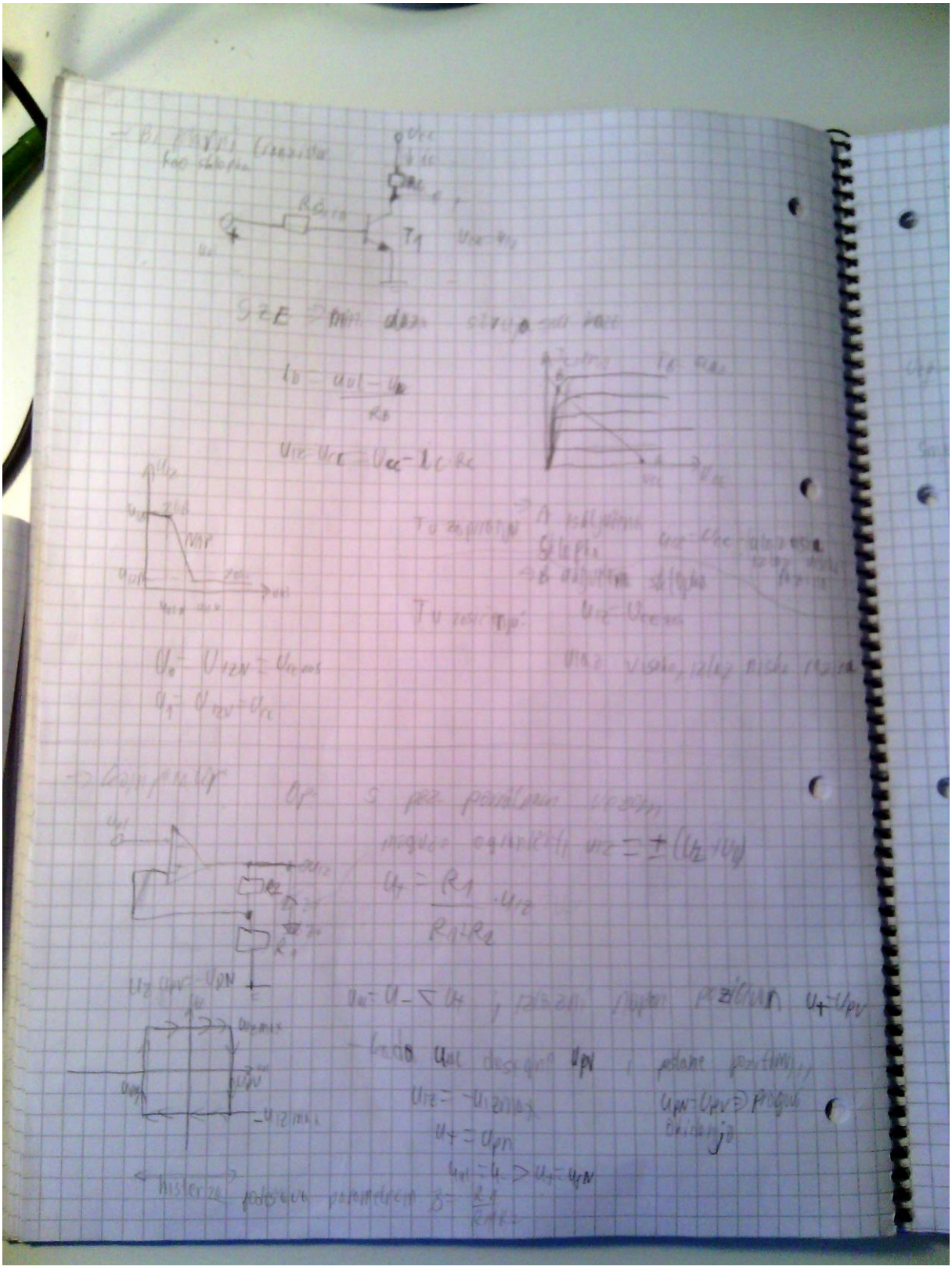
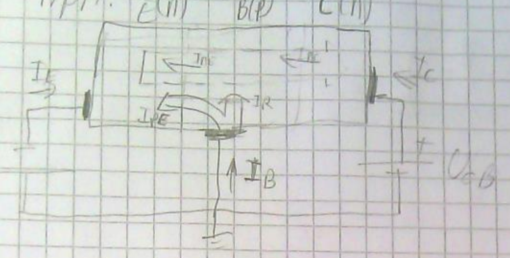


→ Dinamika u NAP

npn:



Emiter injektira elektrone u bazu, a baza šupljine u emiter

Smjer str. I_{nE} supr. smjeru kretanja elektrona, I_{pE} jednak

- niska injekcija: injektirane šup. u emiteru i elektroni u bazi udaljavaju se od osiromašenog sloja difuzijom pa stvaraju struje

Difuzijske struje manjinskih nosioca

- U bazi, dio manjinskih elektrona rekombinira se s većinskim šupljinama u bazi, dio dolazi do kol. baze
- Vrlo mali se dio rekombinira $= I_R$
- prelazak el. u kolektor određuje I_{nC}

$I_E + I_B + I_C = 0$

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

$I_C = I_{nC} + I_{CBO}$

str. zasićenja I_C

strujna poj. SZE $\alpha = \frac{I_C}{-I_E}$

SZB $\beta = \frac{\alpha}{1-\alpha} = h_{FE} = \frac{I_C}{I_B}$

fak. inj. $\gamma = \frac{I_{nE}}{-I_E}$

trans. $\beta^* = \frac{I_{nC}}{I_{nE}}$

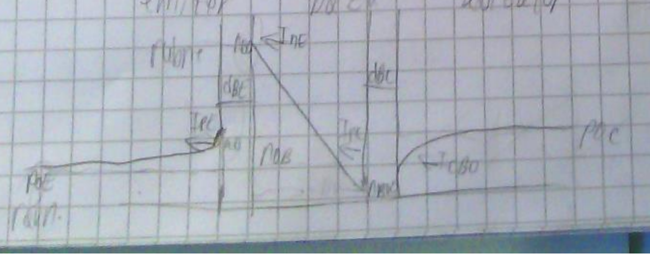
$I_B = I_{pE} + I_R - I_{CBO}$

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

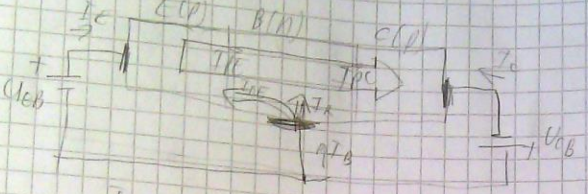
$n_{0B} = \frac{n_i^2}{N_{AB}}$ $p_{0E} = \frac{n_i^2}{N_{DE}}$

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

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



pnp



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

$I_C = -I_{pC} + I_{CBO}$

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

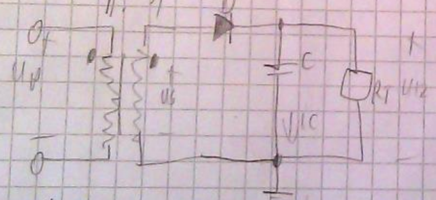
$I_B = -I_{nE} - I_R - I_{CBO}$

$\gamma = \frac{I_{pE}}{I_E}$

$\beta^* = \frac{I_{pC}}{I_{pE}}$

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

→ Ispravljač sa kapacitivnim opterećenjem

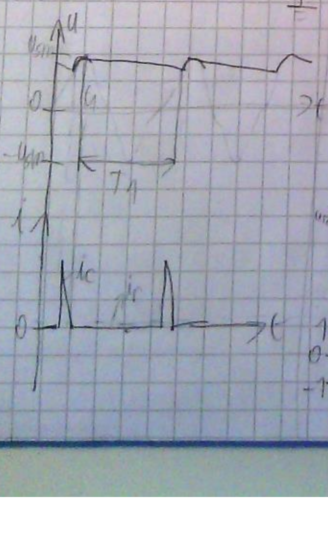


– kondenzator paralelno spojen kao filtar za glačenje izmj. komponente

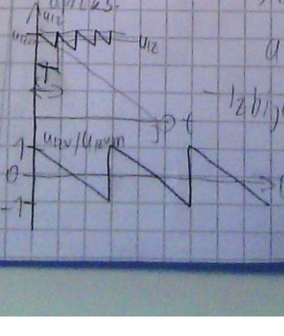
– Dioda vodi struju pri porastu u_s, s njime i C (1→U_{sm}), a nakon toga u_s se počinje smanjivati, obično zbog nakrcanog naboja napon ne može slijediti u_s i u_{iz} ostaje pozitivniji od u_s

– Izbijanje traje dok je D zap. pol.

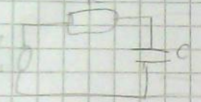
$\tau = R_T \cdot C$



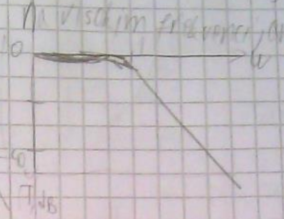
Veliki C da bude $\tau \gg T$



- RC mreža: odaziv na pravokutni napon na početku djelovanja u stacionarnom i u karakt. parametri

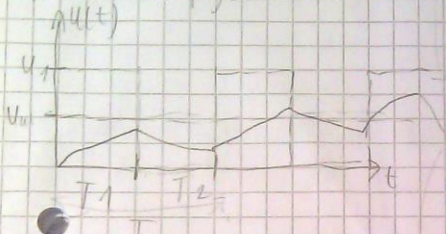


- Niskopropusni filtar = dobro propušta signal na niskim i srednjim, a guši izlazni signal na visokim frekvencijama

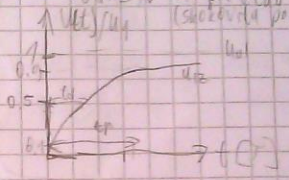


→ suprotstavlja se brzim promjenama izlaznog napona

Prijelazna pojava



Odziv na početku djelovanja (skokovita pobuda)

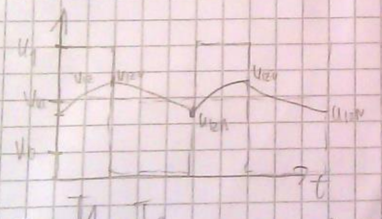


t_r = vrijeme porasta da napon poraste s 10 % na 90 % svoje konačne vrijednosti

t_d = razlika vremena kad ulazni napon postigne 50 % konačne vrijednosti i kad izlazni napon postigne 50 % konačne vrijednosti = vrijeme kašnjenja

$t_d = 0.69\tau$

Nakon završetka prijelazne pojave:
→ stacionarno stanje



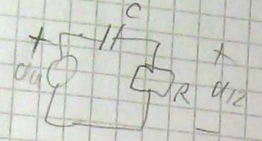
$T = T_1 + T_2$

$$U_{ul} = \frac{U_1 \cdot T_1 + U_0 \cdot T_2}{T}$$

$$t = T_1 \quad U_{izv} = U_1 + (U_{izn} - U_1) \cdot e^{-\frac{T_1}{\tau}}$$

$$t = T_1 + T_2 \quad U_{izn} = U_0 + (U_{izv} - U_0) \cdot e^{-\frac{T_2}{\tau}}$$

→ CR mreža

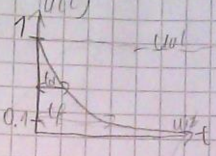


$\tau = RC$

brzina opadanja napona povećava se smanjenjem konstante; manji τ, prijelaz kraći

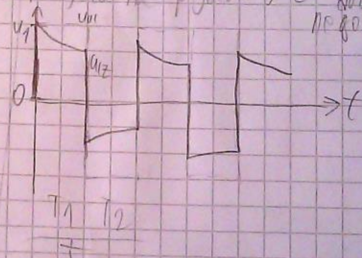
t_d = vrijeme kašnjenja ($= 0.69\tau$) razlika vremena kad ulazni napon postigne 50% konačne vrijednosti i kad izlazni napon postigne 50% kon. vrijednosti

Odaziv na početku (skokovitu pobudu)



t_f = vrijeme pada izlaznog napona s 90 % poč. vrijednosti na 10% početne

→ prijelazna pojava; C dobiva više naboja nego što ga gubi



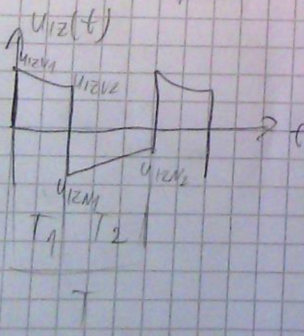
– visokopropusni filtar dobro prenosi brze promjene ulaznog signala, suprotstavlja se sporim promjenama

→ stacionarno stanje

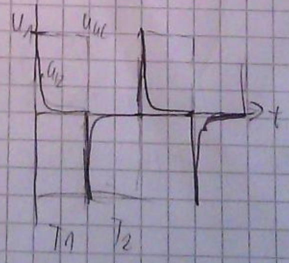
izlazni napon periodički se ponavlja i nema istosmjernu komponentu

$u_{izv2} = U_{izv1} \cdot e^{\left(-\frac{T_1}{\tau}\right)}$

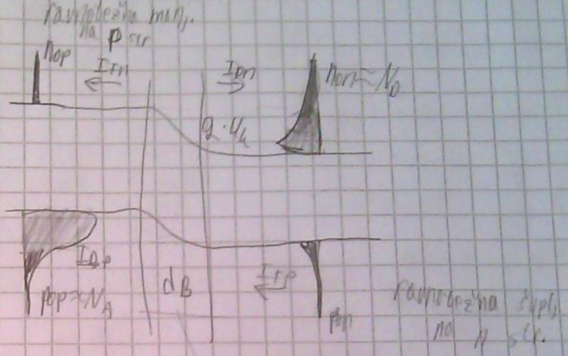
$u_{izn2} = u_{izn1} \cdot e^{\left(-\frac{T_2}{\tau}\right)}$



za $\tau << T$



→ Energetski dijagram pn spoja i U_k



kontaktni potencijal
U_k = određen razlikom Fermijevih energija neutralnih područja poluvodiča na obje strane spoja

- koncentracije primjesa više, Fer. ener. bliže rubu, raste U_k

→ na višim temp. Fer. ener. se približavaju sredini pa opada razlika sa stivne i U_k

$$U_k = U_T \cdot \ln\left(\frac{N_D \cdot N_A}{n_i^2}\right) = \frac{E_{Fn} - E_{Fp}}{q}$$

osiromašeni pojas (razlike nosilaca)

- I_D ⇒ difuzijske komponente
- I_F ⇒ driftne (prosječni naboj od n prema p)

$q U_k$ – energetska barijera

mali dio većinskih nosilaca s energijom većom od $q U_k$ savladava barijeru i difundira na drugi dio spoja

→ osiromašeni sloj – koncentracija slobodnih nosilaca zanemariva u odnosu na koncentraciju primjesa

$q \cdot N_A \cdot d_{Bp} = q \cdot N_D \cdot d_{Bn}$

$$\frac{d_{Bn}}{d_{Bp}} = \frac{N_A}{N_D}$$

$d_B = d_{Bp} + d_{Bn}$

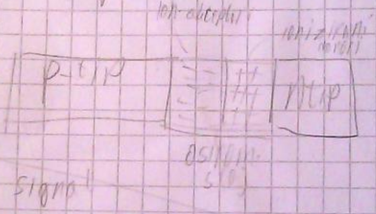
Na p-strani negativno ionizirani atomi akceptora, a na n strani pozitivno ionizirani atomi donora. Posljedica prostornog naboja u osiromašenom sloju se formira el. polje i javlja se promjena potencijala

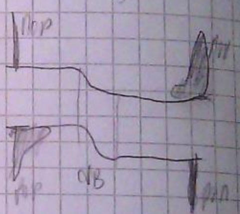
– osiromašeno područje se širi jače na slabije dopiranu stranu spoja

– propusna polarizacija: energetska barijera se smanjuje, o.s. sužava

– zaporna: energ. bar. se povećava, o.s. širi

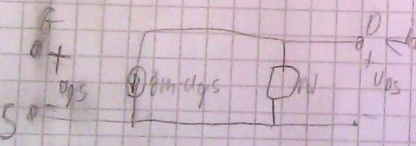
Prostorni negativni naboj akceptora jednak je pozitivnom naboju donora zbog čega možemo zaklj. da je OSIROMAŠENI SLOJ KAO CJELINA NEUTRALAN

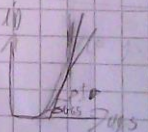




→ Model FETa za mali signal

1)





$$g_m = \frac{\partial i_d}{\partial u_{gs}} = k \cdot (U_{GSQ} - U_{GS0})(1 + \lambda U_{DS})$$

strmina = tangenta na pravac u prijenosnoj kar.

$$g_d = \frac{1}{r_d} \qquad r_d = \frac{1}{\frac{\partial i_d}{\partial u_{ds}}} = \frac{1}{\frac{k}{2} \cdot \lambda \cdot (U_{GSQ} - U_{GS0})^2}$$

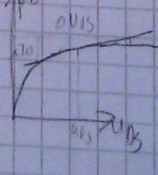
izlazna vodljivost

dinamički otpor = tang. na pravac u izlaznoj kar.

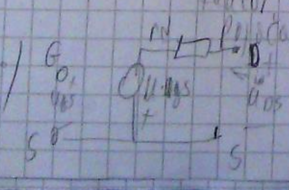
$i_d = g_m u_{gs} + g_d \cdot u_{ds}$

$\mu = g_m \cdot r_d$

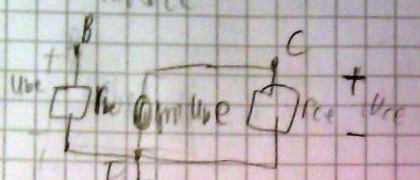
faktor naponskog pojačanja



2)



⇒ nadomestna shema za mali signal
model



2°)

$U_T = \frac{T}{11600}$ napetostni ekvivalent temperature

$S_m = \frac{h_{fe}}{r_{be}}$ $r_{be} = \frac{U_T}{I_B}$

$r_{ce} = \frac{U_{A0} + U_{CE}}{I_{C0}}$

$h_{fe} = \beta = \frac{I_C}{I_B}$

$U_{be} = U_\gamma = 0.7\ V \Rightarrow$ napeta kolena

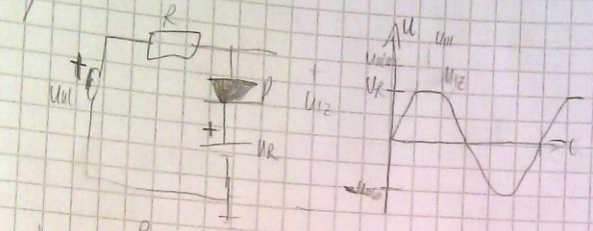
Da postane pravilno polarizirana $\Rightarrow$ služijo pasivi

$U_{CE} = U_{CC} - R_C \cdot I_C$

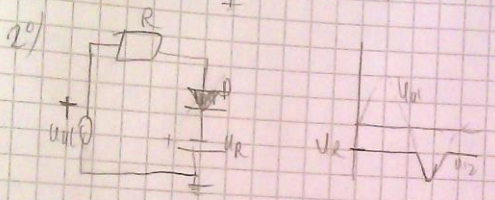
- Diodni ograničivači
  - koriste se za ograničenje hoda naponskog signala
  - temelji rada na (ne)linearnoj karakteristici diode

jednostavni paralelni

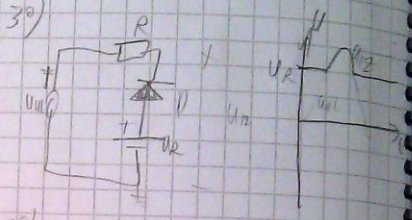
1o/



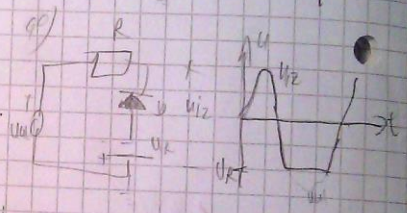
2o/



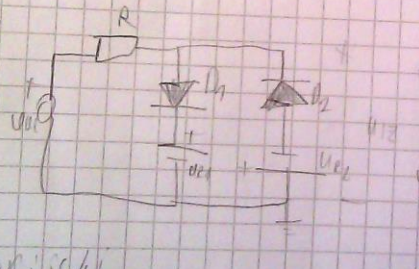
3o)



4o)

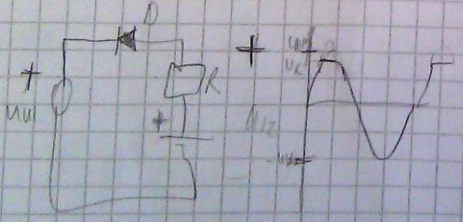


dvostrani; sugra pozitivna

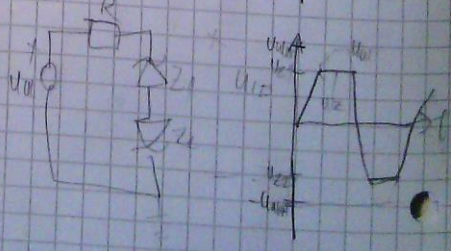


Dioda propusno: kad $u_{ul} > U_R$
Dioda zaporno: kad $u_{ul} < U_R$
U_R prema masi / usp. s pozitivnim U_R prema višem potencijalu u_2

serijski

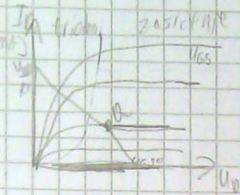


dvostrani sa zenerovim diodama



→ MOSFET izlazna i prijenosna, podr. rada, vrste MOSFETA
s obzirom na prijenosnu kar.

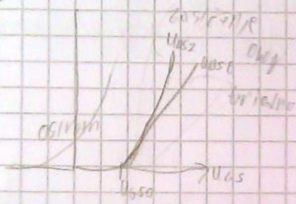
→ izlazna n kan obog. (?)



$U_{DS} = U_{GS} - U_{GS0}$ $U_{IZ} = U_{DS} = U_{DD} - I_D \cdot R_D$

Oba područja $U_{GS} > U_{GS0}$, za $U_{DS} = U_{GS}$ kanal ne postoji, područje zapiranja

→ prijenosne karakteristike



osiromašeni → pri U_{GS0} kanal formiran, inače nije

n, p tip

veći U_{DS} struja raste

što je veći U_{GS}, struja raste

→ s obzirom na prijenosnu karakt. : sklopka
– pojačalo : $A_V = \frac{U_{IZ}}{U_{UL}}$ ⇒ nagib tang. na prijenosnu karakt. u Q

→ Shockleyeva jednadžba

Difuzijska konstanta

ravnotežne manjinskih

$$I_S = q \cdot S \cdot \left(D_n \frac{n_{0p}}{L_n} + D_p \cdot \frac{p_{0n}}{L_p} \right) \Rightarrow \text{zasićenje}$$

$W_p \gg L_n$ ⇒ široka, obrnuto uska

W_p ili L_n, L_p ili W_n ⇒ što je manje to uzimamo

$$I_D = I_S \cdot \left(e^{\frac{U_D}{m U_T}} - 1 \right)$$

difuzijska duljina $W_n \gg L_p$ široko, obrnuto uska

→ u slučaju asimetričnog spoja dominirat će član s konc. manjinskih nosioca slabije dopirane strane

$$J = q \cdot \left(D_n \frac{n_{0p}}{L_n} + D_p \cdot \frac{p_{0n}}{L_p} \right) \cdot \left(e^{\frac{U_D}{U_T}} - 1 \right)$$

J_S

$U_D = U_{AK}$

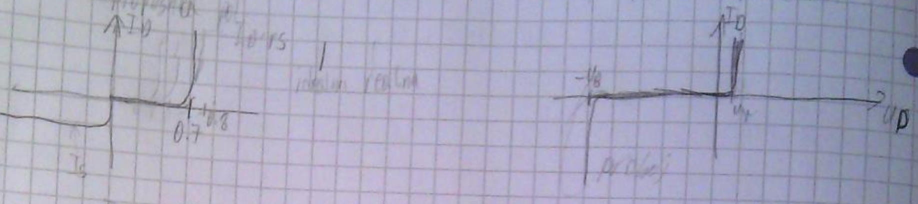
$I = J \cdot S$

m = 2 visoka injekcija, pola u osirom. sloju, pola se troši u kvazineutralnom području

m režim visoke injekcije

, niska injekcija m = 1, sav napon U_D u osirom. sloju

→ strujno-naponska karakteristika realne i idealne diode



I_S pri zapornoj polarizaciji = idealni

→ veći propusni naponi, režim visoke injekcije gdje pad napona u kvazineutralnim područjima nije zanemariv.
→ pogledati m slr prije
r_S – utjecaj pada napona zbog otpora kvazineutralnih područja
se dodaje
također utječe rekomb. struja

→ Pri zapornoj polarizaciji
u idealnoj teče samo I_S, a u realnoj teče i dodatna I_G generacijska struja uzrokovana generacijom nosilaca u osiromašenom području
– probojni napon pn-spoja U_B ⇒ ionizacija atoma poluvodiča u o.s.
$U_B > 8V$, U_B raste s temp. – el. polje ubrzava elektrone te pri U_B postižu dovoljnu energiju da ioniziraju druge atome te stvaraju nove parove elektron-šupljina
lavinski proboj = konc. slobodnih nosilaca i struja naglo rastu
– diode s jako dopiranim n i p stranama imaju tunelski/Zenerov proboj, širina barijere uska pa ih više nego što je lavinski
$U_B <$ (5 – 8) [V], pada s temp. U_B
– struja raste eksponencijalno s temp.

Struje u poluvodiču

→ Driftna:

Uzrokovana el. poljem tj. driftnim gibanjem nosilaca
- raste s porastom
primjesa

spec. vodljivost

$$J_F = \sigma \cdot F = q \cdot (n \cdot \mu_n + p \cdot \mu_p) \cdot F$$

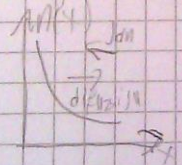
driftna brzina se smanjuje zbog većeg broja sudara (kristalna rešetka → vibracije)

- u vodiču samo driftna elektrona

→ Difuzijska struja

zbog nejednolike konc. dolazi do difuzije tj. gibanja s mjesta više prema mjestu niže konc. s tendencijom izjednačavanja konc.

usmjereno gibanje uslijed difuzije = difuzijska struja



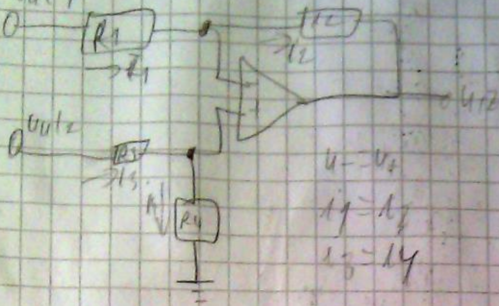
$D_{n,p}$ → difuzijska konstanta $= U_T \cdot \mu_{n,p}$

$$U_T = \frac{T}{11600}$$

$$J_{Dn} = q \, D_n \frac{dn(x)}{dx}$$

$$J_{Dp} = -q \cdot D_p \cdot \frac{dp(x)}{dx}$$

→ Diferencijsko pojačalo op. p.



$U_- = U_+$

$I_1 = I_2$

$I_3 = I_4$

$\frac{U_{ul1} - U_-}{R_1} = \frac{U_- - U_{iz}}{R_2}$

$-U_{iz} = \frac{R_2}{R_1}(U_{ul1} - U_-) \ldots$

$U_z \; A_{ud} = \infty$

$\frac{U_{ul2} - U_-}{R_3} = \frac{U_-}{R_4}$

$U_{iz} = \frac{R_2}{R_1} \cdot \left(U_{ul1} - \frac{U_{ul2} \frac{R_4}{R_3}}{1 + \frac{R_4}{R_3}}\right)$

$\frac{R_4}{R_3}(U_{ul2} - U_-) = U_-$

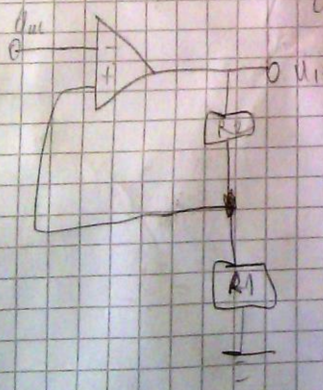
$\frac{R_4}{R_3} U_{ul2} = U_-\left(1 + \frac{R_4}{R_3}\right)$

$U_- = \frac{U_{ul2} \frac{R_4}{R_3}}{1 + \frac{R_4}{R_3}}$

$A_{vd} = \frac{U_{iz}}{U_{ul2} - U_{ul1}} = \frac{R_2}{R_1}$

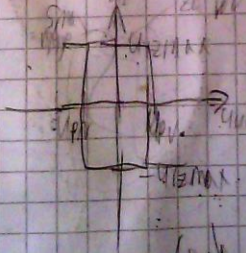
$U_{iz} = \frac{R_2}{R_1}(U_{ul2} - U_{ul1})$ uz $R_1 = R_3$ i $R_4 = R_2$

→ komparator:



$U_+ = \frac{R_1}{R_1 + R_2} U_{iz} = \beta \cdot U_{iz}$

usporedba 2 ulazna napona



U_{pv} U_{pn} → pragovi okidanja

kada napon U_{ul} dosegne U_{pv}, skokovito se mijenja na negativnu vrijednost, kad se U_{ul} (z)smanjuje i postane malo negativniji od U_{pn}, skokovito $U_{iz} = U_{iz\,max}$

→ Poluvalni ispravljač ns3

u_p i u_s u fazi

$u_p = U_{pm} \cdot \sin \omega t$

$U_{sm} = \frac{U_{pm}}{n}$

$u_s = U_{sm} \cdot \sin \omega t$

$u_{iz} \{ u_s$, $u_s \geq 0$; 0, $u_s < 0$ dioda vodi struju

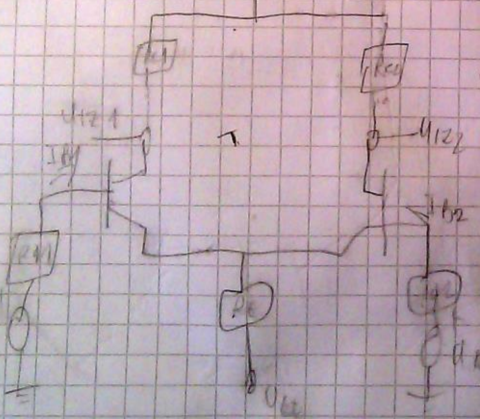
Dioda vodi struju samo za vrijeme poz. pol. ($u_{iz} = u_s$)

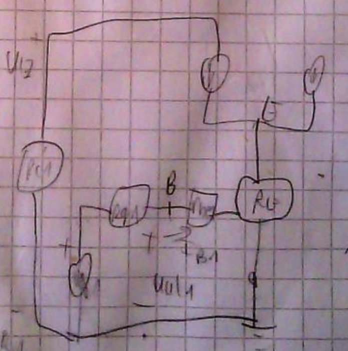
$r = \frac{U_{iz\,ef}}{U_{iz}}$

– ispravljač ispravlja izm. napon da bude pulsirajući i da osim istosmjerne sadrži i izmjenične komponente

→ Diferencijsko izvedeno bipolarnim

– najraširenije tranzistorsko pojačalo, pojačava sve signale od 0 pa dalje do gornje granice te se koristi kao ulazno





$A_{ud} = \frac{u_{iz}}{u_d}$

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

$u_d = u_{g2} - u_{g1}$ diferencijski

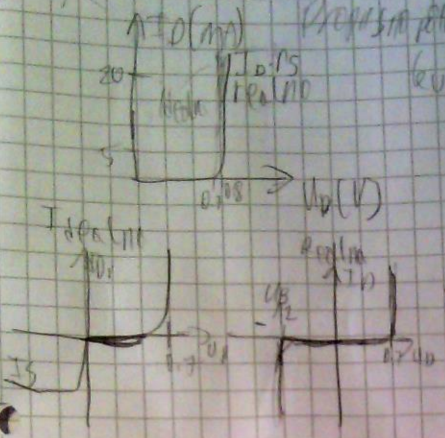
→ diode u optoelektronici

– svijetleća dioda: pretvara el. energiju u optičko zračenje. Propusna polarizacija

– Fotodioda: energija upadnog optičkog zračenja pretvara u električni signal

– sunčana ćelija: pretvara energiju u el. energiju, istosmj. napon, s to većom jačom strujom zračenja

→ Razlika između Re i idealne diode



Propusno polarizirana dioda

kroz početna područja predstavljaju otpore na kojima se pri vođenju stvaraju padovi napona koji dodatno smanjuju porast struje diode s naponom pri pol.

— $a(t)$ [illegible] se aprox s I_s u seriji s idealnom

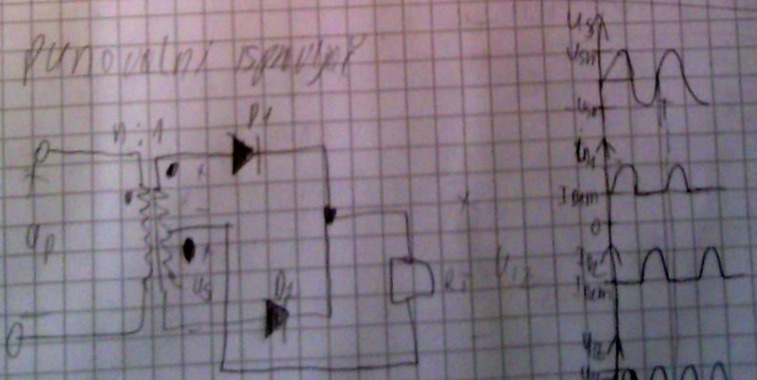
— Zaporno:

— kroz idealnu diodu pri zap. teče samo mala struja I_s zasićenja, zakod realne teče i I_G generacijska uzrokovana generacijom nositelja u osiromašenom sloju $I_G >> I_s$

— porastom napona polarizacije dolazi do PROBOJA pn spoja — nagli porast struje, probojni napon U_B

→ Strujno naponska karakteristika pn spoja → ovisi o temp. polariz.

→ Punovalni ispravljač

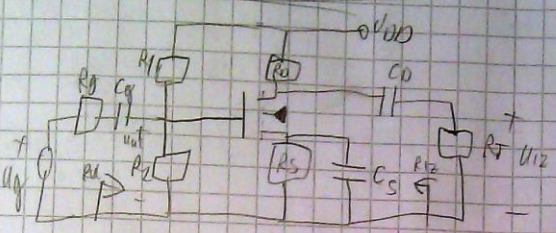


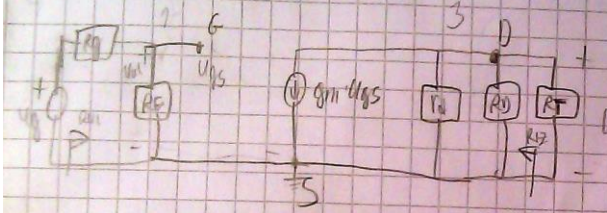
— poz. poluperioda propusno polarizira D_1, a zaporno D_2 $u_{iz} = u_s$

— neg. poluperioda D_1 zaporno, D_2 propusno $u_{iz} = -u_s$

ŠEME MOSFET

1.) Spoj zajedničkog uvoda





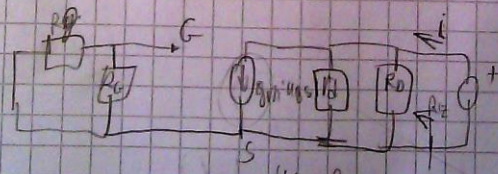
$$A_V = \frac{u_{iz}}{u_{ul}} = \frac{-g_m \cdot u_{gs} \cdot (r_d \| R_D \| R_T)}{u_{gs}} = -g_m(r_d \| R_D \| R_T) \approx -10 \qquad R_{ul} = R_G$$

$$u_{iz} = i \cdot r = -g_m \cdot u_{gs} \cdot (r_d \| R_D \| R_T)$$

$$u_{ul} = u_{gs}$$

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

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

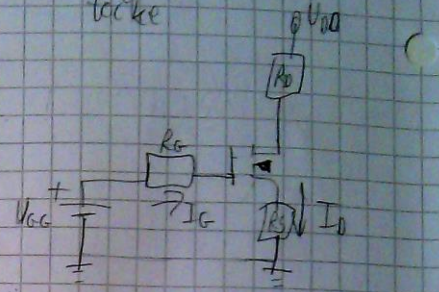


$$i = \frac{u}{r_d \| R_D}$$

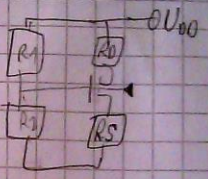
$$R_{iz} = \frac{u}{i} = \frac{u}{\frac{u}{r_d \| R_D}} = r_d \| R_D$$

zavisni izvor, u_{gs} ne postoji, pa i on ne postoji

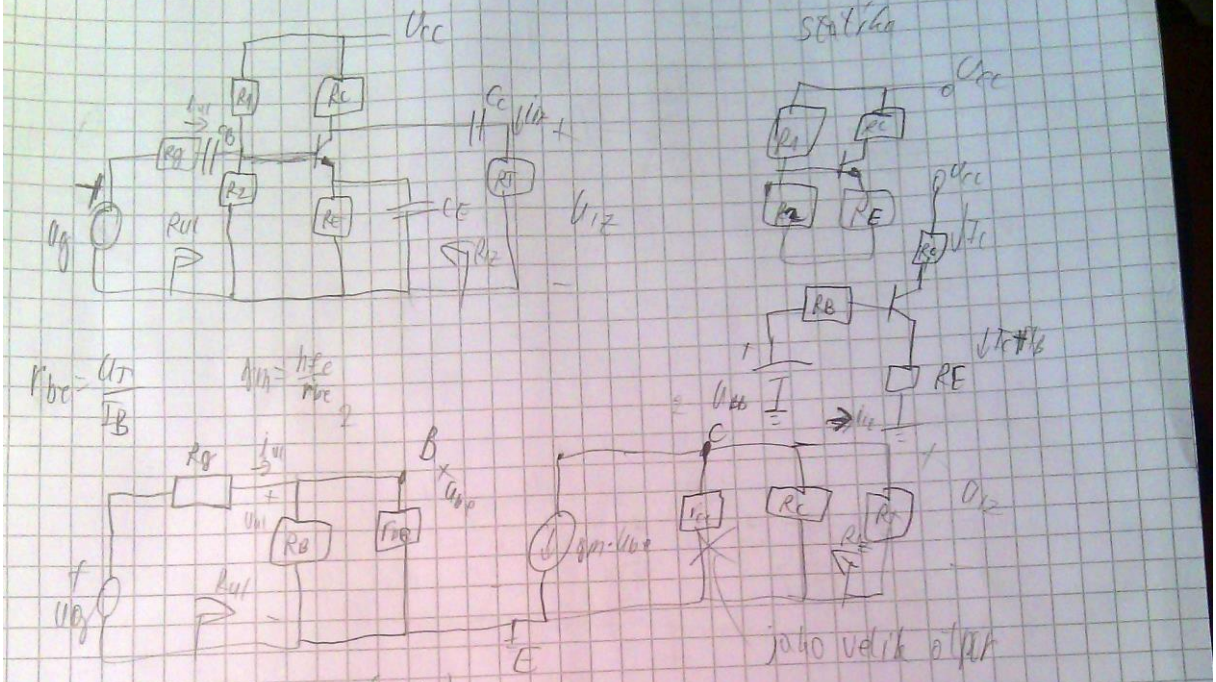
proračun statičke radne točke



stabilizacija SRT



BTJ
spoj zajedničkog emitera



$r_{be} = \frac{U_T}{I_B}$ $\quad g_m = \frac{h_{fe}}{r_{be}}$?

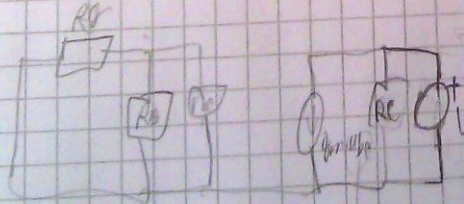
$A_V = \frac{U_{iz}}{U_{ul}} = \frac{-g_m U_{be} (R_C \| R_T)}{U_{be}} = -g_m \cdot (R_C \| R_T)$ $\quad R_{ul} = R_B \| r_{be} \approx r_{be}$

oko 100, invertirna

$A_I = \frac{i_{iz}}{i_{ul}} = \frac{\frac{U_{iz}}{R_T}}{\frac{U_{ul}}{R_{ul}}} = A_V \cdot \frac{R_{ul}}{R_T} = A_V \cdot \frac{R_B \| r_{be}}{R_T} = \frac{-g_m U_{be} \cdot R_C}{R_C + R_T} = -g_m \cdot R_B \| r_{be} \cdot \frac{R_C}{R_C + R_T}$

$\frac{U_{be}}{R_B \| r_{be}}$

oko 100 puta veće



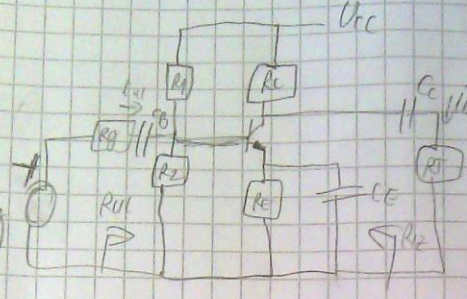
$R_{iz} = R_C \| r_{ce} \approx R_C = 4k\Omega$

$A_{Vg} = \frac{U_{iz}}{U_g} = \frac{U_{iz} \cdot U_{ul}}{U_{ul} \cdot U_g} = A_V \cdot \frac{R_B \| r_{be}}{R_g + R_B \| r_{be}}$

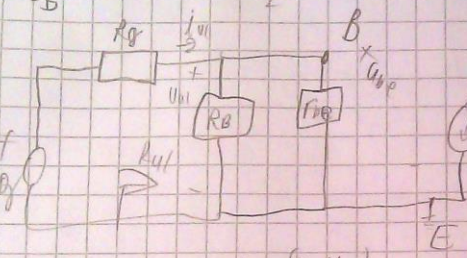
$U_{be} = 0$, sklopi se kao

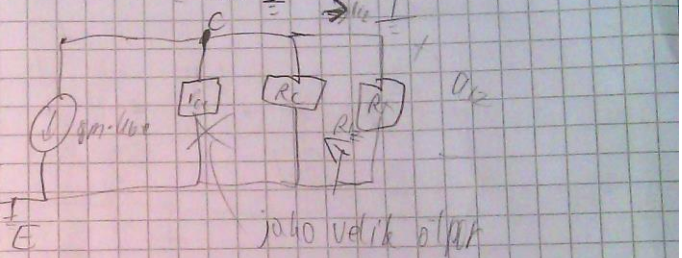
BTJ:

→ spol. zesilovač emitorem



$r_{be} = \frac{U_T}{I_B}$ $\quad g_m = \frac{h_{fe}}{r_{be}}$





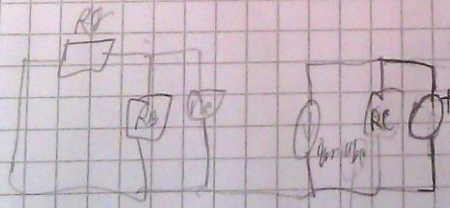
jako velký odpor

$A_V = \frac{U_{iz}}{U_{ul}} = \frac{-g_m \cdot U_{be} \cdot (R_C \| R_T)}{U_{be}} = -g_m \cdot (R_C \| R_T)$ $\quad R_{ul} = R_B \| r_{be} \approx r_{be}$

oko 100, invertuje

$A_I = \frac{i_{iz}}{i_{ul}} = \frac{\frac{U_{iz}}{R_T}}{\frac{U_{ul}}{R_{ul}}} = A_V \cdot \frac{R_{ul}}{R_T} = A_V \cdot \frac{R_B \| r_{be}}{R_T} = \frac{-g_m \cdot U_{be} \cdot R_C}{R_C + R_T} = -g_m \cdot R_B \| r_{be} \cdot \frac{R_C}{R_C + R_T} = \frac{U_{be}}{R_B \| r_{be}}$

oko 100



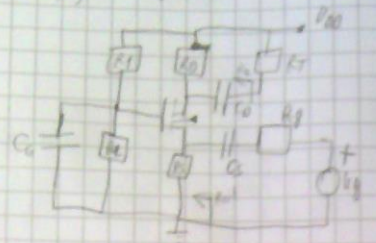
$A_{VG} = \frac{U_{iz}}{U_g} = \frac{U_{iz}}{U_{ul}} \cdot \frac{U_{ul}}{U_g} = A_V \cdot \frac{R_B \| r_{be}}{R_g + R_B \| r_{be}}$

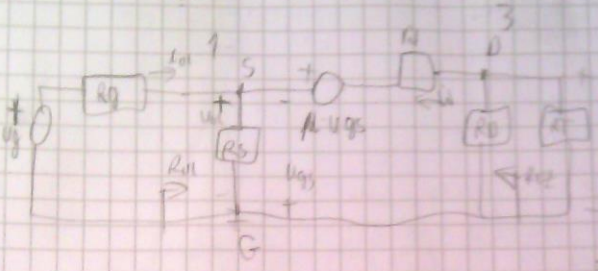
$U_{be} = 0$, signál je zkratován

$R_{iz} = R_C \| r_{ce} \approx R_C$ – kolm

MOSFET

→ spoj zajedničke upravljačke elektrode





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

$= g_m (r_d \| R_D \| R_t) > 10$

$R_{ul} = \frac{u_{ul}}{i_{ul}} = R_S \| \frac{r_d + R_D \| R_t}{1+\mu}$

$i = \frac{u}{R_D} + i_D$

$u = (r_d + R_S \| R_g) i_d - \mu u_{gs}$

$u_{gs} = -u_{ul} \cdot R_S / R_g$

$u = [r_d + (1+\mu) \cdot R_S / R_g] i_d$

$R_{ik} = \frac{u}{i_d} = R_D \| [r_d + (1+\mu) R_S \| R_g]$

$-i_d \cdot [(r_d + R_S \| R_t] = \mu u_{gs} - u_{gs}$

$i_d \cdot [r_d + R_D \| R_t] = u_{gs}(\mu+1)$

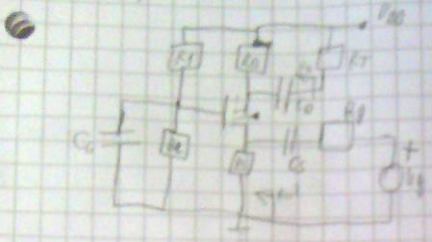
$i_d = \frac{u_{gs}(\mu+1)}{r_d + R_D \| R_t}$

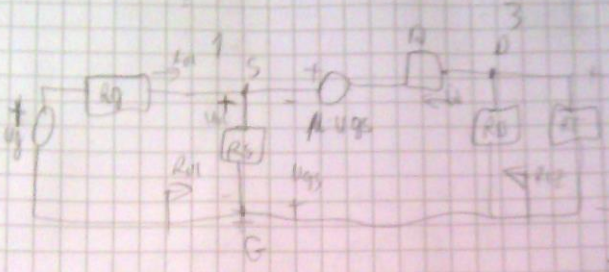
$A_{vg} = \frac{u_{iz}}{u_g} = A_v \frac{u_{ul}}{u_g} = \frac{A_v \cdot u_{ul}}{R_g + R_{ul}} =$

$= \frac{A_v \cdot R_S \| \left(\frac{R_D + R_t}{1+\mu} \right)}{R_g + R_S \| \left(\frac{R_D + R_t}{1+\mu} \right)}$

MOSFET

→ spoj zajedničke upravljačke elektrode





$A_v = \frac{u_{iz}}{u_{ul}} = \frac{-i_d \cdot R_D \| R_L}{u_{gs}} = \frac{u_{gs} \cdot g_m \cdot (r_d \| R_D \| R_L)}{u_{gs}} = g_m (r_d \| R_D \| R_L) > 10$

$u_{ul} = u_{gs}$

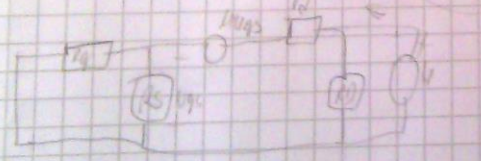
$-i_d \cdot (r_d \| R_D \| R_L) = \mu u_{gs} - u_{gs}$

$i_d \cdot [r_d + (R_D \| R_L)] = u_{gs}(\mu + 1)$

$i_d = \frac{u_{gs}(\mu+1)}{r_d + R_D \| R_L}$

$R_{ul} = \frac{u_{ul}}{i_{ul}} = R_S \| \frac{r_d + R_D \| R_L}{1+\mu}$ puta

$A_{ug} = \frac{u_{iz}}{u_g} = A_v \frac{u_{ul}}{u_g} = \frac{A_v R_{ul}}{R_g + R_{ul}} = A_v \cdot R_S \| \left(\frac{R_D \| R_L + r_d}{1+\mu} \right) \Big/ R_g + R_S \| \left(\frac{R_D \| R_L + r_d}{1+\mu} \right)$



$i = \frac{u}{R_D} + i_D$

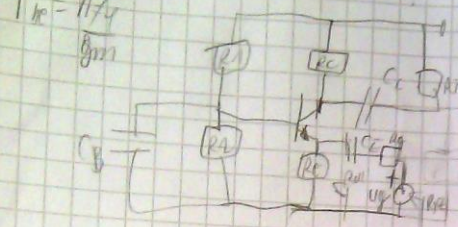
$u = (r_d + R_S \| R_g) i_d - \mu u_{gs}$

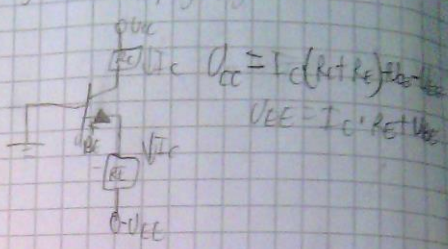
$u_{gs} = -i_d \cdot R_S \| R_g$

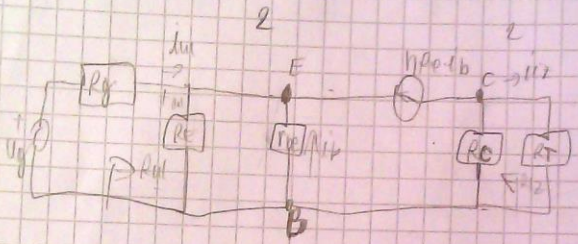
$u = [r_d + (1+\mu) \cdot R_S \| R_g] i_d$

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

Bipolární





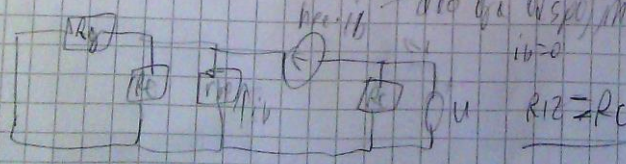


$$A_V = \frac{u_{iz}}{u_{ul}} = \frac{-h_{fe} \cdot i_b \cdot (R_C \| R_T)}{+ i_b r_{be}} = -g_m (R_C \| R_T) \approx -100$$

$$R_{ul} = R_E \| \frac{r_{be}}{1+h_{fe}} \approx 70\,\Omega$$

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

$$A_{VZ} = A_V \frac{R_{ul}}{R_g + R_{ul}} = A_V \cdot \frac{R_E \| \frac{r_{be}}{1+h_{fe}}}{R_g + R_E \| \frac{r_{be}}{1+h_{fe}}}$$

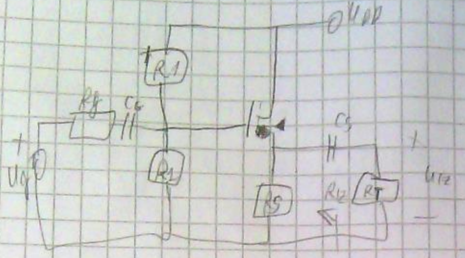


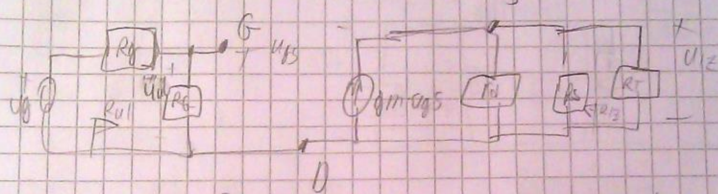
$i_b = 0$

$R_{IZ} = R_C \| R_{ul}$

MOSFET

→ Zajednički odvod (Uvodsko sljedilo)



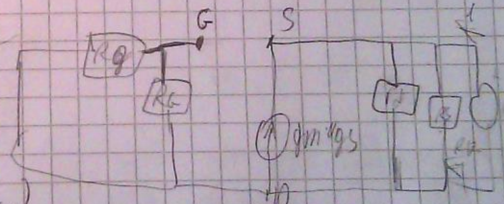


$R_{ul} = R_G$ velki

$$A_v = \frac{u_{iz}}{u_{ul}} = \frac{g_m u_{gs} (r_d \| R_S \| R_T)}{u_{gs} + u_{iz}} = \frac{g_m u_{gs} (r_d \| R_S \| R_T)}{u_{gs} + g_m u_{gs} (r_d \| R_S \| R_T)} = \frac{g_m (r_d \| R_S \| R_T)}{1 + g_m (r_d \| R_S \| R_T)} < 1$$

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

R_{iz}:



$u = (r_d \| R_S) \cdot (i + g_m u_{gs})$

$u = (r_d \| R_S) \cdot (i - g_m u)$

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

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

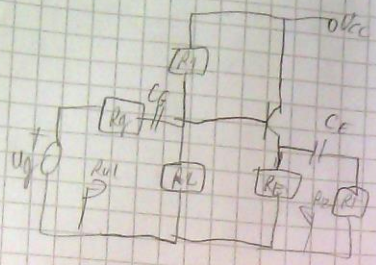
$$R_{iz} = \frac{r_d \| R_S}{1 + g_m (r_d \| R_S)}$$

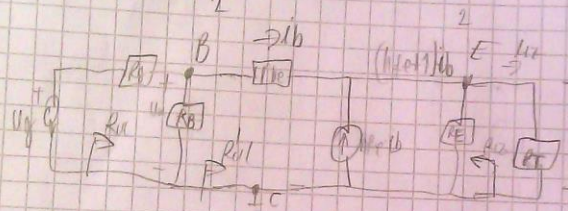
$R_{iz} = R_S \| \frac{r_d}{1+\mu}$ mali — preslikano iz DvS

spojimo uS → $R_{iz} = R_S \| \frac{1}{g_m}$

$$R_{iz} = \frac{r_d \| R_S}{1 + g_m (r_d \| R_S)}$$

→ Bipolarno spoj zajedničkog kolektora

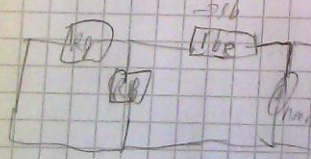




$A_V = \frac{u_{iz}}{u_{ul}} = \frac{(1+h_{fe})\cdot i_b \cdot (R_E \| R_T)}{i_b r_{be} + (1+h_{fe})\cdot i_b \cdot (R_E \| R_T)} = \frac{(1+h_{fe})\cdot (R_E \| R_T)}{r_{be} + (1+h_{fe})\cdot (R_E \| R_T)} \approx \frac{h_{fe}\cdot R_E \| R_T}{r_{be} + h_{fe}\cdot R_E \| R_T} = \frac{g_m \cdot R_E \|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

$R_{ul} = R_B \| R_{ul} = R_B \| (r_{be} + (1+h_{fe})\cdot R_E \| R_T)) \Rightarrow R_{ul} = r_{be} + (1+h_{fe})\cdot (R_E \| R_T)$

R_{iz}:



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

zato što se otpor u krugu s $1+h_{fe}$ uvijek smanjuje

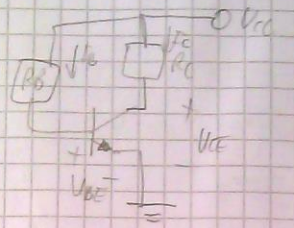
$A_{vg} = A_V \cdot \frac{R_B \| R_{ul}}{R_B \| R_{ul} + R_g}$

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

→ stabilizacija radne točke bipolarnog tranzistora

→ podešavanje statičke radne točke

a) stalnom baznom strujom → za NAP ; ne stabilizira



$B = \frac{I_B}{I_C}$

$U_{BE} = U_\gamma = 0.7V$

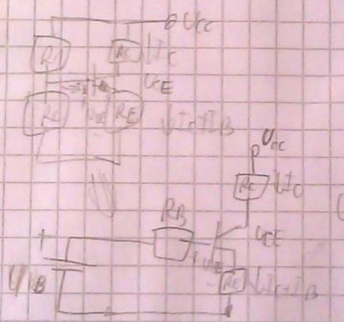
$U_{CC} = I_{CQ} \cdot R_C + U_{CEQ}$

$U_{CC} = U_{BEQ} + I_B \cdot R_B$

b) stabilizacija SRT emiterskim otpornikom

- smanjena osjetljivost

- suprotstavljanje promjeni I_C a time i promjeni položaja radne točke
- R_E smanjuje A_V ⇒ emiterska degeneracija



$B = \frac{I_C}{I_B}$ $R_B = R_1 || R_2$

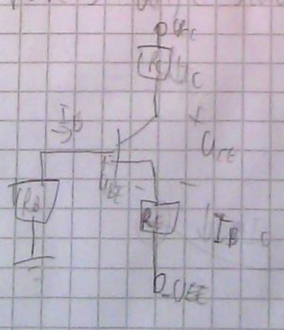
$U_{CC} = I_{CQ} \cdot R_C + U_{CEQ} + (I_{CQ} + I_{BQ}) R_E$

$U_{BB} = \frac{R_2 \cdot U_{CC}}{R_1 + R_2}$

$U_{BB} = I_{BQ} R_B + U_{BEQ} + R_E (I_{CQ} + I_{BQ})$

Theveninova nadomjesna shema

c) podešavanje statičke radne točke s 2 napona napajanja (poz. i neg.)



$U_{EE} = R_B \cdot I_B + U_{BE} + (I_B + I_C) \cdot R_E$

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

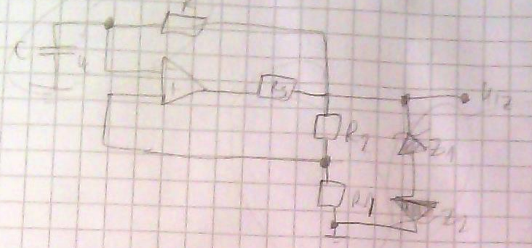
za $B >> 1$

R_E za stabiliziranje SRT

→ Astabil = Multivibrator bez stabilnog stanja (oba kvazistabilna)

RC mreža, automatsko okidanje komparatora

Promijeno stanje komparatora



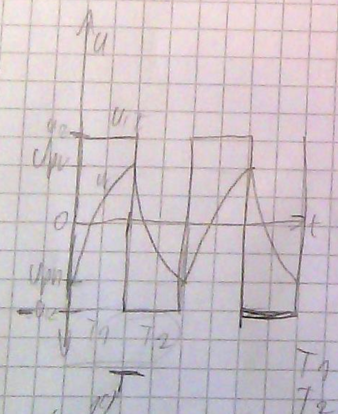
$u_Z = \pm(u_Z + U_D)$

invertirajući $= u_C$

neinvertirajući $= \frac{R_1}{R_1 + R_2} \cdot u_{iz}$

u_{iz} periodički mijenja vrijednost $\pm u_{iz}$

Komparatorski rad:
- nagle promjene izlaznog napona u_{iz} između 2 razine



$\tau = RC$ ⇒ brzina punjenja kondenzatora

ovise o τ, R_1, R_2

T_1 trajanje visoke razine (poz u_{iz}) $T_1 = T_2$

T_2 trajanje niske razine (neg u_{iz}) $T = T_1 + T_2$

u_C počne eksponencijalno rasti

$$u_C(t) = U_{pn} + (u_{iz} - U_{pn})\left[1 - e^{-\frac{t}{\tau}}\right]$$

kada $u_{iz} = +u_{iz}$, teži prema u_{iz}

2.) U trenutku T_1 se mijenja stanje u_{iz} nakon što u_C postane neznatno pozitivniji od u_{pn}, $u_{iz} = -U_{iz}$, C se počne izbijati i napon teži $-U_{iz}$, kada napon

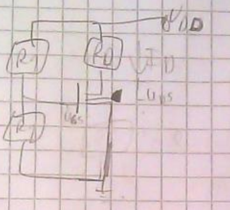
3.) u_C postane neznatno neg. od u_C, u_{iz} opet mijenja napon itd.

→ Podešavanje statičke radne točke s unipolarnim tranzistorima

→ tranzistor mora raditi u području zasićenja, što se osigurava podešavanjem SRT Q → uspostavlja istosmjerni napon U_{GSQ}

→ podešavanje fiksnog napona U_{GSQ} – R_1 i R_2

– primjenom otpornog djelila



$$U_{DD} = (R_D) \cdot I_{DQ} + U_{DS}$$

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

$$U_{GG} = U_{GS}$$

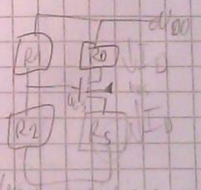
U području zasićenja radi uz uvjet $U_{DSQ} \geq U_{GSQ} - U_{GS0}$

$$I_D = \frac{k}{2} \cdot (U_{GSQ} - U_{GS0})^2$$

→ stabilizacija SRT.

– primjena uvodske degeneracije

– manja osj. SRT na promjene parametara tranzistora



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

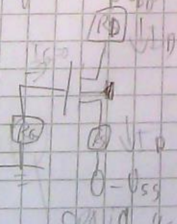
$$U_{DD} = (R_D + R_S) \cdot I_{DQ} + U_{DS}$$

$$U_{GG} = I_{DQ} R_S + U_{GS}$$

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

R_S stabilizira I_D u krugu uvoda tranzistora, smanjuje A_V (uvod. degenerac.)

c) podešavanje s 2 napona (poz. i neg.)

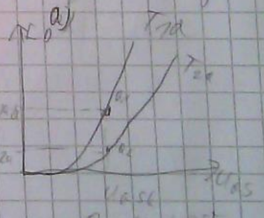


$$U_{DD} = (R_D + R_S) \cdot I_{DQ} - U_{SS} + U_{DSQ}$$

$$U_{SS} = U_{GSQ} + R_S \cdot I_{DQ}$$

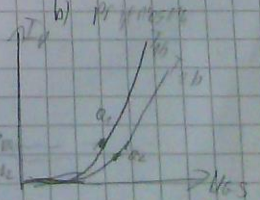
spaja U_{GG} na masu

U_{GSQ} → može poprimiti i poz. i neg. vrijednost pa se može kor. za oba tipa MOSFET-a

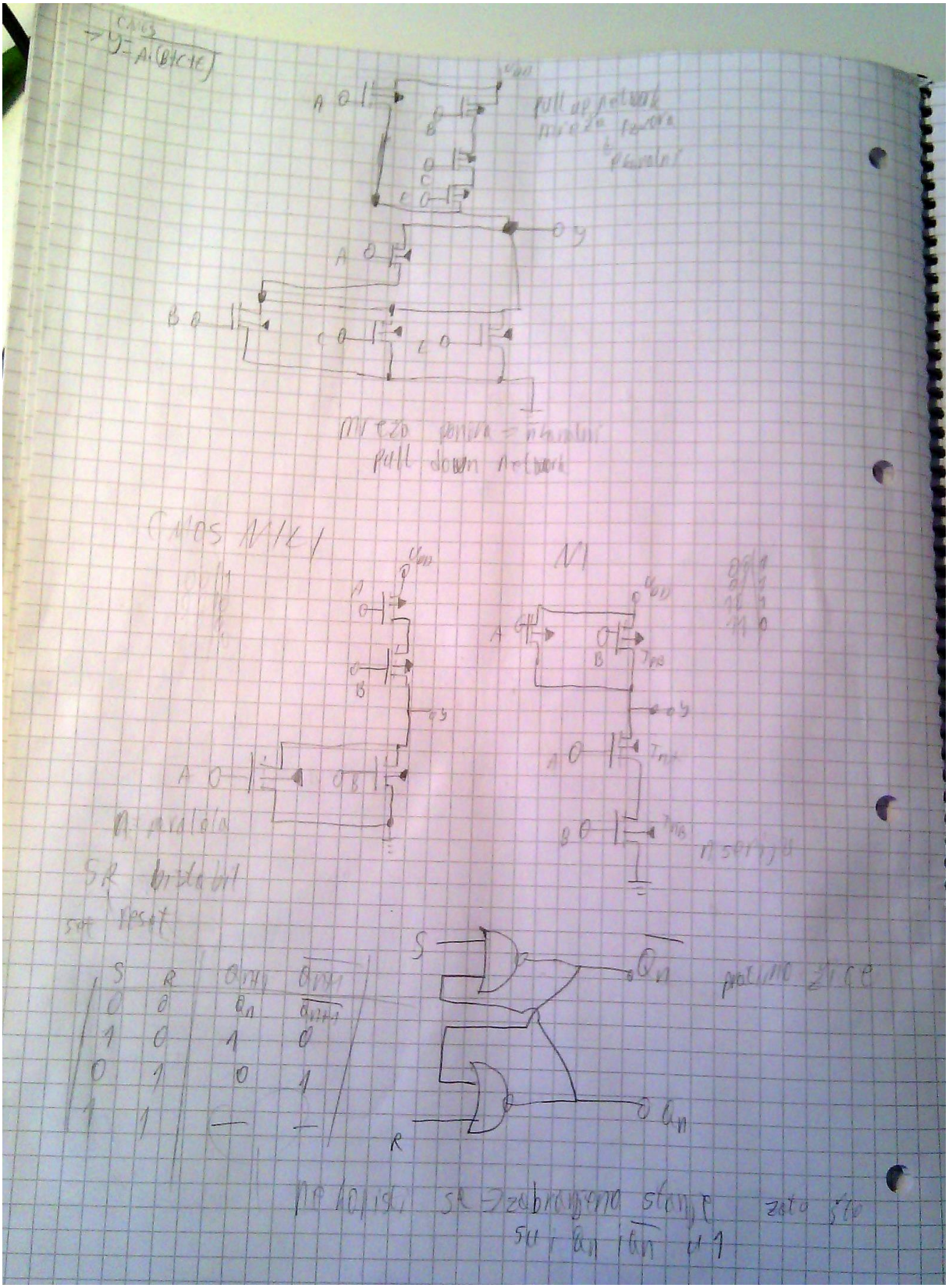


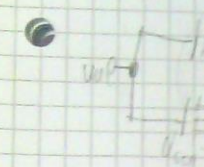
Osjetljivost karakteristike

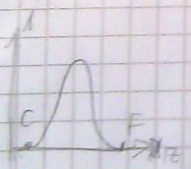
b) Primjer

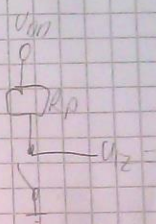


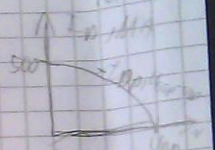
T_1 i T_2 → promjena

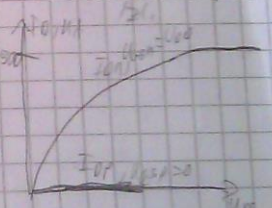












- Diferencijsko pojačalo

$i_1 = i_2$

$i_3 = i_4$

$A_{VOP} \to \infty$

$U_+ = U_-$

$$\frac{U_{ul1} - U_-}{R_1} = \frac{U_- - U_{iz}}{R_2}$$

$$\frac{U_{ul2} - U_+}{R_3} = \frac{U_+}{R_4}$$

$$-\frac{R_2}{R_1} U_{ul1} + \left(\frac{R_2}{R_1} + 1\right) \cdot U_- = U_{iz}$$

$$\frac{R_4}{R_3} U_{ul2} - \frac{R_4}{R_3} U_+ = U_+$$

$$U_{iz} = \left(\frac{R_2}{R_1} + 1\right) \cdot \frac{R_4}{R_3} \cdot U_{ul2} - \frac{R_2}{R_1} U_{ul1} \left(1 + \frac{R_4}{R_3}\right) U_{ul2} = \left(1 + \frac{R_4}{R_3}\right) U_+$$

$$U_+ = \frac{R_4}{R_3} \cdot U_{ul2}$$

$$U_{iz} = \left(\frac{R_2}{R_1} + 1\right) \cdot \frac{R_4}{R_3} \cdot U_{ul2} - \frac{R_2}{R_1} U_{ul1}$$

U_2 $R_3 = R_1$ i $R_4 = R_2$

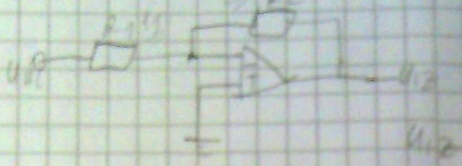
$$U_{iz} = \left(\frac{R_2}{R_1} + 1\right) \cdot \frac{R_2}{R_1} U_{ul2} - \frac{R_2}{R_1} U_{ul1}$$

$$U_{iz} = \frac{R_2}{R_1}\left(U_{ul2} - U_{ul1}\right) = \frac{R_2}{R_1} \cdot U_{uld}$$

$$A_{ud} = \frac{U_{iz}}{U_{uld}} = \frac{R_2}{R_1}$$

diferencijsko pojačanje određeno omjerom $\frac{R_2}{R_1}$

→ invertirajuće pojačalo



$u_{iz} = A_{op} \cdot u_d = A_{op}(u_+ - u_-)$

$u_+ = 0$ $\qquad u_- = -\frac{u_{iz}}{A_{op}}$

$\frac{u_{ul} - u_-}{R_1} = \frac{u_- - u_{iz}}{R_2}$

$R_2 \frac{\left(u_{ul} - \frac{u_{iz}}{A_{op}}\right)}{R_1} = -\frac{u_{iz}}{A_{op}} - u_{iz}$

$\frac{R_2}{R_1} u_{ul} = -u_{iz}\left(1 + \frac{1}{A_{op}} - \frac{R_2}{R_1 A_{op}}\right)$

$u_{iz} = \frac{-\frac{R_2}{R_1} u_{ul}}{1 + \frac{1}{A_{op}}\left(1 + \frac{R_2}{R_1}\right)}$

$A_V = \frac{u_{iz}}{u_{ul}} = \frac{-\frac{R_2}{R_1}}{1 + \frac{1}{A_{op}}\left(1 + \frac{R_2}{R_1}\right)}$

~~VA~~ (idealno) $\qquad A_{op} \to \infty$

$R_{ul} \to \infty$ $\qquad u_- = u_+$

$u_- = u_+ = 0$

$\frac{u_{ul}}{R_1} = -\frac{u_{iz}}{R_2}$

$-\frac{R_2}{R_1} u_{ul} = u_{iz}$

$A_V = -\frac{R_2}{R_1}$

→ Neinv. pojačalo

i1 i2

$$\frac{-u_-}{R_1} = \frac{u_- - u_{iz}}{R_2} \Rightarrow + \frac{R_2}{R_1} u_- + u_- = u_{iz}$$

$u_d = u_+ - u_-$

$u_d = u_{ul} - u_-$

$u_{iz} = A_{vop} \cdot u_d$

$u_d = \frac{u_{iz}}{A_{vop}}$

$$+\frac{R_2}{R_1}\left(-\frac{u_{iz}}{A_{vop}} + u_{ul}\right) + u_{ul} - \frac{u_{iz}}{A_{vop}} = u_{iz}$$

$$+ \frac{u_{iz}}{A_{vop}} + u_{ul} - u_{iz}\left(1 + \frac{1}{A_{vop}} + \frac{R_2}{R_1 A_{vop}}\right) = u_{ul}\left(1 + \frac{R_2}{R_1}\right)$$

$$u_{iz} = u_{ul} \cdot \frac{\left(1 + \frac{R_2}{R_1}\right)}{1 + \frac{1}{A_{vop}} + \frac{R_2}{R_1 A_{vop}}}$$

u_{iz} teži u $u_+ = u_- \Rightarrow A_{vop} = \infty$

$u_+ = u_- = u_{ul}$

$R_{ul} = \infty$

$$\frac{-u_{ul}}{R_1} = \frac{u_{ul} - u_{iz}}{R_2}$$

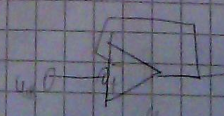
$$A_v = \frac{u_{iz}}{u_{ul}} = \frac{\left(1 + \frac{R_2}{R_1}\right)}{1 + \frac{1}{A_{vop}} + \frac{R_2}{R_1 A_{vop}}}$$

$$u_{ul}\left(\frac{R_2}{R_1} + 1\right) = u_{iz}$$

$$A_v = \frac{R_2}{R_1} + 1$$

Neinv. sljedilo

$A_v = 1 = \frac{u_{iz}}{u_{ul}}$

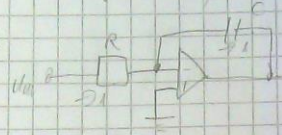


$u_+ = u_- = u_{ul} = u_{iz}$

$R_1 = \infty$

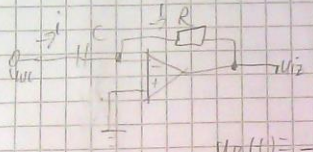
$R_2 = 0$

→ integrator RC



$$U_{iz}(t) = -U_C(t) = -\frac{1}{RC} \cdot \int_0^t U_{ul}(t) \cdot dt - U_{C0}$$

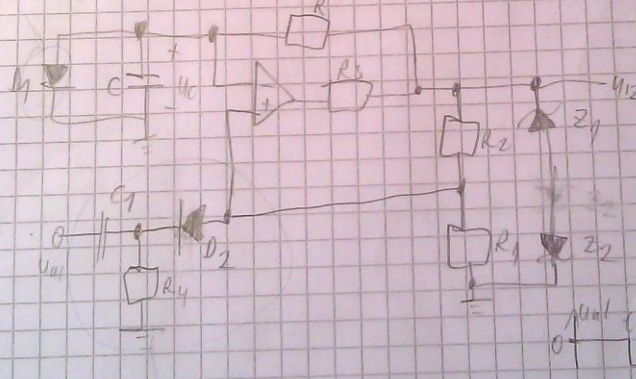
→ derivator CR



$$U_{iz}(t) = -R \cdot i(t) = -R \cdot C \cdot \frac{dU_{ul}(t)}{dt}$$

ASTABIL: MULTIVIBRATOR S DVEMA STABILNIMA I DVEMA

stabilna stanja QUASI STABILNIM STANJEM

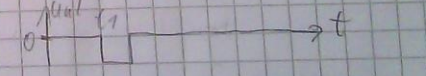


$$U_{iz} = \pm(U_0 + U_Z)$$

Trajanje kvazi stabilnog stanja

$T = RC$

T_r = vrijeme oporavka monostabila



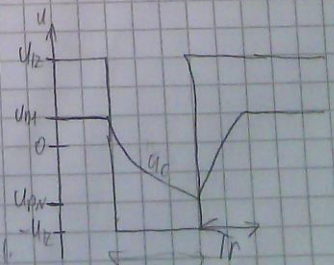
mreža za okidanje

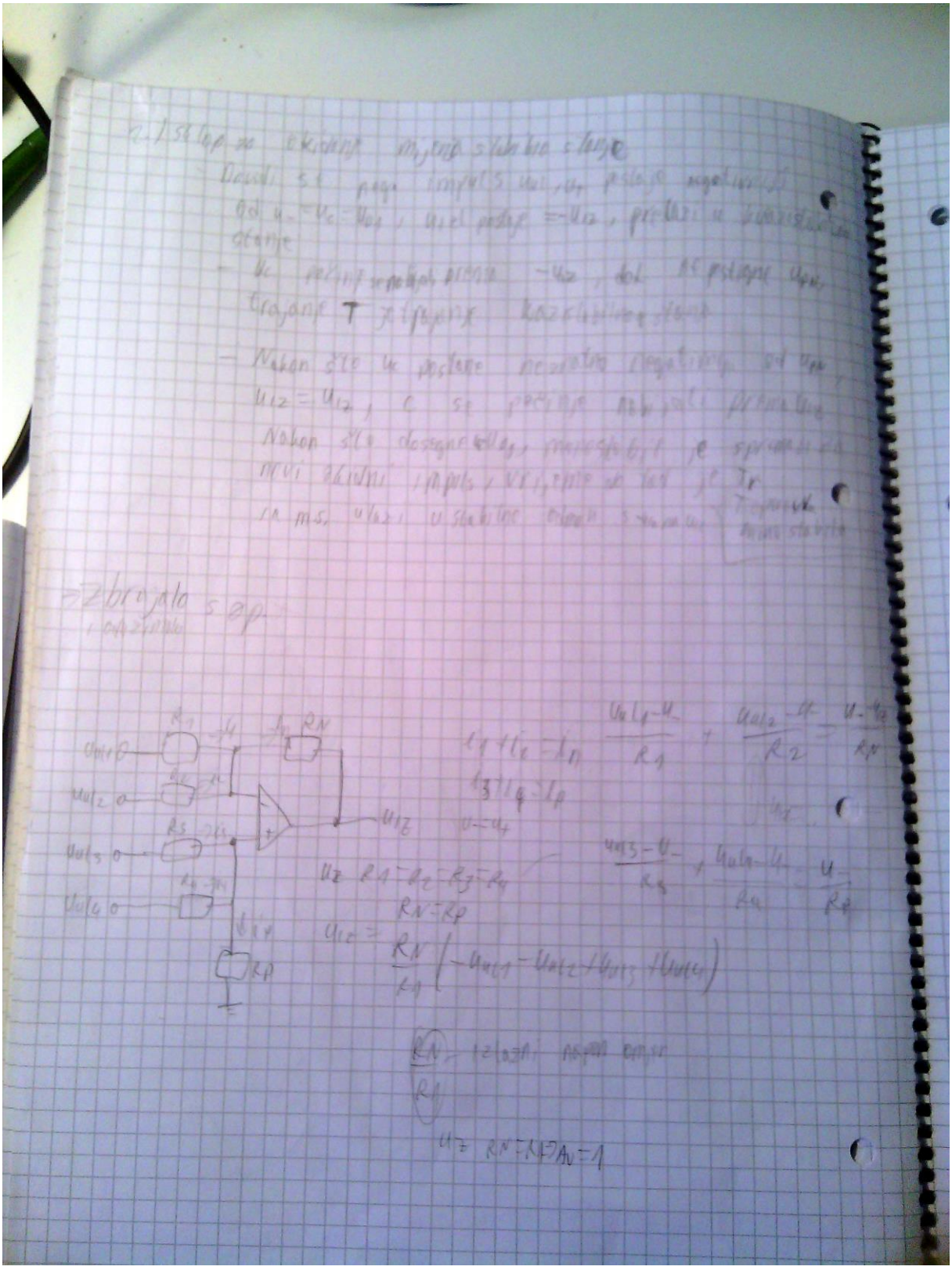
1°) U_{iz} pozitivno, U_C pa i D_1 prop. polarizirana

U_C ograničen na 0.7 V

$U_H = \frac{R1}{R1+R_2} \cdot U_{iz}$, pošto je napon ograničen

$a = U_C < \frac{R_1}{R_1+R_2} U_{iz}$ tj. $U_- < U_+$ i pozitivni U_{iz} u stabilno stanje



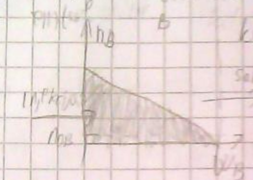


→ Područja rada bipolarnog tranzistora

polarizacija pn spojeva		emiter-baza propusno	emiter-baza zaporno
kolektor-baza	propusno	zasićenje	inverzno aktivno područje
	zaporno	Nor. akt. pod.	zapiranje

propusna ako je emiter tj. kolektor na nižem potencijalu od baze

NAP - tranzistor posjeduje svojstva pojačanja i koristi se u pojačalima



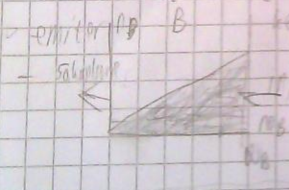
U_{CB} zaporan, može mijenjati u širokim granicama

ΔU_{EB} mala promjena, velika promjena I_C

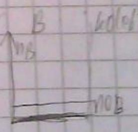
- elektroni injektirani od emitera ulazu se gibaju prema spoju kolektor-baza, najveći dio dolazi, mali dio se rekombinira

→ IAP kao normalno aktivno uz zamijenjenu ulogu emitera i kolektora
- kolektor-baza spoj injektira nosioce, a emiter ih skuplja
- teoretski se ponaša kvalitativno kao i NAP, no tranzistori nisu izvedeni simetrično te su optimizirani za NAP

$\beta_{NAP} > \beta_{IAP}$ [illegible]

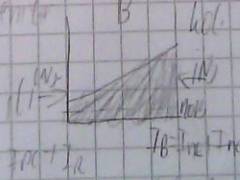


→ Zapiranje:



teku male struje zasićenja I_{EB0} i I_{CB0}

→ zasićenje



$I_B = I_{pE} + I_{pC} + I_R$ $\quad$ $I_B = I_{pE} + I_{pC} + I_R$

iz emitera veći, iz kolektora I_{pC}

uključena i isključena stanja

oba pn spoja injektiraju nosioce na drugu stranu

B zasićena manjinskim [illegible]