Naponsko pojačanje otvorenog kola

$$A_{vo} = \frac{v_o}{v_I}\Big|_{R_L \to \infty}$$

$R_L \to$ ucrtano g_m

$$v_o = \boxed{-}\, g_m \cdot v_\pi \,(r_o \parallel R_c)$$

jer teče suprotno od str. gen

$$v_\pi = v_I$$

$$v_o = -g_m\, v_I\,(r_o \parallel R_c)$$

$$\boxed{\begin{aligned} A_{vo} &= -g_m\,(r_o \parallel R_c) \\ &\simeq -g_m R_c \end{aligned}}$$

Ulazno naponsko pojačanje

$$A_v = \frac{v_o}{e_T}$$

$$v_o = -g_m\, v_\pi\,(r_o \parallel R_c \parallel R_L)$$

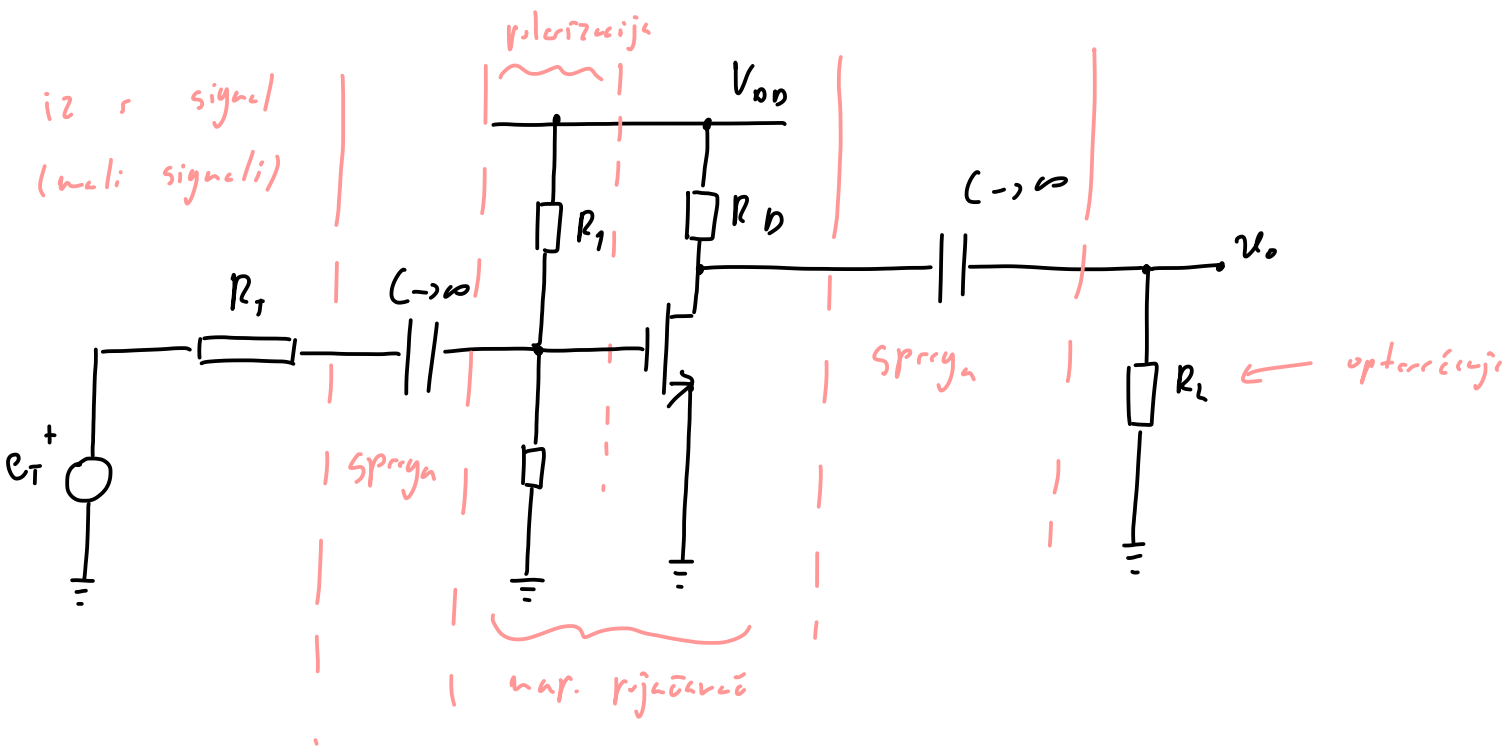
$$v_\pi = v_I$$

iz ulazne razdjelnice

$$v_I = \frac{R_B \parallel r_\pi}{R_B \parallel r_\pi + R_T} \cdot e_T$$

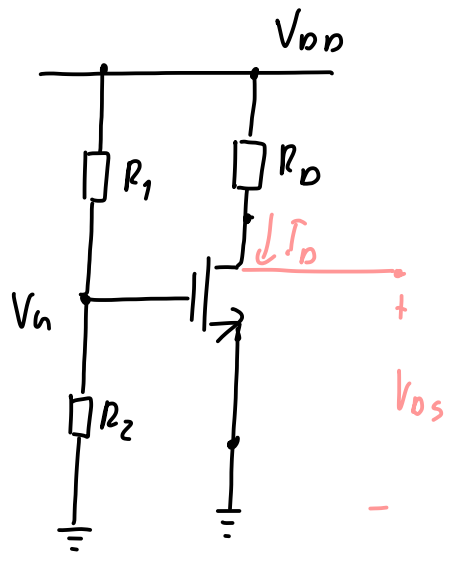
$$A_v = -g_m \cdot (r_o \parallel R_c \parallel R_L)\,\frac{R_B \parallel r_\pi}{R_B \parallel r_\pi + R_T}$$

Pojačavač sa zaj. su-sum (ZS pojačavač)



Statička analiza

C otvoren krug



$$V_G = \frac{R_2}{R_1+R_2} \cdot V_{DD}$$

$$V_S = 0$$

$$V_{GS} = V_G = \frac{R_2}{R_1+R_2} \cdot V_{DD}$$

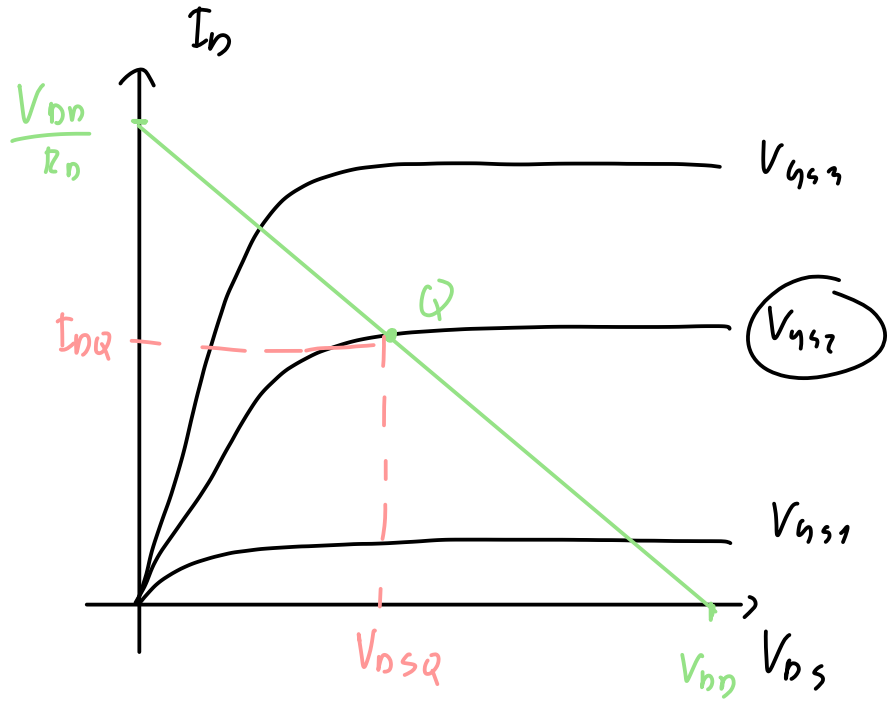
$V_{GS} > V_{tn}$ uspostavljen kanal

$$I_D = k_n (V_{GS} - V_{tn})^2$$

tr. u zasićenju

$$\boxed{V_{DS} = V_{DD} - R_D I_D}$$

radna prava



$I_D = 0 \rightarrow V_{DS} = V_{DD}$

$V_{DS} = 0 \rightarrow I_D = \frac{V_{DD}}{R_D}$

Dinamička analiza

C → kratki spoj

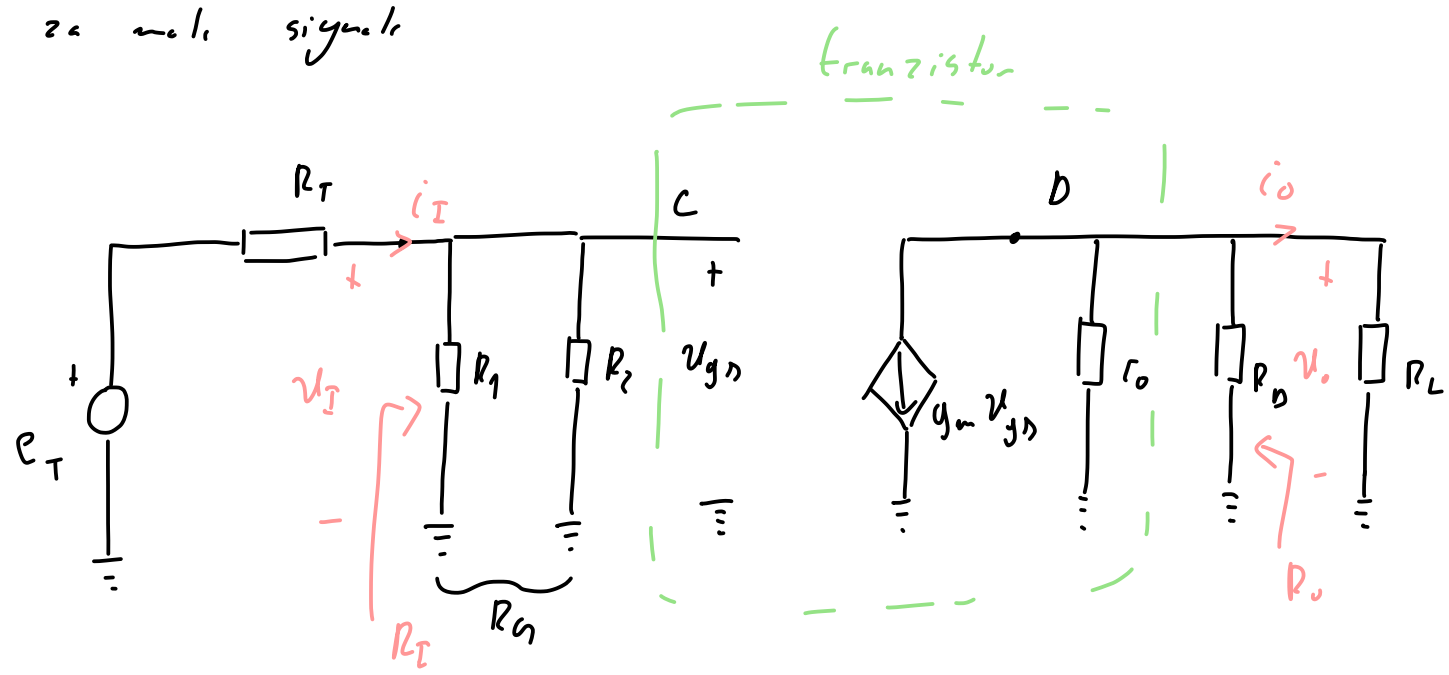
V_{DD} → 0 V (masa)

tranzistor → model za male signale

parametri modela:

$$g_m = 2\sqrt{k_n I_{DQ}}$$

$$r_o = \frac{1}{\lambda_n I_{DQ}}$$



$$R_I = \frac{v_I}{i_I} = R_1 \| R_2 = R_G$$

$$R_o = \frac{v_o}{i_o}\Big|_{v_I=0,\ R_L\to\infty}$$

$v_I = 0 \rightarrow v_{gs} = 0 \rightarrow g_m v_{gs} = 0$

$R_o = r_o \parallel R_D \qquad (r_o \gg R_D)$

$R_o \simeq R_D$

$$A_{vo} = \left.\frac{v_o}{v_I}\right|_{R_L \to \infty}$$

$A_{vo} = -g_m v_{gs} \cdot (r_o \parallel R_D)$

$v_{gs} = v_I$

$A_{vo} = -g_m \underset{\simeq D}{(r_o \parallel R_D)}$ pojačivači obično

$\simeq -g_m R_D$

$$A_v = \left.\frac{v_o}{e_T}\right|_{R_L \neq \infty}$$

$v_o = -g_m v_{gs} (r_o \parallel R_D \parallel R_L)$

$v_{gs} = v_I$

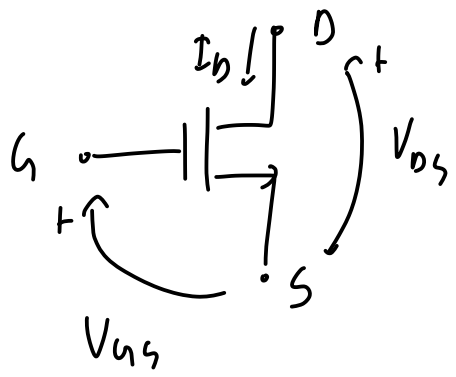
$$v_I = \frac{R_G}{R_G + R_T} e_T$$

$$A_v = -g_m (r_o \parallel R_D \parallel R_L) \cdot \frac{R_G}{R_G + R_T} \rightarrow 1 \quad \text{ja } R_G \gg$$

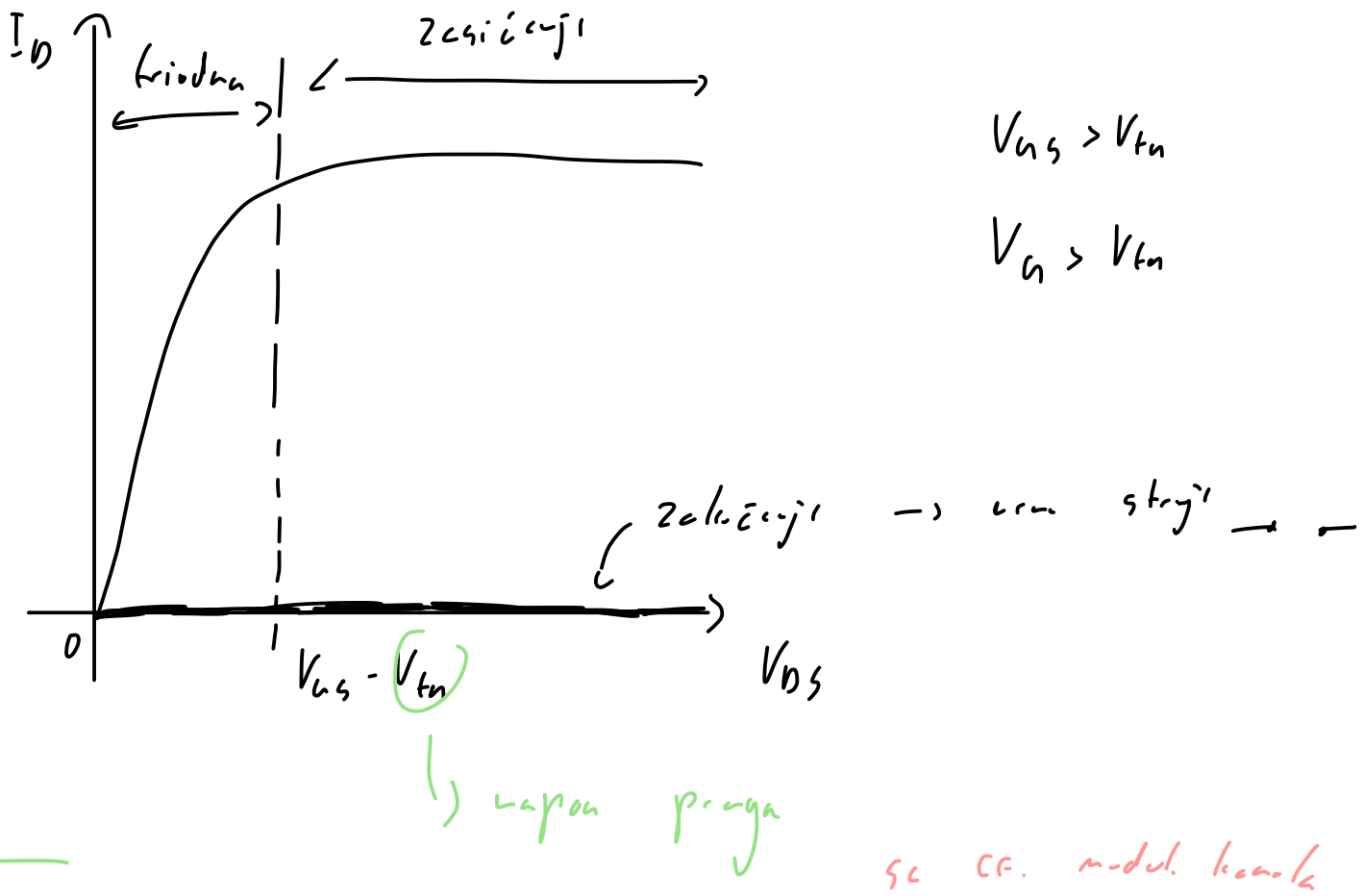
Vježbe 22.11.2024.

MOS tranzistori

NMOS



Izlazna karakteristika



Uslovi za oblasti rada:

1. $V_{DS} > V_{GS} - V_{tn}$

   → zasićenje $I_D = \underbrace{\frac{1}{2}\mu_n C_{ox}\frac{W}{L}}_{k_n}(V_{GS} - V_{tn})^2$, $I_D = \frac{1}{2}\mu_n C_{ox}\frac{W}{L}(V_{GS} - V_{tn})^2(1+\lambda V_{DS})$

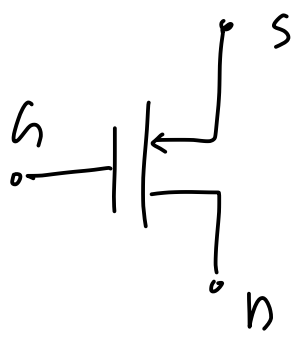
   sa CF. modul. kanala

2. $V_{DS} < V_{GS} - V_{tn}$

   → triodna oblast $I_D = \frac{1}{2}\mu_n C_{ox}\frac{W}{L}\left[2(V_{GS} - V_{tn})V_{DS} - V_{DS}^2\right]$

3. $V_{GS} < V_{tn}$ → zaključenje $I_D = 0\,A$

PMOS



1. $V_{SG} < |V_{tp}|$

   → zaključenje

2. $V_{SD} < V_{SG} - |V_{tp}|$ → triodna

3. $V_{SD} > V_{SG} - |V_{tp}| \rightarrow$ zasićenje

$\mu_n \rightarrow \mu_p$

$V_{tn} \rightarrow |V_{tp}|$

1. Odrediti oblast rada NMOS tranzistora sa slike ako je dato

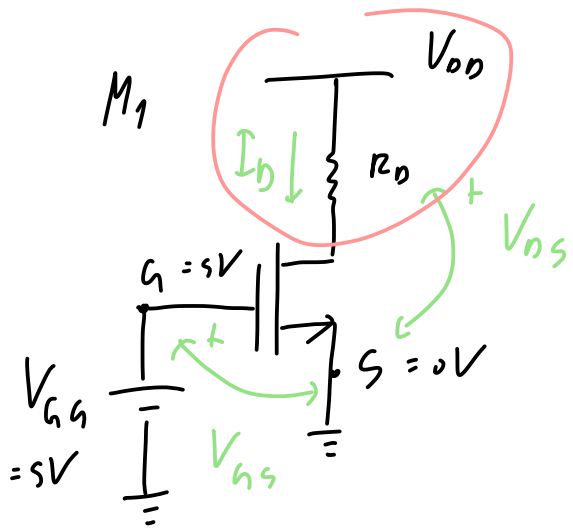
$V_{tn} = 1\,V$

$k_n = 0.5\,mA/V^2$

$V_{DD} = 15\,V$

$V_G = 5\,V$

$R_D = 10\,k\Omega$



$V_{GS} = 5\,V$

$V_{GS} > V_{tn} \rightarrow M_1$ ON

Pretpost zasićenje:

$I_D = k_n (V_{GS} - V_{tn})^2 = 8\,mA$

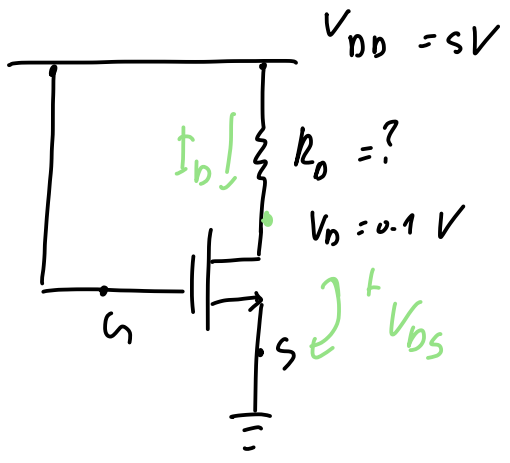
$V_{DS} = V_D$

$V_{DS} = V_{DD} - R_D I_D = -65\,V$ → a $V_{DD} = 15\,V$ ↯

↓

triodna oblast

2. Projektovati k.l. tako da napon na drainu bude 0.1 V. Odrediti otpornost između draina i sourcea



Poznato: $V_{tn} = 1\,V$

$k_n = 0.5\,mA/V^2$

$V_D = 0.1\,V$

$V_{GS} = V_{DD} = 5V$

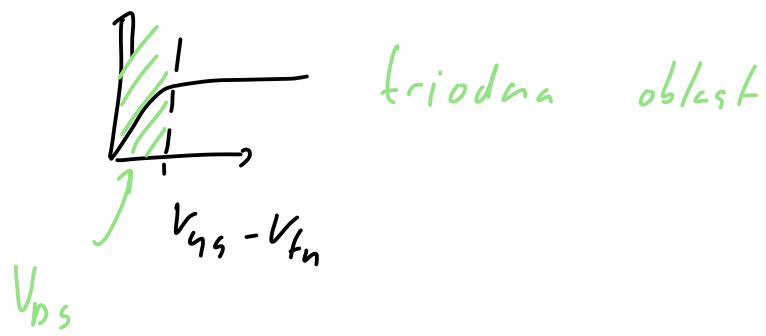
$V_{GS} > V_{tn} \rightarrow M_1$ ON

$V_{DS} = 0.1\ V$

granica

$V_{GS} - V_{tn} = 5 - 1 = 4V$

$V_{DS} < V_{GS} - V_{tn} \rightarrow$



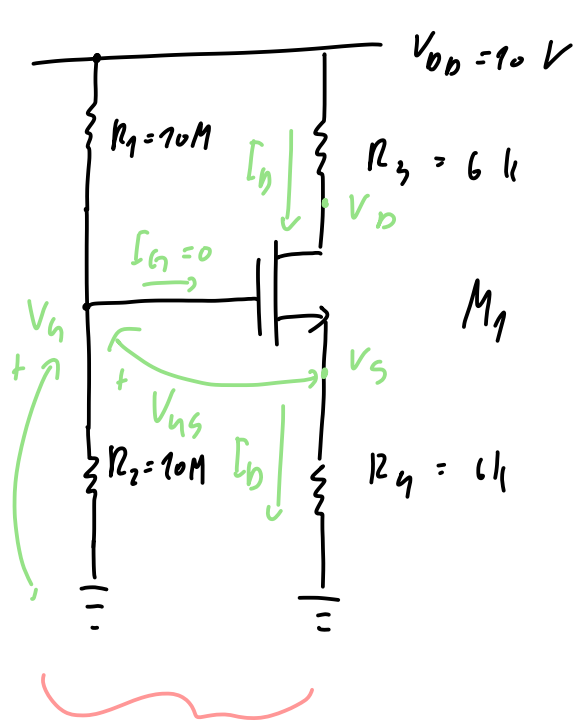
$I_D = k_n \left[2 (V_{GS} - V_{tn}) V_{DS} - V_{DS}^2 \right] = 0.395\ mA$

$R_D = \dfrac{V_{DD} - V_D}{I_D} = 12.4\ k\Omega$

Otpornost između drejna i source:

$r_{DS} = \dfrac{V_{DS}}{I_D} = 253\ \Omega$

3. Naći sve I i V u kolu sa slike.



$V_{tn} = 1V$

$k_n = 0.5\ mA/V^2$

$V_G = V_{DD} \dfrac{R_2}{R_1 + R_2} = 5V$

$V_G > V_{tn} \rightarrow M_1$ ON

$V_D = V_{DD} - I_D \cdot R_3$?

$V_S = R_4 I_D$?

Pretpost saturaciju:

$I_D = k_n (V_{GS} - V_{tn})^2$

$V_{GS} = V_G - V_S = 5 - 6k\, I_D$

$I_D = k_n (5 - 6k I_D - V_{tn})^2$

$18 I_D^2 - 25 I_D + 8 = 0$

$I_{D1} = 0.89\ mA$ $\quad V_S = 5.34V$ $\quad V_S > V_G$ $\quad V_{GS}$ neg

$I_{D2} = 0.5\ mA$ $\quad V_S = 3V$

$V_D = 7V$

4. Projektirati R_D tako da je struja drajna $0.4\ mA$, $V_D = 0.5V$, poznato je:

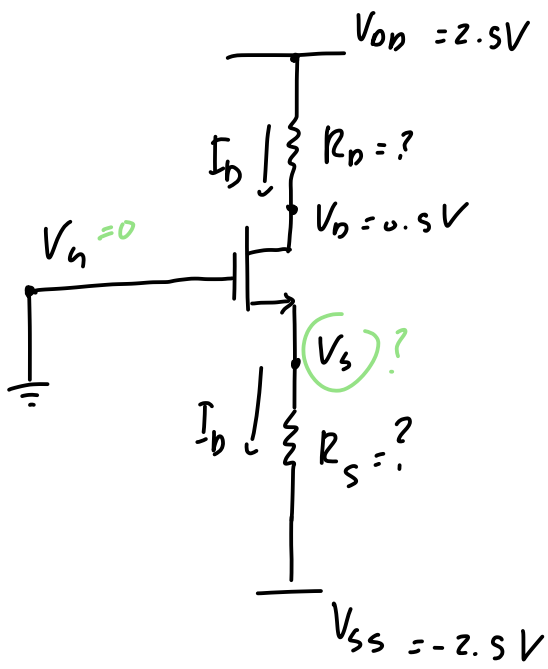
$V_{tn} = 0.7V$

$\mu_n C_{ox} = 100\ \mu A/V^2$

$L = 1\ \mu m$

$W = 32\ \mu m$

Predpost zasićenje.



$R_D = \dfrac{V_{DD} - V_D}{I_D} = 5k\Omega$

$I_D = \frac{1}{2} \mu_n C_{ox} \frac{W}{L} (V_{GS} - V_{tn})^2$

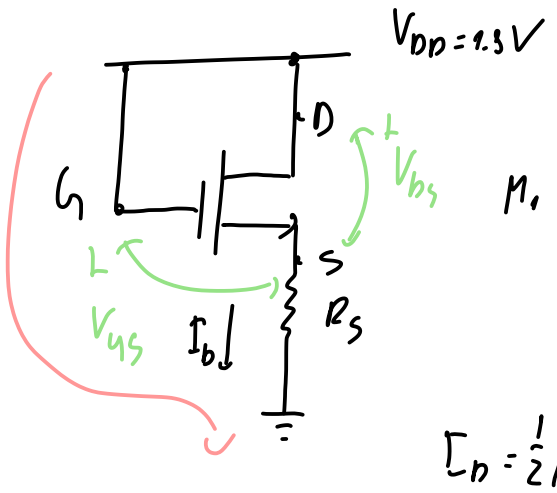
$V_G = 0$ $\quad$ iz njega dobijam V_S jer je $V_G = 0$

$V_{GS} = 1.2V$

$V_{GS} = V_G - V_S = 0 - 1.2V \Rightarrow V_S = -1.2V$

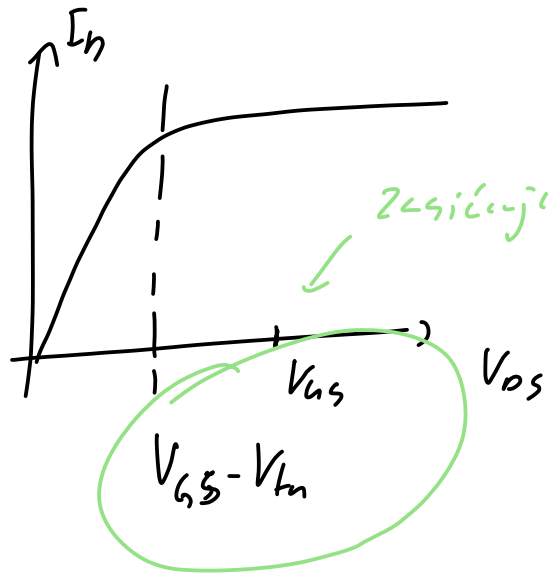
$R_E = \dfrac{V_S - V_{SS}}{I_D} = \dfrac{-1.2V + 2.5V}{0.4\ mA} = 3.25\ k\Omega$

5. Odrediti $\frac{W}{L}$:



$I_D, R_S, \mu_n C_{ox}, V_{tn}$ poznati

$$V_{DS} = V_{GS}$$



$$I_D = \frac{1}{2}\mu_n C_{ox} \frac{W}{L} (V_{GS} - V_{tn})^2$$

$$V_{GS} = V_{DD} - R_S I_D$$

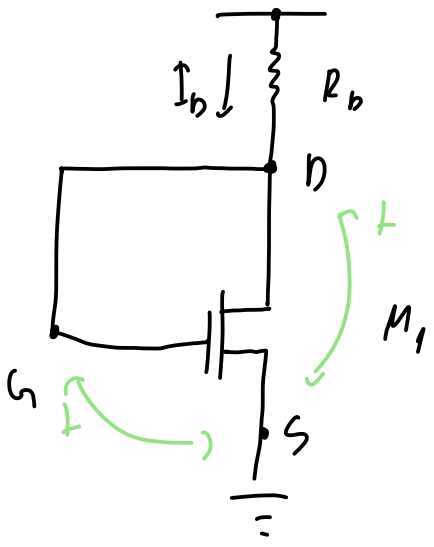
$$I_D = \frac{1}{2}\mu_n C_{ox} \frac{W}{L} (V_{DD} - R_S I_D - V_{tn})^2$$

$$\boxed{\frac{W}{L} = \frac{2 I_D}{\mu_n C_{ox} (V_{DD} - R_S I_D - V_{tn})^2}}$$

Naći biti na kolokvijumu: !!

6. Naći I_D za kol. : $\lambda = 0.1\,V^{-1}$

zasićenje

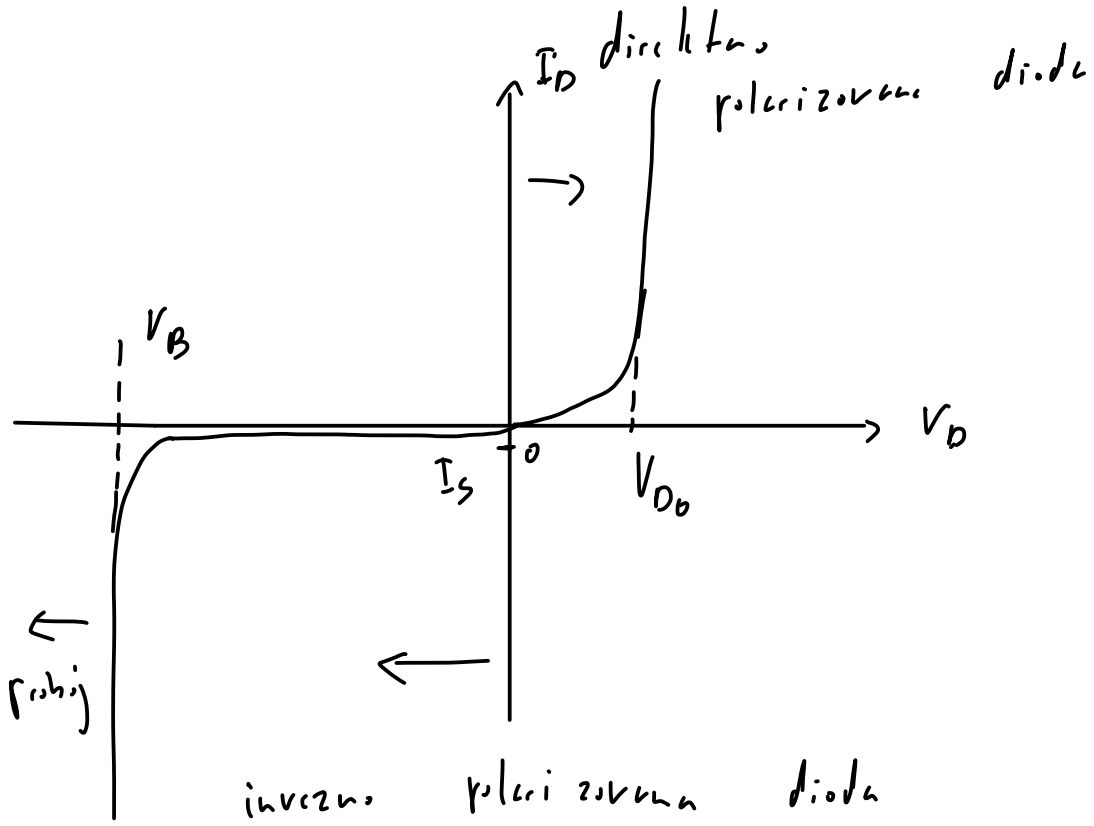


$$I_D = \frac{1}{2}\mu_n C_{ox} \frac{W}{L} (V_G - V_{tn})^2 (1 + \lambda V_G)$$

Lab 1

Priprema za vježbe

1. $I_D = f(V_D)$



dir pol: $I_D = I_S \left(e^{\frac{V_D}{nV_t}} - 1 \right)$ $n \in (1,2)$

inv pol: $I_D = -I_S \simeq 0$

V_B probojni napon

U oblasti direktne polarizacije ($V_D > 0$):

- struja: $I_D = I_S \left(e^{\frac{V_D}{nV_t}} - 1 \right)$, I_S - inverzna struja zasićenja PN spoja

  V_t termički potencijal

- struja ima malu vrijednost do V_{D0} (napona praga)

- za $V_D > V_{D0}$ struja eksponencijalno raste u funkciji V_D

Oblast inverzne polarizacije ($V_D < 0$)

- struja: $I_D = -I_S$ (I_S vrlo mala

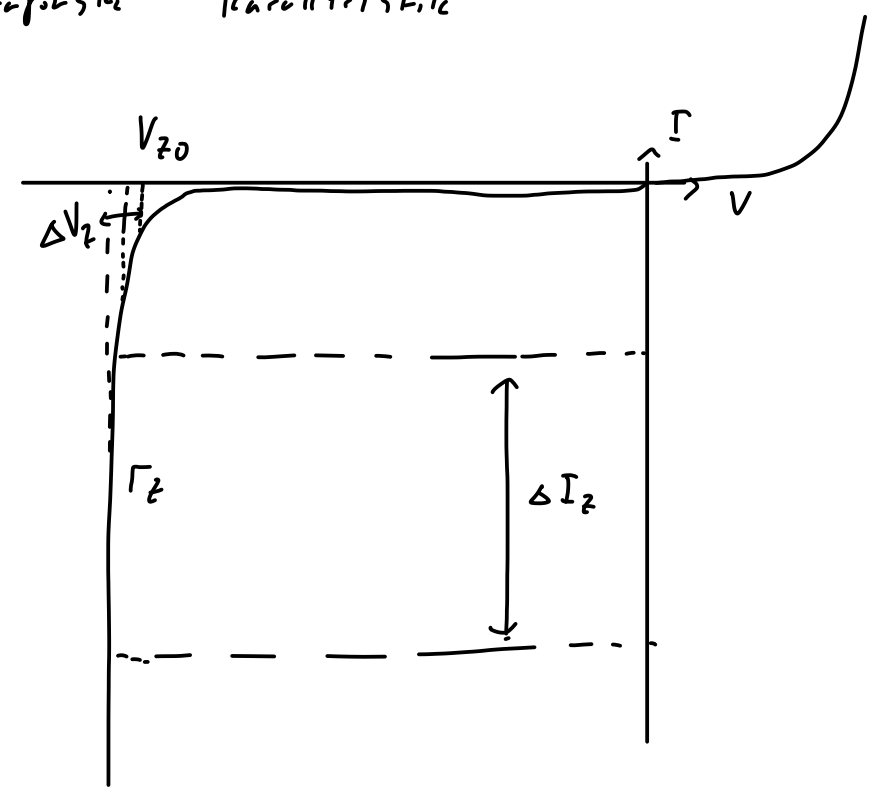
- u stvarnosti struja nije konstantna i polako raste

Oblast proboja:

- za $V_D > |V_B|$ dolazi do proboja i struja diode naglo raste

2. Zener dioda radi u oblasti proboja

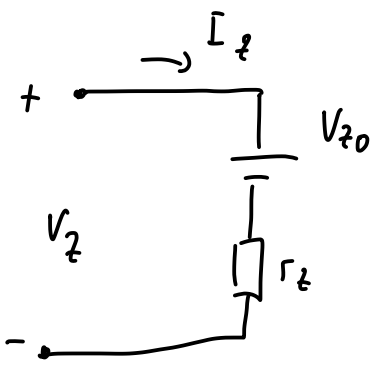
Strujno naponska karakteristika



Vidimo da zener dioda za veliku promjenu struje ima malu promjenu napona, to jasno kompenzira veliku promjenu struje

Inkrementalna otpornost Zener diode : $r_Z = \frac{\Delta V_Z}{\Delta I_Z}$

Model zener diode : (u oblasti inverznog proboja)

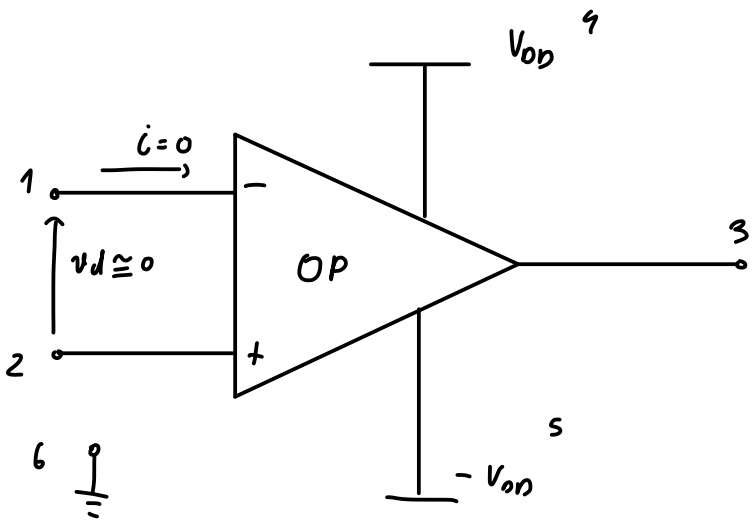


1. Zadatak

napon iznosi 599.03346 mV

Predavanje 27.4.2024.

Standardne primjene operacionih pojačavača (OP)

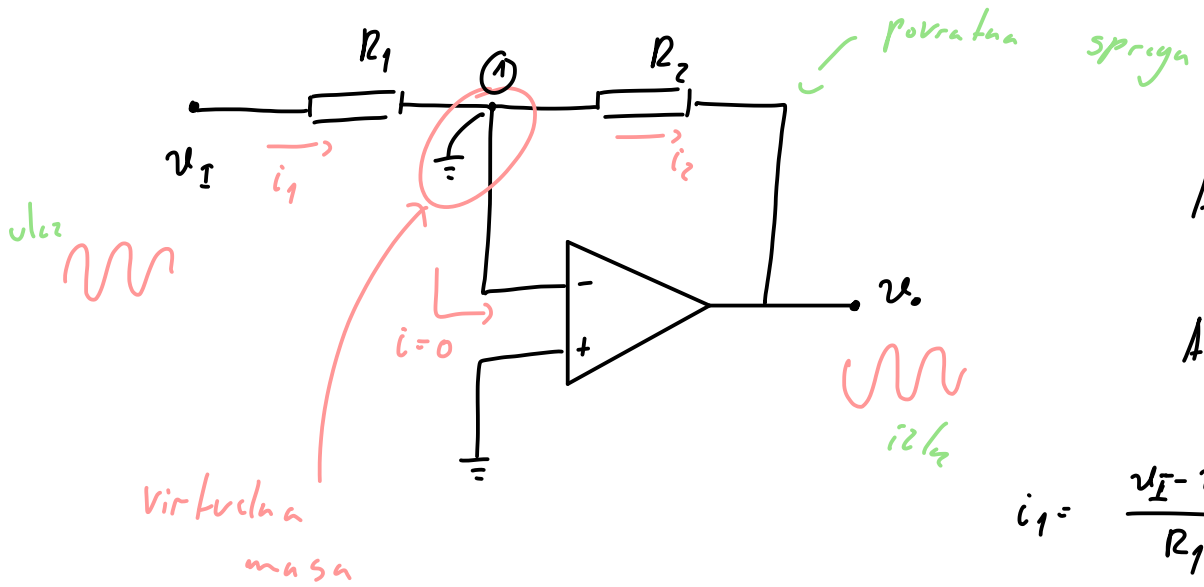


1. Invertujući ulaz
2. Neinvertujući ulaz
3. Izlaz

K-ke idealnog OP:

1. Beskonačno pojačanje
2. Beskonačna ulazna otpornost ($R_i \to \infty$)
3. Nulta izlazna otpornost ($R_o = 0$)
4. Beskonačni propusni opseg (pojačanje se ne mijenja sa promjenom frekv.)

Invertujući pojačavač



A_v - naponsko pojačanje

$$A_v = \frac{v_o}{v_i}$$

1 KZ za 1

$$i_1 = \frac{v_I - v_1^{=0}}{R_1} = \frac{v_I}{R_1}$$

$$i_2 = \frac{v_1^{=0} - v_o}{R_2} = -\frac{v_o}{R_2}$$

$$i_1 = i_2$$

$$\frac{v_I}{R_1} = -\frac{v_o}{R_2}$$

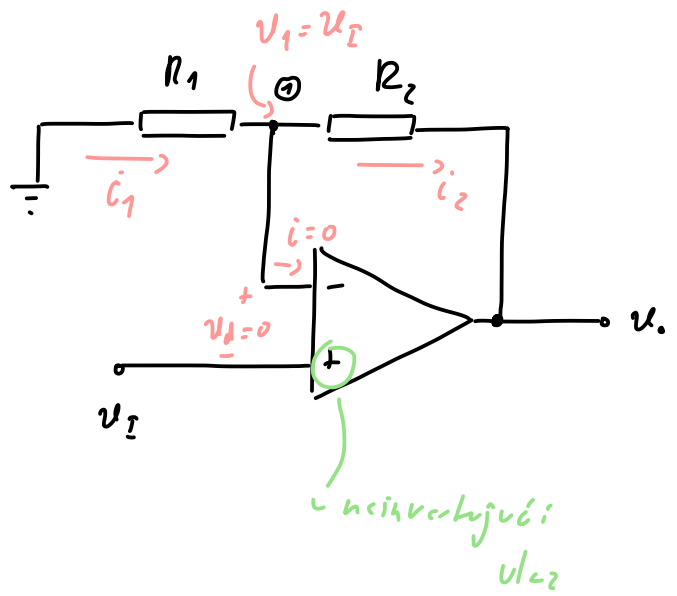
$$\boxed{A_v = \frac{v_o}{v_I} = -\frac{R_2}{R_1}}$$

ulazni i izlazni signal u protufazi (pomjereni za π)

ulazna otpornost

$$R_i = \frac{v_I}{i_I} = \frac{v_I}{i_1} = R_1$$

Neinvertirajući pojačavač



$$i_1 = \frac{0 - v_I}{R_1} = -\frac{v_I}{R_1}$$

$$i_2 = \frac{v_I - v_o}{R_2}$$

$$i_1 = i_2 \qquad -\frac{v_I}{R_1} = \frac{v_I - v_o}{R_2}$$

$$\frac{v_o}{R_2} = \frac{v_I}{R_2} + \frac{v_I}{R_1} \quad / R_2$$

$$v_o = v_I \left(1 + \frac{R_2}{R_1}\right)$$

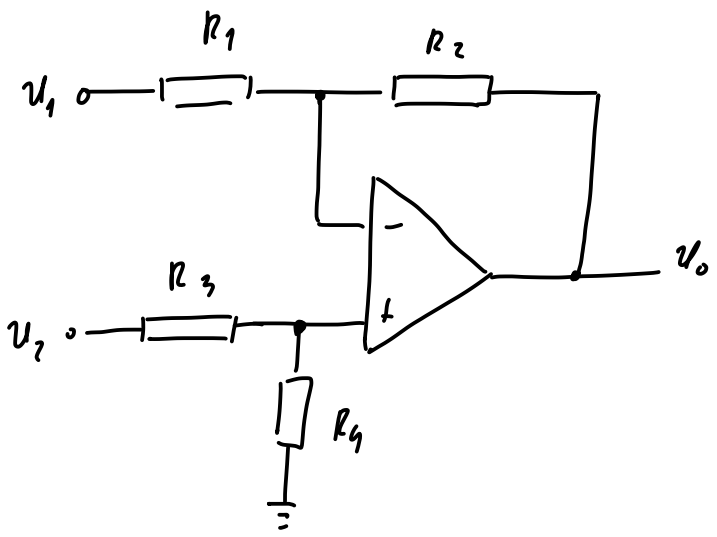
$$\boxed{A_v = \frac{v_o}{v_I} = 1 + \frac{R_2}{R_1}}$$

↳ >0, u fazi

neinv $\quad A_v = 1 + \frac{R_2}{R_1}$ → >1

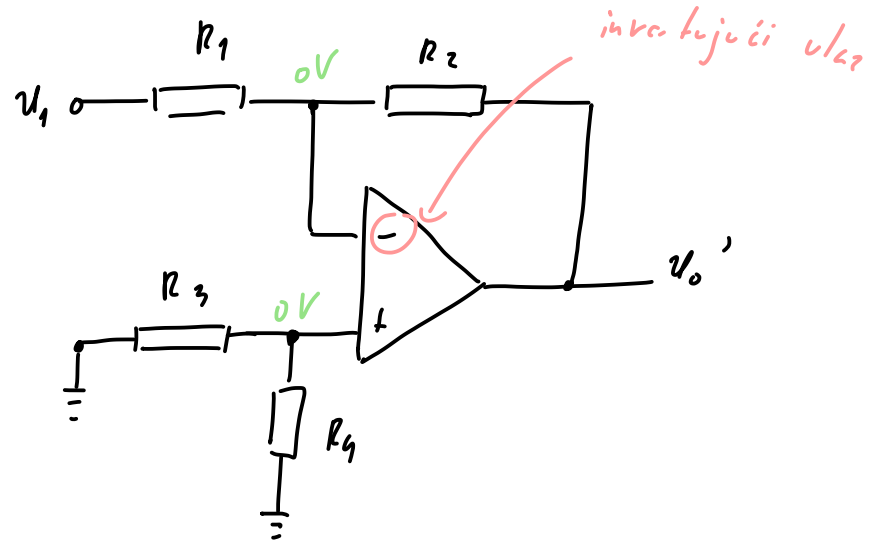
inv $\quad A_v = -\frac{R_2}{R_1}$

Diferencijalni pojačavač

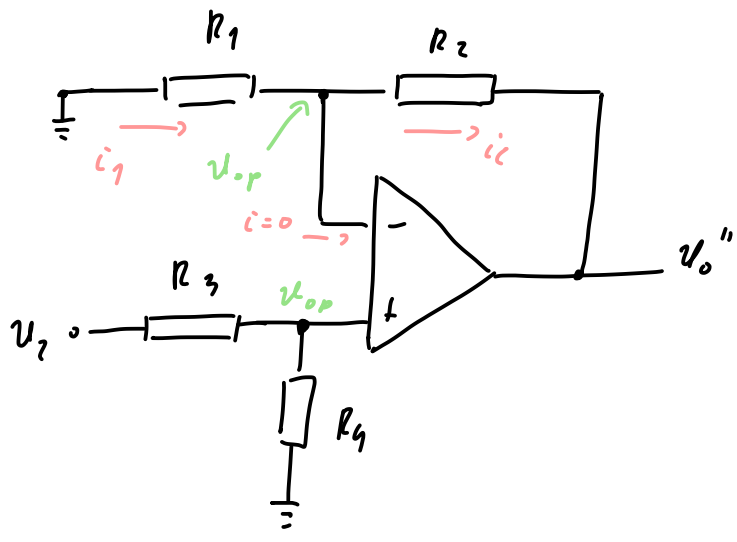


Koristimo princip superpozicije:

1. Djeluje v_1, v_2 se mijenja sa masom (unutrašnjom otpornošću)



2. Djeluje v_2, v_1 se mijenja masom



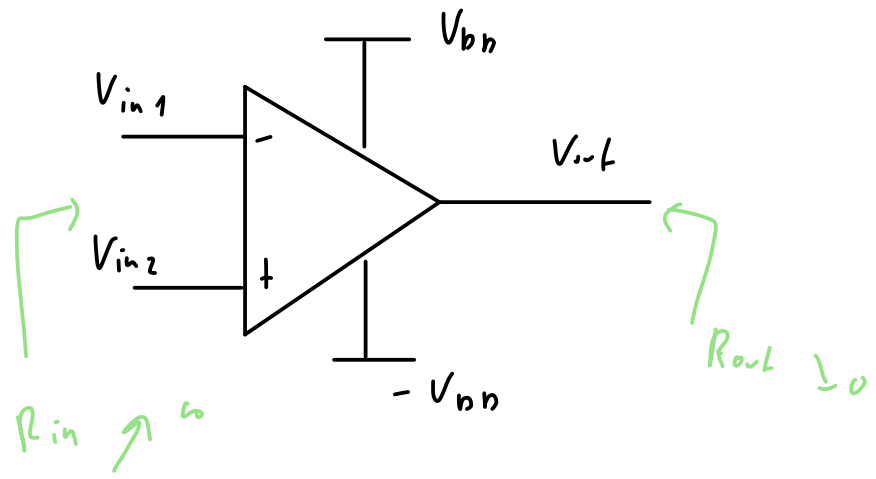
- invertirajući pojačavač

$$A_v' = -\frac{R_2}{R_1} \rightarrow v_o' = -\frac{R_2}{R_1} \cdot v_1$$

pojačanje a ulazni napon

Vježbe 29.11.2024.

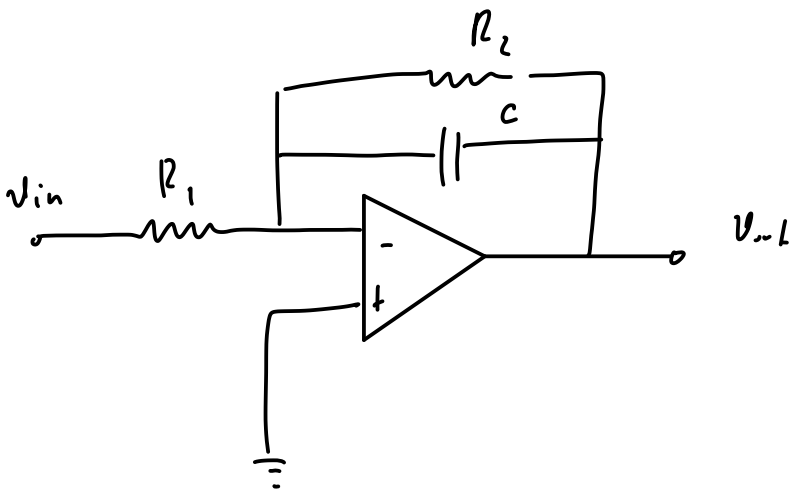
Operacioni pojačivači



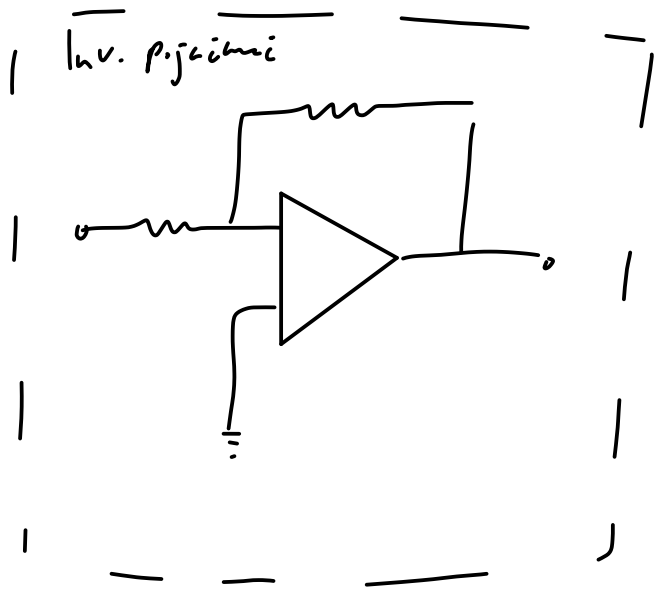
$$v_{out} = A\,\underbrace{(v_{out} - v_{in})}_{v_{in}}$$

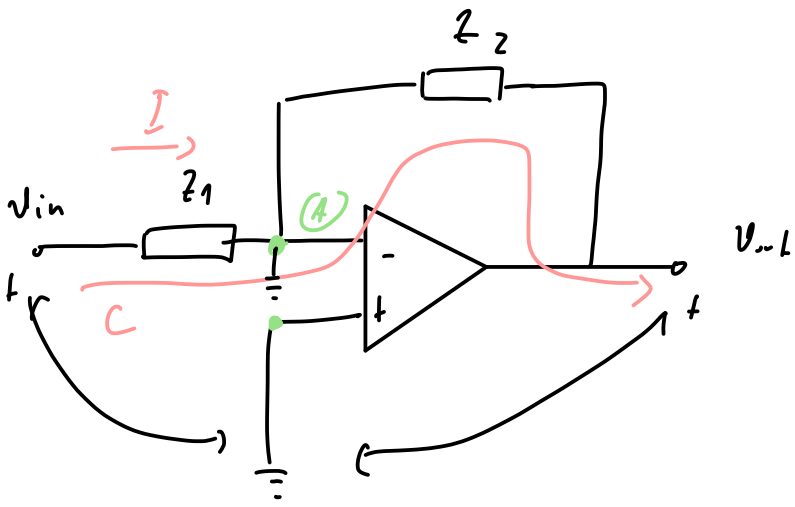
$$A = \frac{v_{out}}{v_{in}}$$

1. Odrediti pojačanje u funkciji $A(j\omega)$



$$A(j\omega) = \frac{v_{out}(j\omega)}{v_{in}(j\omega)}$$





A: virtuelna masa

$$Z_1 = R_1$$

$$Z_2 = \frac{\frac{R_2}{j\omega C}}{R_2 + \frac{1}{j\omega C}} = \frac{R_2}{1 + j\omega R_2 C}$$

$$v_{out} = f(v_{in})$$

C: $v_{in} - I(Z_1 + Z_2) - v_{out} = 0$

$$I = \frac{v_{in}}{Z_1}$$

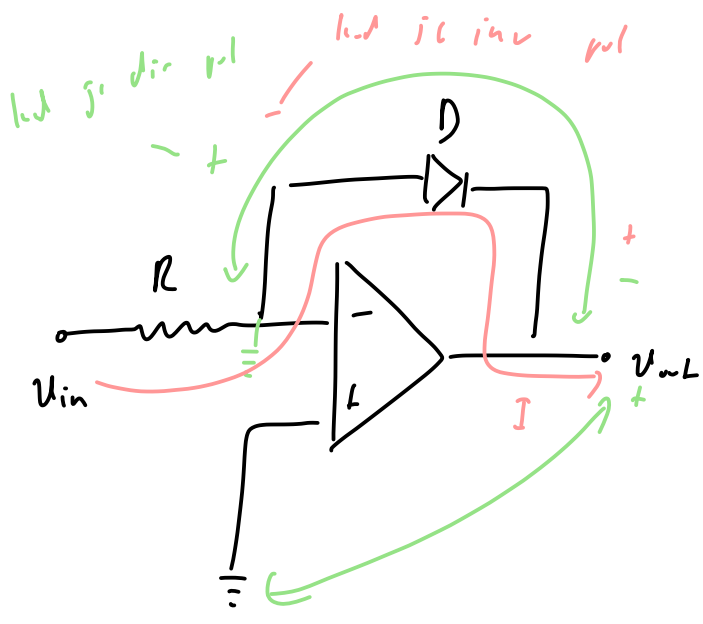
$$v_{in} - \frac{v_{in}}{Z_1}(Z_1 + Z_2) = v_{out}$$

$$v_{out} = v_{in}\left(\cancel{1} - \cancel{1} - \frac{Z_2}{Z_1}\right)$$

$$v_{out} = \underbrace{-\frac{Z_2}{Z_1}}_{A} v_{in}$$

$$A(j\omega) = -\frac{Z_2}{Z_1}$$

2. Odrediti prenosnu karakteristiku kola sa slike.



Predpost $I_D = I_S\left(e^{\frac{V_D}{V_{Tm}}} - 1\right)$

(1) $I = I_S e^{\frac{V_D}{V_t}}$, $V_t = 25\,mV$

(2) $I = \frac{v_{in}}{R}$

(1) = (2) : $\frac{v_{in}}{R} = I_S e^{\frac{V_D}{V_t}}$

$$\frac{v_{in}}{R} = I_S e^{-\frac{v_{out}}{V_t}} \quad / : I_S$$

$$\frac{v_{in}}{R I_S} = e^{-\frac{v_{out}}{V_t}} \quad / \ln$$

$$-\frac{v_{out}}{V_t} = \ln\frac{v_{in}}{R I_S}$$

$$\boxed{v_{out} = -V_t \ln\frac{v_{in}}{R I_S}}$$

prenosna karakteristika

invertujuće

kola za logaritmovanje signala

$v_{out} = -V_D$

3. Odrediti prenosnu karakteristiku ako se ulazni signal v_{in} mijenja u rasponu $(-5 \div 5)\,V$

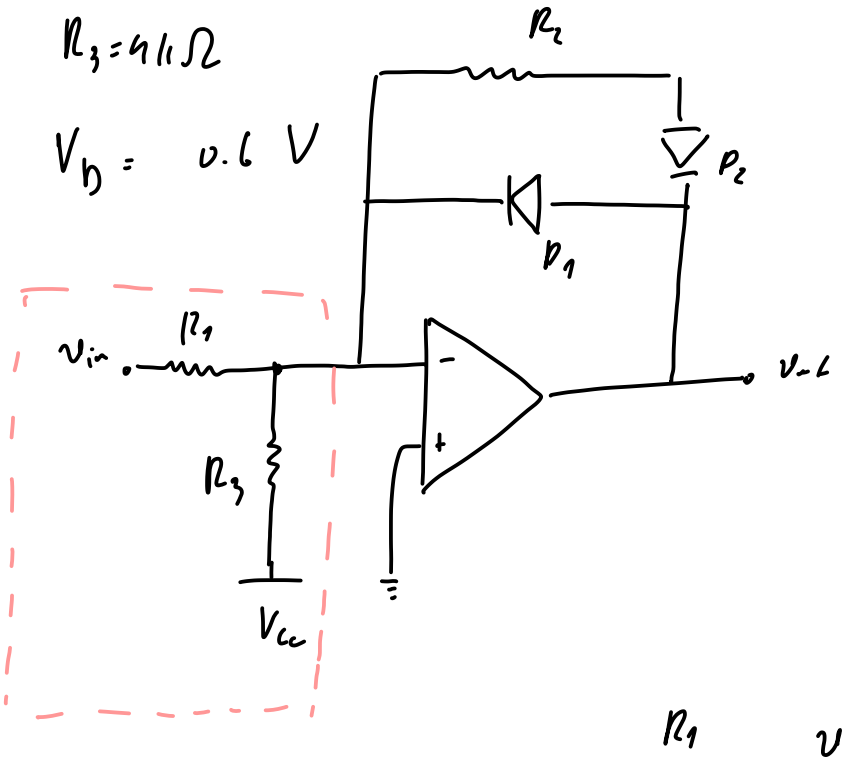
$V_{CC} = 15\,V$

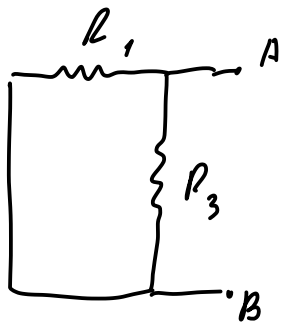
$R_1 = 16\,k\Omega$

$R_2 = 26\,k\Omega$

$R_3 = 4k\Omega$

$V_D = 0.6\ V$

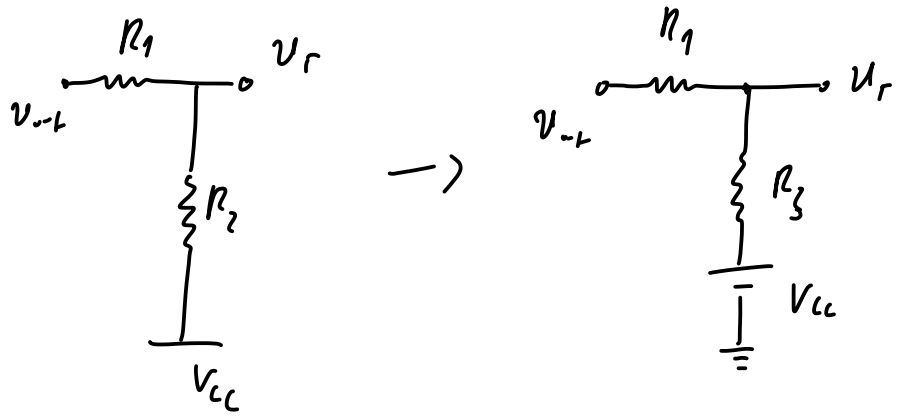


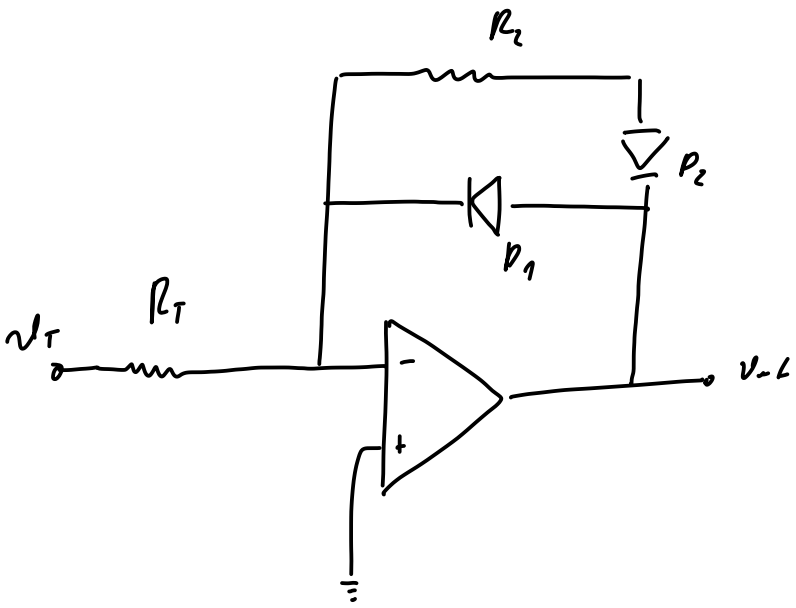


$$R_T = \frac{R_1 R_3}{R_1 + R_3}$$

$$v_T = V_{cc}\frac{R_1}{R_1+R_3} + v_{out}\frac{R_3}{R_1+R_3}$$

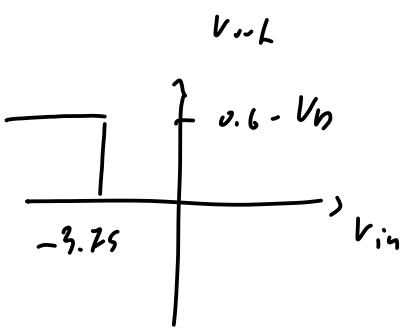
$v_T,\ R_T$

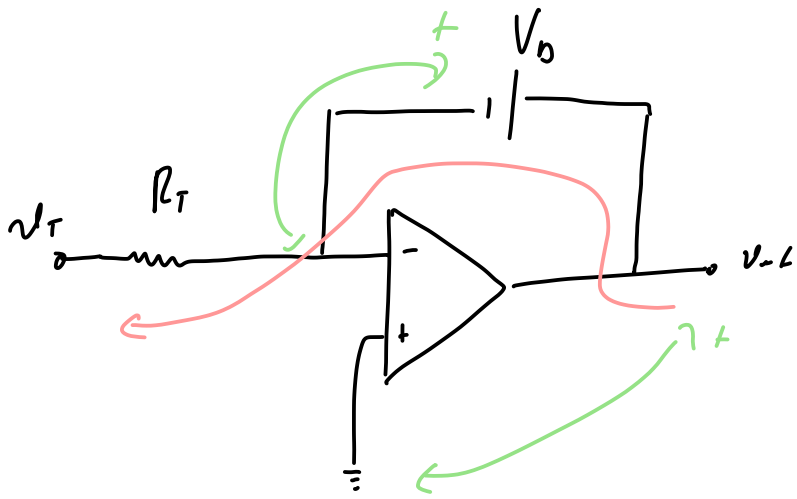




$v_{out} = f(v_T)$

1° D_1 ON , D_2 OFF





$V_{out} = V_D$

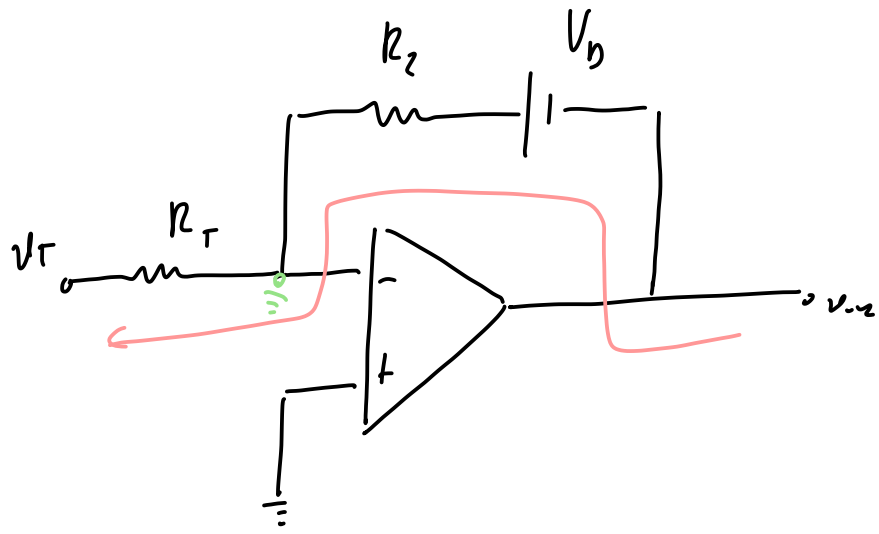
$v_T \approx 0.1\, v_{in} + 3$

$v_T < 0 \longrightarrow$ da bi provodio D_1

$0.1 \cdot v_{in} + 3 < 0$

$v_{in} < -3.75V$

2. D_2 ON, D_1 OFF



$$v_{out} = -V_b - R_2 I$$

$$I = \frac{v_T}{R_T}$$

$$v_{out} = \underbrace{-V_b}_{\text{pomjeraj}} \underbrace{- \frac{R_2}{R_T}}_{\text{nagib}} v_T$$

D_1 hi

D_2 provodi

$$\boxed{v_T > 0} \Rightarrow 0.5\, v_{in} + 3 > 0, \quad v_{in} > -8.25\,V$$

Tražim granicu

3. $v_{out} = -15\,V$

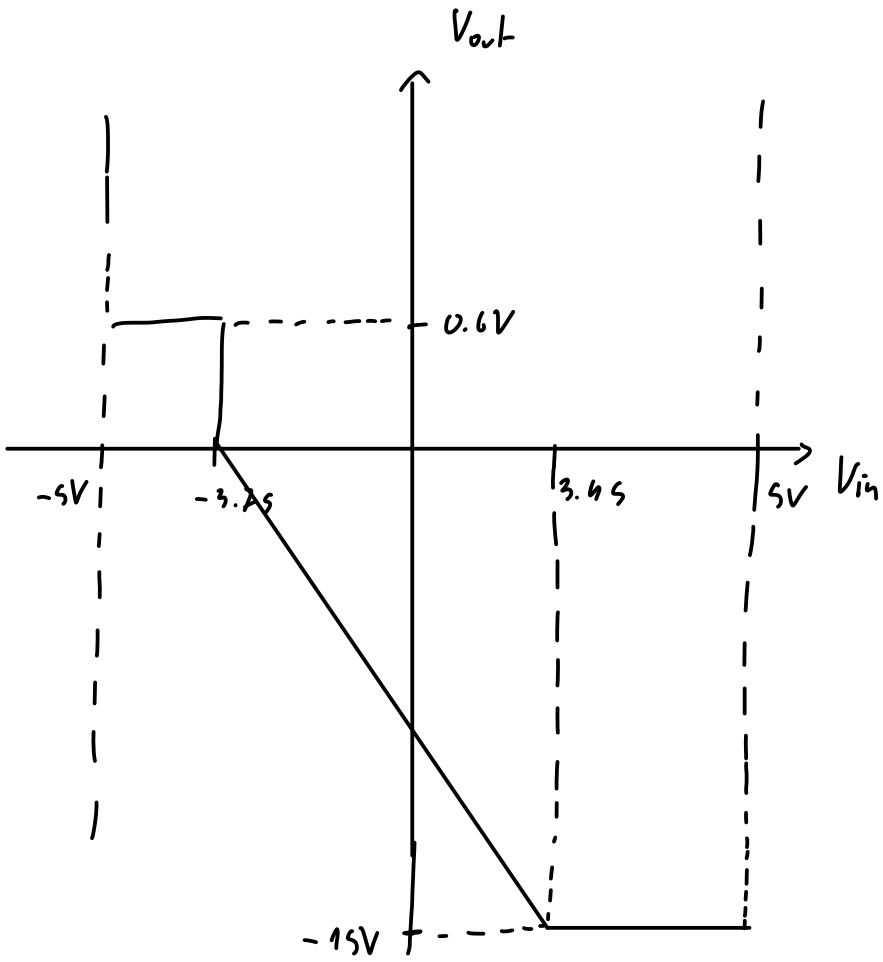
$v_{out} = -2\, v_{IN} - 8.1$

$v_{IN} = 3.95\,V$

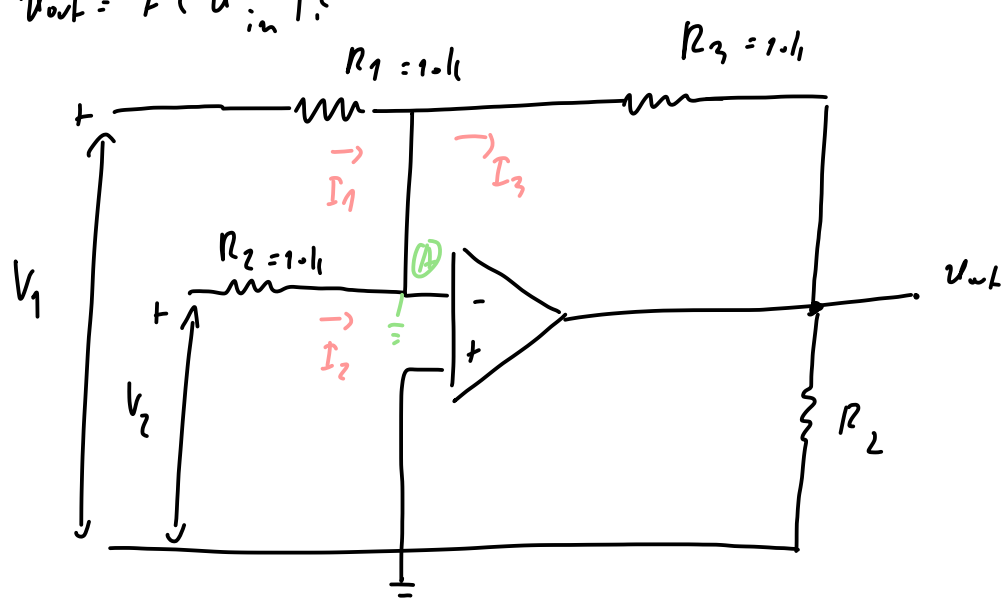
Karakteristika:

od -5 do 5 V

jer si ulazni napon mijenja u tom rasponu



4. $v_{out} = f(v_{in})$?



A: $I_3 = I_1 + I_2$

$$I_1 = \frac{V_1 - V_A}{R_1}$$

$$I_2 = \frac{V_2 - V_A}{R_2}$$

$$I_3 = \frac{V_A - V_{out}}{R_3}$$

$$\frac{V_1 - V_A}{R_1} + \frac{V_2 - V_A}{R_2} = \frac{V_A - V_o}{R_3} \quad / \cdot 1\,k\Omega$$

$R_1 = 1\,k\Omega$, $R_2 = 1\,k\Omega$, $R_3 = 1\,k\Omega$

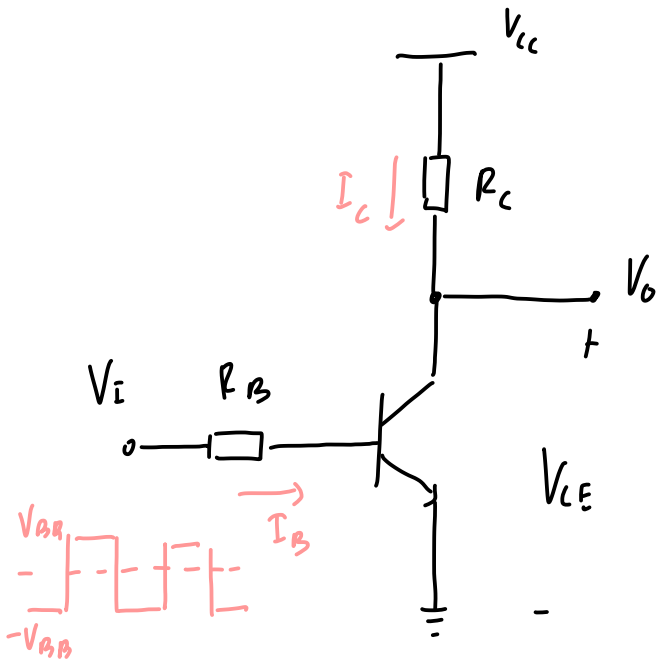
$$V_1 - \cancel{V_A} + V_2 - \cancel{V_A} = \cancel{V_A} - V_{out}$$

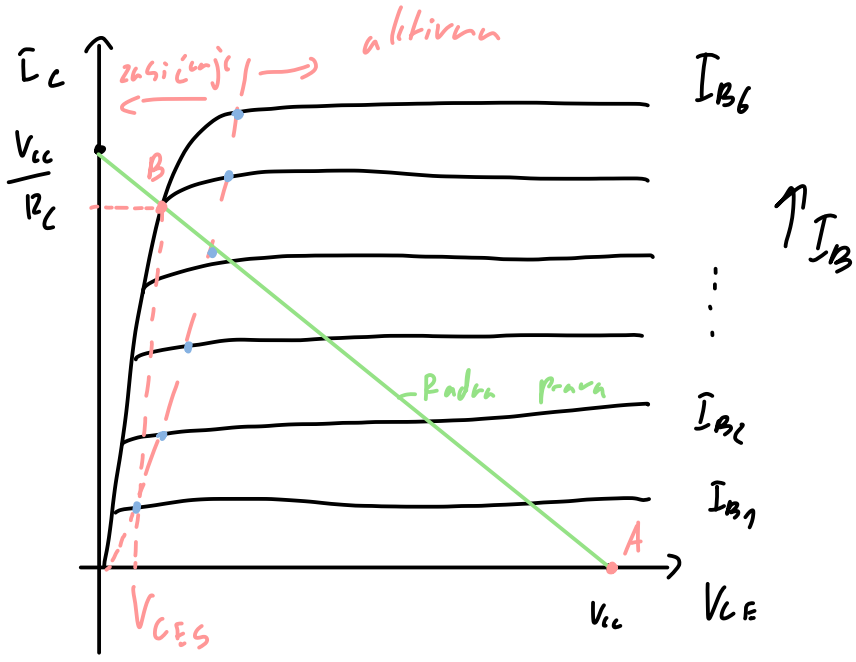
$$\boxed{V_{out} = -(V_1 + V_2)}$$

invertujući sabirač

Predavanje 4.12. 2024.

Prekidačke karakteristike BJT-a





$$\left[V_O = V_{CE} = V_{CC} - R_C I_C \right]$$

Radna prava

$$V_{CE} = 0 \Rightarrow I_C = \frac{V_{CC}}{R_C}$$

$$I_C = 0 \Rightarrow V_{CE} = V_{CC}$$

BJT prekidač:
- zakočenje A
- zasićenje B

$V_I = -V_{BB}$ BE spoj nije otvoren (ne vodi) } tranzistor isključen $\Rightarrow$ $I_C = 0$, $V_O = V_{CC}$ (A)

$V_I = V_{BB}$ BE spoj dir pol (tr. vodi) u zasićenju } tranzistor uključen $\Rightarrow$ $V_O = V_{CES}$ (B)

$V_{CES} = (0.1 \div 0.3)\,V$ – napon saturacije

$$I_B = \frac{V_I - V_{BE}}{R_B} = \frac{V_{BB} - V_{BE}}{R_B}$$

na granici

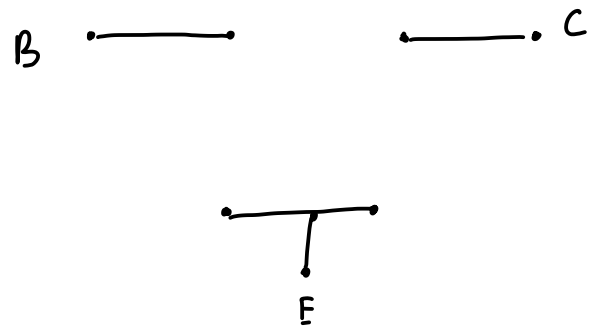
$$\boxed{I_{CS} = \beta I_{BS}}$$

$$\boxed{I_B > I_{BS}}$$ tr u zasićenju

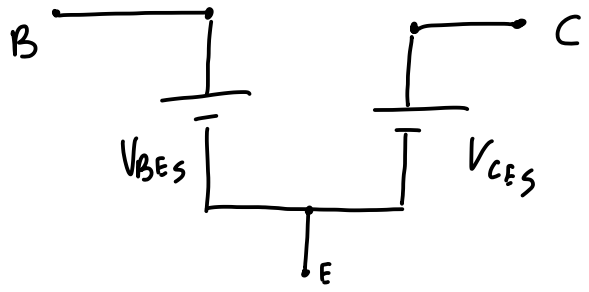
$I_B < I_{BS}$ – tr. u aktivnoj oblasti

Modeli BJT-a kao prekidača

tranzistor isključen:



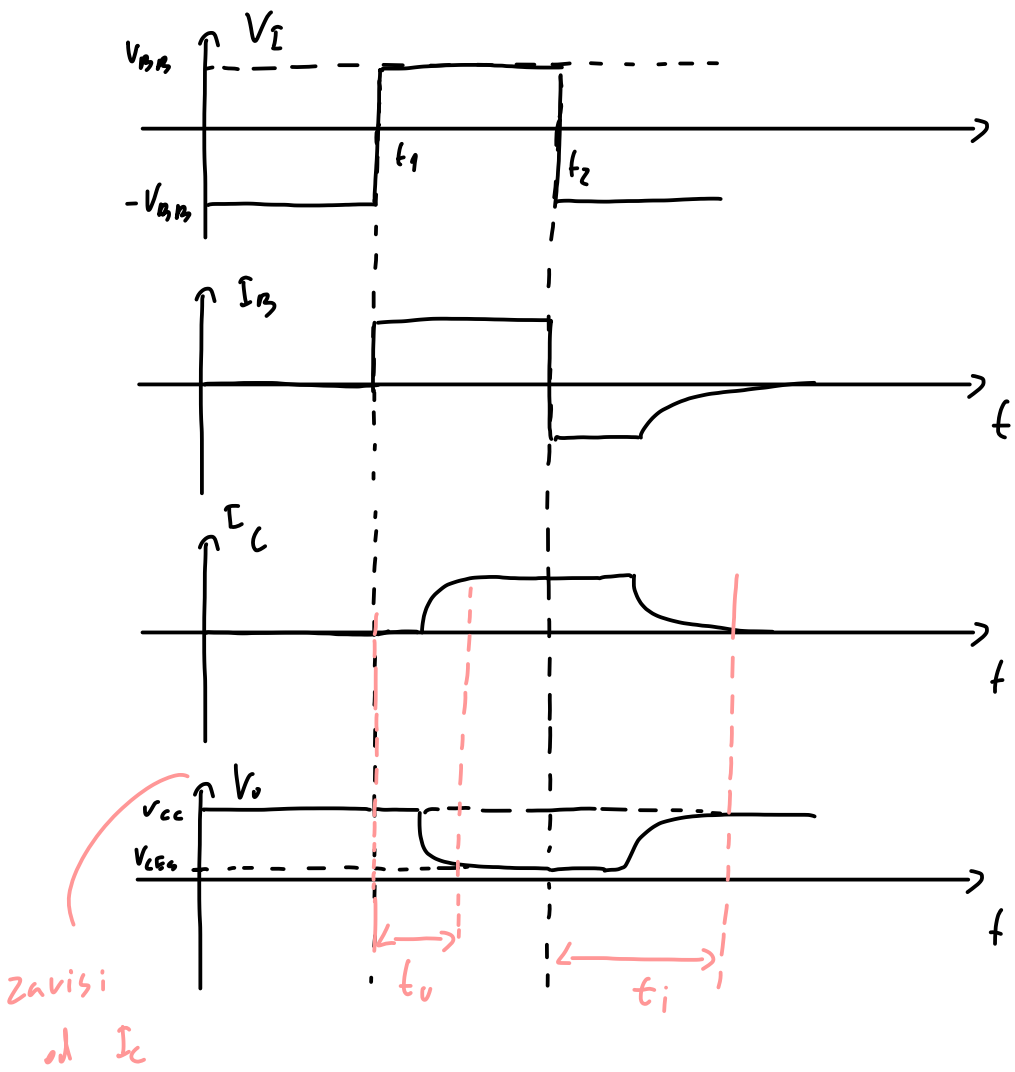
tranzistor uključen: (u zasićenju)



$V_{BES} = (0.6 \div 0.7)\,V$

$V_{CES} = (0.1 \div 0.3)\,V$

Prelazni režim BJT-a kao prekidača



t_u – vrijeme uključivanja tranzistora

t_i – vrijeme isključivanja tranzistora

Minimalna perioda ulaznog signala V_I

$$\boxed{T_{I\,min} = t_u + t_i}\,, \quad T_I \geq T_{I\,min}$$

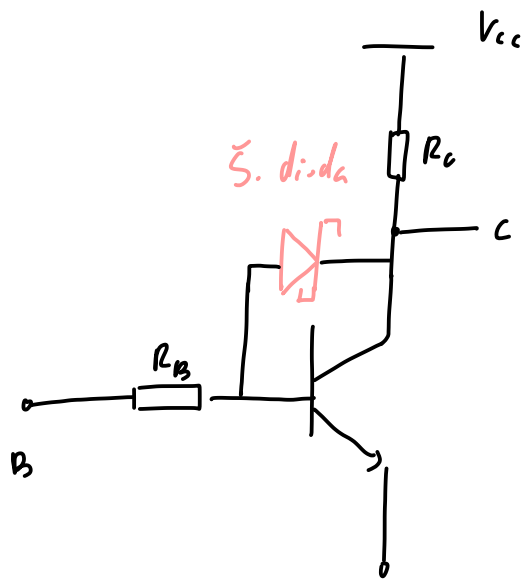
$$\boxed{f_{I\,max} = \frac{1}{T_{I\,min}}}$$

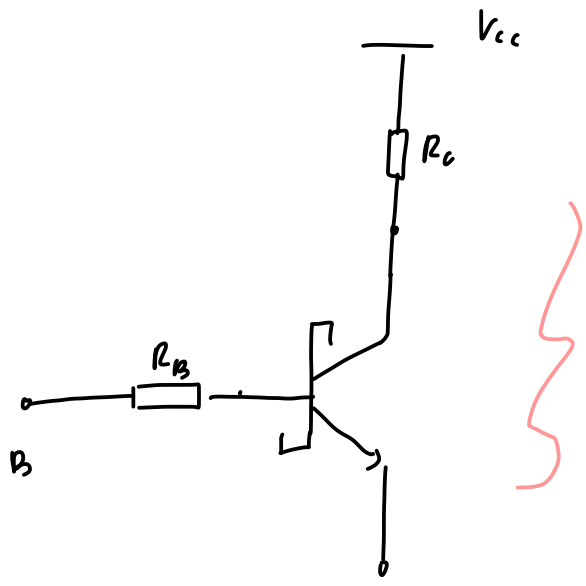
$V_o = V_{CC} - R_C I_C$

Kašnjenje zbog parazitnih kapacitivnosti na ulazu, izlazu i ograničenja nosilaca u bazi

Nezasićeni bipolarni prekidači

- Šotkijeva dioda - manji napon uključivanja - brže prosljeđivanje

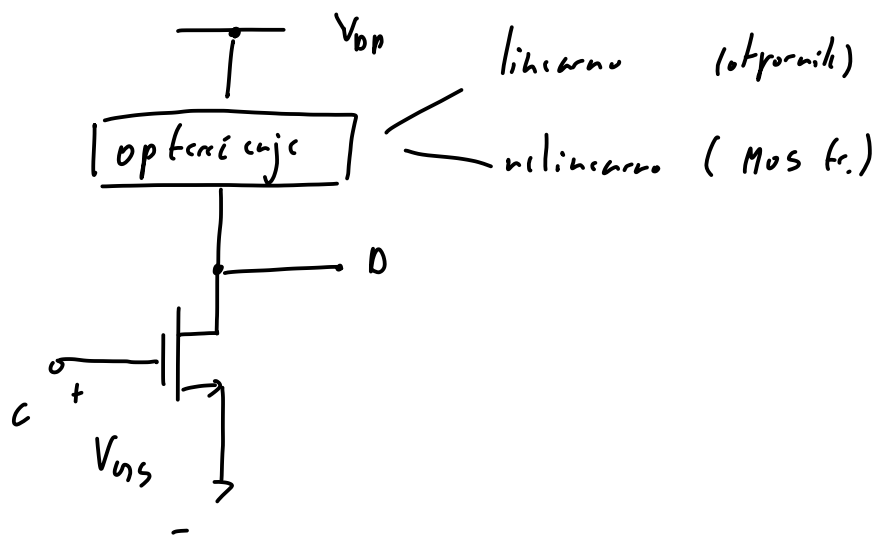




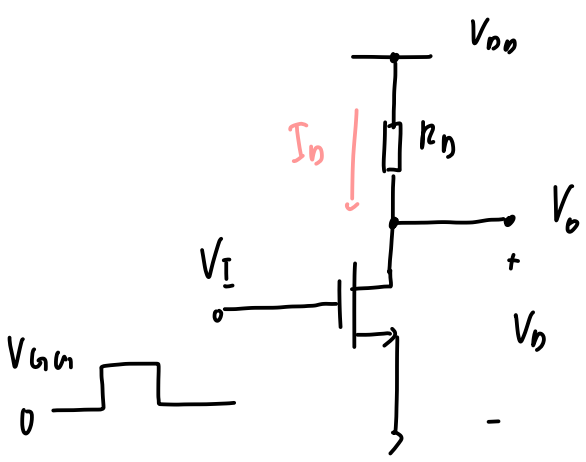
Prednost veća brzina

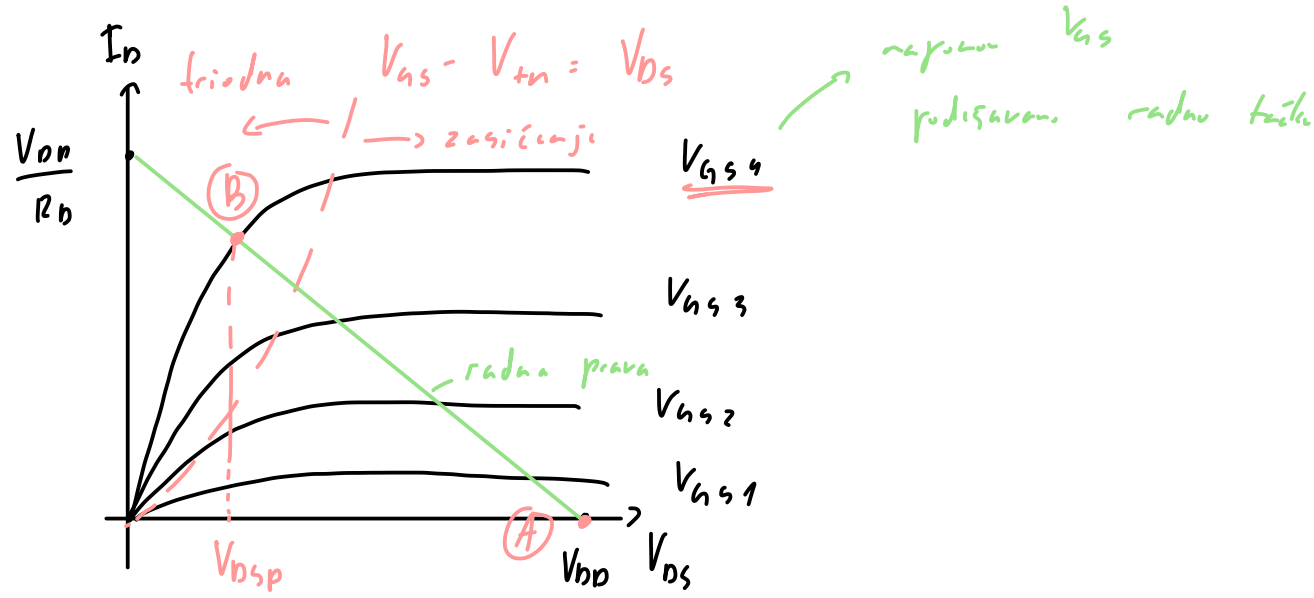
Mana - cijena

MOS tr. kao prekidač



sa lin opterećenjem:





MOS tr. kao prekidač — isključenje / triodna oblast

$$\boxed{V_o = V_{DS} = V_{DD} - R_D I_D}$$

Radna prava

$V_o = V_{DS} = 0 \Rightarrow I_D = \frac{V_{DD}}{R_D}$

$I_D = 0 \Rightarrow V_o = V_{DD}$

$V_I = 0 \Rightarrow$ tr. isključen (A)

tr. $V_{GS} = 0 < V_{tn}$

$I_D = 0$

$V_o = V_{DD}$

$V_I = V_{GG} \Rightarrow$ tr. uključen (B)

$V_{GS} > V_{tn}$

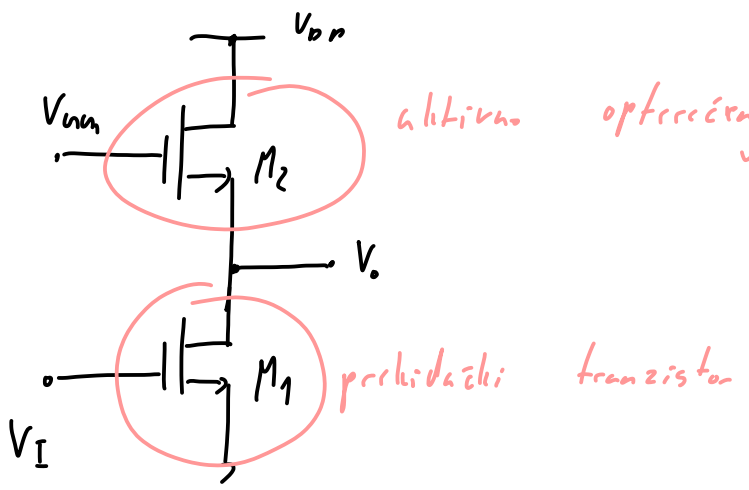
$V_{GS} - V_{tn} > V_{DS}$ (triodna)

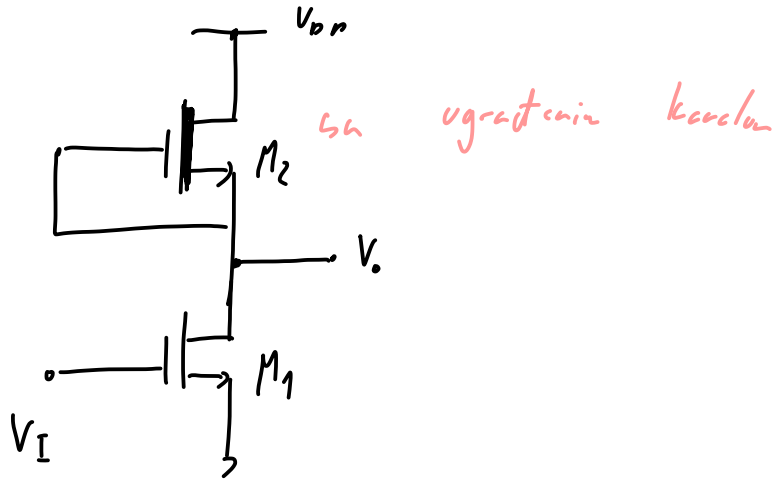
V_{GSM}

$V_o = V_{DSP}$

$$\boxed{I_D = k_n \left[2(V_{GS} - V_{tn}) V_{DS} - V_{DS}^2 \right]}$$

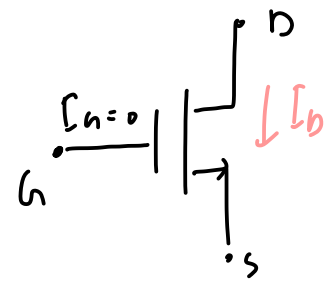
Sa aktivnim opterećenjem.

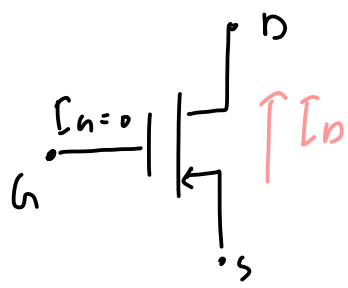


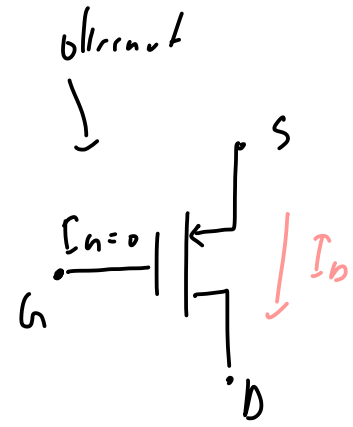


CMOS invertor (osnovno logičko kolo)

- NMOS tr. i PMOS tr.







NMOS: $V_{GS} > 0$

$V_{DS} > 0$

$V_{tn} > 0$

$I_D = k_n \left[2(V_{GS} - V_{tn}) V_{DS} - V_{DS}^2 \right]$ triodna

$I_D = k_n (V_{GS} - V_{tn})^2$ zasićenje

$k_n = \frac{\mu_n C_{ox}}{2} \cdot \frac{W}{L}$

PMOS: $V_{GS} < 0 \rightarrow V_{SG} > 0$

$V_{DS} < 0 \rightarrow V_{SD} > 0$

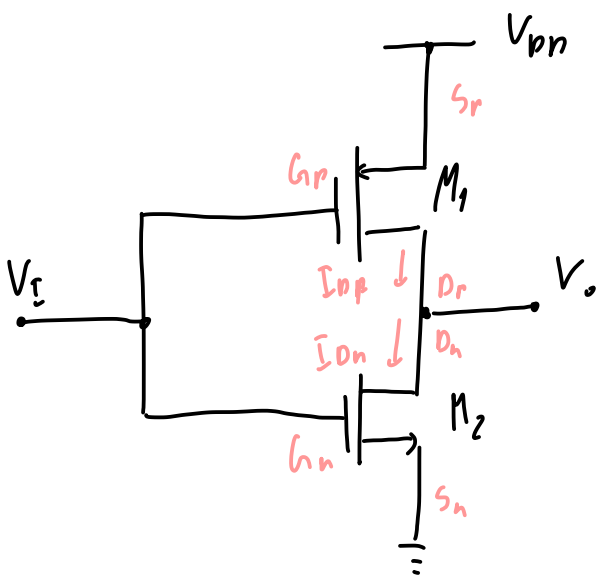
$V_{tp} < 0 \rightarrow |V_{tp}|$

$I_D = k_p \left[2(V_{SG} - |V_{tp}|) V_{SD} - V_{SD}^2 \right]$ triodna

$I_D = k_p (V_{SG} - |V_{tp}|)^2$ zasićenje

$k_p = \frac{\mu_p C_{ox}}{2} \cdot \frac{W}{L}$

pravi se sa 2÷3 puta većom širim

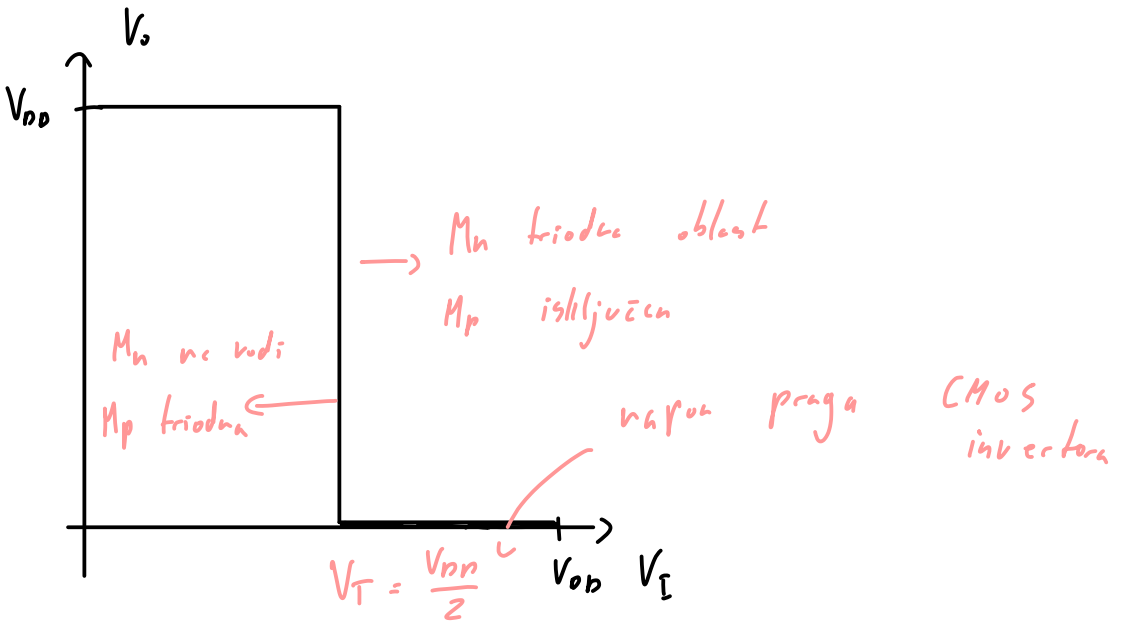


$\boxed{I_{Dn} = I_{Dp}}$

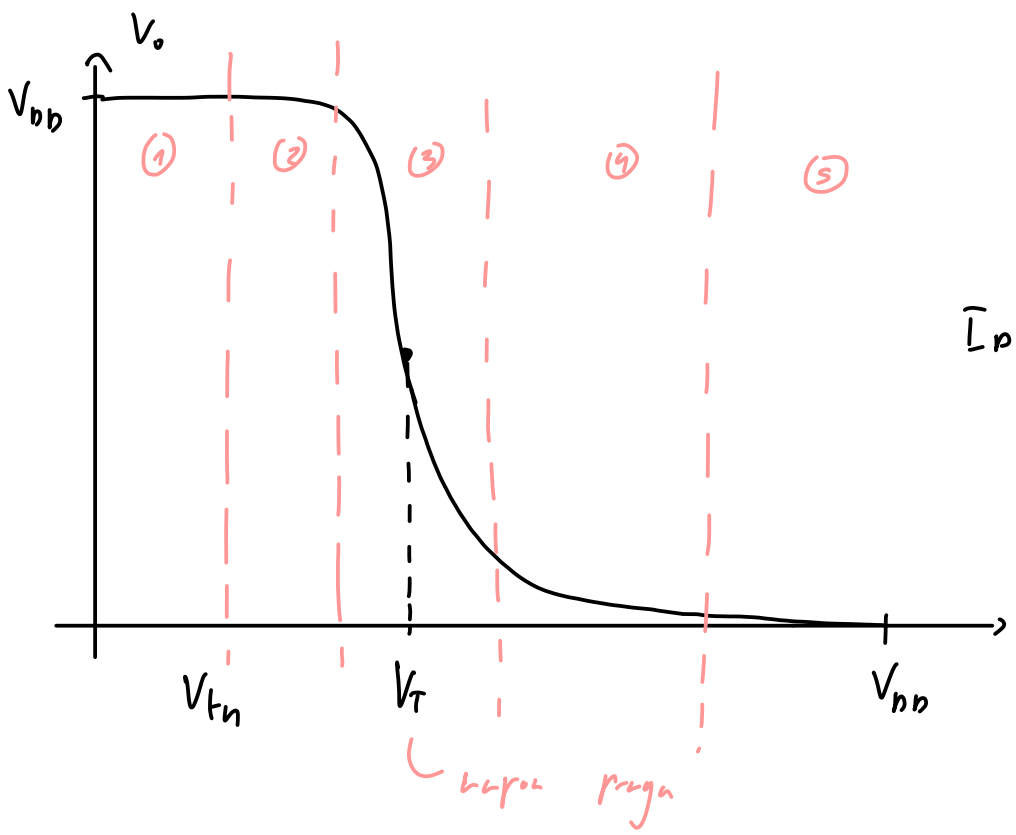
PMOS: $W_p = (2 \div 3) W_n$ → da bi bile jednake struje

Naponska prenosna karakteristika

idealna



. Realna



1 M_n je isključen

M_p je u triodnoj oblasti

$$I_{Dn} = I_{Dp} = 0$$

$$I_{Dp} = k_p \left[2(V_{DD} - |V_{tp}| \cdot (V_{DD} - V_o) - (V_{DD} - V_o)^2 \right] = 0$$

$$V_{DD} - V_o = 0 \quad \Rightarrow \quad V_o = V_{DD}$$

2 M_n u zasićenju

M_p u triodnoj

$$V_{tn} < V_I < \overbrace{V_o + V_{tp}}^{\text{uvodi } M_p \text{ u zasićenje}}$$ – nap. uslovi

$$I_{Dn} = I_{Dp}$$

$$k_n (V_{GS} - V_{tn})^2 = k_p \left[2(V_{DD} - V_I - |V_{tp}|)(V_{DD} - V_o) - (V_{DD} - V_o)^2 \right]$$

$$V_o = V_I - |V_{tp}| + \sqrt{(V_{DD} - V_I - |V_{tp}|)^2 - \frac{k_n}{k_p}(V_I - V_{tn})^2}$$

3 M_n u zasićenju $\qquad V_o + V_{tp} < V_I < V_o + V_{tn}$

M_p u zasićenju

$$I_{Dn} = I_{Dp}$$

$$k_n (V_I - V_{tn})^2 = k_p (V_{DD} - V_I - |V_{tp}|)^2$$

$$V_I = V_T = \frac{V_{DD} - |V_{tp}| + \sqrt{k_n/k_p} \cdot V_{tn}}{1 + \sqrt{k_n/k_p}} \qquad V_T \in (0.45 \div 0.55)\, V_{DD}$$

4 M_n triodna oblast $\qquad V_o + V_{tn} < V_I < V_{DD} + V_{tp}$

M_p u zasićenju

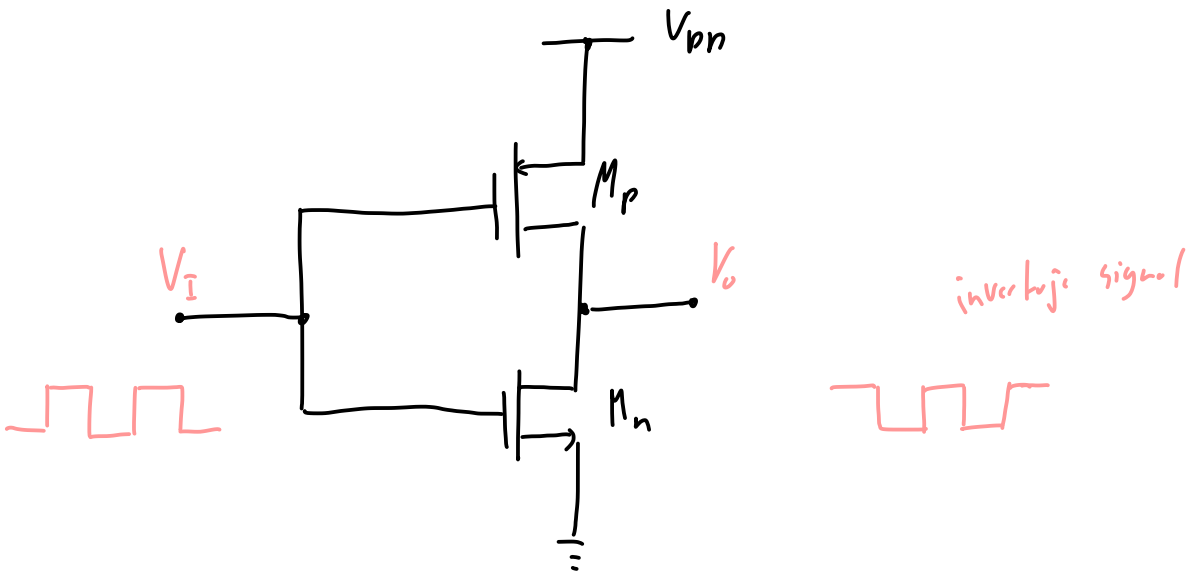
$$k_n \left[2(V_I - V_{tn}) V_o - V_o^2 \right] = k_p (V_{DD} - V_o - |V_{tp}|)^2$$

$$V_o = V_I - V_{tn} - \sqrt{(V_I - V_{tn})^2 - \frac{k_n}{k_p}(V_{DD} - V_o - |V_{tp}|)^2}$$

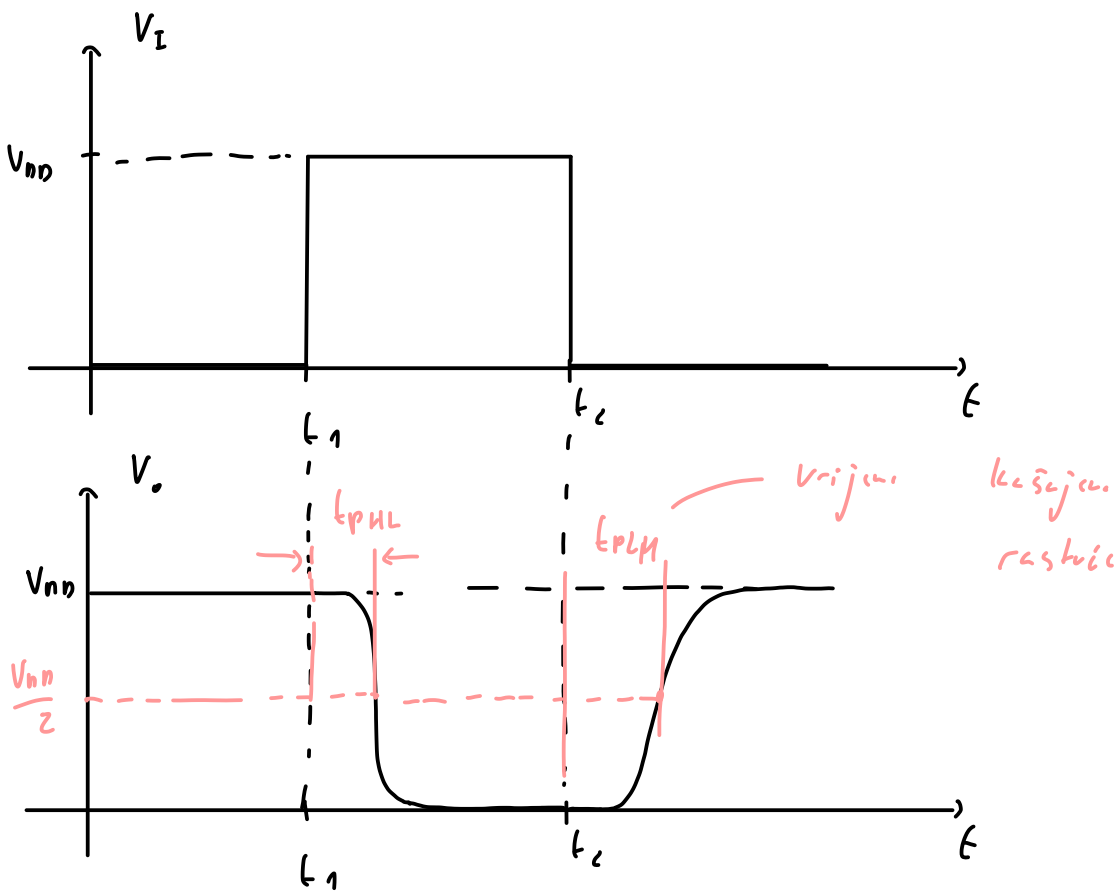
(5) M_n u triodnoj

M_p isključen

$I_{DN} = I_{Dp} = 0 \Rightarrow V_o = 0$



Prelazni režim CMOS tranzistora



t_{pHL} - vrijeme kašnjenja opadajuće ivice

t_{pLH} - -||- rastuće ivice

t_p vrijeme kašnjenja

$$t_p = \frac{t_{pHL} + t_{pLH}}{2}$$

$$T_{I\,min} = t_{pHL} + t_{pLH} = 2t_p$$

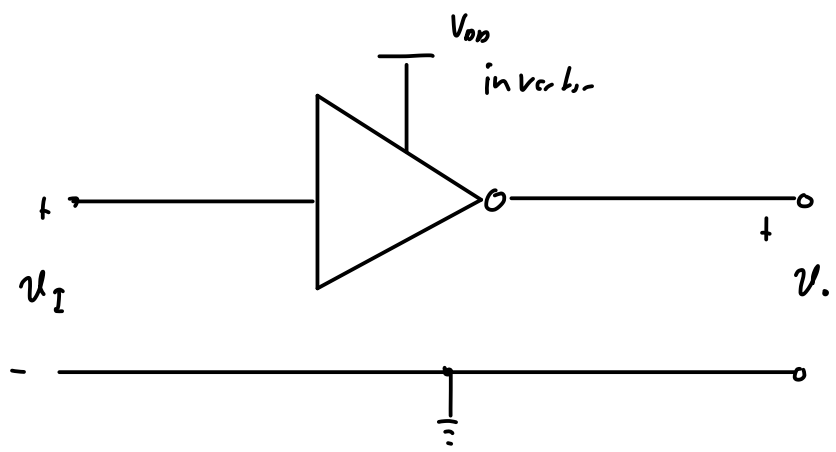
$$f_{I\,MAX} = \frac{1}{T_{I\,min}} = \frac{1}{2t_p}$$

Logička kola

Familije logičkih kola

- bipolarne
  - TTL
  - ECL
- CMOS
- Bi CMOS
- GaAs

Osnovne karakteristike log. kola



V_{OL} MAX izlazni napon "0"

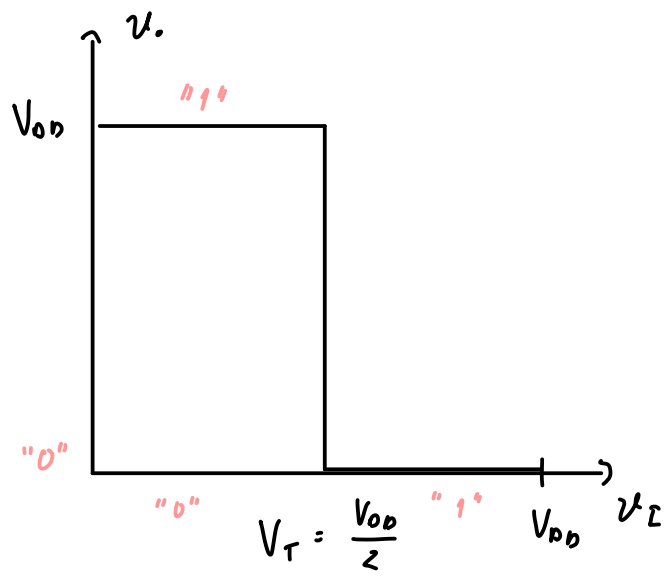
V_{OH} MIN izlazni napon "1"

V_{IL} MAX ulazni napon "0"

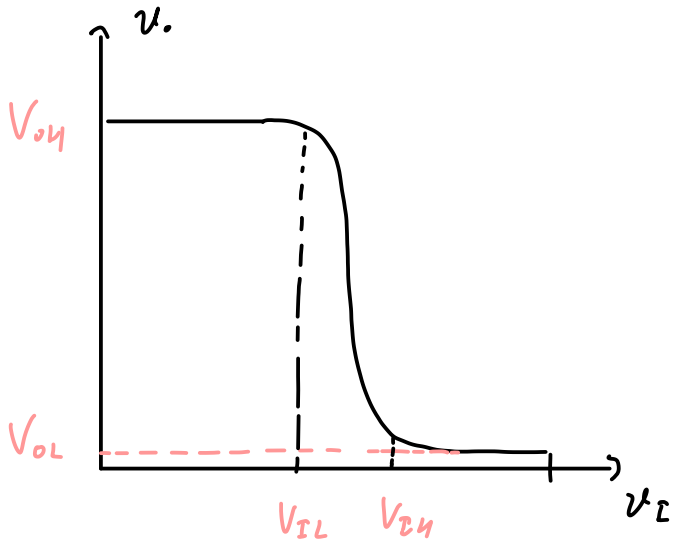
V_{IH} MIN ulazni napon "1"

I Naponska prenosna kr-ka

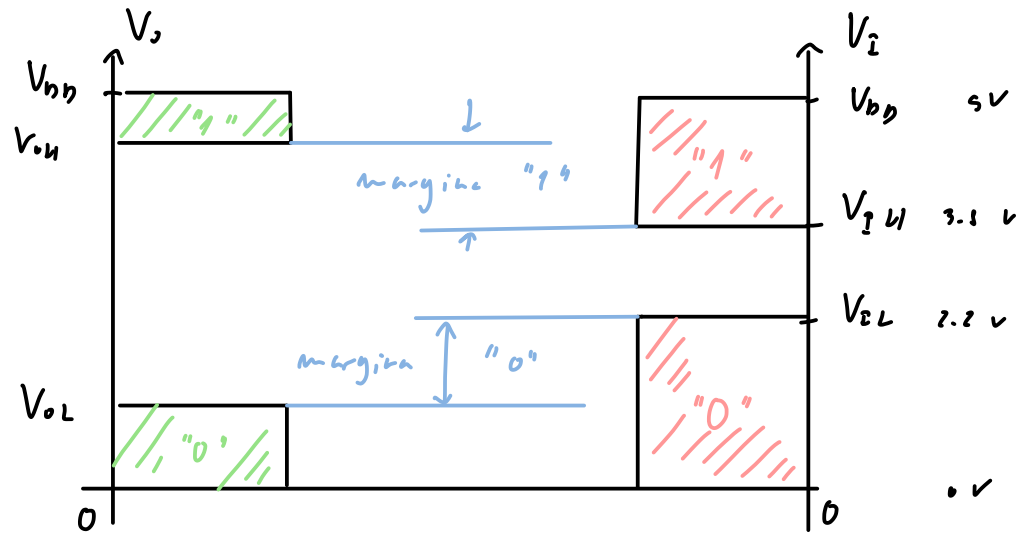
Idealna



Realna



II Margine logičkih kola



Margine šuma

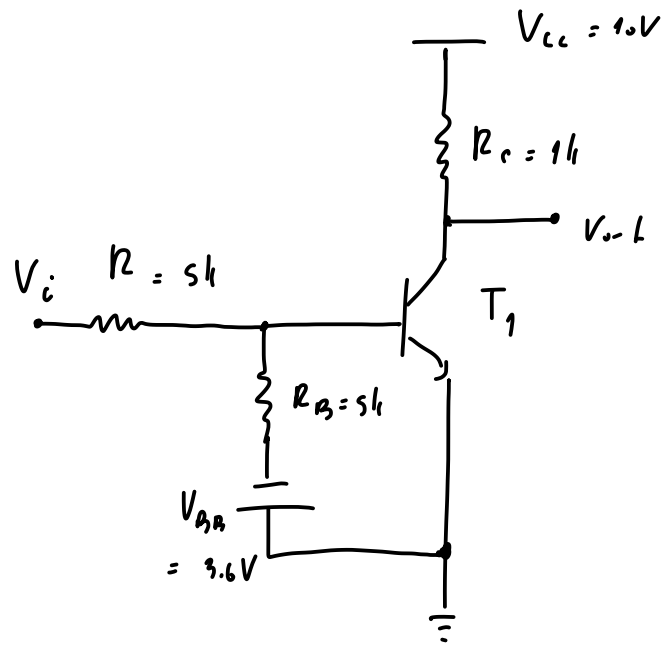
$$NM_0 = V_{IL} - V_{OL}$$
$$NM_1 = V_{OH} - V_{IH}$$

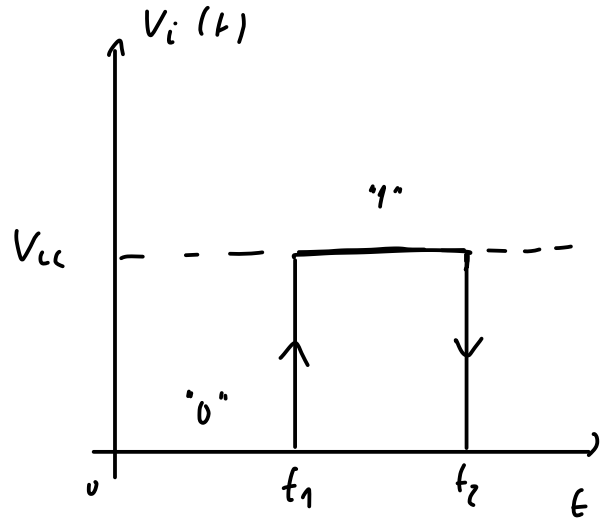
idealno što manje

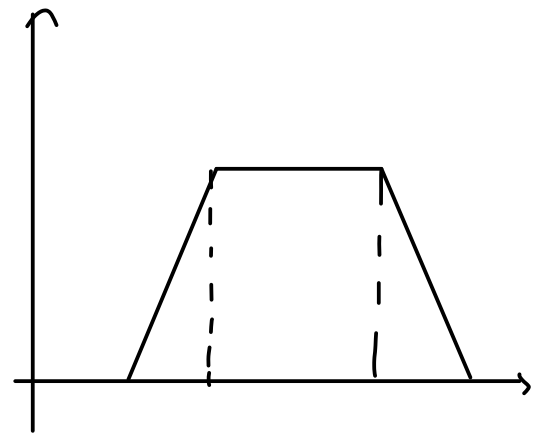
III Kašnjenje log

Vježba 6.12.2024.

1. Za prikazani krug se zadaje izvršiti statičku analizu. Poznato je $\beta_F = 200$, $\beta_{inv} = 20$, $V_{BE} = 0.6\,V$, $V_{BES} = 0.7\,V$, $V_{BET} = 0.5\,V$, $V_{CES} = 0.1\,V$







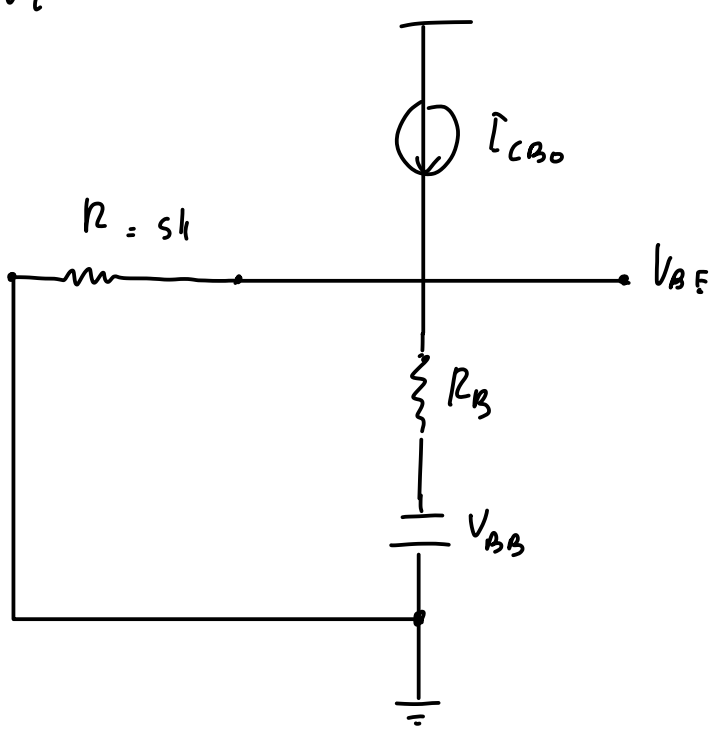
Stacionarna stanja

1° $0 < t < t_1$

2° $t_1 + t_{on} < t < t_2$

1° $0 < t < t_1$

$V_i = 0\,V$



Predpostavimo zakočenje

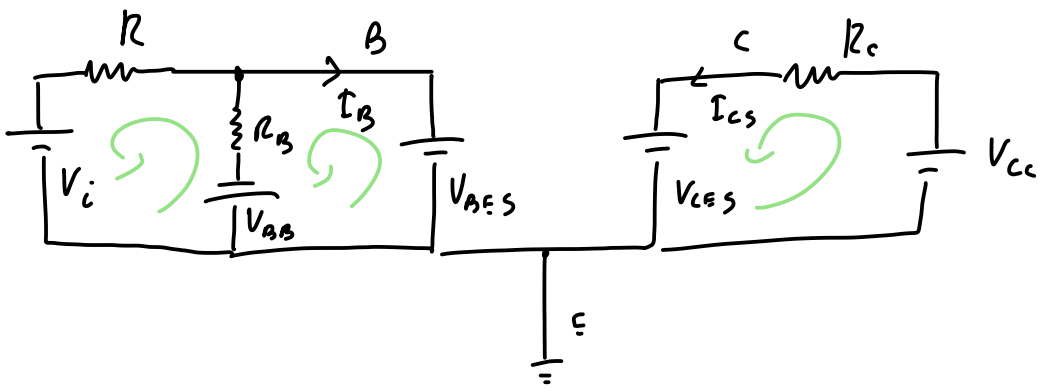
$$V_{BE} = -V_{BB}\frac{R}{R+R_B} + \cancel{(R \parallel R_B)\, I_{CBO}}^{\,0}$$

$$V_{BE} = -V_{BB}\frac{R}{R+R_B}$$

$$\boxed{V_{BE} = -1.5\,V}$$ ✓ Predpostavka točna

2° $t_1 + t_{on} < t < t_2$

Predpost zasičenje → moram zamijeniti modelom za velike signale



$F = \frac{I_B}{I_{BS}}$ – faktor zasičenja → kada je $I_B = I_{BS}$ $F = 1$, za $F \geq 1$ ↳ tranzistor je u zasičenju

$I_B > I_{BS}$

$I_{BS} = \frac{I_{CS}}{\beta_{min}}$ → β u zasičenju minimalan

$$I_B = \frac{V_{CC} - V_{BES}}{R} - \frac{V_{BB} + V_{BES}}{R_B} = 1\,mA$$

$$I_{CS} = \frac{V_{CC} - V_{CES}}{R_C} = 10\,mA$$

$$I_{BS} = \frac{I_{CS}}{\beta_{min}} = 0.5\,mA$$

$F = 2$

$F > 1$ → predpostavka ✓

2. Za log. i zl. f.

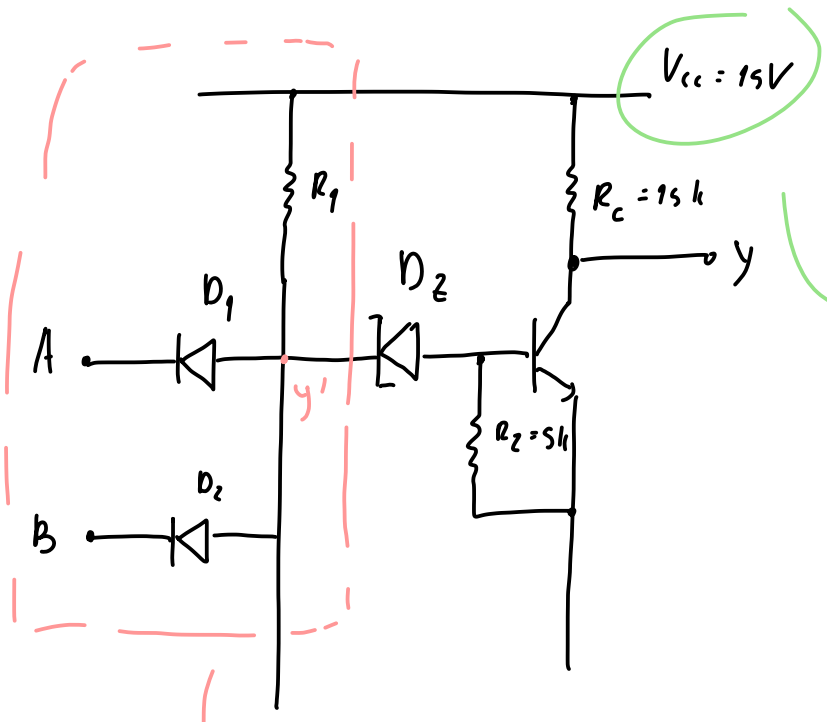
a) logičku funkciju koja f. obavlja

b) R_{1max} tak da je faktor zasičenja $F = 2$

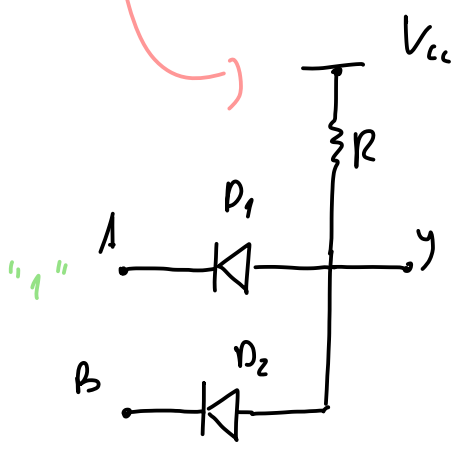
Podaci $V_{CC} = 15V$, $\beta = 100$, $\beta_{min} = 20$, $V_{CES} = 0.2V$, $V_{BET} = 0.6V$, $V_D = V_{D1} = 0.2$, $V_{BES} = 0.6V$

$V_Z = 6.9V$

Diodno tranzistorska logika



"1" → 15V

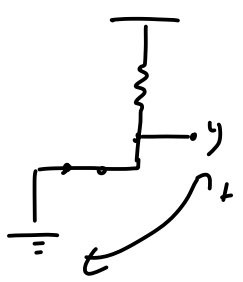


A	B	y'
0	0	0
0	1	0
1	0	0
1	1	1

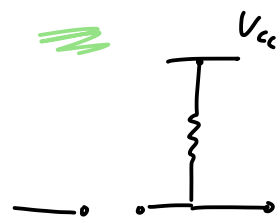
→ AND funkcija

→ D_2 će provesti jer ima pr. V_{cc}

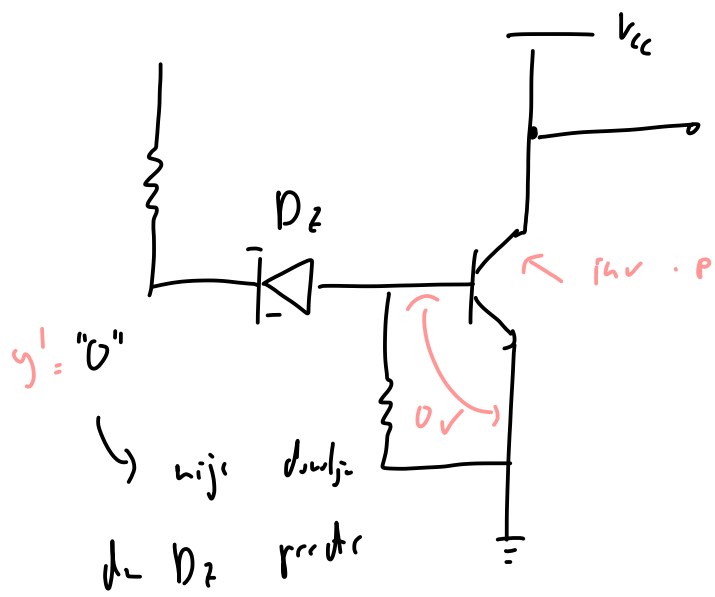
⇓



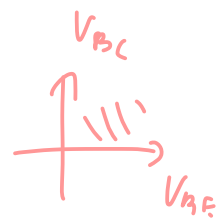
= "0"



1°



V_{BE} ; V_{BC}



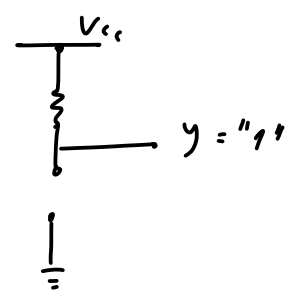
obrn dir pol.

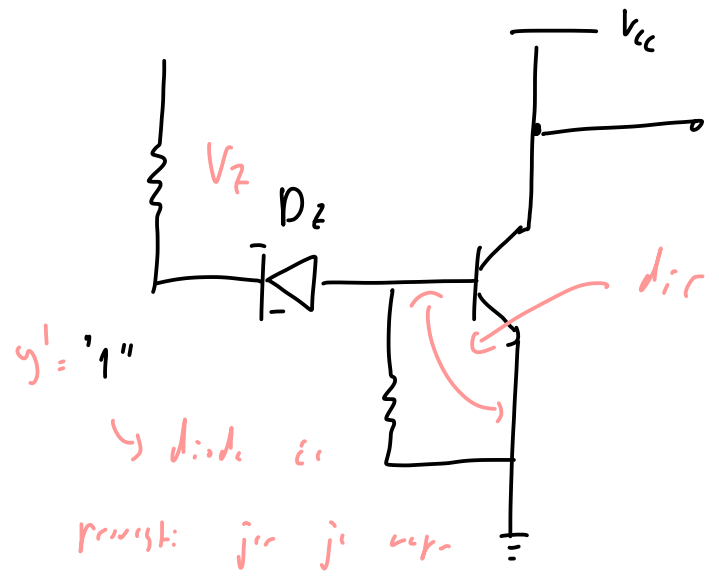
← inv. pol → tranzistor zaključen → otvoren spoj

y' = "0"

↳ nije dovoljno da D_Z provede

u red in inv. pol → otvoren vez.

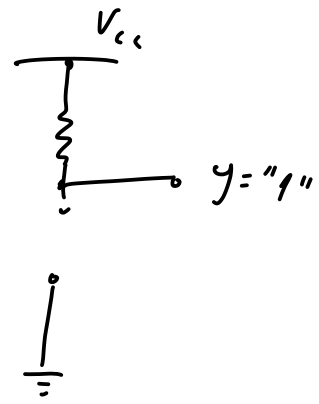




dir. pol → tranzistor u zasićenju

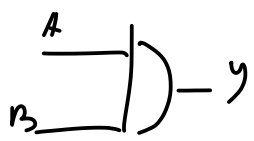
y' = "1"

↳ diode ći provesti jer je napon veći od V_Z → mijenjam, diodu ću zamijeniti naponom

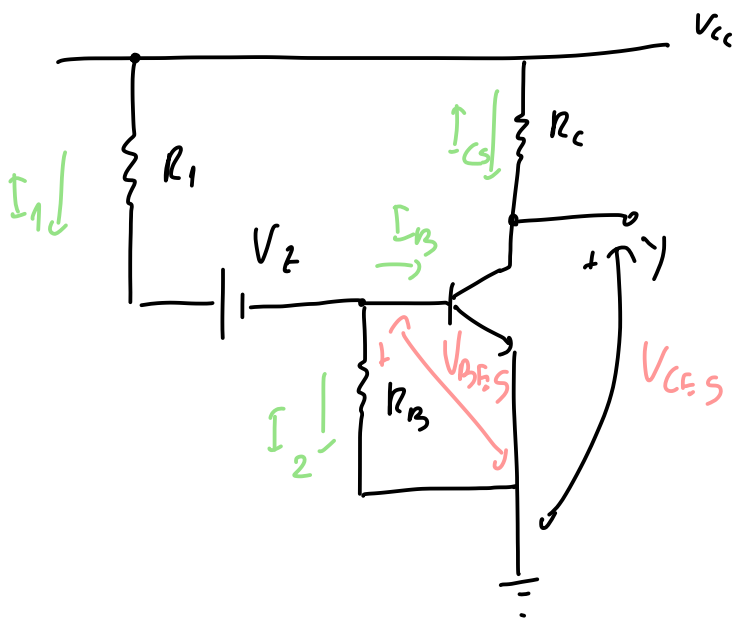


A	B	y
0	0	1
0	1	1
1	0	1
1	1	0

nand



b) tr u zasićenju → mora biti A i B 1 1



$$I_B = I_1 - I_2$$

zasićenje

$$I_B = \frac{V_{cc} - V_Z - V_{BES}}{R_1} - \frac{V_{BES}}{R_2}$$

$$I_{Cs} = \frac{V_{cc} - V_{CES}}{R_c}$$

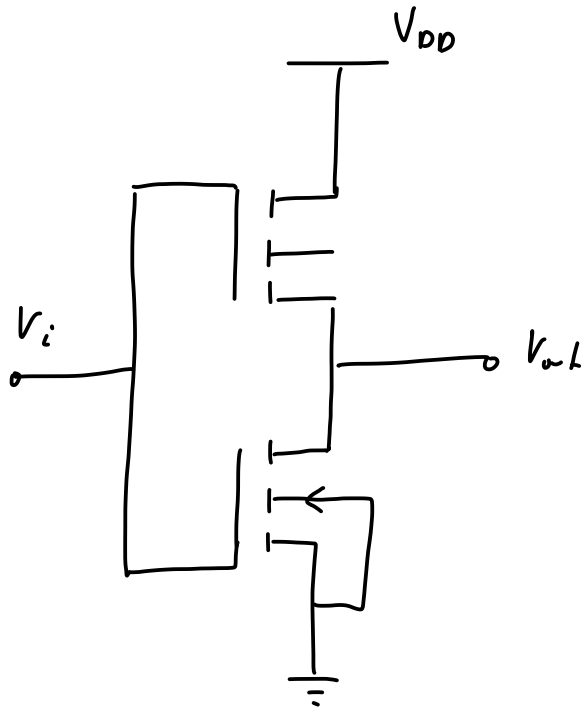
$$I_{Bs} = \frac{I_{Cs}}{\beta_{min}} \qquad F = 2 \longrightarrow I_B = 2\, I_{Bs}$$

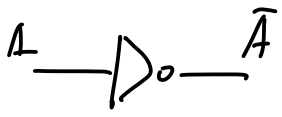
$$I_{Bs} = \frac{V_{cc} - V_{CES}}{\beta_{min} R_c}$$

$$\frac{V_{cc} - V_Z - V_{BES}}{R_1} - \frac{V_{BES}}{R_2} = 2 \cdot \frac{V_{cc} - V_{CES}}{\beta_{min} R_c}$$

$$R_1 = R_{max} = 2\,8\,k\Omega$$

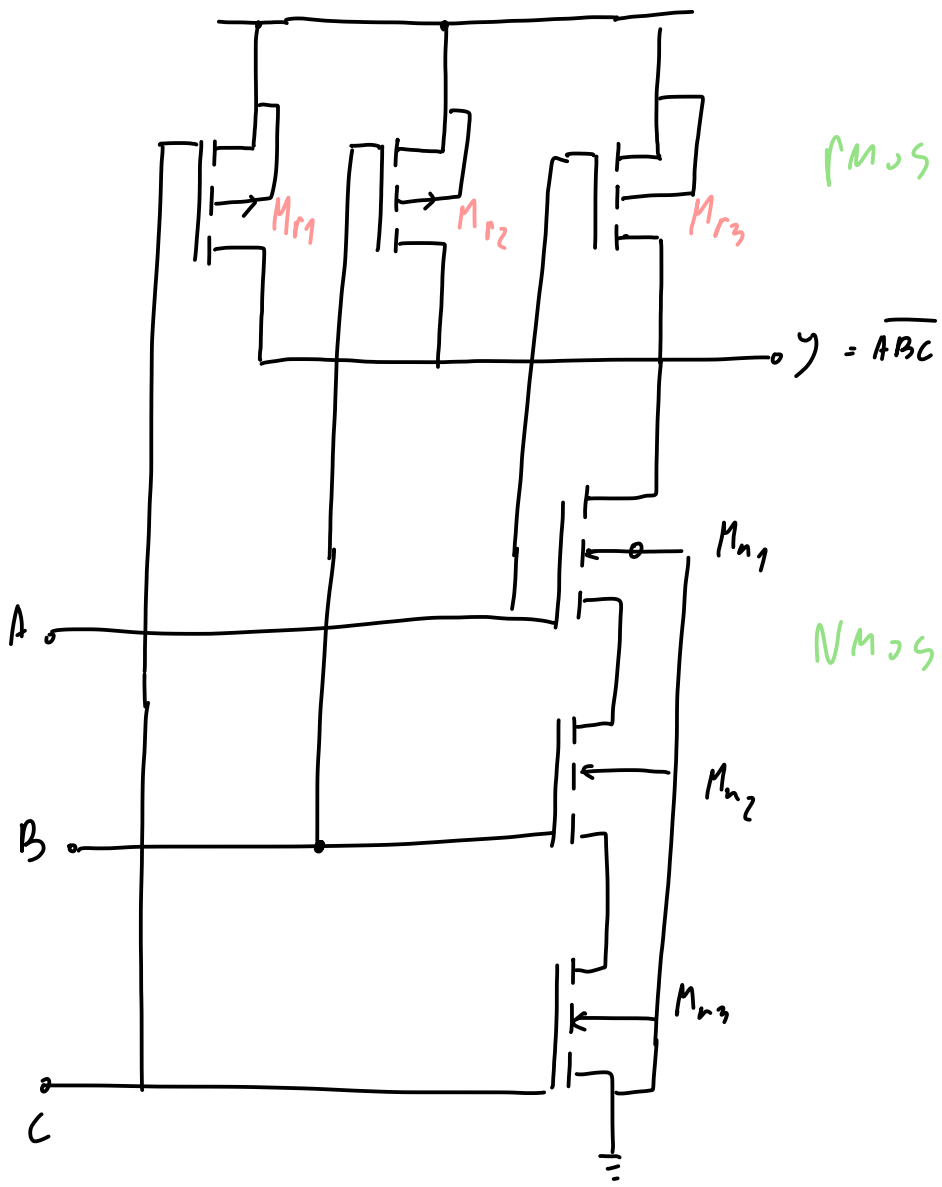
CMOS Logička kola





1. Implementirati troulazno NI kolo

$y = \overline{ABC}$



* ako imamo redno PMOS
↳ moramo imati paralelno NMOS i obrnuto

2. $Y = y = \overline{A+B+C}$

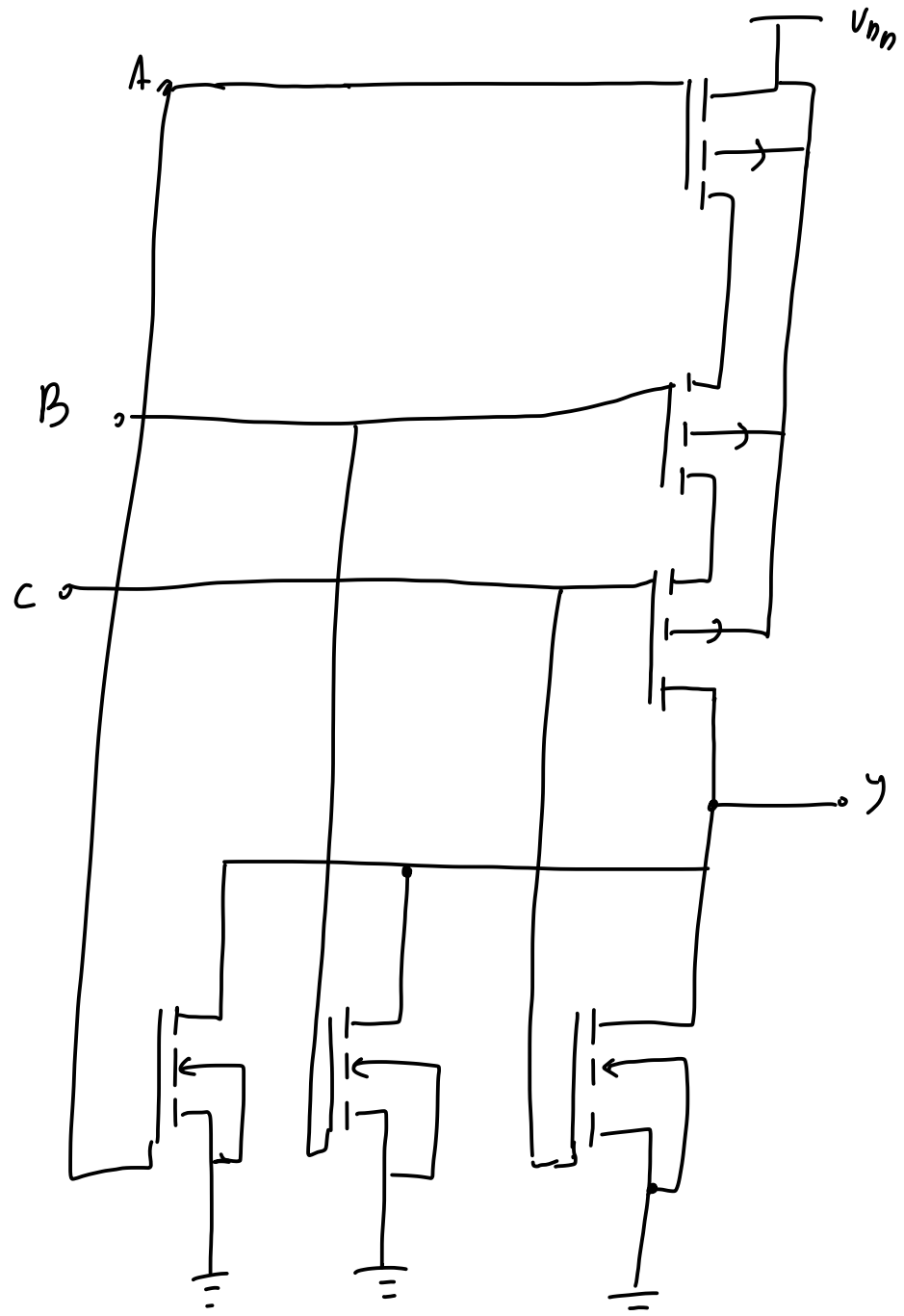
1. $Y_n = \overline{Y}$

2. $Y_n = A+B+C$

3. Y_p dualna Y_n

paralelno NMOS je serijski

a redno NMOS je paralelno



3. $Y = \overline{(A \oplus B)\,C}$

$A \oplus B = \bar{A}B + A\bar{B}$

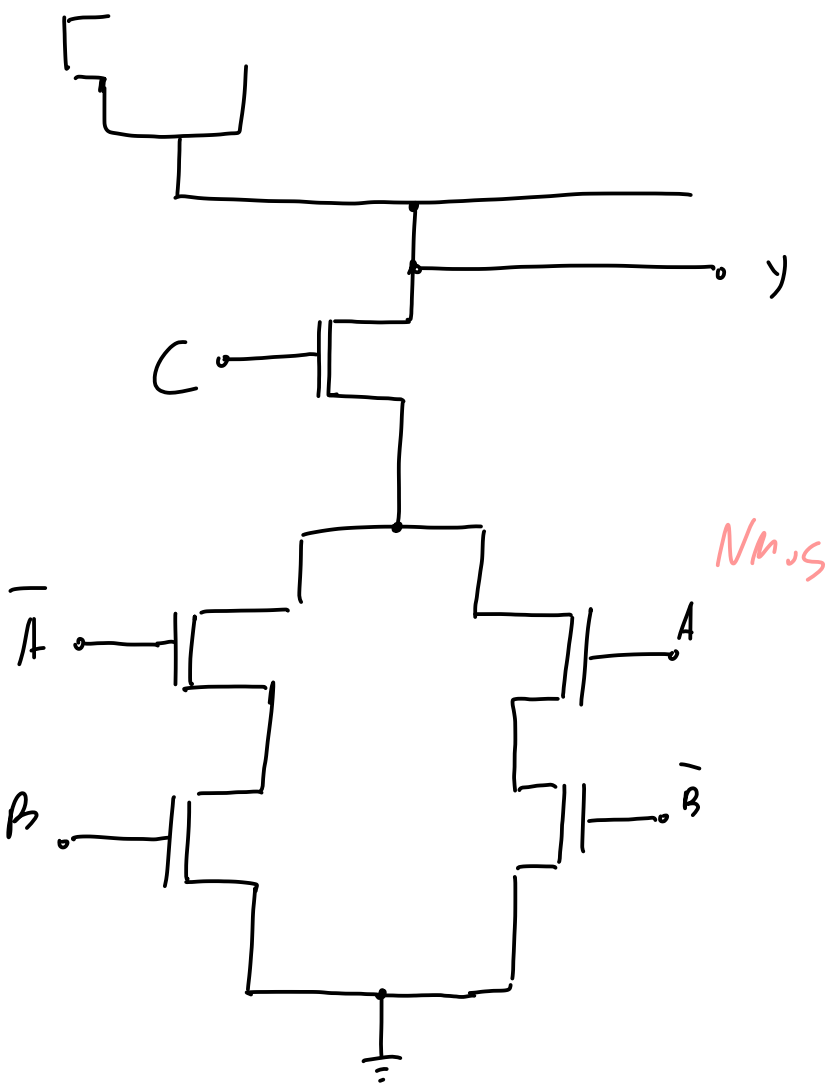
$Y_n = (\bar{A}B + A\bar{B})C$

$Y_p = (\bar{A}+B)(A+\bar{B})+C$

Udaljen pa

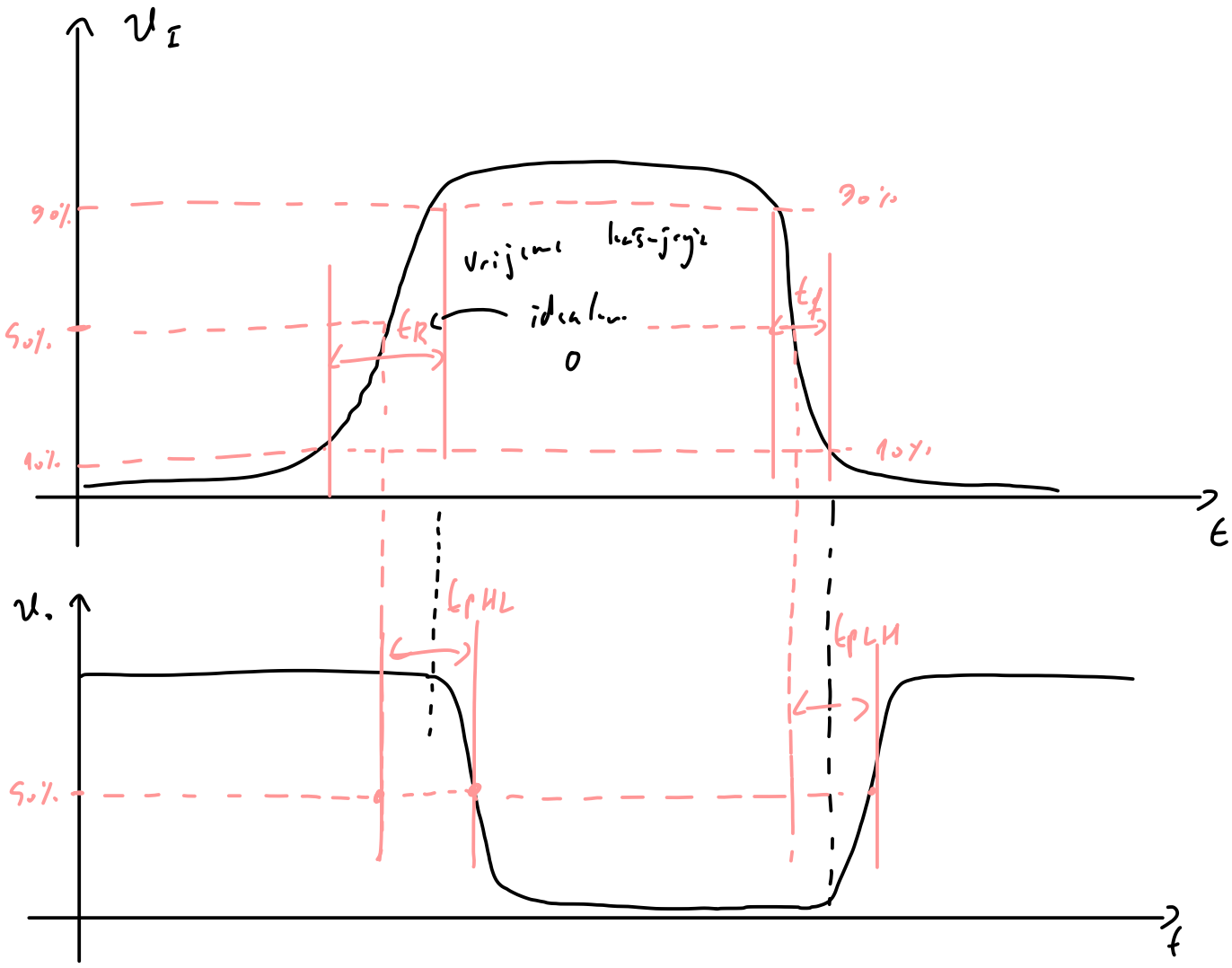
C

redno



Predavanje 11.12.2024.

3. Dinamičke k-ke



t_{pHL}, t_{pLH}

– vremena kašnjenja opadajuće i rastuće ivice izlaznog signala

$$t_p = \frac{t_{pHL} + t_{pLH}}{2}$$

ukupno vrijeme kašnjenja izlaznog signala

$$f_{max} = \frac{1}{2t_p}$$

4. Disipacija → potrošnja. log. kola

- statička DC, bez kašnjenja
- dinamička ima kašnjenja – disipacija tokom prelaza

$$P_D = V_{DD} \cdot I_{SIZ}$$

Statička

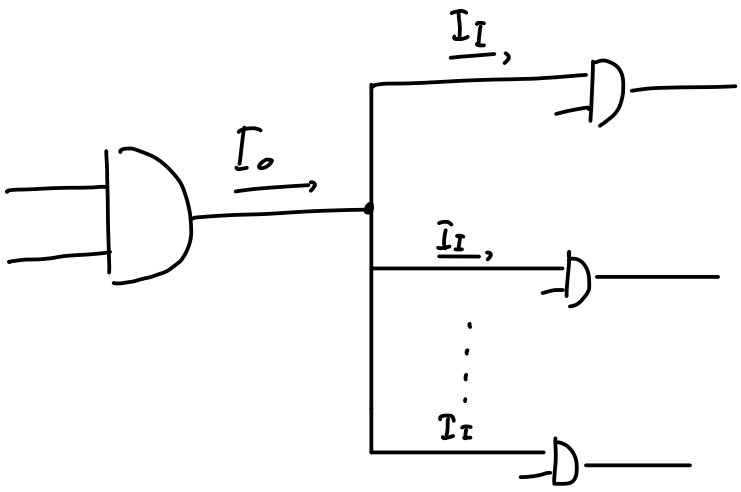
cilj → 0

$$PDP = P_D \cdot t_p$$

→ 0 (malo vrijeme kašnjenja i malo P_D)

! proizvod disipacije i kašnjenja

5. Faktor grananja



$$\boxed{I_o \geq n \cdot I_I}$$

n faktor grananja

$$n \leq \frac{I_o}{I_I}$$

$$\boxed{n_{max} = \frac{I_o}{I_I}}$$

jer mora da radi i za "0" i "1"

"0" $\quad I_o^0 \quad I_I^0$

"1" $\quad I_o^1 \quad I_I^1$

$$n^0 = \frac{I_o^0}{I_I^0}$$

$$n^1 = \frac{I_o^1}{I_I^1}$$

$n^0 \neq n^1$

$$\boxed{n = \min\{n^0, n^1\}}$$

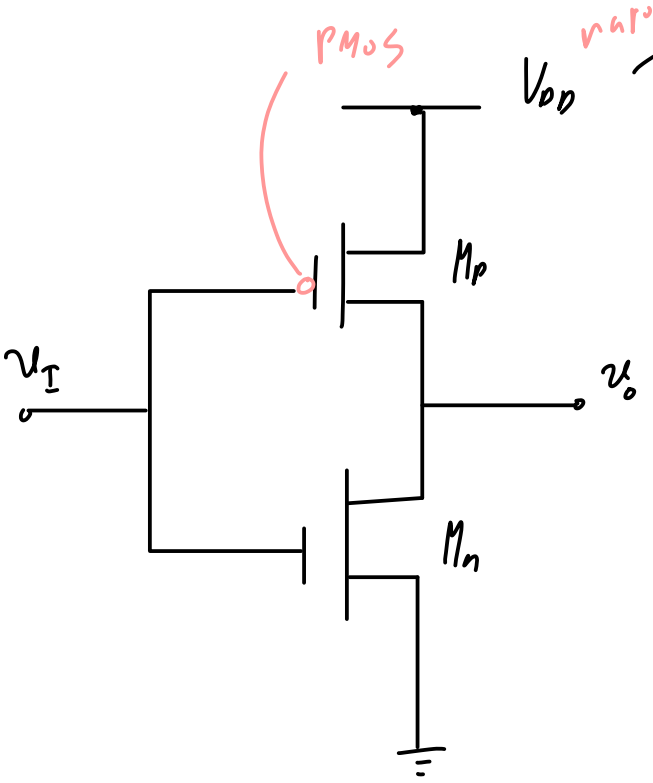
$n \in (3, 8)$

complementary CMOS Logička kola

- statička disipacija $= 0$
- NMOS i PMOS – velika otpornost ∞ → omogućava da možemo povezati veliki br log jedinica na izlaz drugog → veliki stepen integracije
  - mala izlazna otpornost → projektovanje memorija
  - temperaturna stabilnost (jer su NMOS i PMOS temp. stabilni)
  - velika izlazna struja – nisu osjetljivi na smetnje

CMOS invertor

- Osnovno k.l.



napon napajanja (1.2V ÷ 5V)

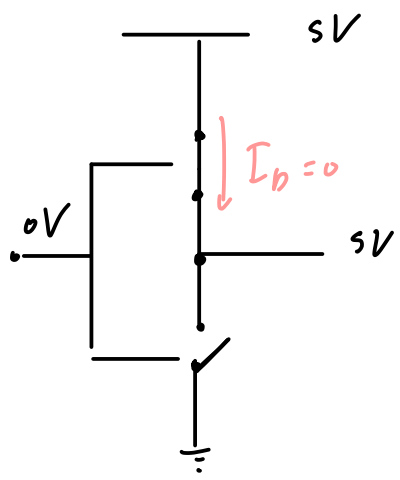
veći napon → više vremena da se uspostavi 5V napon → veća kašnjenja i PDP

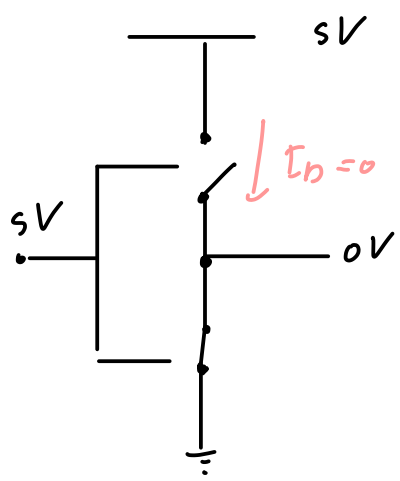
manji napon V_{DD} → manje dim tranzistora → više integracija

Idealno stanje:

tr. idealni prekidači

$V_I = 0V$ $V_{DD} = 5V$ $V_I = 5V$





$P_D = 0$
↳ jer $I_D = 0$

Realno stanje:

- tr koji vodi – u $\boxed{\text{triodnoj}}$ oblasti
  - ponaša se kao $\boxed{\text{otporniki}}$ → nijansa se otpornika

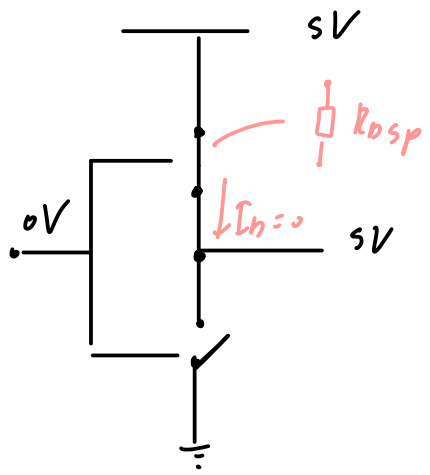
PMOS vodi

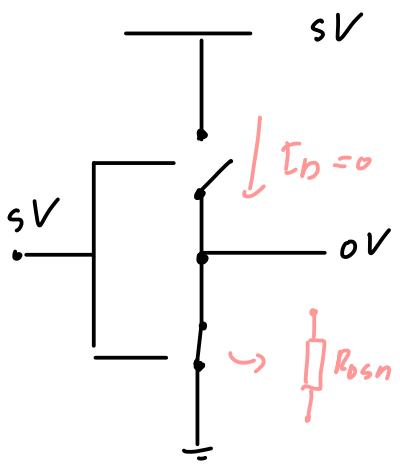
$$R_{DSp} = \frac{1}{2k_p(V_{SG} - |V_{tp}|)}$$

NMOS vodi:

$$R_{DSn} = \frac{1}{2k_n(V_{GS} - V_{tn})}$$

male izlazne otpornosti





Disipacija

Statička = 0

Dinamička disipacija:

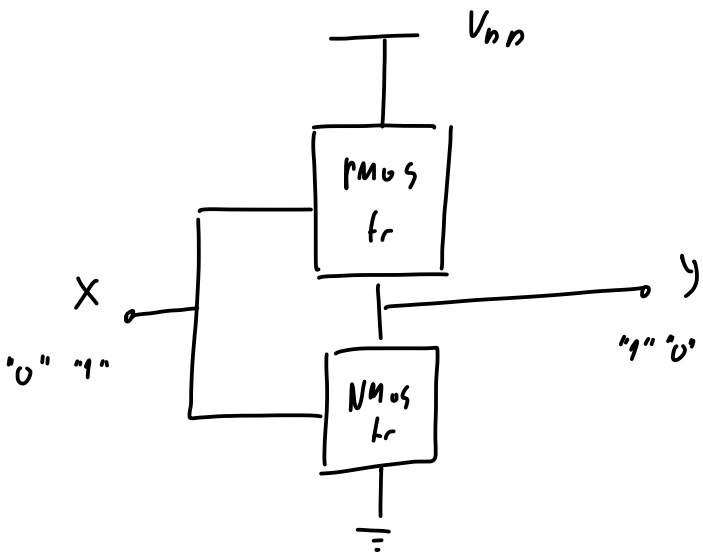
C – ekvivalentna kapacitivnost svih parazitnih kondenzatora

$$\boxed{P_{din} = f \cdot C \cdot V_{DD}^2}$$

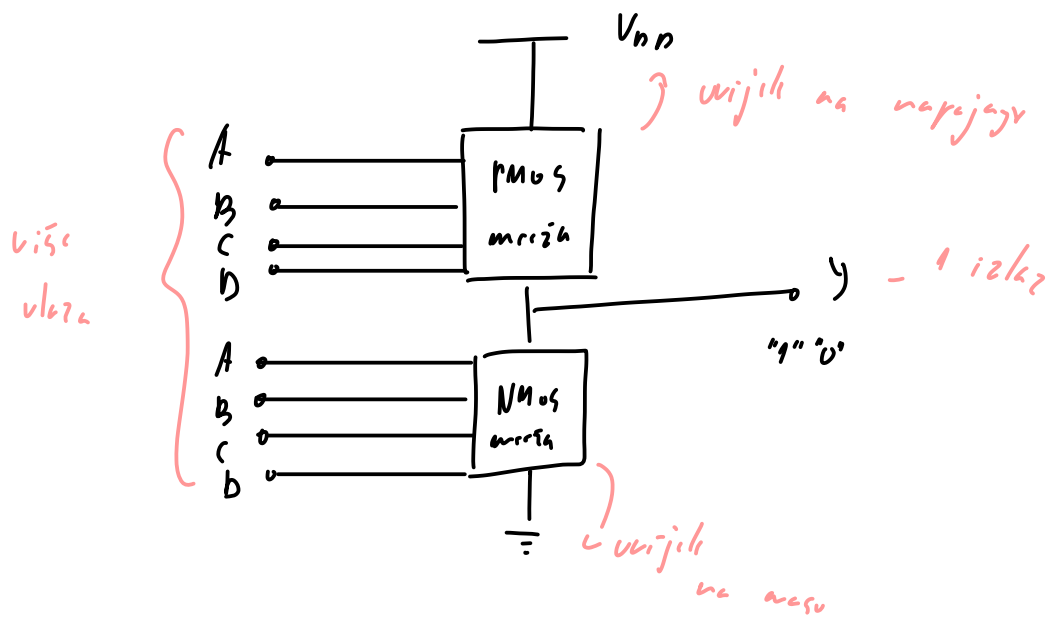
min

Osnovna i složena CMOS log. kola

Osnovno log kolo: CMOS inverter



Složena log. kola:

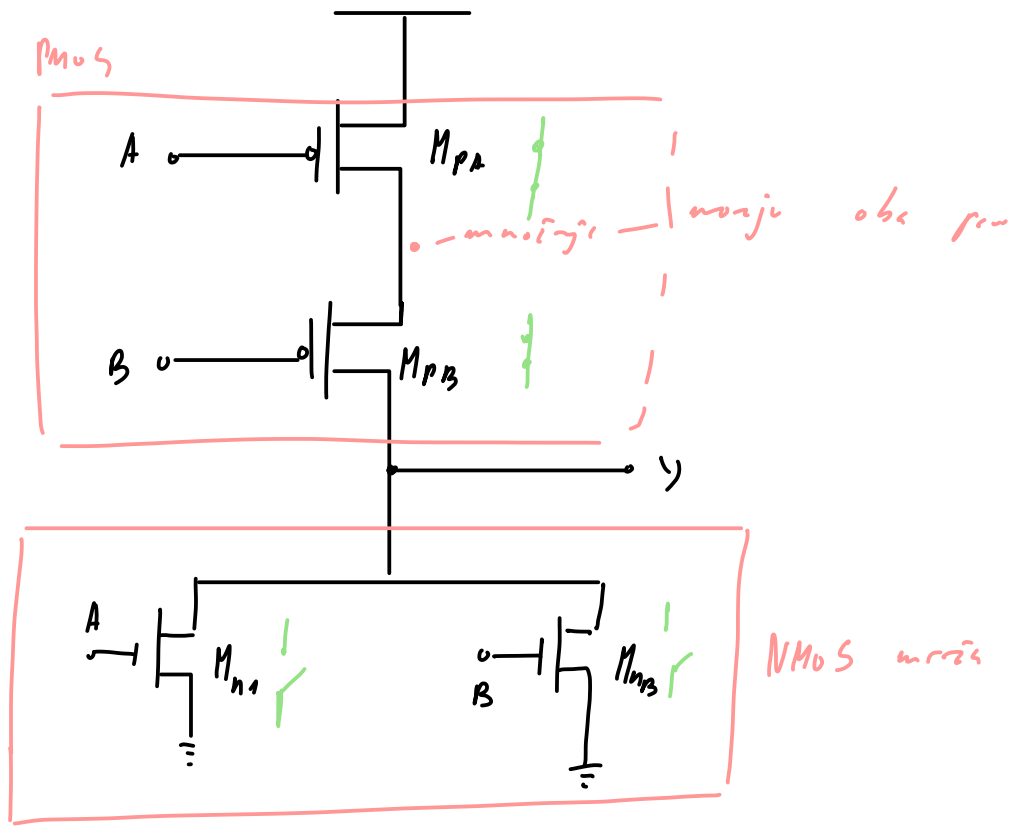


NILI log. kolo

A, B ulazi, Y izlaz => $\boxed{Y = \overline{A+B} = \bar{A}\cdot\bar{B}}$

ali je prije komplement onda projektiramo kolo tako da izgledi PMOS mreže

$\bar{A}\cdot\bar{B}$ -> PMOS redno
$\bar{A}+\bar{B}$ -> PMOS paralelno } NMOS suprotno



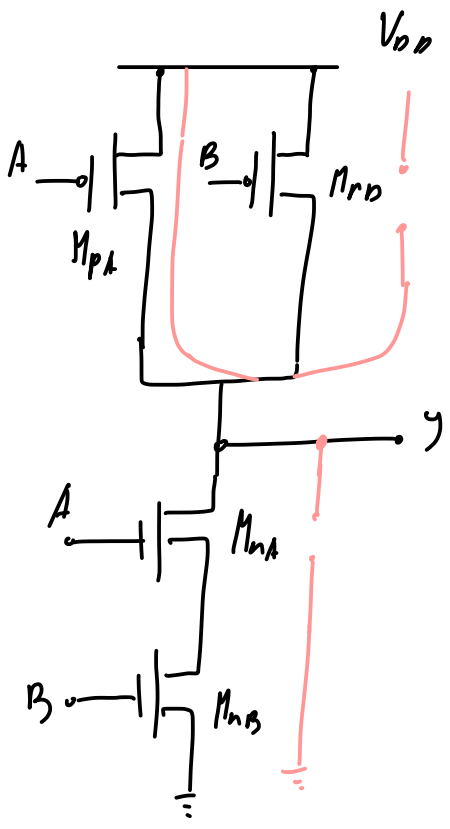
- množiti — moraju oba prekidači -> redno vez

A	B	Y
0	0	1
0	1	0
1	0	0
1	1	0

Sam kod kada tr koji su redno vezani -> moćan imati put do napajanja

NI kol.

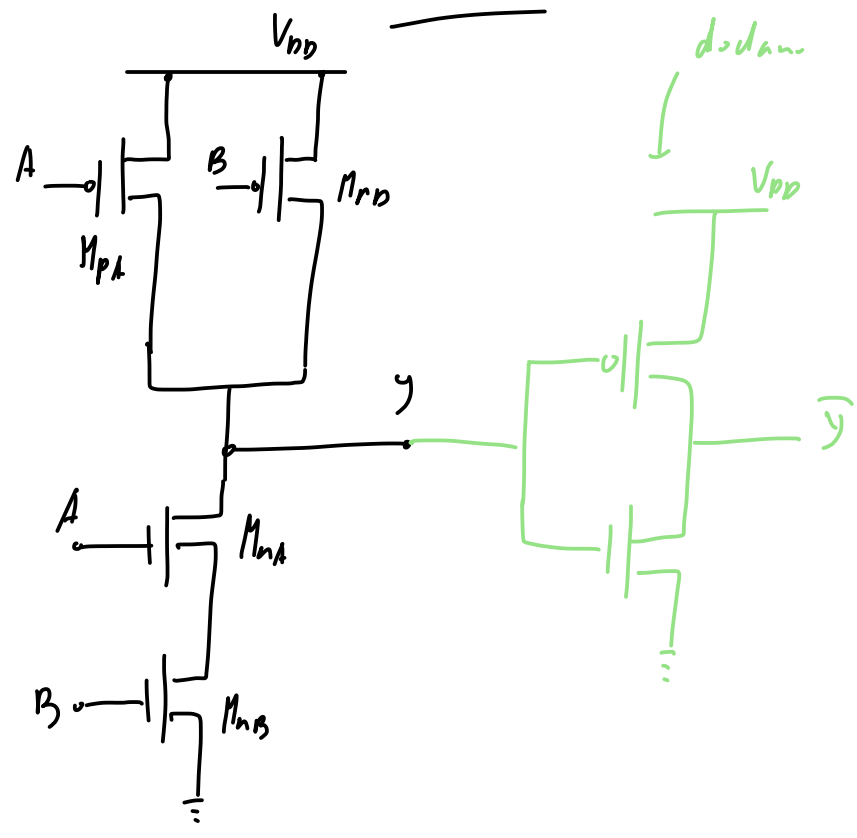
$Y = \overline{AB} = \bar{A}+\bar{B}$ -> 1 imam ako bilo koji od PMOS vodi
-> paralelna veza prema napajanju



A	B	Y
0	1	1

I kol.

dodamo invertor na NI

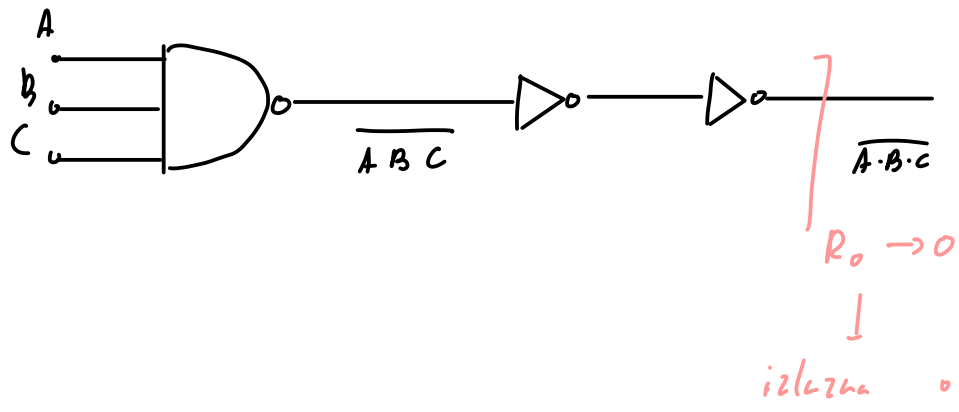


Osnovna logička kol.:

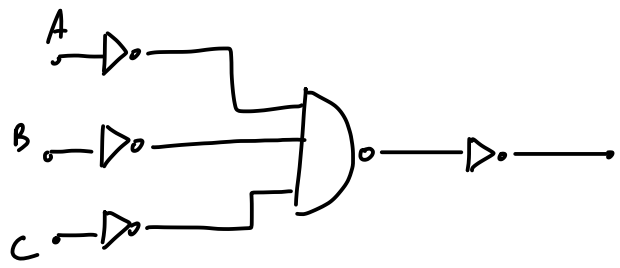
invertor

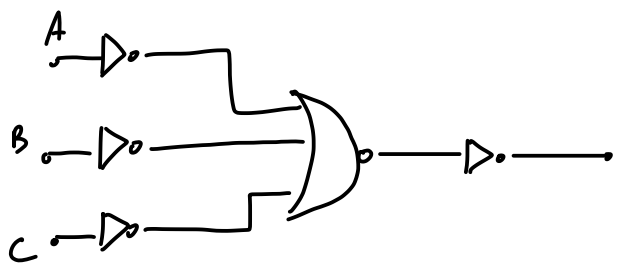
NILI i NI

Baferirana CMOS logika



cilj: isti izraz ali sa malom vrijednosti izlazne otpornosti

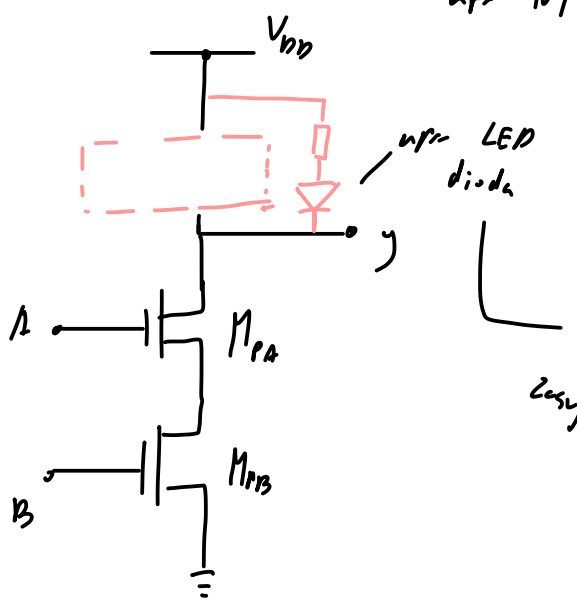




CMOS logika sa otvorenim drejnom

- izostavljanje PMOS mreže

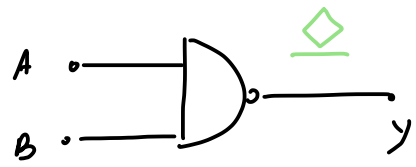
npr. NI



A	B	Y
0	0	otvoren
0	1	otvoren
1	0	otvoren
1	1	0

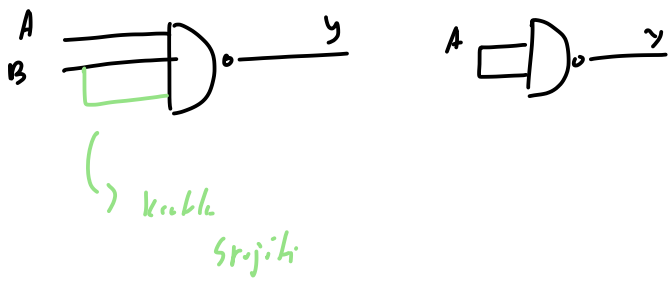
zasvijetli za 11

simbol

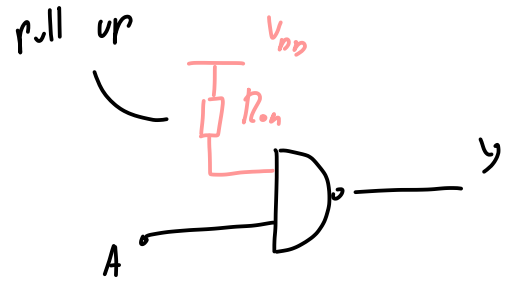


Spajanje nisko korištenih ulaza

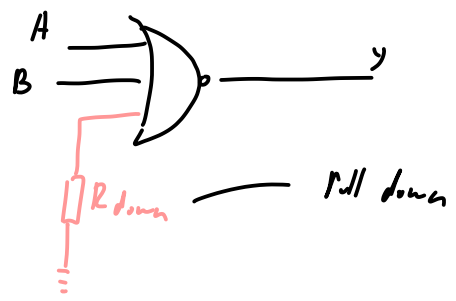
NI tehnologija



ili



NILI tehnologija



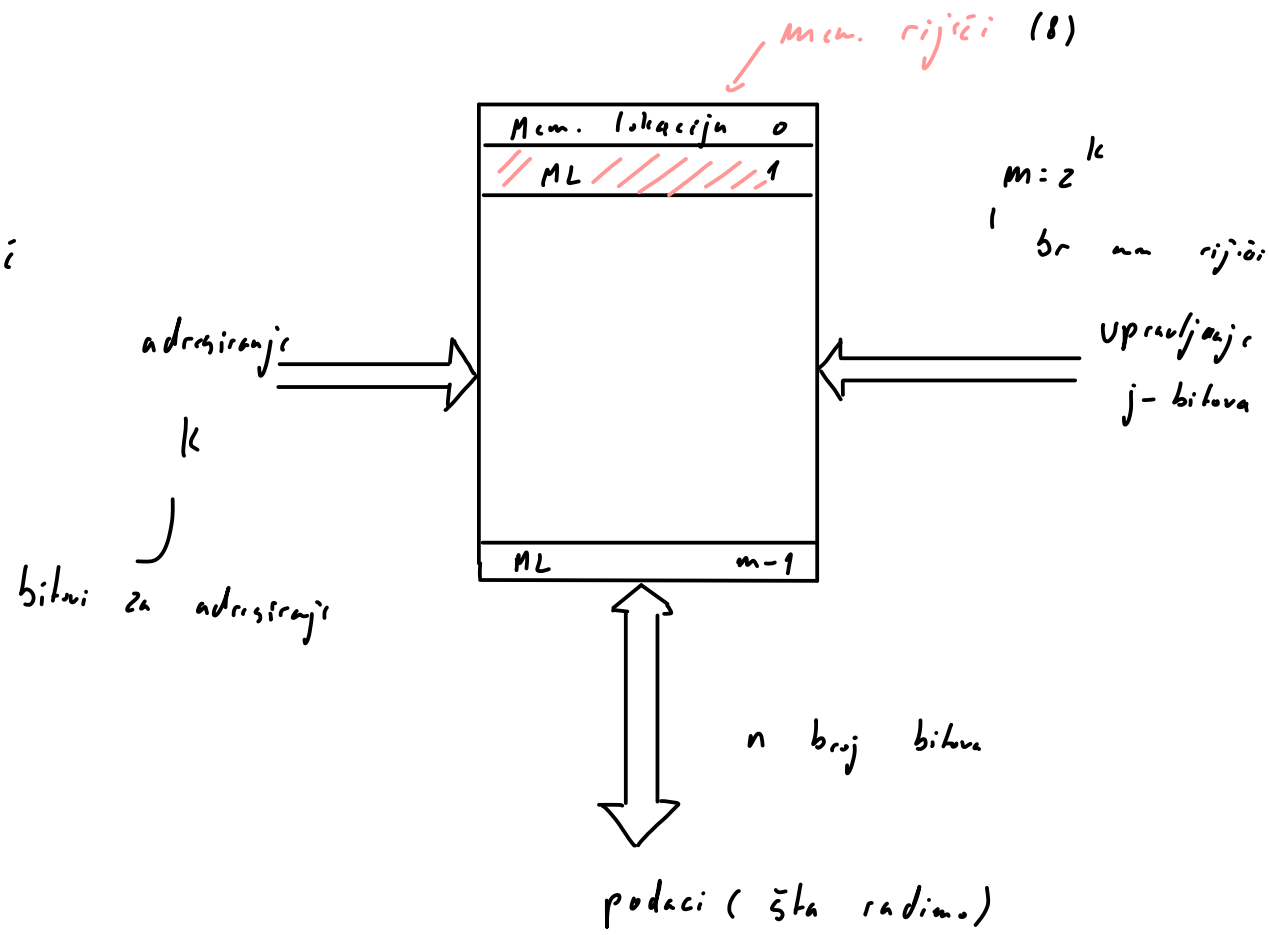
Poluprovodničke memorije

Osnovni parametri :

1. Kapacitet memorije
2. Brzina funkcionisanja

1. Kapacitet memorije

- ćelija → 1 bit
- više ćelija → memorijska riječ
- više mem. riječi → memorija



Kapacitet memorije :

po broju bitova :

$$\boxed{K_b = n \cdot 2^k}$$

po broju mem riječi :

$$\boxed{K_R = 2^k}$$

2. Brzina funkcionisanja

- brzina pristupa
- brzina F-je koja se obavlja

Podjela memorija

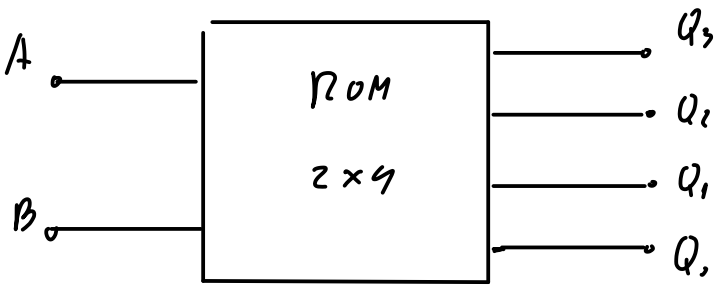
1. ROM (memorije stalnog sadržaja)
2. RAM (memorije promjenljivog sadržaja)

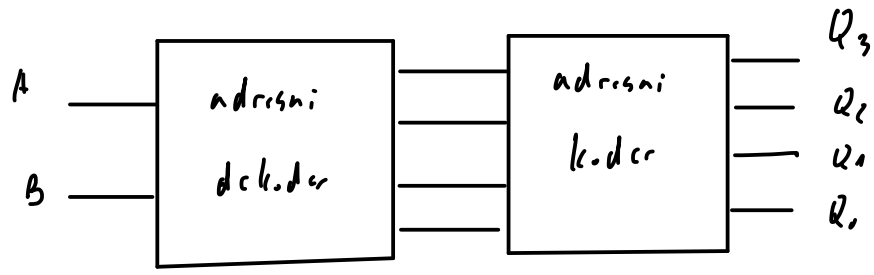
ROM memorije

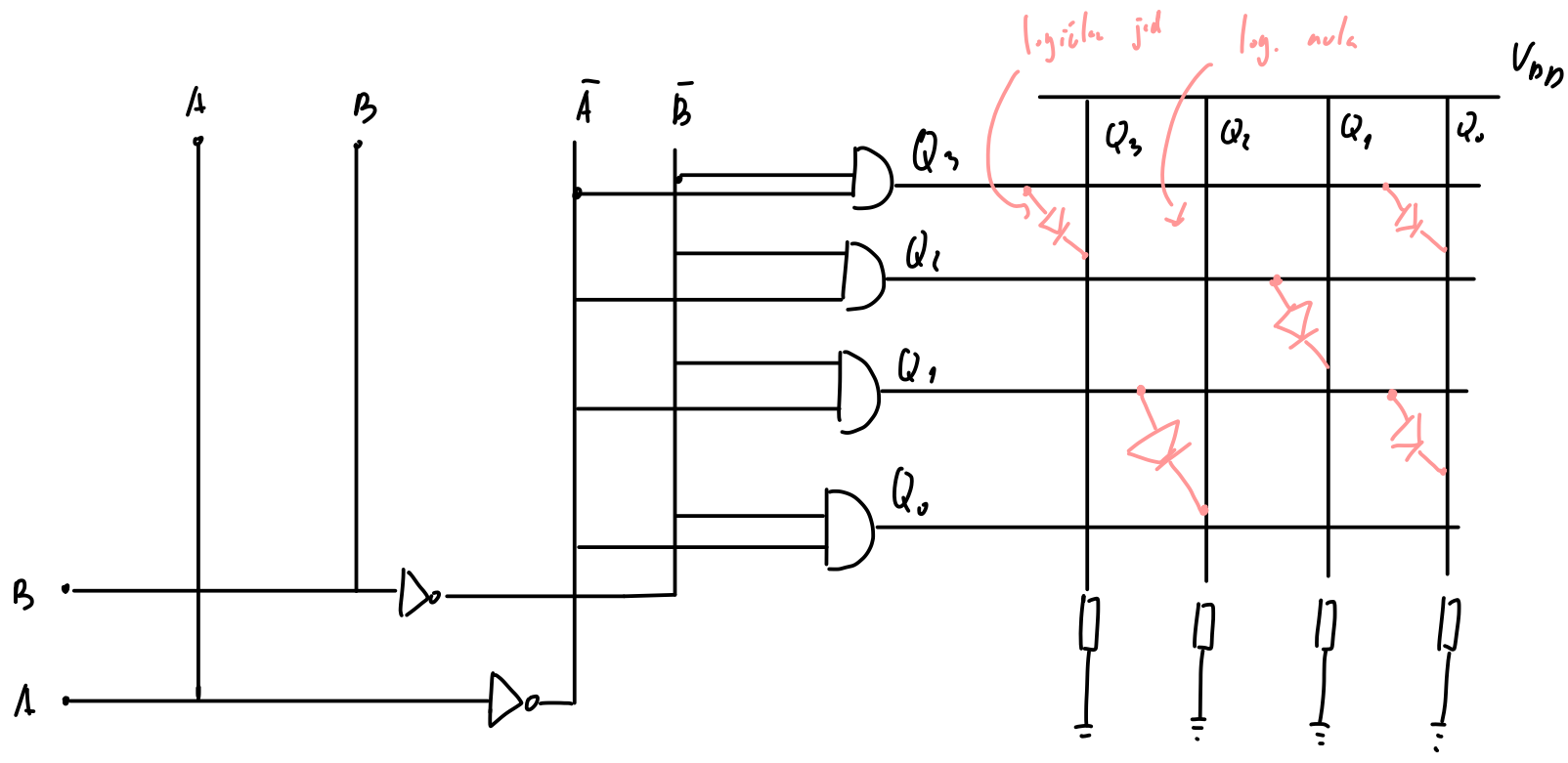
1. ROM memorije
2. PROM memorije (programabilni ROM) — korisnik može 1 kada kupi memoriju da je programira i tj.
3. REPROM mem. (reprogramabilni ROM) -> može više puta

- EPROM — UV zraci brisanje
- E^2PROM — el. polem brisanje → može da čuva podatke kad je isključena napajanje

ROM memorija

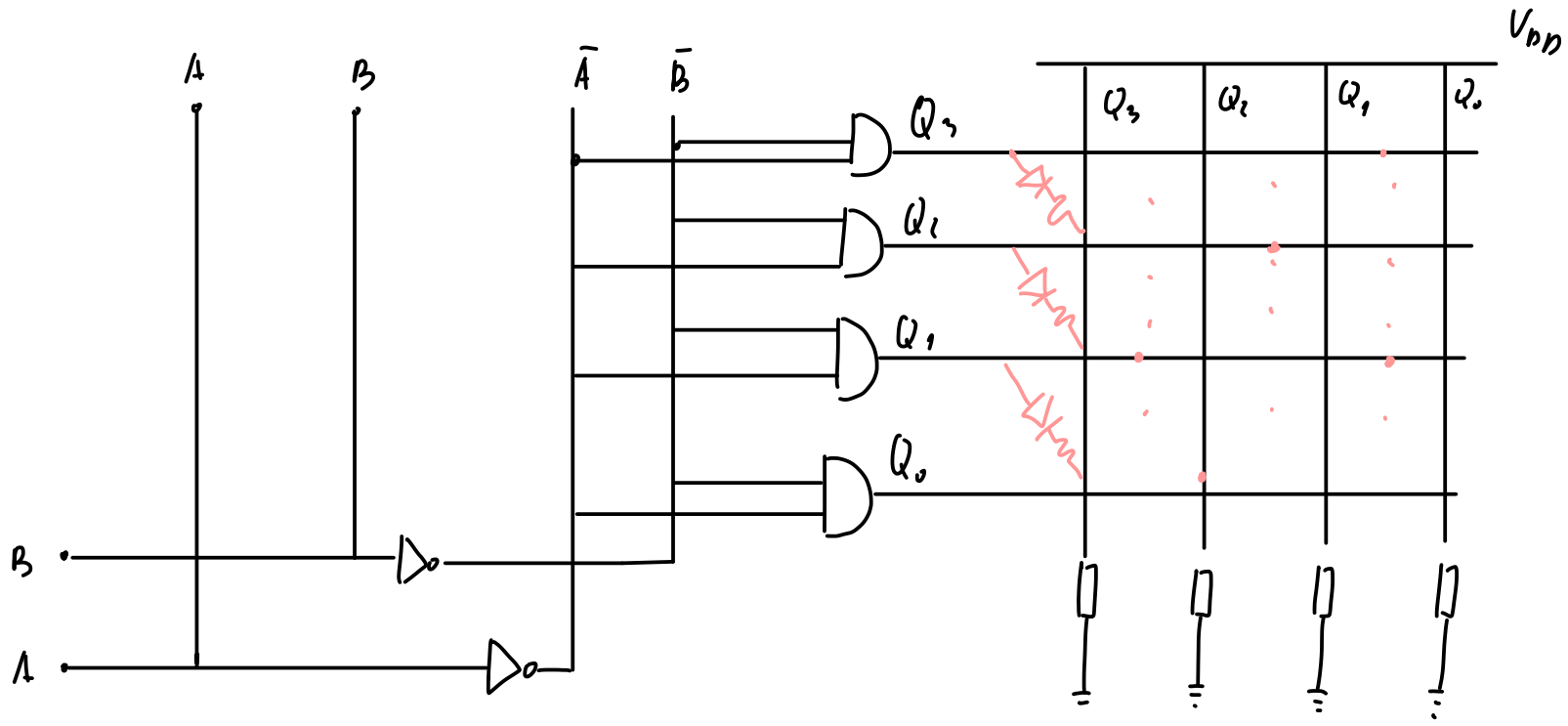






PROM

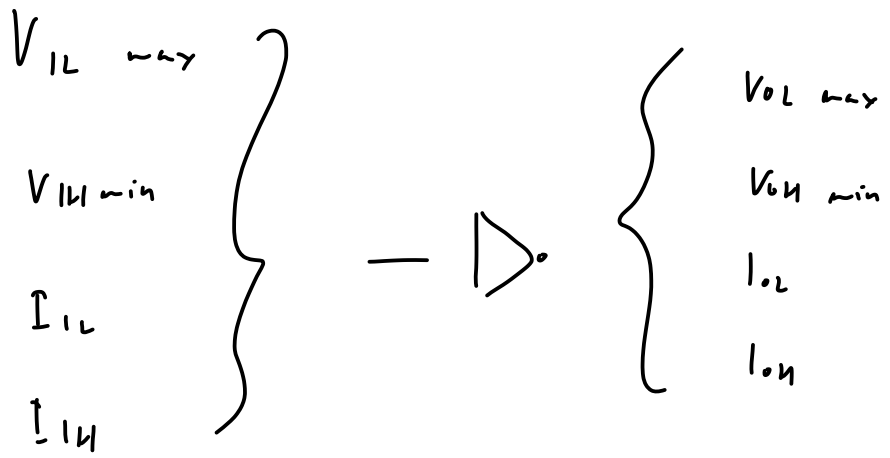
početno: svi su log. 1.

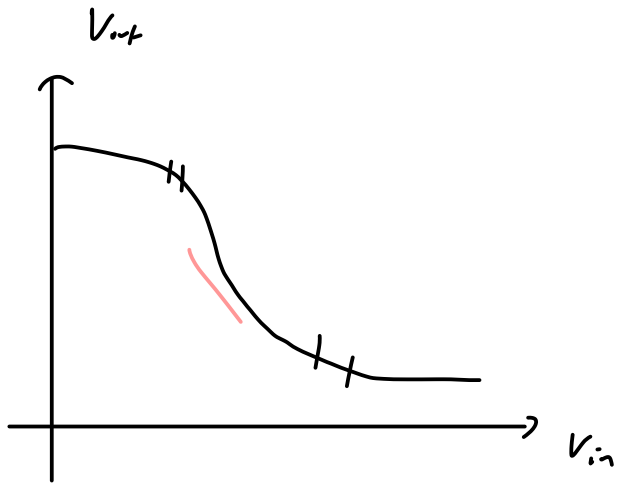


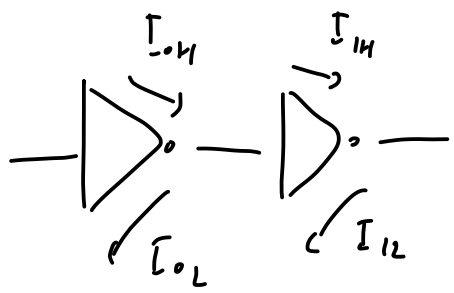
upisivanje 0 : električno

pregorijevanjem osigurača

Vježbe 13.12.2024.







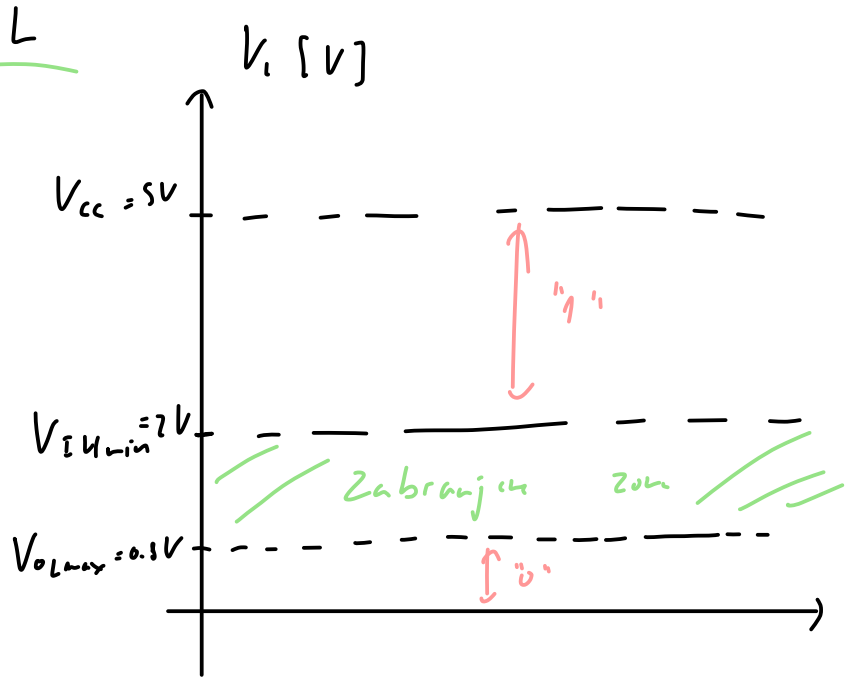
Margine šuma

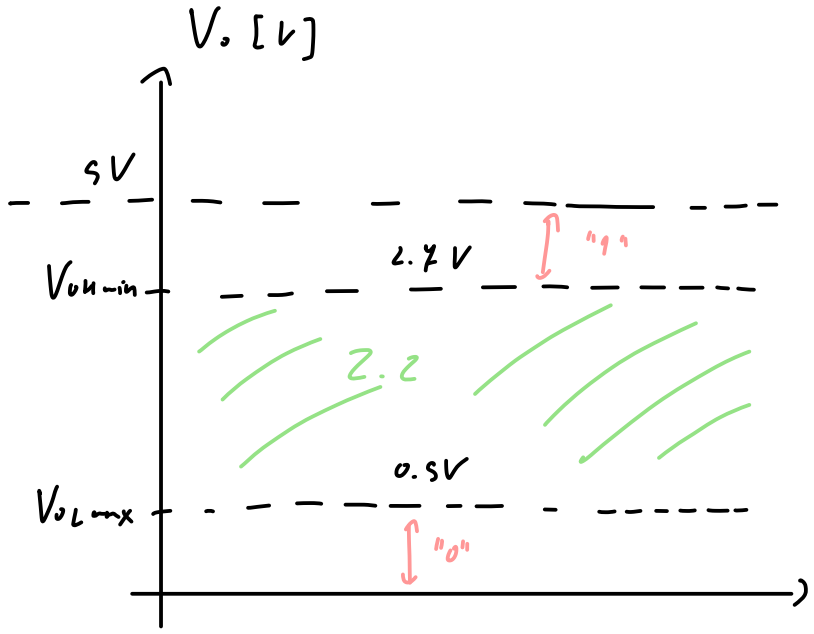
$NM_H = V_{OH\,min} - V_{IH\,min}$ gornja margina

$NM_L = V_{IL\,max} - V_{OL\,max}$ donja margina šuma

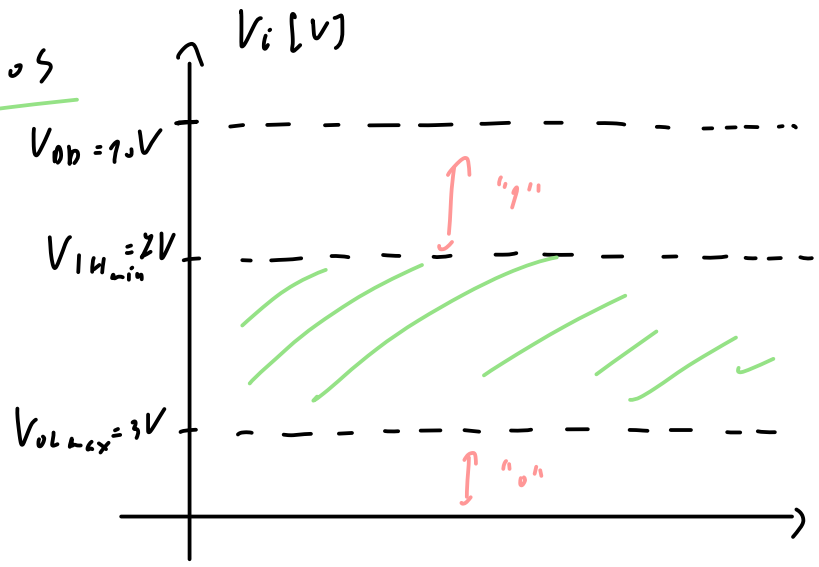
$NM_G = \min\{NM_H, NM_L\}$ garantirana -||-

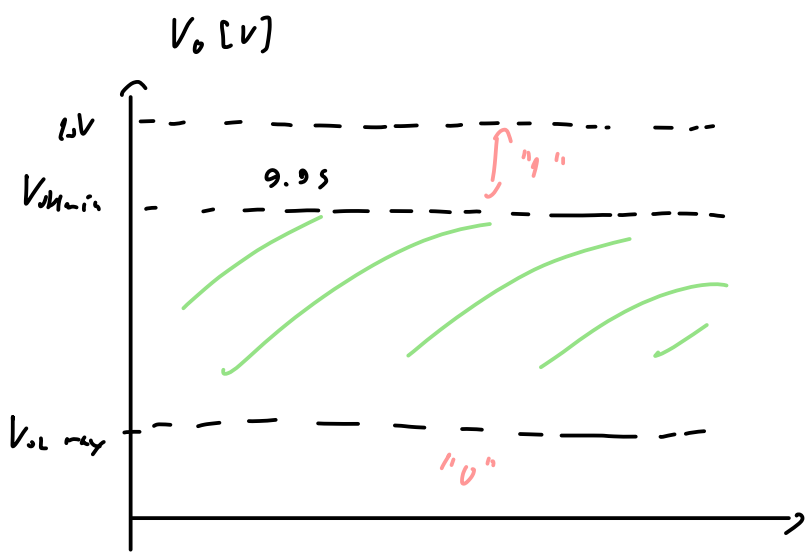
TTL



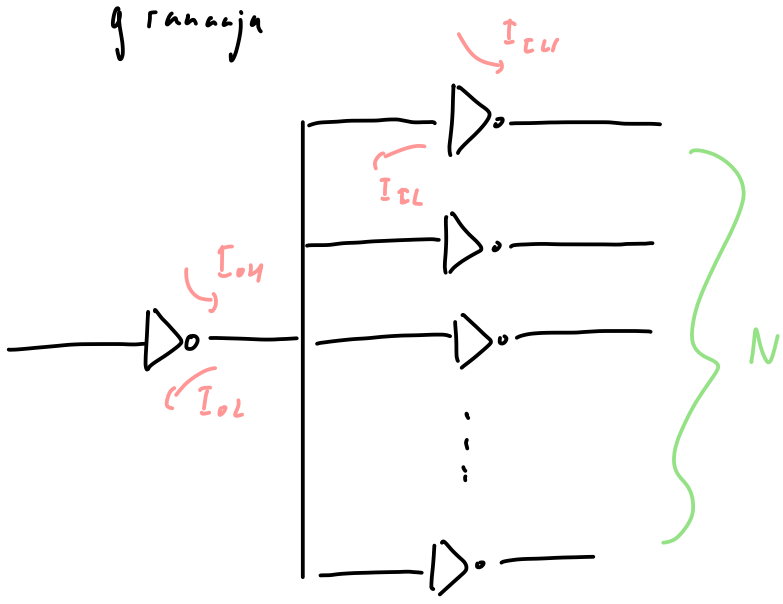


CMOS



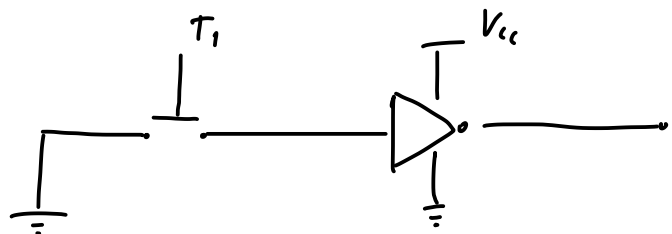


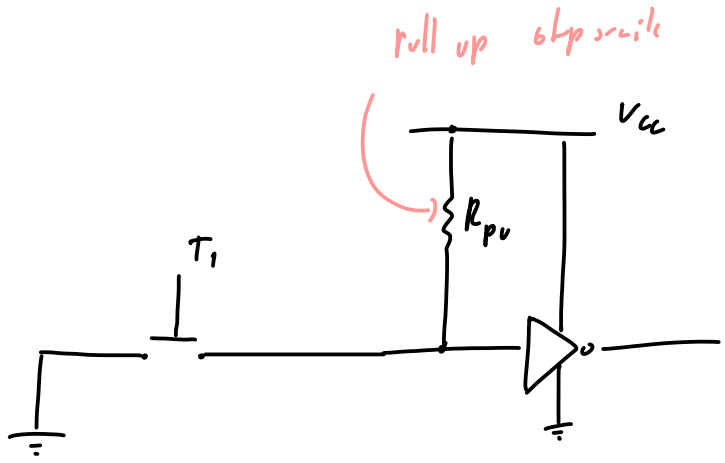
Faktor granaranja



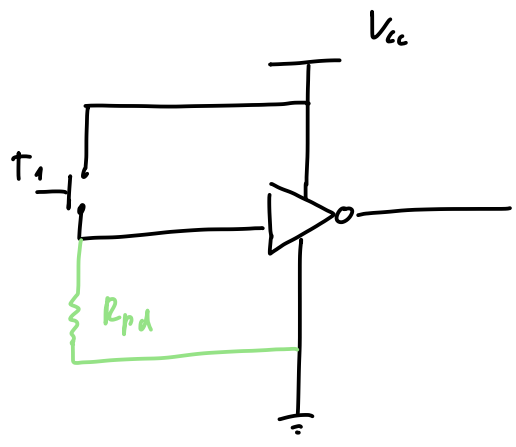
$$N_H = \frac{I_{OH}}{I_{IH}} \qquad N_L = \frac{I_{OL}}{I_{IL}}$$

$$N = \min\{N_H, N_L\}$$





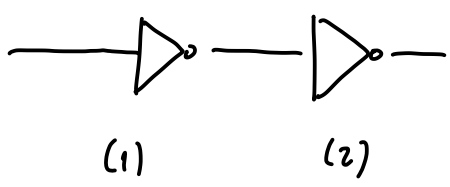
$$\boxed{R_{pu} < \frac{V_{CC} - V_{IH\,min}}{I_{IH\,max}}}$$



$$\boxed{R_{pd} < \frac{V_{IL\,max}}{I_{IL\,max}}}$$

Kriterijumi:

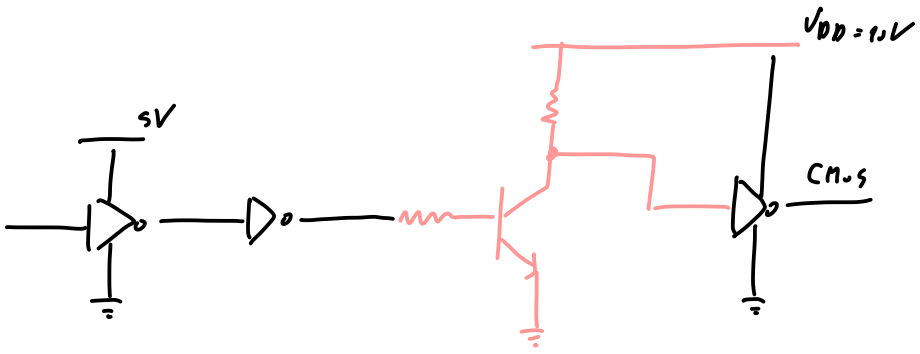
$V_{OH\text{-}in}(1)$	>	$V_{OH\text{-}in}(2)$
$V_{OL\,max}(1)$	<	$V_{OL\,max}(2)$
$I_{OH\,max}(1)$	>	$I_{OH\,max}(2)$
$I_{OL\,min}(1)$	>	$I_{OL\,min}(2)$



↳ ako ne ispunjavaju krit. → koristimo interfejse

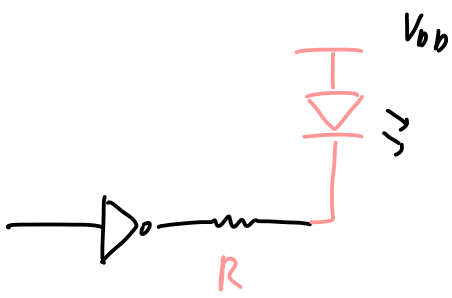
TTL - CMOS ($V_{SP} > 5V$)

— TTL ne smije imati napon napajanja > 5V



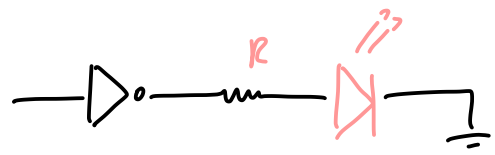
Spajanje led dioda

1° na nizak log nivo



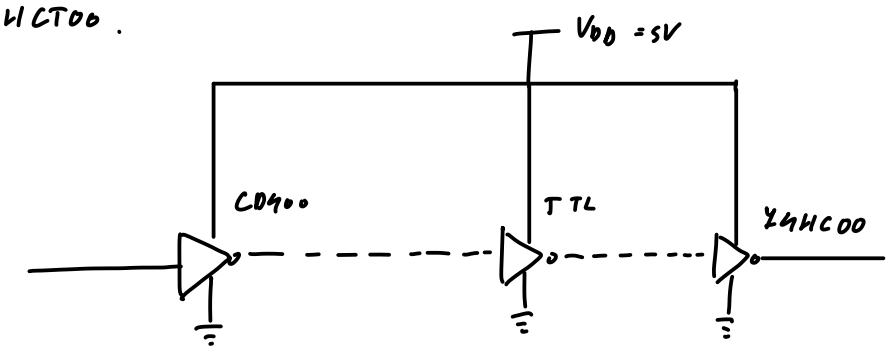
$$R = \frac{V_{CC} - V_{LED} - V_{OL}}{I_{LED}}$$

2° Na visok log n.



$$\boxed{R = \frac{V_{OH} - V_{LED}}{I_{LED}}}$$

1. Odrediti način povezivanja čipa sa slike ako su na raspolaganju interfejs kola 74HCT00.



CD400

$V_{OH\,min} = 4.95\,V$

$V_{OL\,max} = 0.05\,V$

$I_{OH\,max} = I_{OL\,max} = 400\,\mu A$

74HC00

$V_{IH\,min} = 3.5\,V$

$V_{IL\,max} = 1\,V$

$I_{IH\,max} = I_{IL\,max} = 1\,\mu A$

74HCT00

$V_{OH\,min} = 4.3\,V$

$V_{OL\,max} = 0.3\,V$

$I_{OH\,max} = I_{OL\,max} = 24\,\mu A$

$V_{IH\,min} = 2\,V$

$V_{IL\,max} = 0.8\,V$

$I_{IH\,max} = I_{IL\,max} = 1\,\mu A$

TTL

$V_{OH\,min} = 2.4\,V$

$V_{OL\,max} = 0.4\,V$

$I_{OH\,max} = 400\,\mu A$

$I_{OL\,max} = 16\,mA$

$V_{IH\,min} = 2\,V$

$V_{IL\,max} = 0.8\,V$

$I_{IH\,max} = 40\,\mu A$

$I_{IL\,max} = 1.6\,mA$

1° Vcza CD4000 i TTL

CD4000		TTL	
V_{OHmin} (4.95)	>	V_{IHmin} (2V)	✓
V_{OLmax} (0.05 V)	<	V_{ILmax} (0.3V)	✓
I_{OHmax} (400 μA)	>	I_{IHmax} (40μA)	✓
I_{OLmax} (400 μA)	<	I_{ILmax} (1.6 mA)	✗

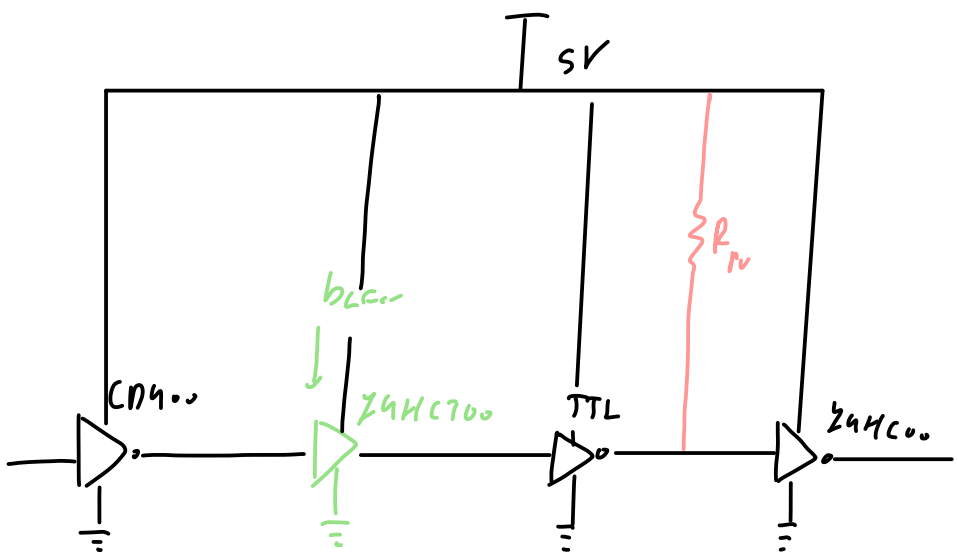
ukręcujemy bufor

2° Vcza TTL i 74HC00

TTL		74HC00	
V_{OHmin} (2.4)	>	V_{IHmin} (3.5V)	✗
V_{OLmax} (0.3V)	<	V_{ILmax} (1V)	✓
I_{OHmax} (40μA)	>	I_{IHmax} (1μA)	✓
I_{OLmax} (1.6 mA)	>	I_{ILmax} (1 mA)	✓

obciążenie

interfejs dobar



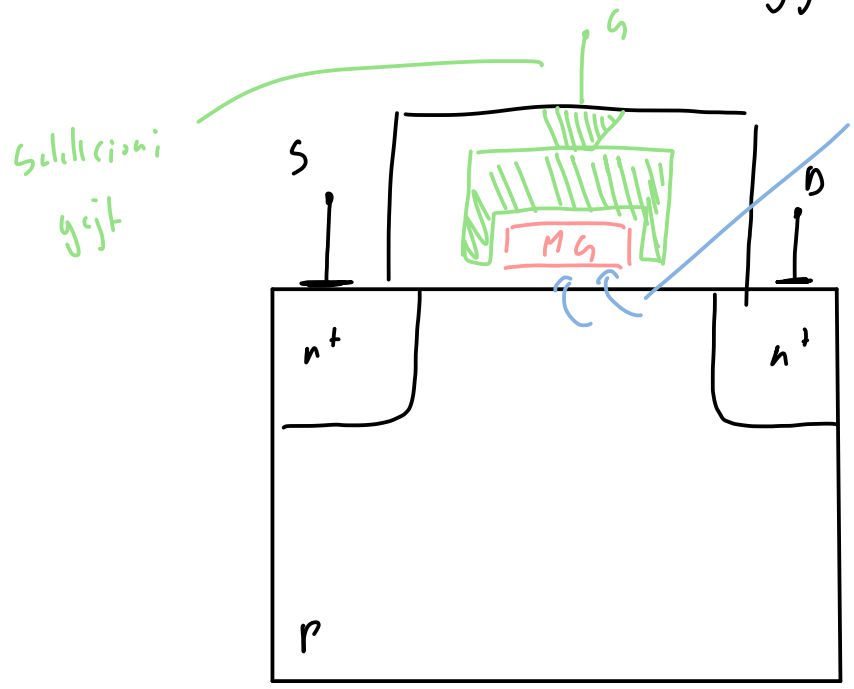
$$R \geq \frac{V_{CC} - V_{OLmax}}{I_{OLmax}}$$

$R \geq 237.5\,\Omega$

Predavanje 25.12.2024.

EPROM

- FAMOS - sa 1 ili 2 gejta



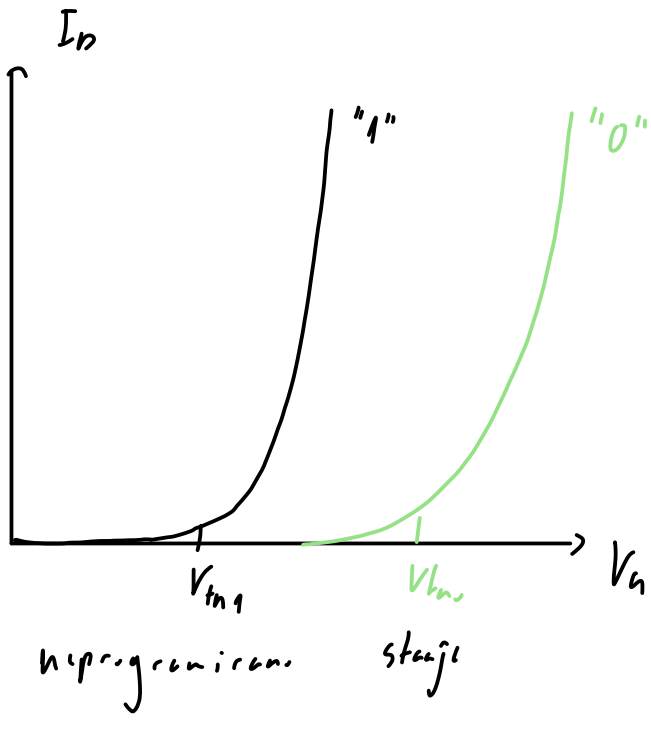
prekida se kanal → log nula

MG - memorijski gejt
- plivajući - nema kontakt
- polisilicijum

"1" - neprogramirano stanje

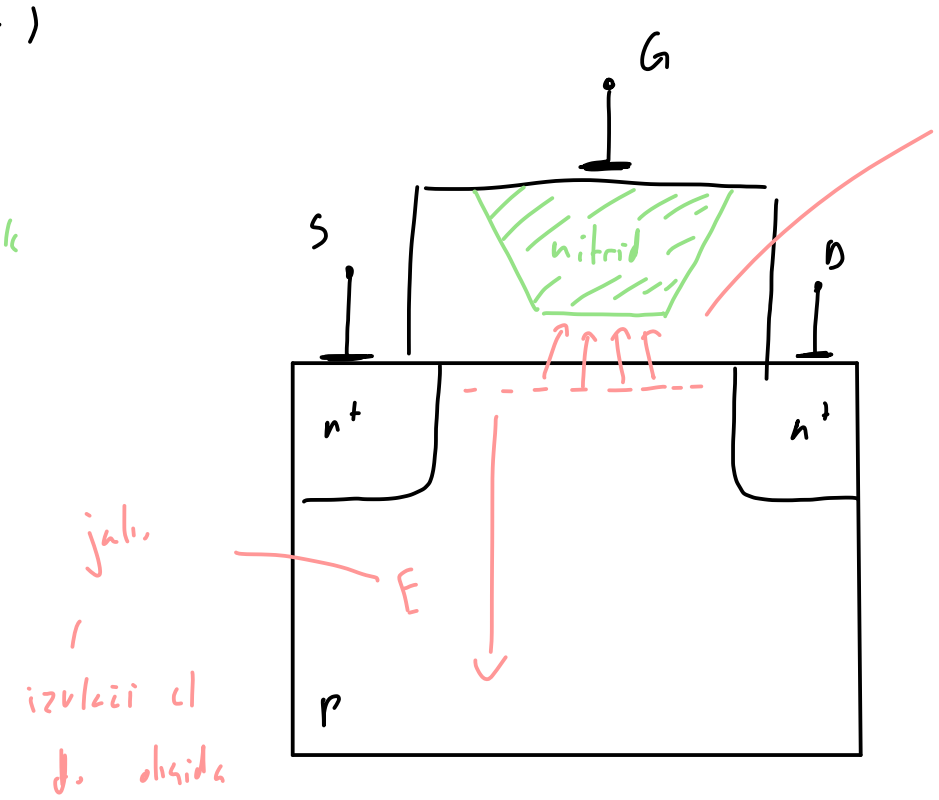
Upisivanje log "0" - programiranje
- velike V_{DS}

Brisanje - UV → fotoni dobijaju veliku energiju da se vrate u kanal



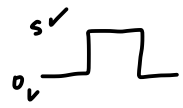
E^2PROM (Flash memorije)

MNOS
- oksid
- poluprovodnik
- metal
- nitrid / alumina



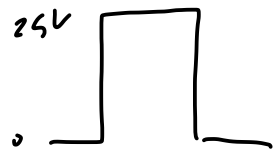
neprogramirano : log 1 (isto kao u prethodnom)

čitanje : V_{GS}



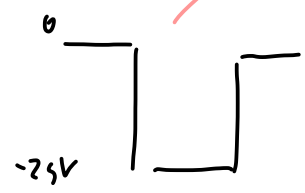
upisivanje "0" :

- veliki V_{GS}



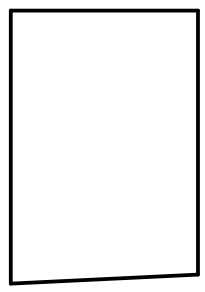
brisanje :

- veliki V_{GS} suprotnog polariteta



polje suprotnog smjera
el se vraćaju u kanal

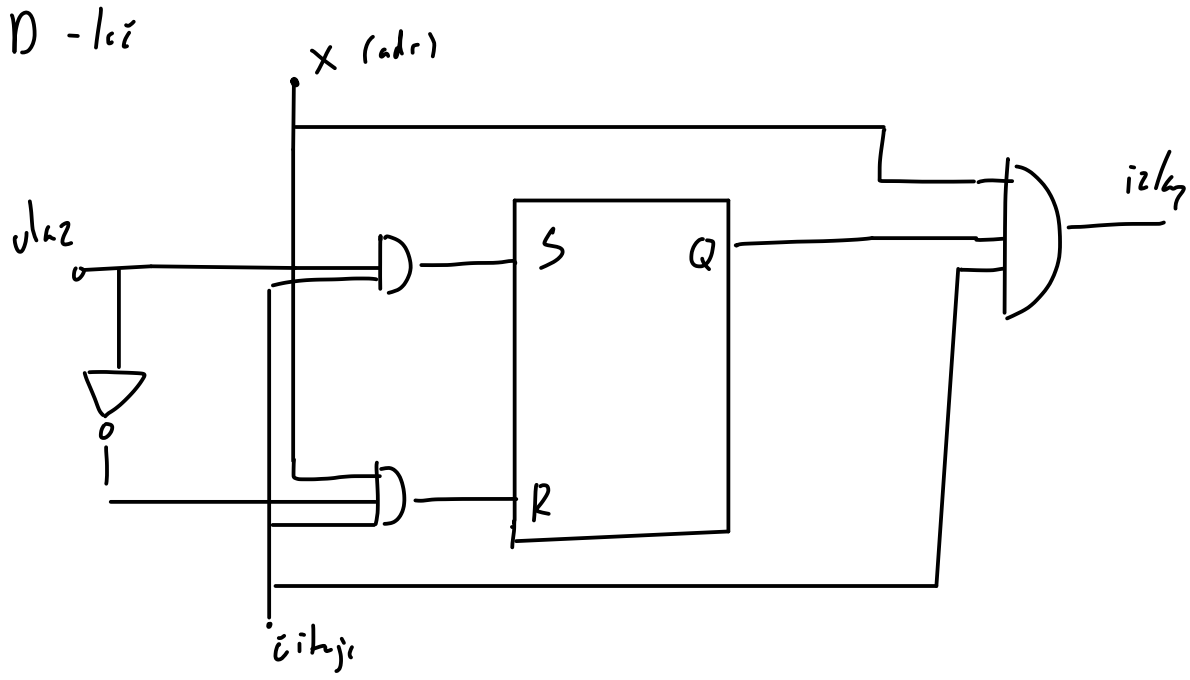
RAM memorije



- flip flop ili leč

SR
set reset

D - leč



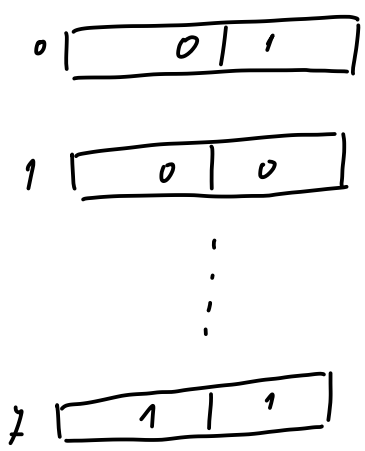
Proširivanje kapacitета memorije

- kapacitet m x n

m - br mem lokacija / riječi

n - br bitova

8x2



Proširivanje br bitova

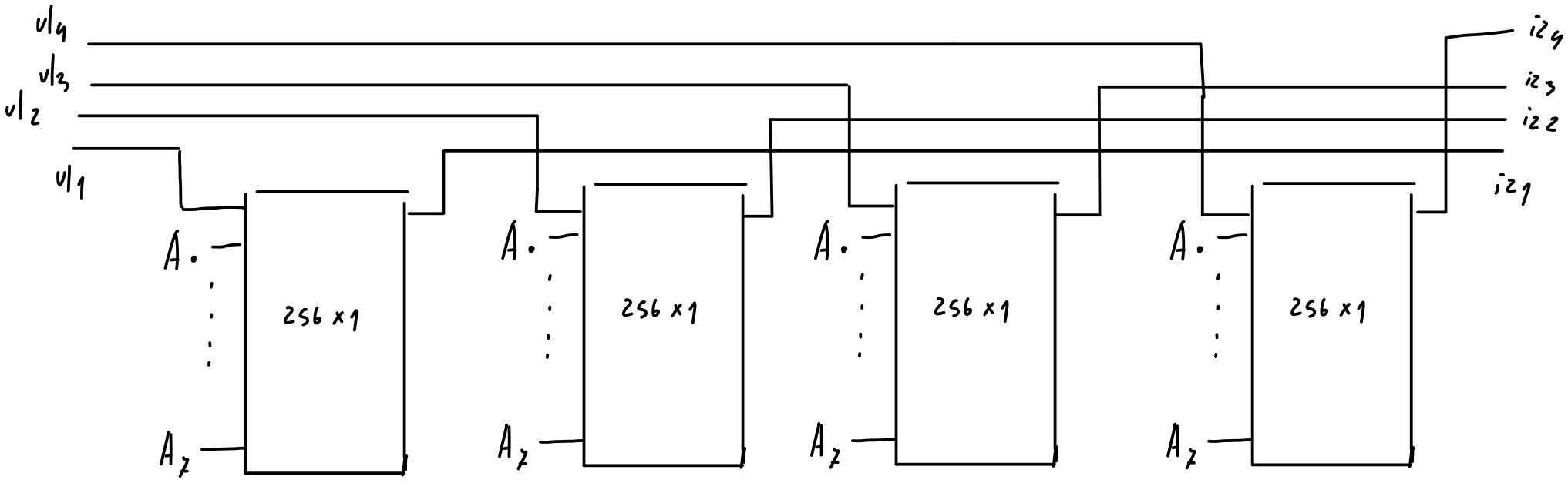
$m \times n \rightarrow m \times N$

$N = k_i \cdot n$

$m \times n = 256 \times 1$

$m \times N = 256 \times 4$

$\left.\begin{array}{l} N = 4 \\ n = 1 \end{array}\right\} k_i = 4$



Proširenje broja bitova nem lokacija

$m \times n \rightarrow M \times n$

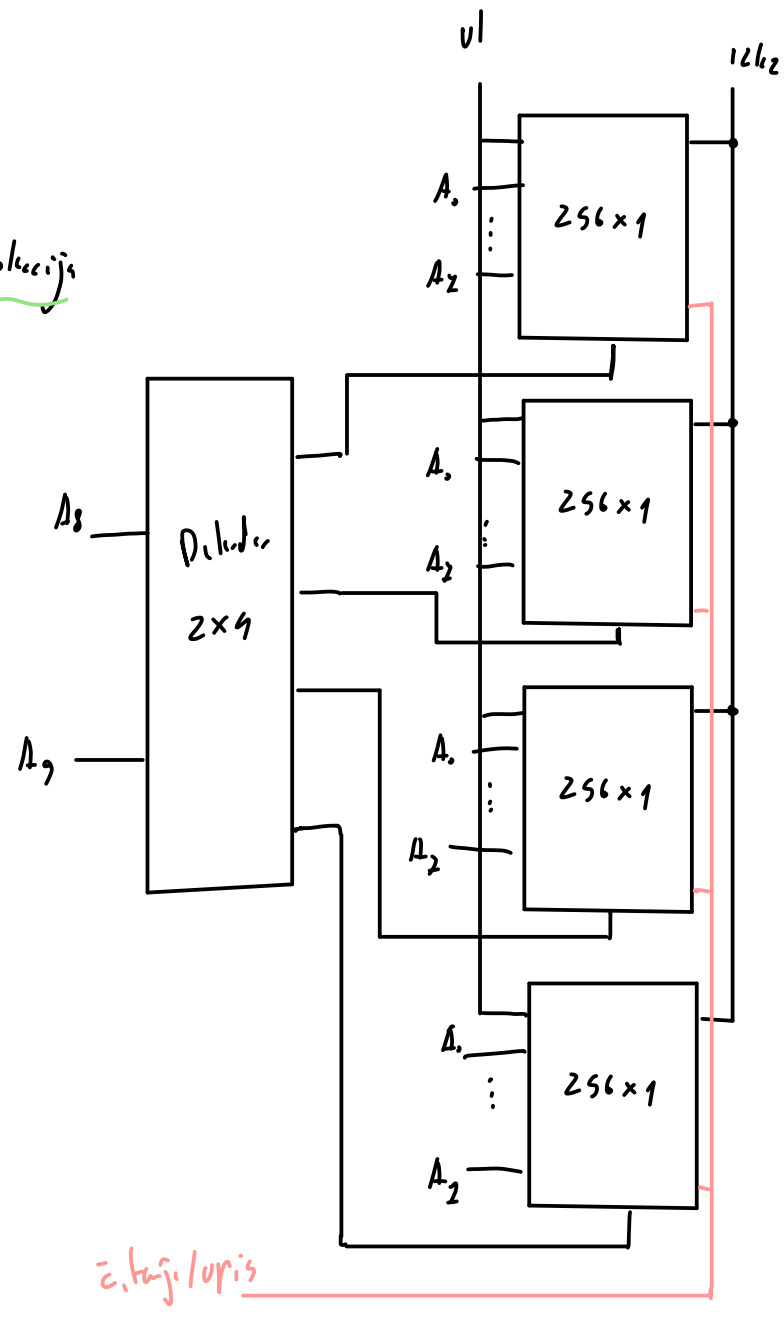
$M = k_2 \times m$

$m \times n = 256 \times 1$

$M \times n = 1024 \times 1$

$M = k_2 \cdot m$

$k_2 = \frac{1024}{256} = 4$



Proširivanje i broja bitova i br. lokacija

$m \times n \rightarrow M \times N$

$M = k_2 \cdot m$

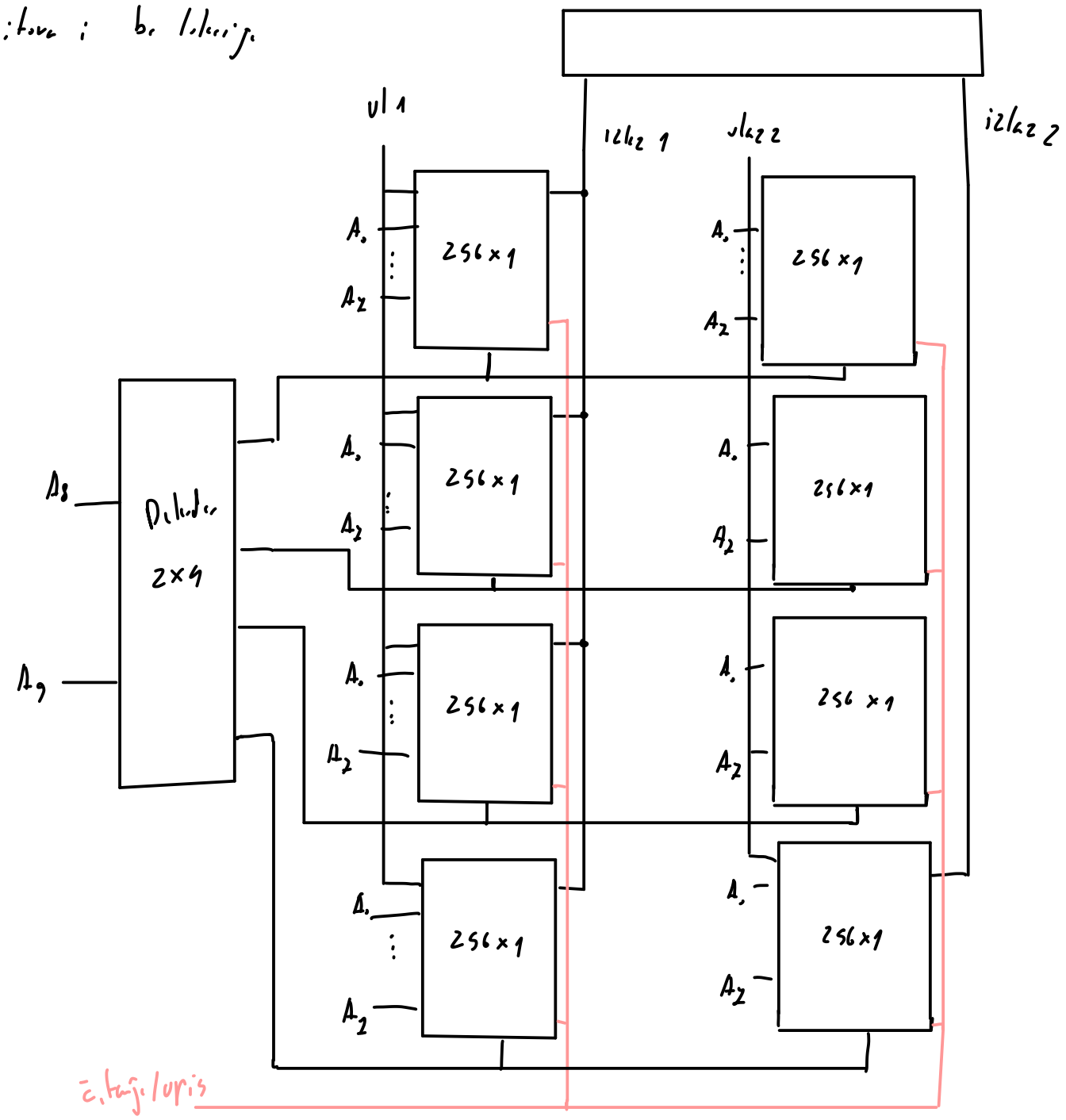
$N = k_1 \cdot n$

256×1

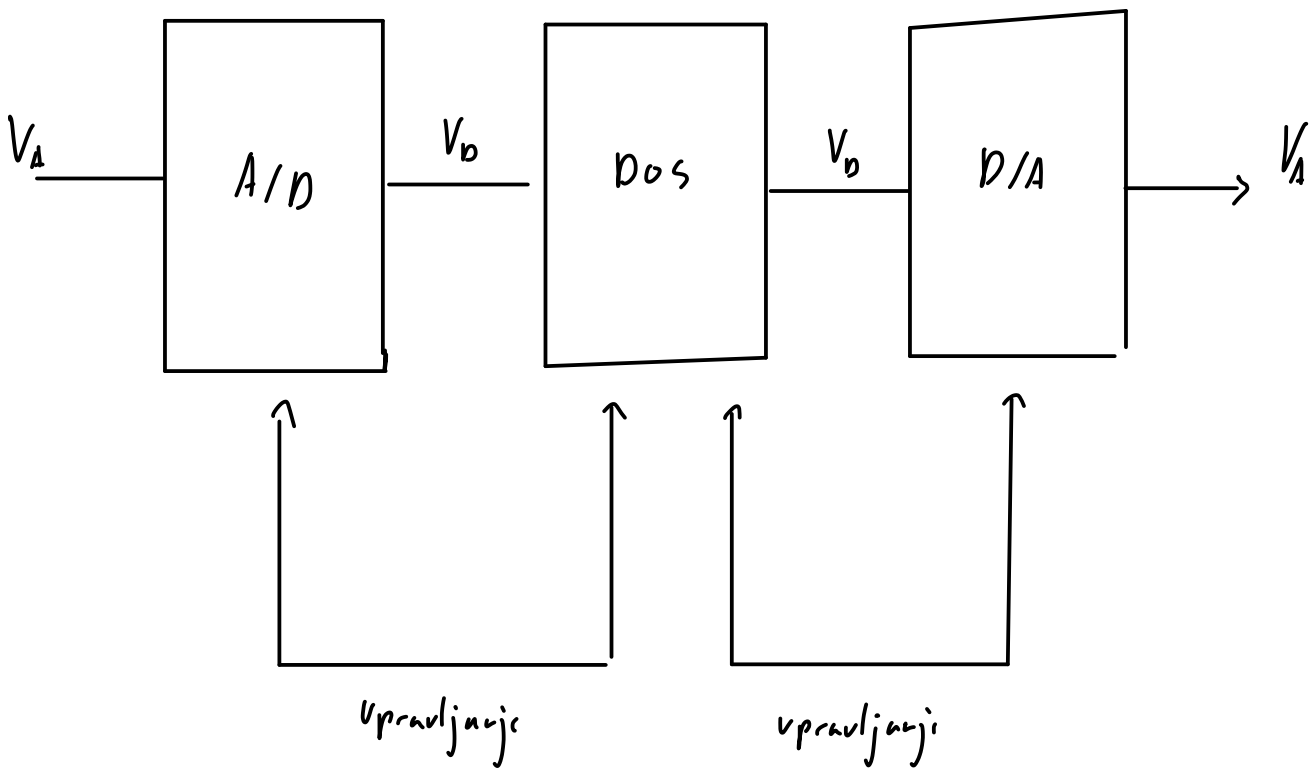
1024×2

$k_2 = 4$

$k_1 = 2$



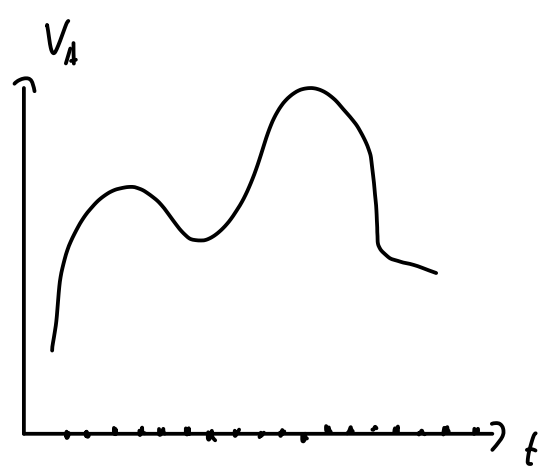
A/D i D/A konverzija



AD:

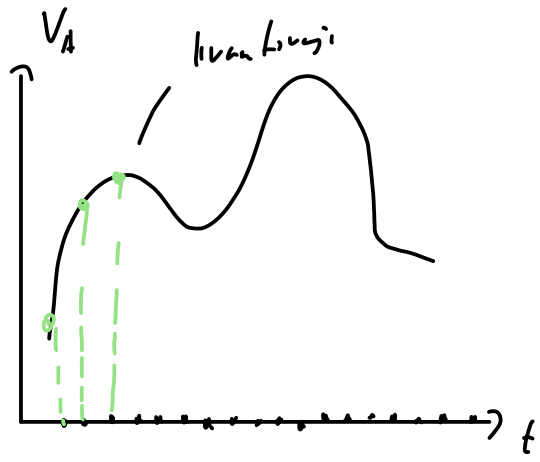
1. odmjeravanje

- određujemo vrem trenutk.
  u kojima ćemo
  očitati signal



2. kvantiziranje

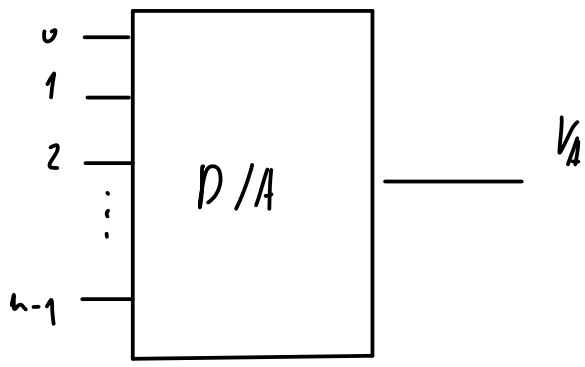
3. kodiranje



D A :

1. Regeneriranje signala
2. Dekodiranje signala

D/A konverzija



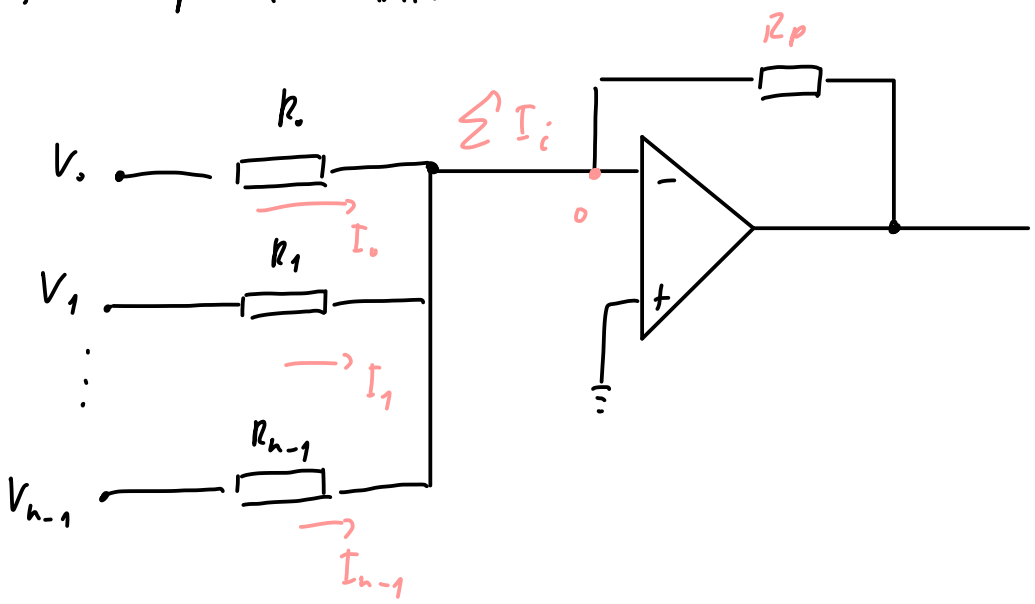
Tehnike D/A konverzije:

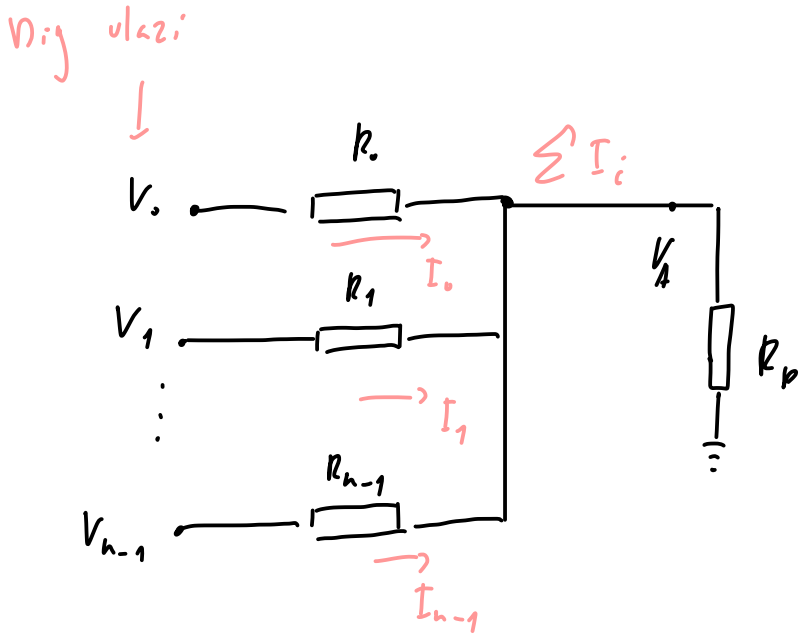
1. Sumiranje / Zbrajanje komponenata struje
2. Integriranje naponskih impulsa

- težinska otporna mreža
- ljestvičasta otporna mreža

* ne mora se učiti izvođenje

Težinska otporna mreža





V_i – "0" ili "1" – strogo def vrijednosti

samo na V_0 log "1"
sve drugo su log "0" $\Big\}$ $V_A = D_v$

D_v – napon kvanta

samo na V_1 log "1"
sve drugo log "0" $\Big\}$ $V_A = 2D_v$

R_i – ne mogu imati proizvoljne vrijednosti

R_0 – ima najveću vrijednost

samo na V_2 log "1"
sve drugo "0" $\Big\}$ $V_A = 4D_v$

$$\boxed{R_i = \frac{R_0}{2^i}}$$

$$V_i = a_i \cdot V_R$$

$a_i = 0$ ili 1

ref. napon

$$R_p = R_0 \parallel R_1 \parallel R_2 \parallel \ldots \parallel R_{n-1}$$

$$V_A = \sum_{i=0}^{n-1} I_i \cdot R_p$$

$$\sum_{i=0}^{n-1} I_i = \frac{V_A}{R_p}$$

$$\frac{1}{R_p} = \frac{1}{R_0} + \frac{1}{R_1} + \ldots + \frac{1}{R_{n-1}}$$

$$I_i = \frac{V_i}{R_i}$$

$$V_A = \frac{\frac{V_0}{R_0} + \frac{V_1}{R_1} + \ldots + \frac{V_{n-1}}{R_{n-1}}}{\frac{1}{R_0} + \frac{1}{R_1} + \ldots + \frac{1}{R_{n-1}}} = \frac{a_0 \cdot 2^0 + a_1 \cdot 2^1 + \ldots + a_{n-1} 2^{n-1}}{2^0 + 2^1 + \ldots + 2^{n-1}} V_R = \boxed{\frac{V_R}{2^n - 1} \sum_{i=0}^{n-1} a_i 2^i}$$

$$R_i = \frac{R_0}{2^i}, \quad V_i = a_i V_R$$

* 2_n $\quad a_0 = 1$, $a_i = 0$, $i = 1 \dots, n-1$

D_V – napon koraka (najmanja vrijednost napona na izlazu)

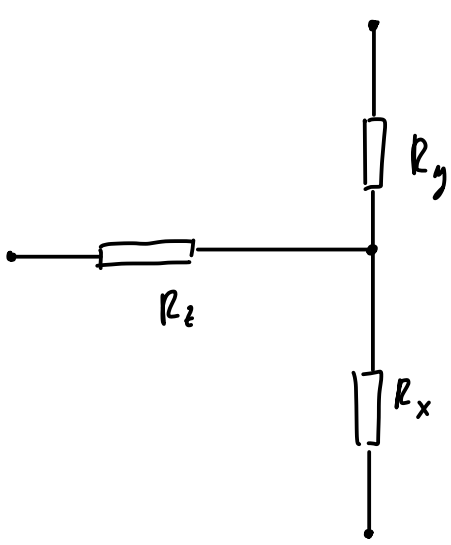
$$\boxed{D_V = \frac{V_R}{2^n - 1}}$$

* $a_i = 1$, $i = 0, \dots, n-1$

V_{APS} – napon pune skale (maks moguća vrijednost napona na izlazu)

$$V_{APS} = \frac{V_R}{2^n - 1}\left(2^0 + 2^1 + \dots + 2^{n-1}\right) = \frac{V_R}{\cancel{2^n - 1}} \cdot \cancel{2^n - 1} = \boxed{V_R}$$

Ljestvičasta otporna mreža



uslov: $R_z \parallel R_x + R_y = R_x$

npr. $R_x = R \rightarrow R_y = \frac{R}{2}$

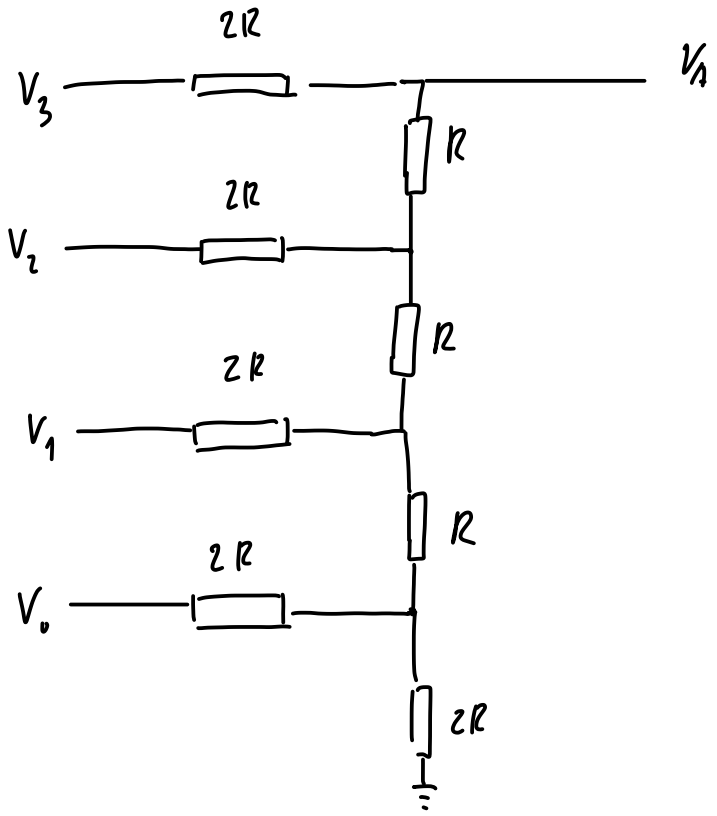
$R_z \parallel R_x = \frac{R}{2}$

$R_z = R_x$

uzimamo:

$R_x, R_z = 2R$

$R_y = R$



iz bil. ky čvora prema masi

→ ekv. otporenost R

!

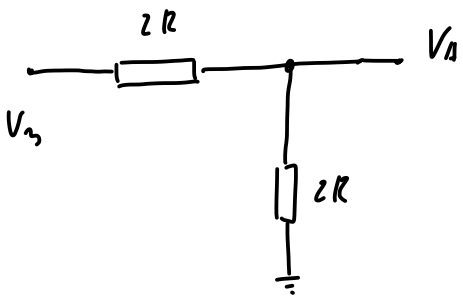
lakše crtanje ekviv. šeme

$V_3 = a_3 V_R \qquad a_3 = 1$

$V_A = \frac{2R}{2R+2R} \cdot V_3$

$a_0 = a_1 = a_2 = 0$

$V_A = \frac{R}{2} V_R$



$$\boxed{V_A = \frac{V_R}{2^n} \sum_{i=0}^{n-1} a_i 2^i}$$

Napon koraka $\qquad a_0 = 1 \qquad a_i = 0 \qquad i = 1, \dots n-1$

$$\boxed{D_V = \frac{V_R}{2^n}}$$

Napon pune skale $\qquad a_i = 1, \quad i = 0, \dots, n-1$

$$V_A = \frac{V_R}{2^n} \underbrace{(2^0 + 2^1 + \dots + 2^{n-1})}_{2^n - 1} = \boxed{\frac{2^n - 1}{2^n} V_R} < R$$

Karakteristike/parametri D/A konverzije

1. Rezolucija

   n - broj digitalnih ulaza $\rightarrow$ rezolucija $1/2^n$ (ili u postocima $1/2^n \cdot 100\%$)

2. Napon pune skale

3. Napon greške $\leq \pm \frac{1}{2} D_V$

4. Linearnost $\leq D_V$

   $\hookrightarrow$ ne smije odstupati više od D_V

5. Brzina konverzije

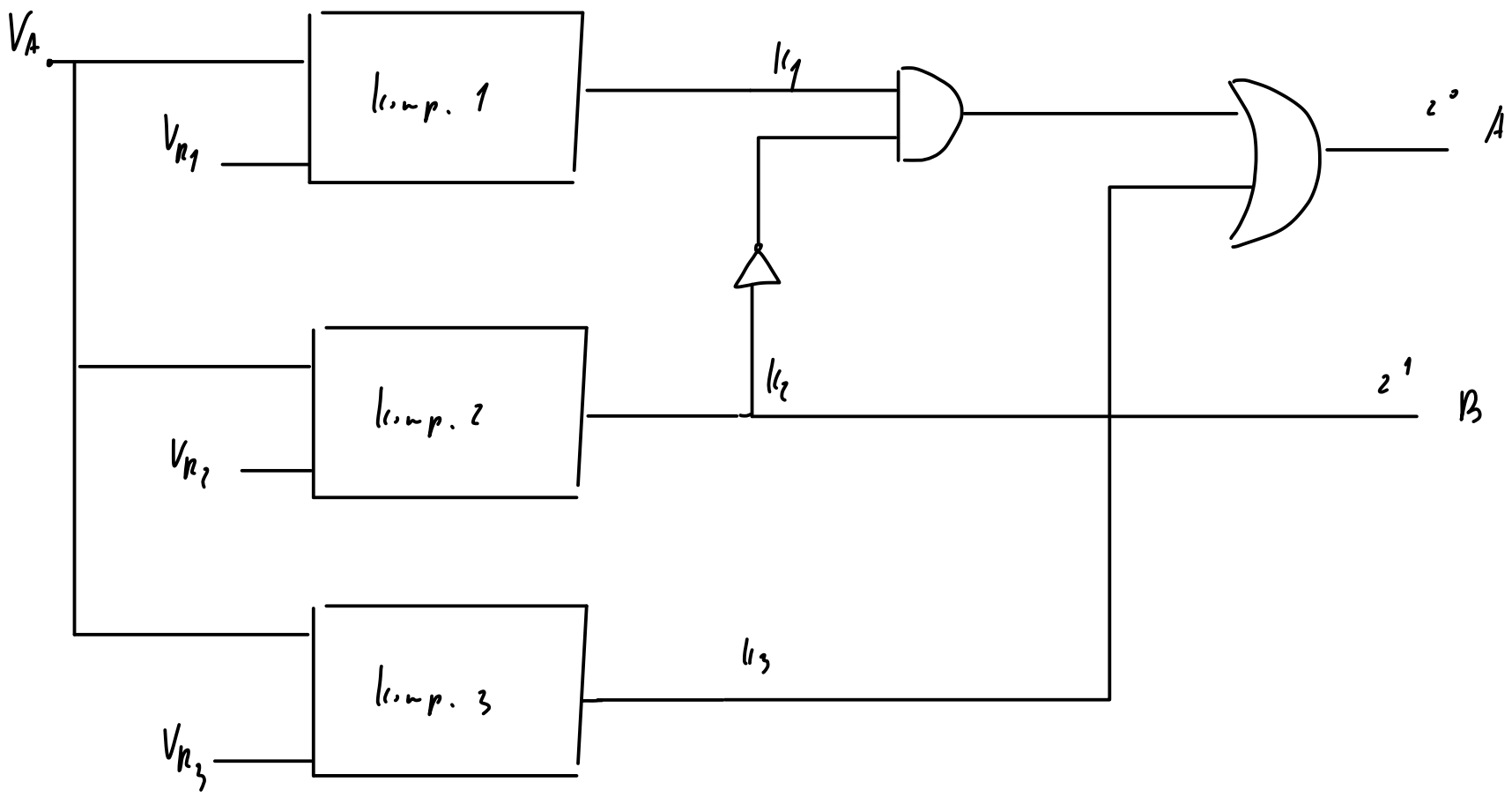
A/D konverzija

Tehnike:

1. Podatak po podatak → najbrža i najskuplja (flaš konvertori)
2. Bit po bit → analiza faktnih intervala kolika je bitova
3. Kvant po kvant

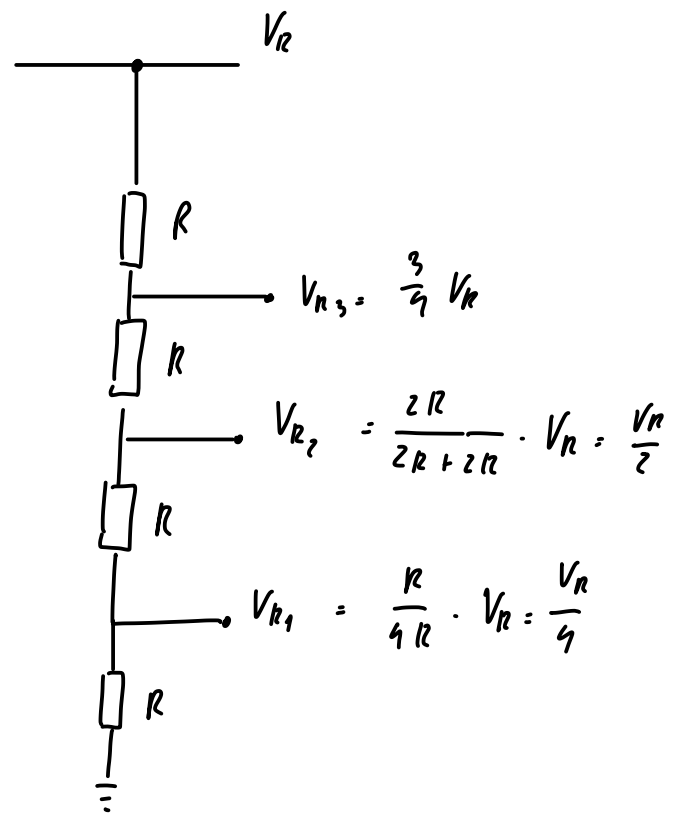
Konverzija sa paralelnim komparatorima

- podatak po podatak



$A = K_1 \cdot \overline{K_2} + K_3$

$B = K_2$



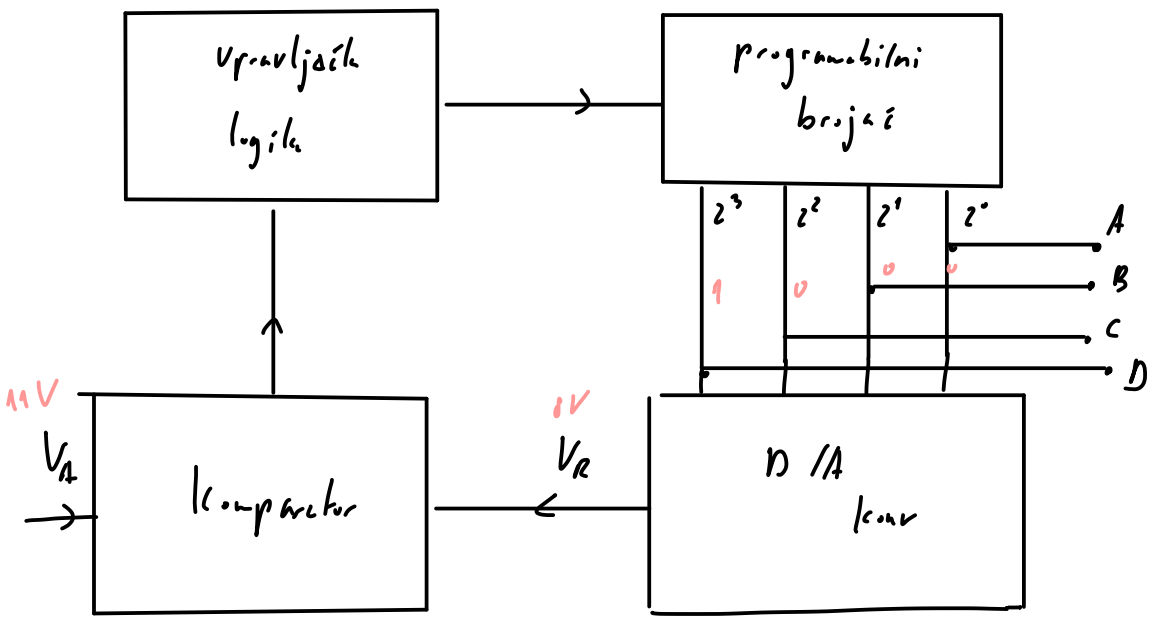
V_A (analogni ulaz)	K_1	K_2	K_3	B	A
$0 < V_A < V_{R1}$	0	0	0	0	0
$V_{R1} < V_A < V_{R2}$	1	0	0	0	1
$V_{R2} < V_A < V_{R3}$	1	1	0	1	0
$V_{R3} < V_A < V_{Rmax}$	1	1	1	1	1

U 1 taktnom signalu

$V_A = 11\,V$ $\quad D_V = 1\,V$

Komparatori sa programabilnim brojačem

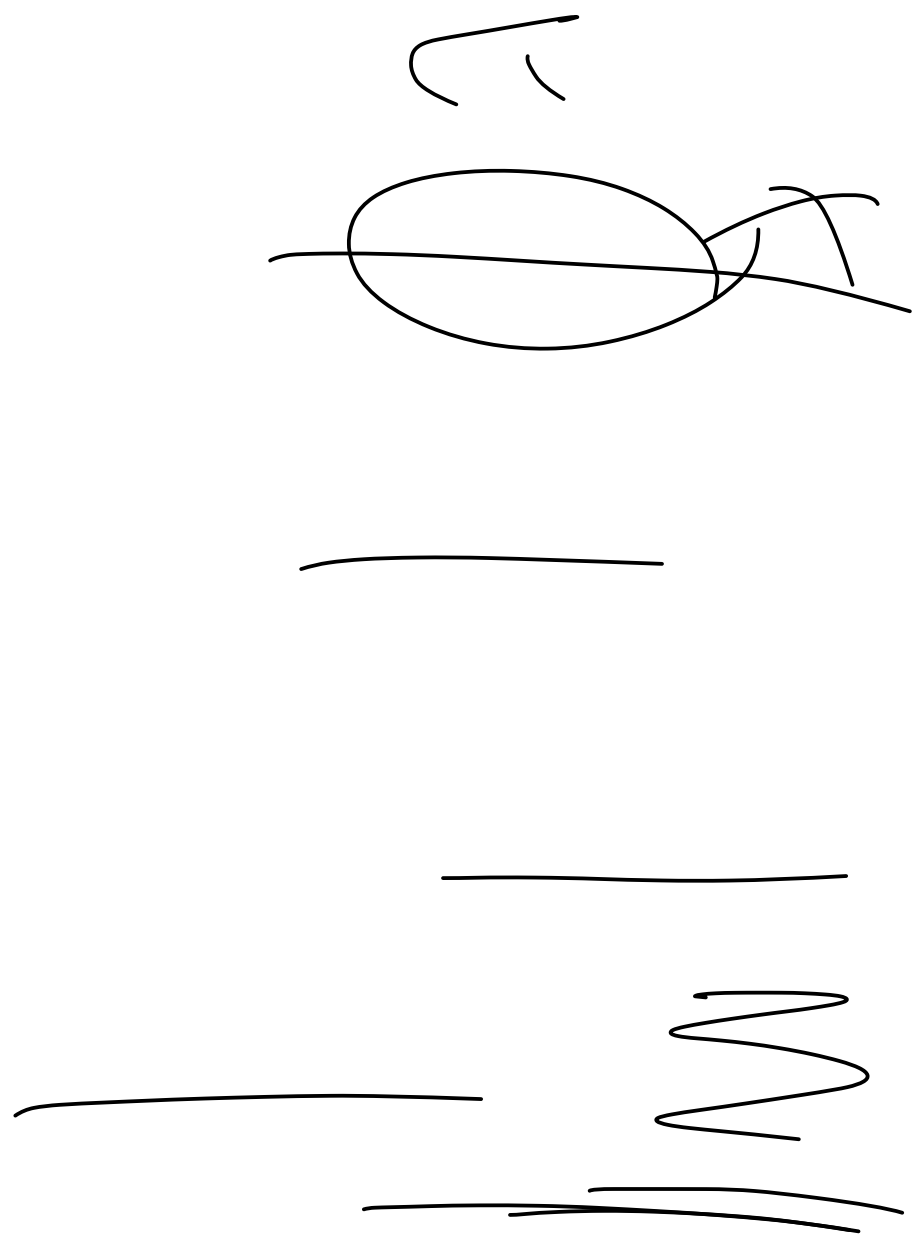
- bit po bit



	stanje brojača	V_R	konv.	dig. izlaz
1. taktni interval	1 0 0 0 (D C B A)	8 V	$V_A > V_R$	D = 1
2. taktni interval	1 1 0 0	12 V	$V_A < V_R$	C = 0
3. taktni interval	1 0 1 0	10 V	$V_A > V_R$	B = 1
4. taktni interval	1 0 1 1	11 V	$V_A = V_R$	A = 1

→ zadržavam vrijednost

zaustavljam.

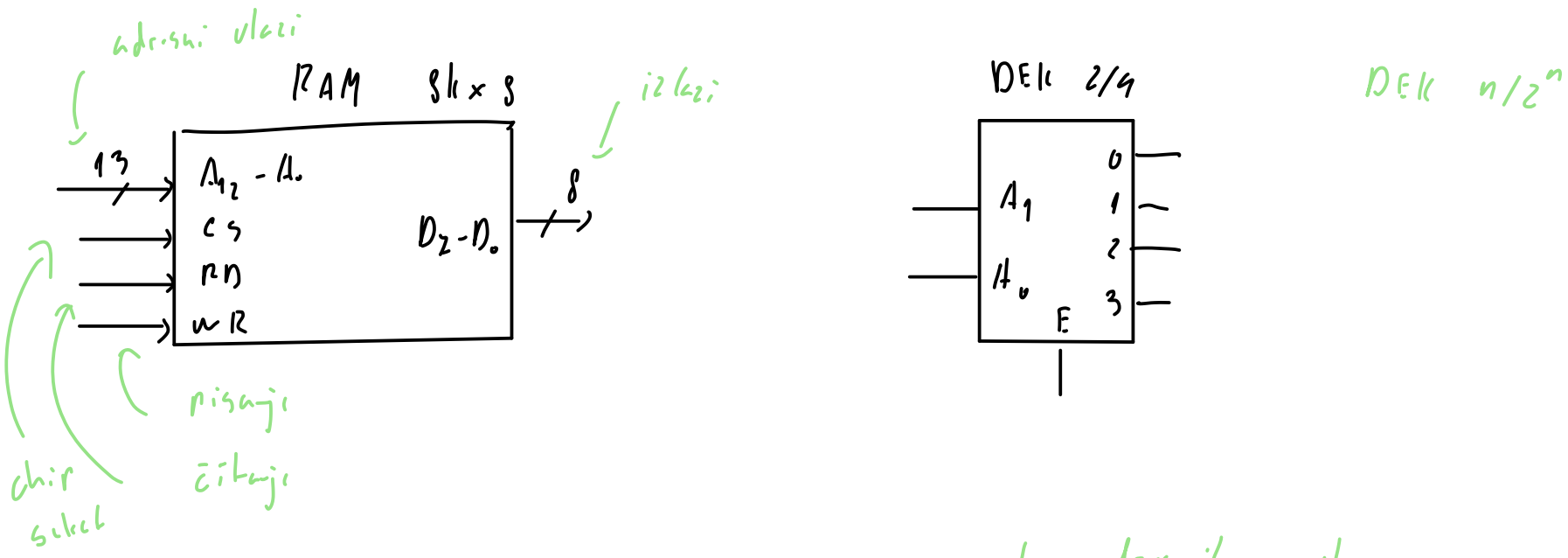


Vježbe 27.12.

1. Nacrtati blok shemu mem. RAM tipa kapacitete 128x8 kb ako su na raspolaganju mem. komponente kap 8kx8 i dekoderi 2x4

Koraci:

1. Određujemo br adresnih ulaza komponente koja nam je na raspolaganju
2. Određujemo n dekodera
3. Određujemo br RAM komponenti koje su nam na raspolaganju
4. Određujemo ukupan br adresnih ulaza
5. Određujemo br nivoa dekoderske mreže
6. Određujemo br nivoa u n-tom nivou dek. mreže
7. Crtamo shemu



8k x 8 $\quad 8 \cdot 1024 = 2^3 \cdot 2^{10} = 2^{13}$ → br adresnih ulaza

DEK 2/4 → $n=2$

$N = \frac{128k \times 8}{8k \times 8}$ → kapac. mem koju želimo da realizujemo / kap mem koju imamo — br komponenti mem

128k x 8 : $128 \cdot 1024 = 2^7 \cdot 2^{10} = 2^{17}$ → br adresnih ulaza čitave mreže

K - br nivoa dekodera

$$K = \left\lceil \frac{12-13}{n} \right\rceil = \left\lceil \frac{9}{2} \right\rceil = 2$$

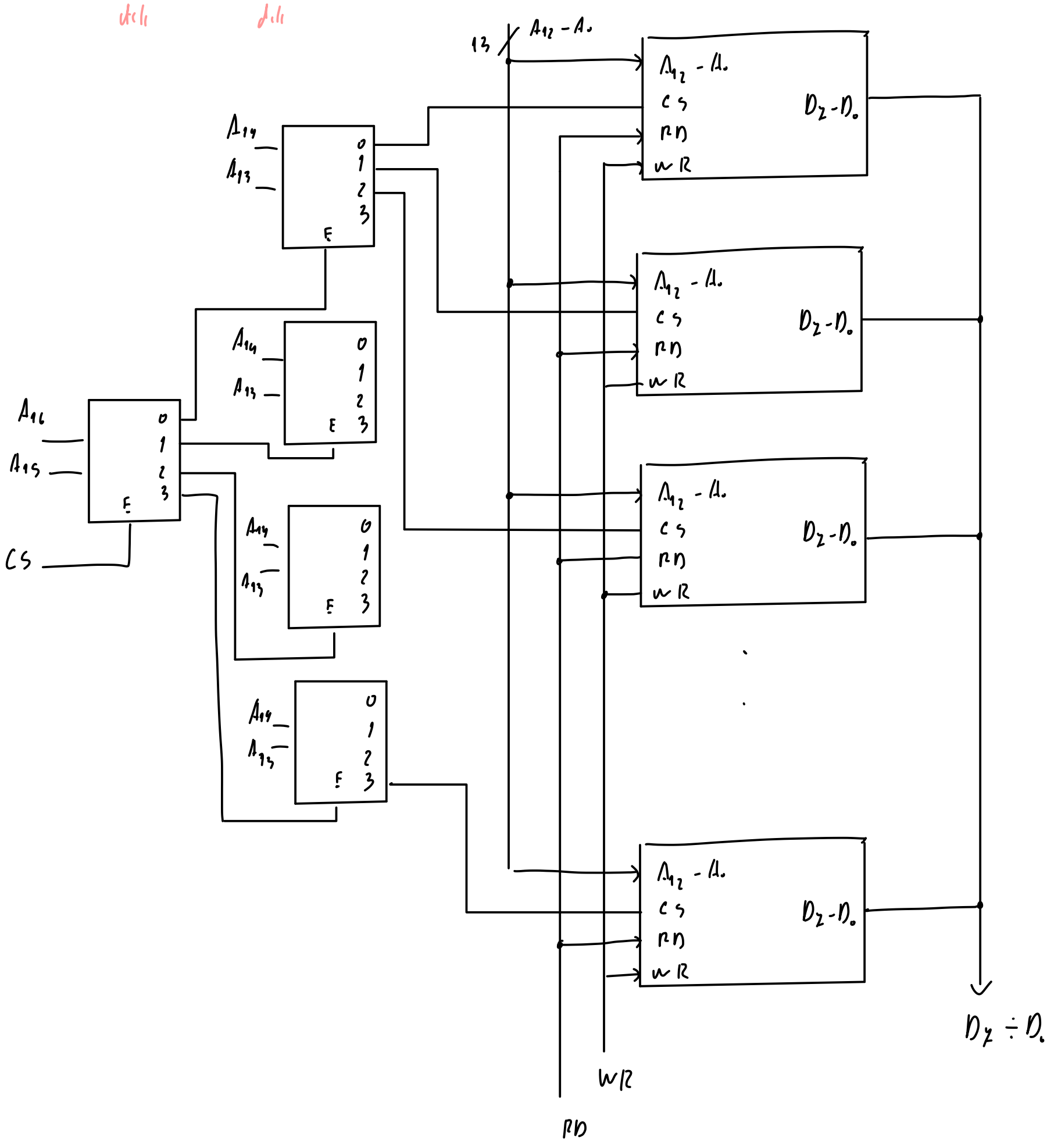
M - br dekodera u n-tom nivou

$$M = \left\lceil \frac{M}{2^n} \right\rceil = \left\lceil \frac{16}{2^2} \right\rceil = 4$$

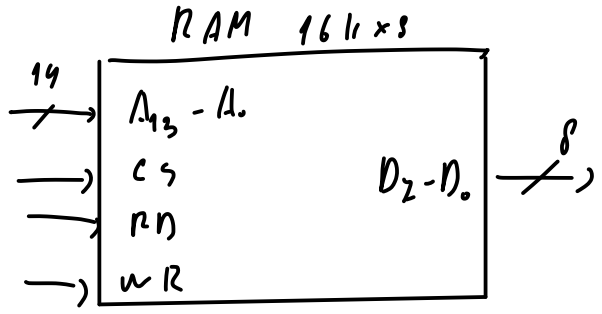
- br dekodera u 2. nivou

Adresni vodovi ulazi u kompl:

$\underbrace{A_{16} \quad A_{15}}_{\text{1 nivo dekodera}} \quad \underbrace{A_{14} \quad A_{13}}_{\text{2 nivo dekodera}} \quad \underbrace{A_{12} \quad \dots \quad A_0}_{\text{svi ostali ulazi}}$



2. Nacrtati blok šemu mem RAM tipa kapacitete 512 k×16 ako su na raspolaganju mem. komp 16k×8 i DEK 3/8



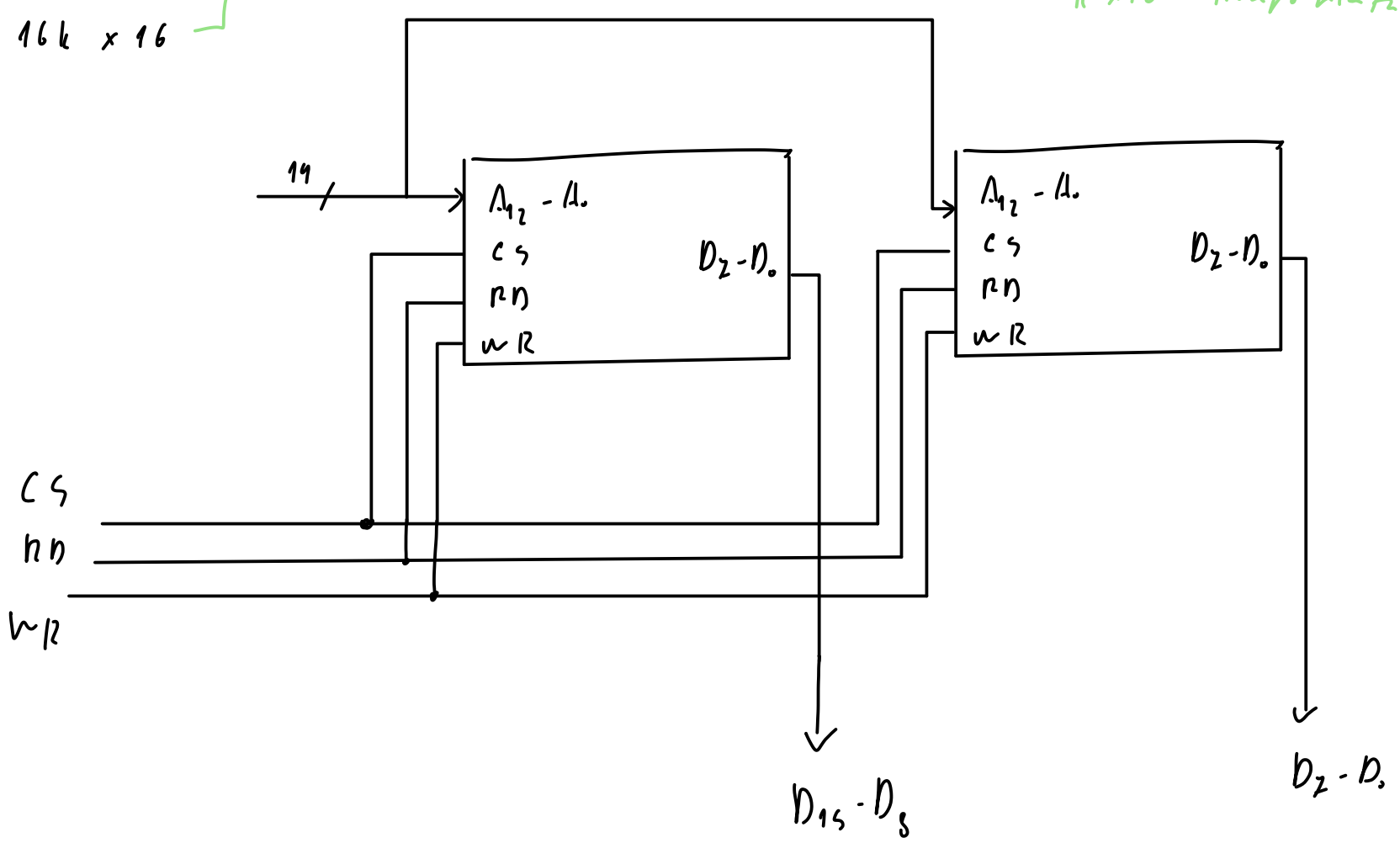
n = 3

16k × 8 16 · 1024 = $2^4 \cdot 2^{10} = 2^{14}$ ulazi komponente

512k × 16

16k × 16

16k × 16 komponenta



19 ulaza

512k×16 $512 \cdot 1024 = 2^9 \cdot 2^{10} = 2^{19}$

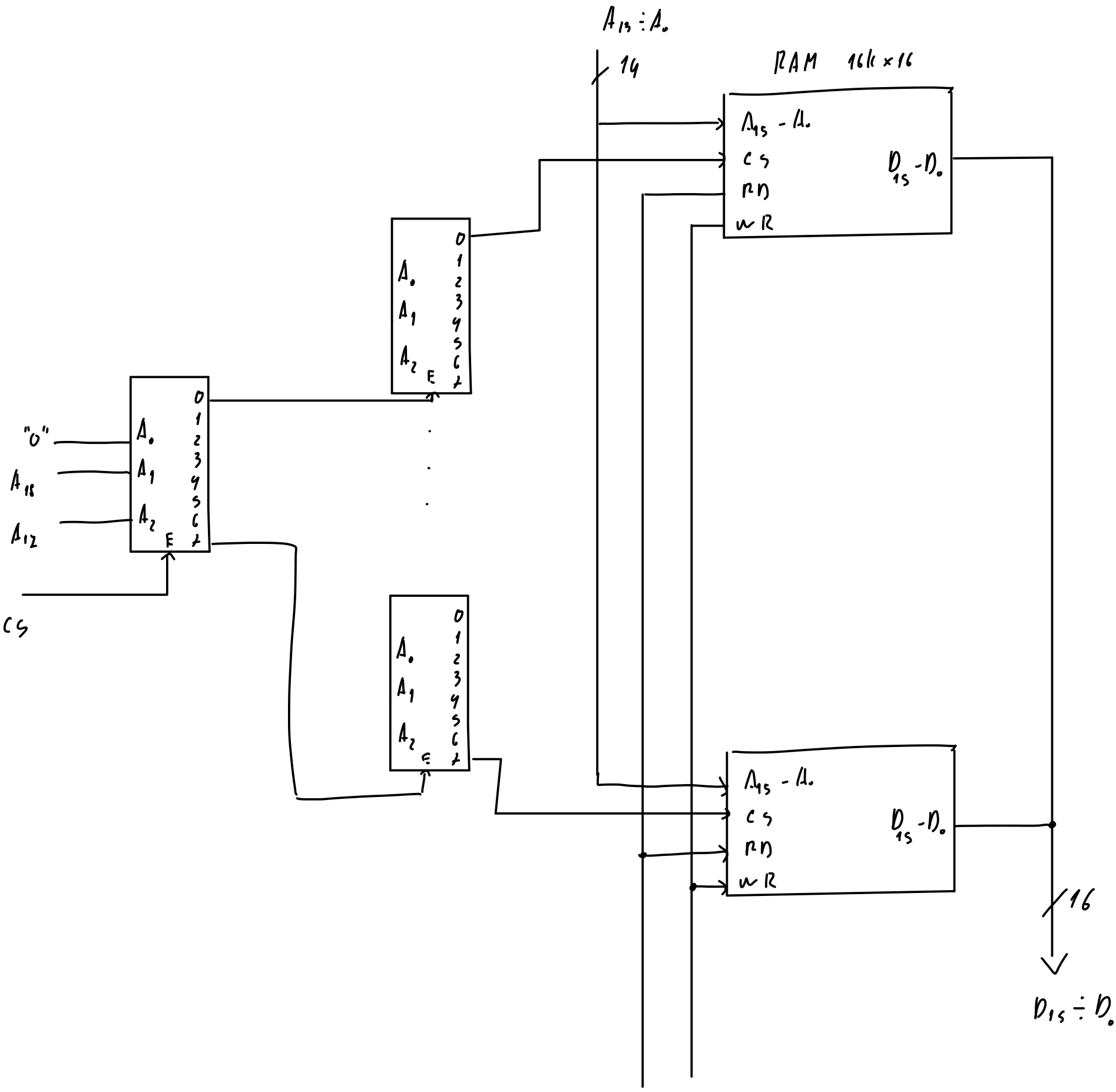
$$K = \left\lceil \frac{19-14}{n} \right\rceil = \left\lceil \frac{5}{3} \right\rceil = 2$$

$$N = \frac{512k \times 16}{16k \times 16} = 32$$

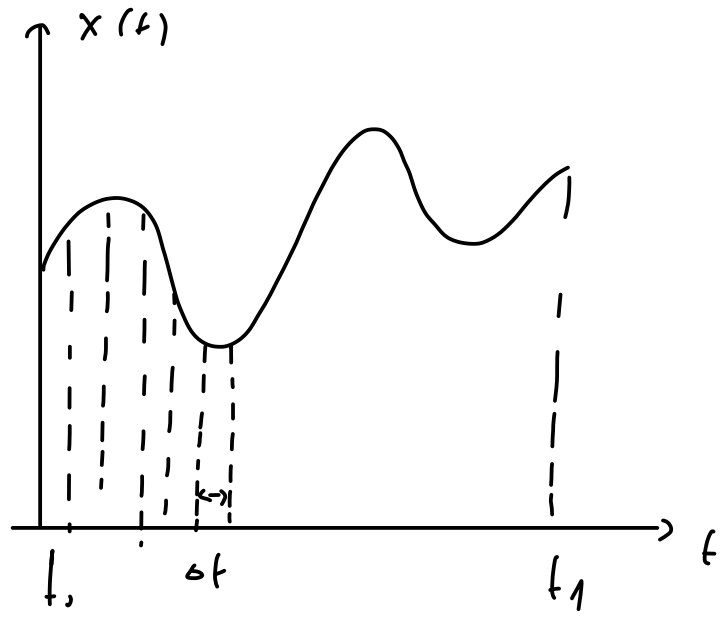
nova komponenta

$$M = \left\lceil \frac{N}{2^n} \right\rceil = \left\lceil \frac{32}{8} \right\rceil = 4$$

$$\underbrace{A_{18}\ A_{17}}_{1\ \text{niv}}\ \underbrace{A_{16}\ A_{15}\ A_{14}}_{2\ \text{niv}}\ A_{13}\ A_{12}\ \dots\ A_0$$


A13 ÷ A0
14
RAM 16k x 16
A13 - A0
CS
RD
WR
D15 - D0
"0"
A13
A12
CS
A0
A1
A2
E
0
1
2
3
4
5
6
7
16
D15 ÷ D0

Vježbe 30.12.2024.



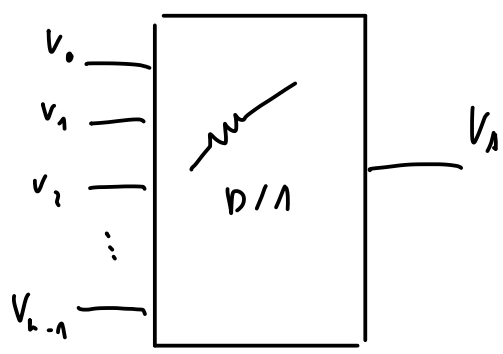
D/A :

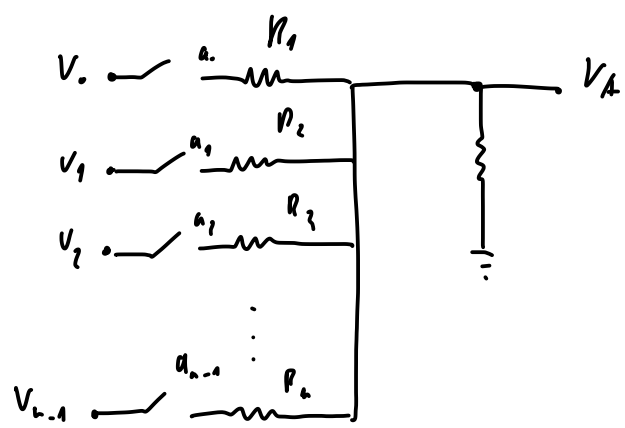
1. diskretizacija
2. kvantizacija

D/A konverter:

1. Otporna mreža
2. Ljestvičasta mreža

1) Otporna mreža





$R_i = \frac{R}{2^i}$

$V_0 \rightarrow D_V$, ΔV

$V_1 \rightarrow 2 D_V$

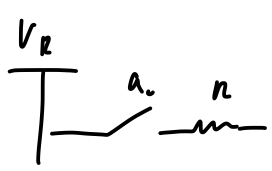
$\vdots$

$V_{n-1} \rightarrow n D_V$

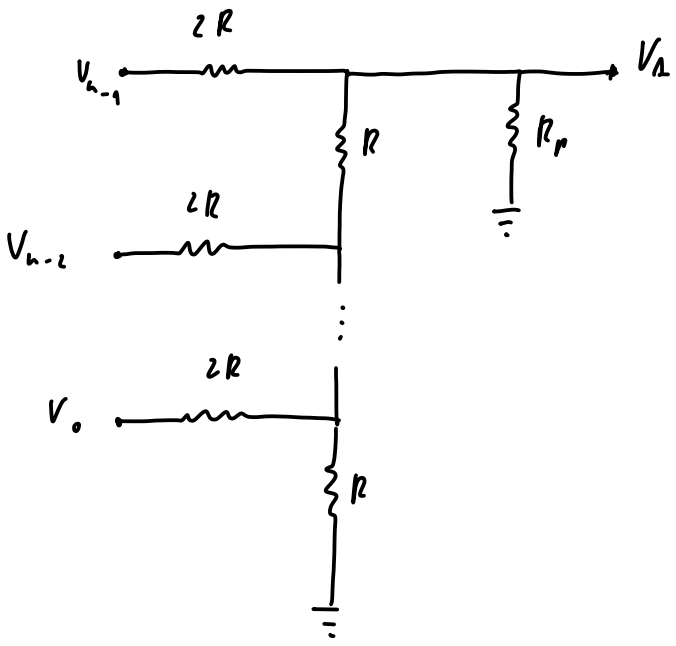
$$V_i = a_i V_R$$

$$V_A = \frac{V_R}{2^n - 1} \sum_{i=0}^{n-1} a_i 2^i$$

$$a_i = \begin{cases} \text{"0"} & \text{, nak.} \\ \text{"1"} & \text{, akt.} \end{cases}$$

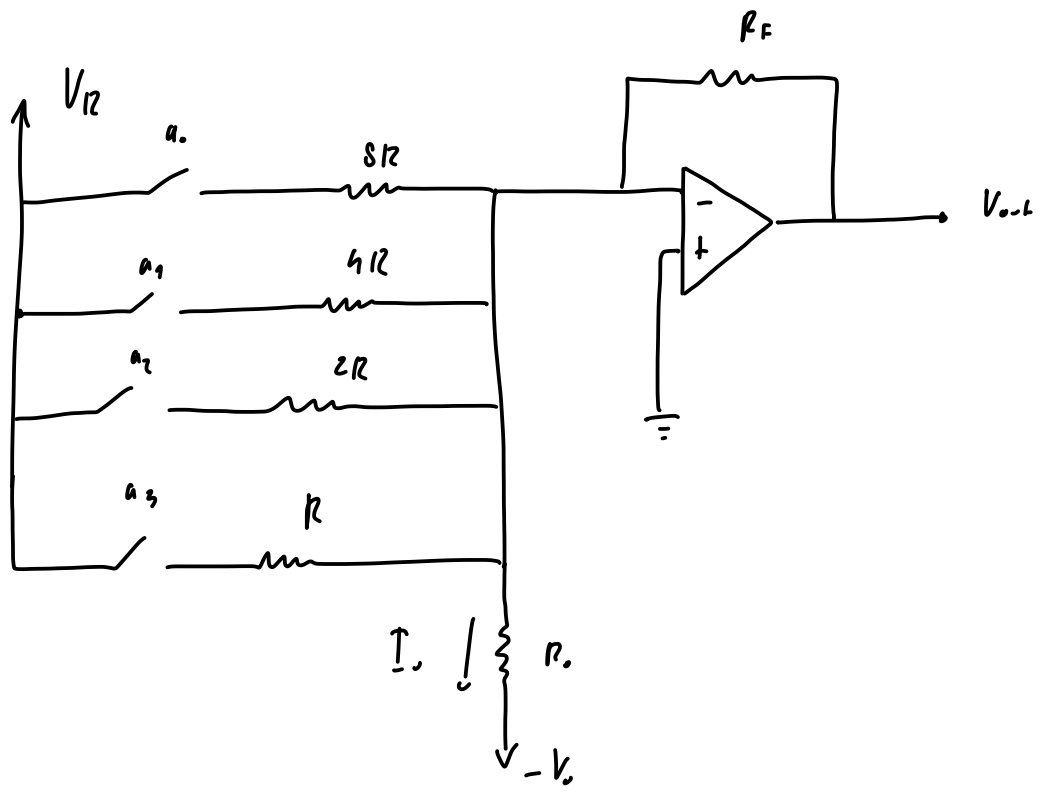


2) Ljestvičasta mreža

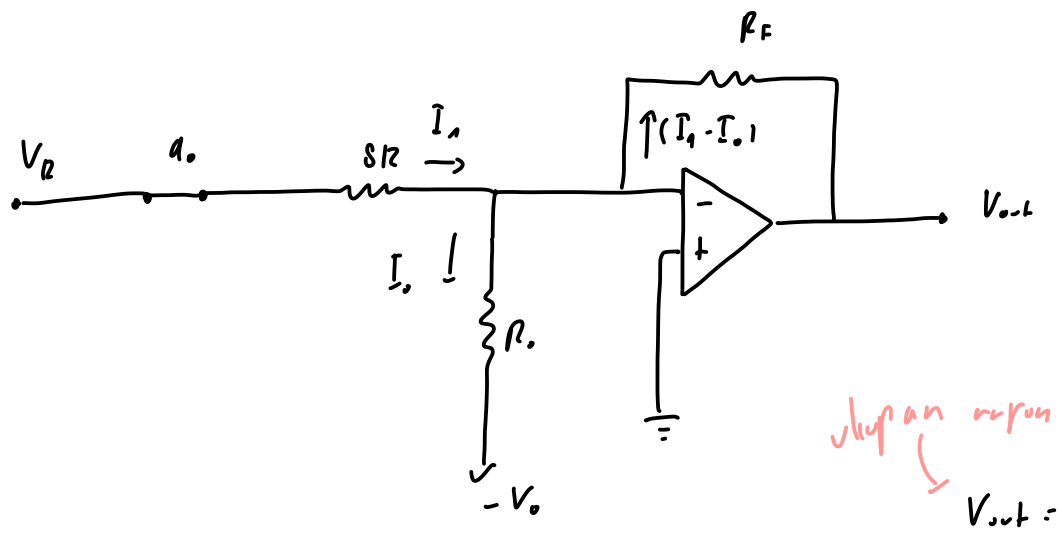


$$V_A = \frac{V_R}{2^n} \sum_{i=1}^{n-1} a$$

Projektirati tri. mreži D/A konvertora za BCDx53 kod. Odrediti napon kvanta i napon pune skale



Sam. a_0 uključen:



$$V_{out} = -(I_1 - I_0)R_F$$

$$I_0 = \frac{V_0}{R_0}, \quad I_1 = a_0 \frac{V_R}{8R}$$

$$V_{out} = \frac{R_F}{R_0} V_0 - a_0 \frac{V_R}{8R} R_F$$

ulazni napon -> svi uključeni

$$V_{out} = \frac{R_F}{R_0} V_0 - V_R \frac{R_F}{R} \left(\frac{a_0}{8} + \frac{a_1}{4} + \frac{a_2}{2} + a_3 \right) \quad (1)$$

"0" ⟶ 0011

a_3 i $a_2 = 0$

a_1 i $a_0 = 1$

$$0 = \frac{R_F}{R_0} V_0 - V_R \frac{R_F}{8R} - V_R \frac{R_F}{4R}$$

$$\frac{R_F}{R_0} V_0 = \frac{3}{8} V_R \frac{R_F}{R} \quad (2) \quad \rightarrow (1)$$

$$V_{out} = \frac{3}{8} V_R \frac{R_F}{R} - V_R \frac{R_F}{8R} \sum_{i=0}^{3} a_i 2^i$$

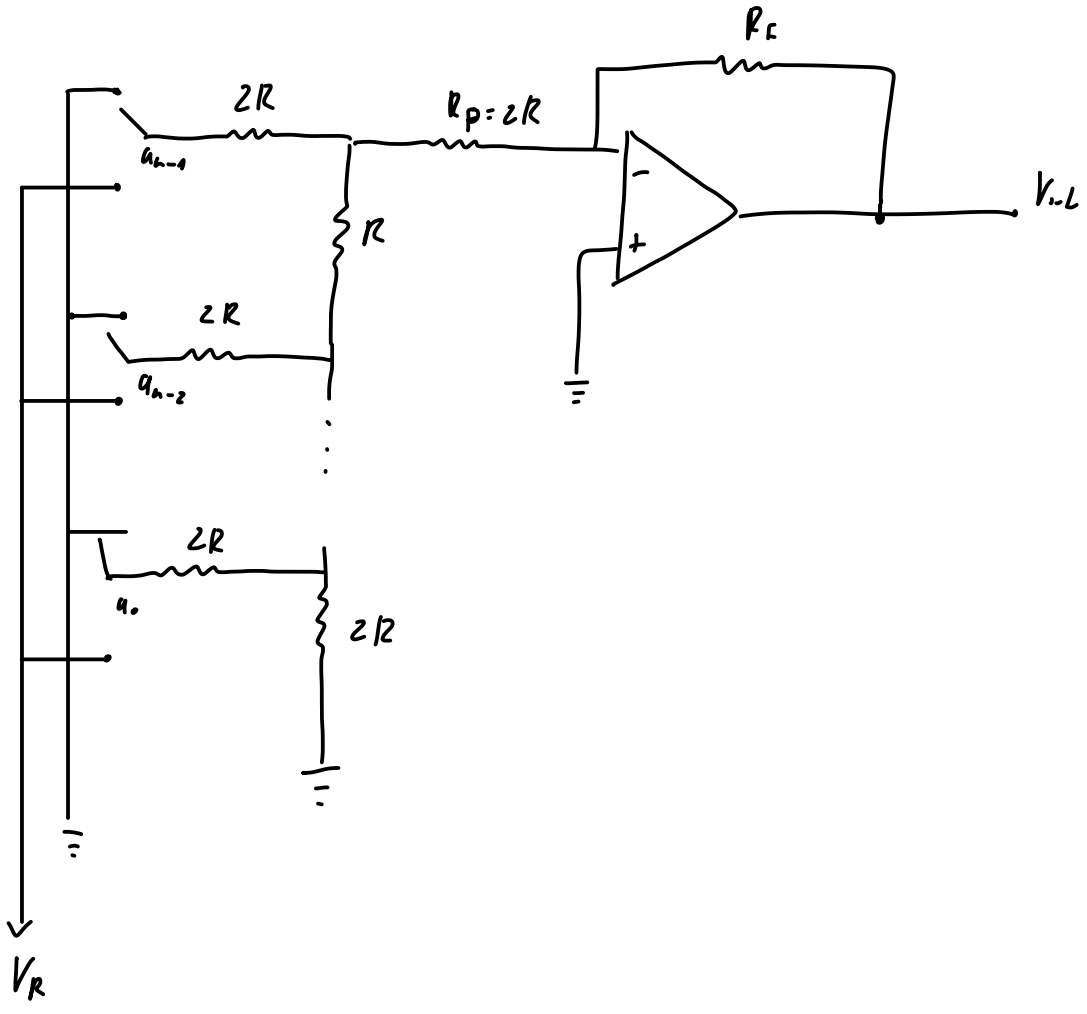
$$\boxed{V_{out} = V_R \frac{R_F}{8R} \left(3 - \sum_{i=0}^{3} a_i 2^i\right)}$$

konačan izraz

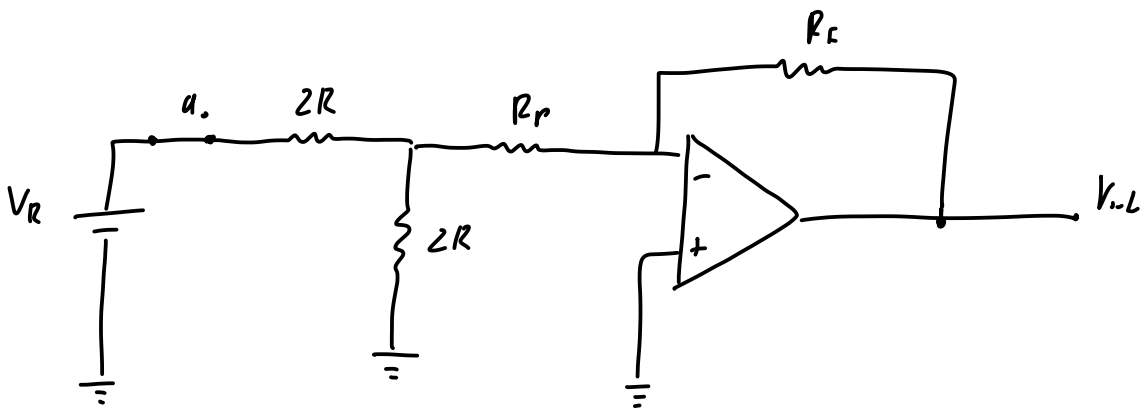
Napon kvanta $\boxed{D_r = V_R \frac{R_F}{4R}}$

Napon pune skale $\boxed{V_{aps} = -\frac{3}{2} V_R \frac{R_F}{2}}$

2. Za D/A konverter odrediti izraz za izlazni napon i odrediti pod kojim uslovima važi da $\Delta V = \frac{V_R}{2^n}$ (napon kvanta)



a_0 ON

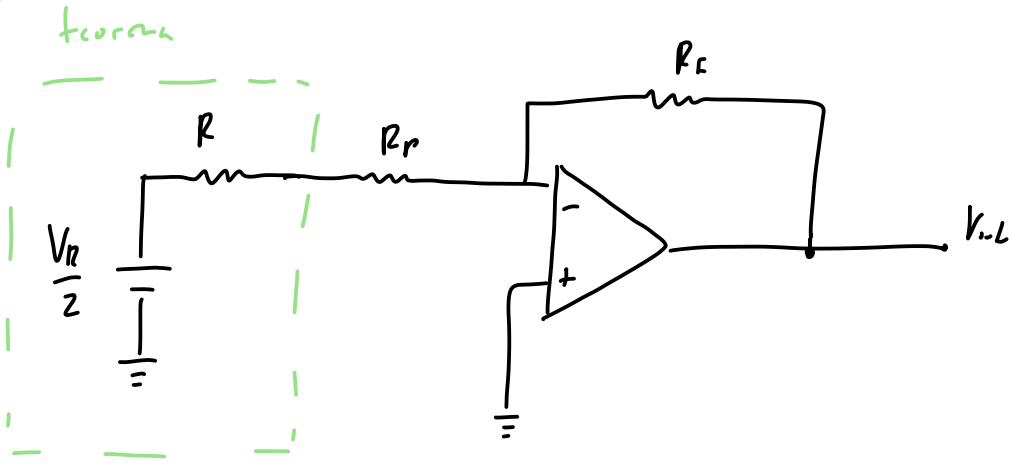


$E_T = \frac{V_R}{2}$ – naponski razdjelnik

$R_T = R$

$\frac{2R}{2}$

Thevenin teorem



$$V_{out} = -\frac{R_F}{R+R_p}\frac{V_R}{2}a_0$$

opći izraz:

$$\boxed{V_{out} = -\frac{R_F}{R+R_p}\frac{V_R}{2^n}\sum_{i=0}^{n-1} a_i 2^i}$$

n-br bita

$$\Delta V = -\frac{R_F}{R+R_p}\frac{V_R}{2^n}$$

$$\Delta V = \frac{V_R}{2^n}$$

$$\cancel{\frac{V_R}{2^n}} = \frac{R_F}{R+R_p}\cancel{\frac{V_R}{2^n}}$$

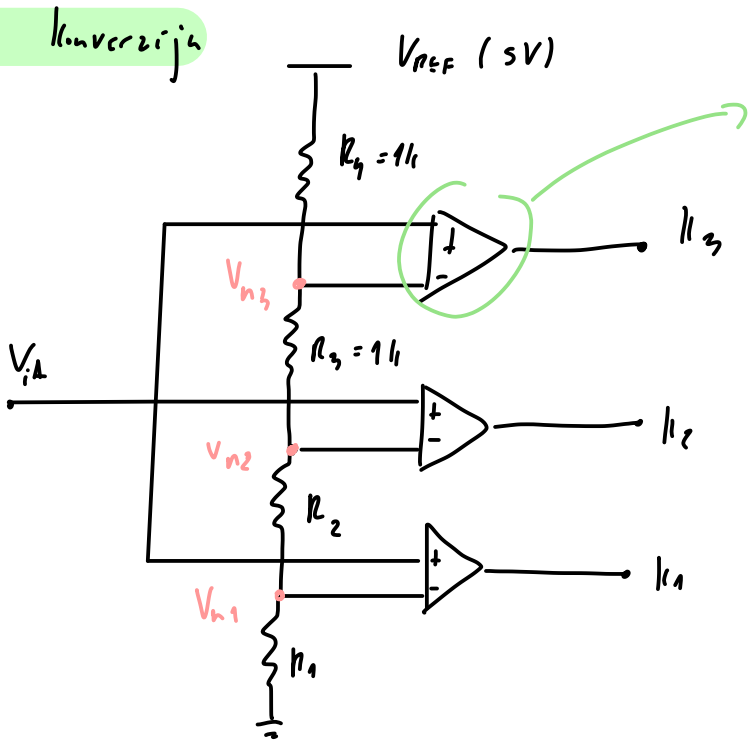
$$\boxed{\frac{R_F}{R+R_p} = 1}$$ uslov

$R_p = 2R$

$$\boxed{R_F = 3R}$$

A/D konverzija

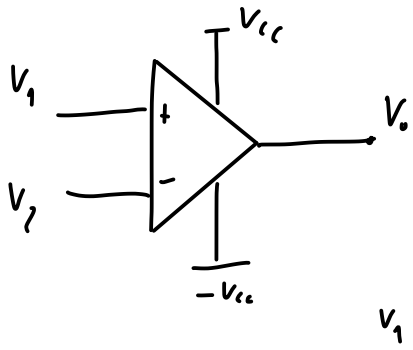
3.

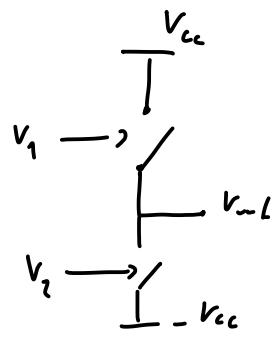


nema potrebe spregu s komparator

$V_1 > V_2 \Rightarrow V_{out} = V_{cc}$

$V_1 < V_2 \Rightarrow V_{out} = -V_{cc}$





$V_{iA} < V_{R1} \Rightarrow K = K_3 K_2 K_1 = 000$

$V_{n1} \leq V_{iA} < V_{n2} \Rightarrow K = 001$

$V_{n2} \leq V_{iA} < V_{n3} \Rightarrow K = 011$

$V_{n2} \leq V_{iA} < V_{REF} \Rightarrow K = 111$

$$\boxed{V_{ni} = \frac{\sum_{j=1}^{i} R_j}{R_n} V_{REF}}$$

$$\boxed{R_n = \sum_{j=1}^{m} R_j}$$

m broj komparatora

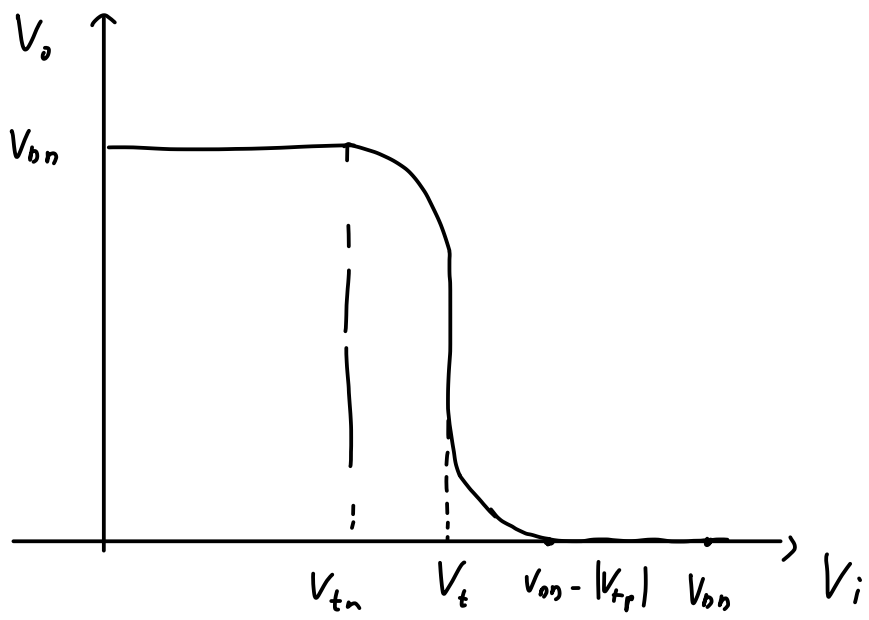
$R_n = 4\,k\Omega$

$V_{n1} = 0.25\,V_{REF} = \Delta V$ najlakši bit

$V_{n2} = 0.5\,V_{REF}$

$V_{n3} = 0.25\,V_{REF}$

Rezolucija

$m + 1 = 4 = 2^{2}$ → 2 bitna rezolucija

Lab 4