Predmet:
Polprevodniška elektronika

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Vrsta gradiva:
Zapiski avditornih vaj

Avtor:
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Študijsko leto:
2014/15

PE avditorne

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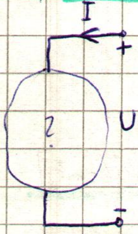
dodatno: Simon Sze

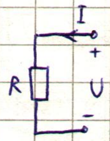
zbrane naloge iz prejšnjih let
list z enačbami (net)
skripta za lab. vaje

Boštjan Glažar (lab. vaje)

a) DVOPOLI ali enovhodni elementi (npr. dioda)

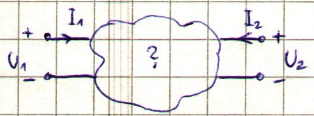


$I(U)$
$I = f(U)$
povezava med tokom in napetostjo



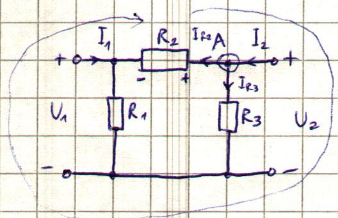
$$I = \frac{U}{R} = \frac{1}{R} U$$

b) ČETVEROPOLI ali dvovhodni elementi



$$I_2 = f(U_1, U_2) = f(I_1, U_1) = f(I_1, U_2)$$

eno veličino izrazimo z dvema veličinama



$I_2 = ?$ zapišimo vozliščno enačbo

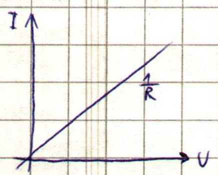
vsota tokov v vozl. je 0
(tok, ki teče ven → minus)

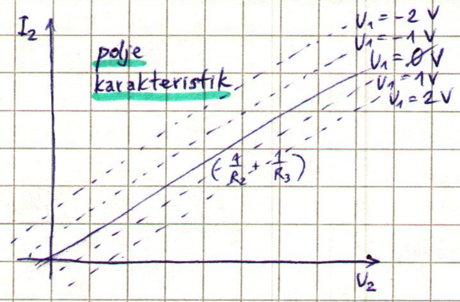
A: $I_2 - I_{R3} - I_{R2} = 0$

$$I_2 - \frac{U_2}{R_3} - \frac{U_2 - U_1}{R_2} = 0$$

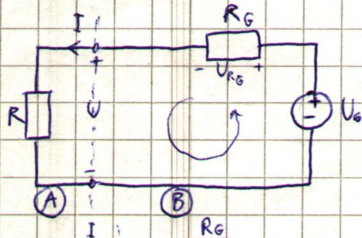
$$I_2 = -\frac{1}{R_2} \cdot U_1 + \left(\frac{1}{R_2} + \frac{1}{R_3}\right) \cdot U_2$$

(linearna zveza)





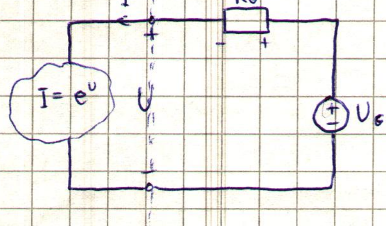
(npr. ki je na isti strani kot tok)
U_2 smo si izbrali kot neodv. spr,
U_1 pa kot parameter



zančna enačba: $U - U_G + U_{R_G} = 0$

$$R \cdot I - U_G + R_G \cdot I = 0$$

$$I = \frac{U_G}{R + R_G}$$

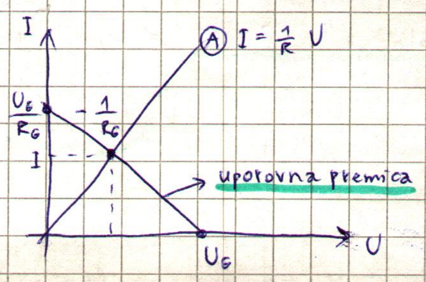


$$U - U_G + U_{R_G} = 0$$

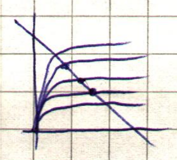
$$\ln I - U_G + R_G I = 0$$

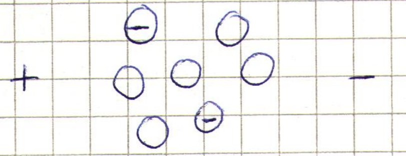
A: $I = \frac{U}{R}$

B: $I = \frac{U_G - U}{R_G} = \boxed{-\frac{1}{R_G} U + \frac{U_G}{R_G}}$



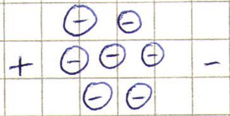
tranzistor





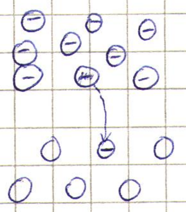
elektroni se začnejo premikat
prosta stanja

v izolatorju so vsa stanja zasedena



ni toka

v polprevodniku
pri abs. ničli

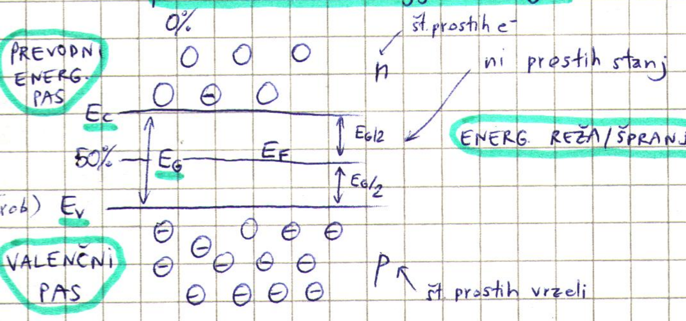


energijo rabim (T temp., svetl.)

dobim koncentracijo prostih elektronov $n\ [1/cm^3]$
predstavljamo si, da se luknja premika = vrzel $p\ [1/cm^3]$

prosta mesta gor in dol prispevajo k toku

prosta mesta so energijska stanja



$$\boxed{n = N_c\, e^{-\frac{E_c - E_F}{kT}} \qquad p = N_v\, e^{-\frac{E_F - E_v}{kT}}}$$

, E_F - Fermijev energ. nivo (obstaja 50% verjetnost, da najdemo e^-)

efekt. koncentracije prostih stanj

$T = 300\,K$, $kT \doteq 26\,meV$
↳ enota za energijo

$1\,eV = |q|\,J = 1{,}6 \cdot 10^{-19}\,J$ ($|q| = 1{,}6 \cdot 10^{-19}$)

vrednost energ. reže za silicij $E_G = 1{,}12\,eV$

1.) INTRINSIČNI SILICIJ

$\boxed{n_i = p_i}$ (št. prostih e^- = št. prostih vrzeli) $= 10^{10}\,cm^{-3}$ (pri $T = 300\,K$)

$\boxed{n_i p_i = n_i^2 = p_i^2}$

Fermijev nivo leži na sredini energ. reže. $E_{F_i} = E_v + \frac{E_c - E_v}{2}$

nevtralnost! $\rho = \emptyset = \underbrace{-q \cdot n_i}_{\text{elektrina zaradi elektronov}} + \underbrace{q\, p_i}_{\text{zaradi vrzeli}} = \emptyset$ (negat. naboj)

2) DOPIRAN SILICIJ

na silo kreiramo proste e^- oz. vrzeli ; vnašamo tujke

- dodajamo donorje (fosfor P - 5 e^- v zunanji orbitali) → vsiljujem proste e^- n (−)
  (za seboj puščajo:)
  N_D - fiksni ioni (+), P^+

- akceptorji (bor B - 3e^-) → v silicij vnašajo proste vrzeli p (+)
  N_A - fiksi ion (−), B^-

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

$p \cdot n$ = konst.
produkt vedno konst.

! skupna koncentracija $\rho = q(-n + N_D + p - N_A) = 0$

Silicij je dopiran z akcept. primesmi, $N_A = 10^{16}\ cm^{-3}$. Izr. konc. prostih nosilcev n in p in narišite energ. diagram!

$$\rho = q(-n + N_D + p - N_A) = 0$$

izhodišče
$$-n + N_D + p - N_A = 0$$
zanemar. $\leq 10^{3}\ cm^{-3}$; 0 ; $\geq 10^{16}\ cm^{-3}$
oklestimo

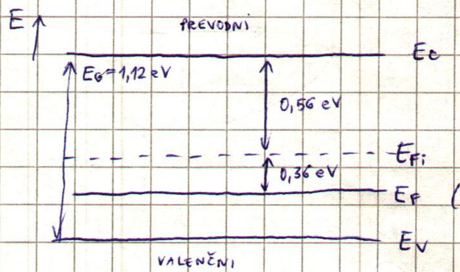
$$n \cdot p = n_i^2 = 10^{20}\ cm^{-3}$$

$p = N_A$, $p = 10^{16}\ cm^{-3}$, $n = \frac{n_i^2}{p} = 10^4\ cm^{-3}$ p-Si (tip, ker prevladujejo proste vrzeli)

$$n = n_i\, e^{\frac{E_F - E_{Fi}}{kT}}$$

$$p = n_i\, e^{\frac{E_{Fi} - E_F}{kT}}$$

$$\Rightarrow E_{Fi} - E_F = kT \cdot \ln\left(\frac{p}{n_i}\right) = 0{,}36\ eV$$
↳ če je pozit. je p-tip



(E_F bližje val. pasu)
last. p-tipa silicija

EL. TOKOVI V POLPREVODNIKU

- konduktivni tok

$U = I \cdot R$, $I = \frac{1}{R} \cdot U$

$$J_{kond} = \sigma \cdot E_{el} \qquad \left[\frac{A}{cm^2} = \frac{S}{cm} \cdot \frac{V}{cm}\right]$$
(σ ↳ specif. prevodnost; S – siemens)

$$\boxed{J_{kond} = J_{kond,n} + J_{kond,p} = \sigma_n E_{el} + \sigma_p E_{el}}$$
zaradi elektronov ; vrzeli

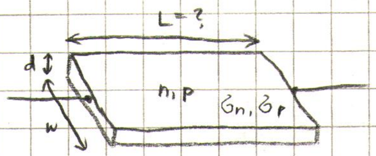
$$\boxed{\begin{aligned} \sigma_n &= q \cdot n \cdot \mu_n \\ \sigma_p &= q \cdot p \cdot \mu_p \end{aligned}}$$
μ_n – gibljivost elektronov

$\mu_n > \mu_p$

↳ koncentracija prostih vrzeli → višja bo prevodnost

Silicij je dopiran z akcept. primesmi s konc. $N_A = 10^{16}\ cm^{-3}$. Kako dolg mora biti integrirani upor z debelino $d = 0{,}5\ \mu m$ in širino $w = 1\ \mu m$, da bo izkazoval upornost $R = 500\ k\Omega$.

$N_A = 10^{16}\ cm^{-3}$
$d = 0{,}5\ \mu m$, $w = 1\ \mu m$
$R = 500\ k\Omega$
$\mu_n = 1200\ cm^2/Vs$
$\mu_p = 400\ cm^2/Vs$
$L = ?$



$$R = \rho \cdot \frac{L}{A} = \frac{1}{\sigma} \cdot \frac{L}{d \cdot W} \quad * \ !$$

$$L = R \cdot \sigma \cdot d \cdot w$$

$$\sigma = \sigma_p + \sigma_n = q \cdot p \cdot \mu_p + q \cdot n \cdot \mu_n = \underline{0{,}641\ \frac{S}{cm}}$$

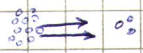
$\hookrightarrow p, n = ?$

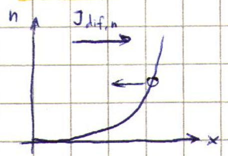
$p \doteq N_A = 10^{16}\ cm^{-3}$ (prejšnja nal.)
$n = 10^4\ cm^{-3}$

$\underline{L = 16\ \mu m}$

- difuzijski tok

nosilci prehajajo iz višje konc. k nižji, dokler ne bo izenačeno

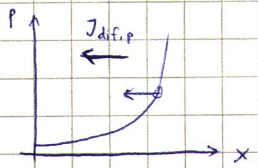




nosilci prehajajo proti levi, ker so e^-, tok teče v desno

$$J_{dif} = J_{dif,n} + J_{dif,p}$$

$$J_{dif,n} = q \cdot D_n \cdot \frac{dn}{dx}$$ odvisen od tega, kako hitro se konc. spreminja



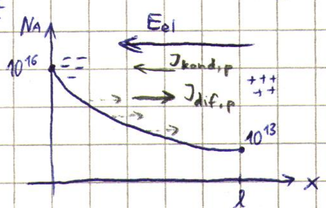
$$J_{dif,p} = -q \cdot D_p \cdot \frac{dp}{dx}$$

$$\boxed{D = \frac{kT}{q} \cdot \mu}$$ EINSTEINOVA RELACIJA

pri višji T, bo tudi D višji

Silicij je dopiran s porazd. akcept. primesi. Izr. vgrajeno el. polje in narišite energ. diagram v termičnem ravnovesju!

$N_A(x) = N_{A0} \cdot e^{-\frac{x}{L}}$
$N_{A0} = 10^{16}\ cm^{-3}$
$L = 1{,}45\ \mu m$
$l = 10\ \mu m$



privzamemo $p(x) \doteq N_A(x)$

1.) $E_{el} = ?$ termično ravnovesje (ni rezultančnih tokov)

$$J = \cancel{0} = J_{kond,p} + J_{dif,p} = \cancel{0}$$
$$= q \mu_p p E_{el} - q D_p \frac{dp}{dx}$$
$$E_{el} = \frac{D_p}{\mu_p p} \cdot \frac{dp}{dx} = \frac{kT}{q \cdot p} \cdot \frac{dp}{dx}$$
$$E_{el} = \frac{kT}{q p} \cdot \frac{d}{dx}\left(N_{A0} \cdot e^{-\frac{x}{L}}\right) \ *$$

$$* \ E_{el} = \frac{kT}{q p} \cdot N_{A0} \left(-\frac{1}{L}\right) e^{-\frac{x}{L}} = -\frac{kT}{q L} = -179\ V/cm$$

energ. diagram

$$p(x) = p_i \cdot e^{\frac{E_{Fi}(x) - E_F}{kT}}$$ (vedno velja)

$\rightarrow$ (E_F = konst) $J = \cancel{0}$

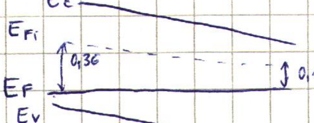
$$E_{Fi}(x) - E_F = kT \ln\left(\frac{p(x)}{p_i}\right)$$
$$E_{Fi}(x) - E_F = kT \ln\left(\frac{N_{A0}\, e^{-\frac{x}{L}}}{p_i}\right) =$$
$$= kT \ln\left(\frac{N_{A0}}{p_i}\right) - kT \frac{x}{L}$$

$$N - kx \quad \text{(lin. upadanje)}$$

$E_{Fi}(x=0) - E_F = 0{,}36\,eV$ upada
$E_{Fi}(x=l) - E_F = 0.18\,eV$

najprej nariši E_F! ker smo v term. ravn. (je horizontalen)

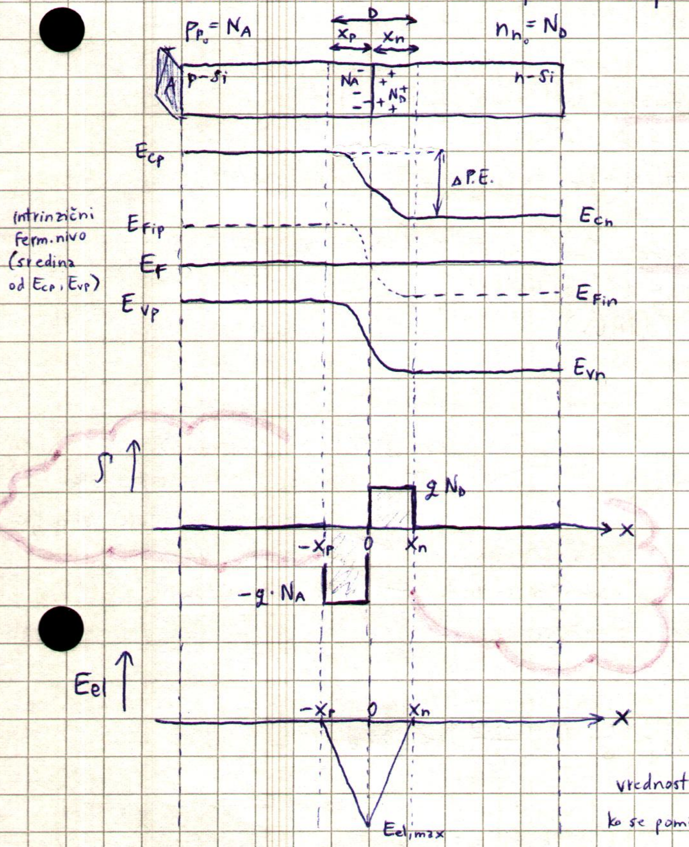
simetrično ostala dva



POLPREVODNIŠKA DIODA

TR

Analiz. razmere v idealnem stopničastem pn-spoju v termičnem ravnovesju! $N_A = 10^{18}\,cm^{-3}$, $N_D = 10^{15}\,cm^{-3}$



vrednost narašča s tem, ko se pomikamo proti meji

na stiku se zgodi proces difuzije

vspostavi se el. polje

difuzija, dokler $\vec{E}$ ne začne preprečevat

okolica spoja = osiromašeno področje

a) Energ. diagram

najprej Ferm. nivo E_F

$$N_A = p_{p_0} = p_i\, e^{\frac{E_{Fip} - E_F}{kT}}, \quad N_D = n_{n_0} = n_i\, e^{\frac{E_F - E_{Fin}}{kT}}$$

nivoji zvezni, če je isti tip polprevodnika

b) Difuzijska napetost

obstaja potenc. razlika med nivoji $\Delta P.E. = E_{Fip} - E_{Fin}$

$$\Delta P.E. = -q \cdot \Delta V = -q \cdot U_D$$

$$-q \cdot U_D = E_{Fip} - E_{Fin}$$

$$-q \cdot U_D = E_{Fip} - E_F + E_F - E_{Fin} = (E_{Fip} - E_F) + (E_F - E_{Fin})$$

$$\boxed{U_D = \frac{kT}{q} \ln\left(\frac{N_A N_D}{n_i^2}\right)}$$

$U_T = 25.66\,mV$

$U_D = 0{,}778\,V$

c) Širina osirom. območja

$$x_n = \sqrt{\frac{2\varepsilon}{q} \frac{N_A}{N_D} \cdot \frac{U_D}{N_A + N_D}}, \quad x_p = \sqrt{\frac{2\varepsilon}{q} \cdot \frac{N_D}{N_A} \cdot \frac{U_D}{N_A + N_D}}$$

$\varepsilon = \varepsilon_r \varepsilon_0$, $\varepsilon_r = 11.7$ (za silicij)

$\varepsilon = 10^{-12}\,\frac{As}{Vcm}$

poenost.:

$$\boxed{x_n = \sqrt{\frac{2\varepsilon}{q} \cdot \frac{U_D}{N_D}}} = 1\,\mu m, \quad \boxed{x_p = \sqrt{\frac{2\varepsilon}{q} \frac{N_D}{N_A^2} \cdot U_D}} = 1\,nm$$

razmerje širin isto kot razmerje dopiranja!

$$\boxed{x_n N_D = x_p N_A}$$

manj dop. → večja širina

$D = x_p + x_n \approx x_n$ kjer je manj dopiranja

d) El. polje

e) Koncentracija naboja

$Q_p + Q_n = 0$ $\qquad Q = \rho \cdot V$

$$\underbrace{-q \cdot N_A \cdot A \cdot x_p} + \underbrace{q \cdot N_D \cdot A \cdot x_n} = 0$$

$$x_n N_D = x_p N_A$$

El. polje: $\frac{dE_{el}}{dx} = \frac{\rho(x)}{\varepsilon} \rightarrow dE_{el} = \frac{\rho(x)}{\varepsilon} \cdot dx$

$$\int_{E_{el,max}}^{0} dE_{el} = \int_{0}^{x_n} \frac{\rho(x)}{\varepsilon} dx$$

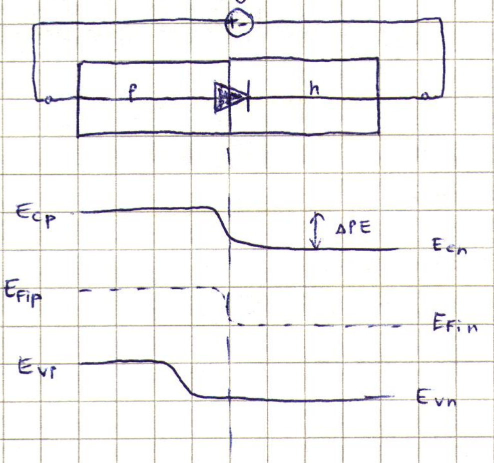
$$0 - E_{el,max} = \frac{q \cdot N_D}{\varepsilon}(x_n - 0)$$

$$\boxed{E_{el,max} = \frac{-q \cdot N_D \cdot x_n}{\varepsilon} = \frac{q N_A x_p}{\varepsilon}} = -16\,kV/cm$$

$$\boxed{U_D = \frac{1}{2} E_{el,max} \cdot D}$$

ploščina ▽ sovpada z

na diodo priključimo zunanjo napetost



a) **brez vzbujanja**

$U = 0$

$\Delta PE = -q \cdot U_D$

b) **prevodna smer** (priklopimo pozit. nap.)

$U = + U_F > 0$

$\Delta PE = -q(U_D - U_F)$ forward

c) **zaporna smer** (-ıı- neg.) MINUS! tudi če ne piše reverse

$U = -U_R < 0$

$\Delta PE = -q(U_D + U_R)$

KOL.

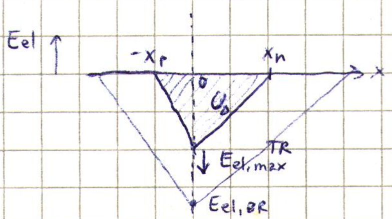
■ Izr. prebojno nap. U_{BR}, če je preb. el. polj. jakost 450 kV/cm.

$N_A = 10^{18}\ cm^{-3}$

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

$E_{el,BR} = 450\ kV/cm$

$U_{BR} = ?$



(reverzno) z zaporno napetostjo dodatno ojačuje el. polje

! širina osiromaš. območja se tudi povečuje

BR - breakdown

$$U_D = \frac{kT}{q} \cdot \ln\left(\frac{N_A N_D}{n_i^2}\right) = \underline{0.84\,V}$$

$$\boxed{|E_{el,max}^{TR}| = \frac{q \cdot N_D \cdot x_n^{TR}}{\varepsilon} = \frac{q \cdot N_A \cdot x_p^{TR}}{\varepsilon}}$$

$$E_{el,BR} = \frac{q \cdot N_D \cdot x_n^{BR}}{\varepsilon} = \frac{q \cdot N_A \cdot x_p^{BR}}{\varepsilon}$$

$$x_n^{BR} = \sqrt{\frac{2\varepsilon}{q} \cdot \frac{N_A}{N_D} \cdot \frac{U_D + U_{BR}}{N_A + N_D}}$$

$$\ldots \quad \boxed{U_{BR} = \frac{\varepsilon}{2q\,\underline{N_D}} \cdot E_{el,BR}^2 - U_D} = \underline{\underline{624\,V}}$$

$$U_D = \frac{1}{2} E_{el,max}^{TR} \cdot D^{TR} \quad ; \quad \underbrace{U_D + U_{BR}}_{\text{pl. velikega } \Delta} = \frac{1}{2} E_{el,BR} \cdot D_{BR}$$

sovpada s ploščino Δ

preb. nap. odvisna od šibkeje dopiranega področja

■ Izr. tok diode pri nap. ±0.7 V !

$I(U = +0.7\,V,\ -0.7\,V)$

$N_A = 10^{18}\ cm^{-3}$

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

$U_D = 0.84\,V$

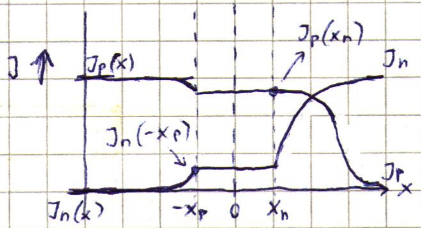
$\mu_n = 1200\ cm^2/Vs$

$\mu_p = 300\ cm^2/Vs$

življ. čas $\tau_n = 0.1\ \mu s$

$\tau_p = 0.1\ \mu s$

$A = 10^{-4}\ cm^2$



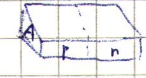
V osirom. obm. sta pribl. konst.

$$J(x) = J_p(x) + J_n(x) = J_p(x_n) + J_n(-x_p)$$

skupna gostota (tok) odvisna od manjšinskih nosilcev

$$J = \underbrace{n_i^2 q \left(\frac{D_n}{L_n N_A} + \frac{D_p}{L_p N_D}\right)}_{J_s} \left(e^{\frac{U}{U_T}} - 1\right)$$

(na listu!)



$$D = \frac{kT}{q} \cdot \mu$$

$$L = \sqrt{D \cdot \tau}$$

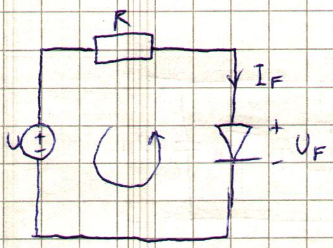
$I = J \cdot A$

$I_s = J_s \cdot A = 1.44 \cdot 10^{-15}\ A$

$I(U = +0.7\,V) = 0.71\ mA$

$I(U = -0.7\,V) = -1.44 \cdot 10^{-15}\ A$

■ Izr. nap. na diodi s pomočjo danega linearnega nadomestnega modela!



$R = 1\,k\Omega$

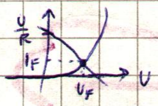
$U = 5V$

dioda ista kot prej

$U - U_F - R \cdot I_F = 0$

$U - U_T \ln\left(\frac{I_F}{I_s} + 1\right) - R \cdot I_F = 0$

grafično

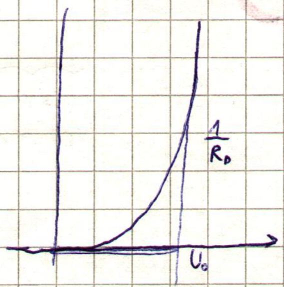


izpiti ✓

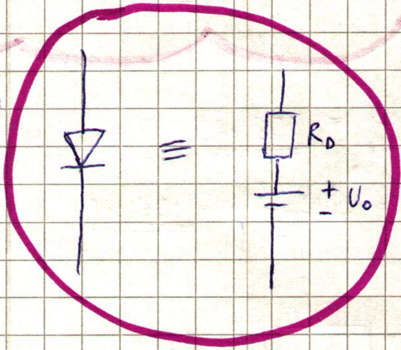
nadomestni lin. model

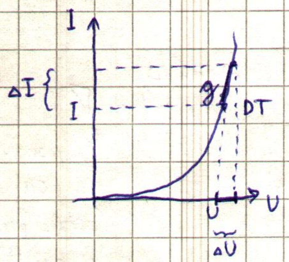
$R_D = 8\,\Omega$

$U_0 = 0.7\,V$



2 odseka





$I(U)$

$I(U + \Delta U) = I(U) + \Delta I$

– če sta ΔU, ΔI majhna $\rightarrow$ $\Delta I = g_{d_{DT}} \Delta U$

če imamo frekv. nihanje, izkazuje tudi parazitno kapacit.

■ Določite malosignalni (inkrem.) model diode pri $f = 5\,kHz$ za dve enosm. nap. $U_1 = +0.7\,V$, $U_2 = -10\,V$

$f = 5\,kHz$

$U_1 = +0.7\,V$

$U_2 = -10\,V$

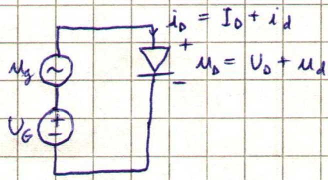
$N_A = 10^{18}\,cm^{-3}$

$N_D = 4 \cdot 10^{14}\,cm^{-3}$

$A = 10^{-4}\,cm^2$

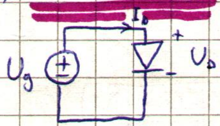
$D_p = 12.5\,cm^2/s$

$\tau_p = 2\,\mu s$



male črke – izmenični signali

a) DC analiza (vezje rešimo za primer enosm. signalov) $u_g \rightarrow 0$



→ dobim DELOVNO TOČKO

1) $U_D = +0.7V$

$I_D = 4mA$

2) $U_D = -10V$

$I_D = -5.72 \cdot 10^{-15}\,A$

→ ko podatek manjka $\times D$

1.) $U_G = +0.7\,V$

$U_D = U_G = +0.7\,V$

$I_D = I_s\left(e^{\frac{U_D}{U_T}} - 1\right) = A \cdot n_i^2\, q\left(\frac{D_p}{L_p N_D} + \cancel{\frac{D_n}{L_n N_A}}\right)\left(e^{\frac{U_D}{U_T}} - 1\right)$ (zanemarimo)

$I_s = 5.72 \cdot 10^{-15}\,A$

$I_D = 4\,mA$

2) $U_G = -10\,V$

$U_D = U_G = -10\,V$

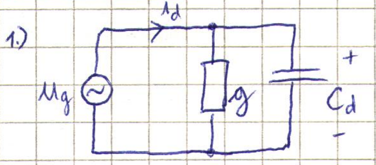
$I_D = -I_s$

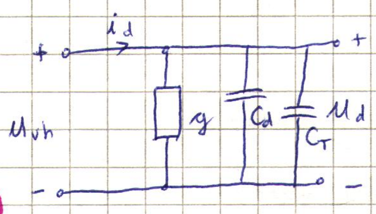
2. del ... b)

$U_G \to 0$

b) AC analiza (izklopimo enosm. vire), namesto diode uporabimo inkrementalni model
(nadomestimo)

1.)





diferenc. prevodnost
difuz. kapacit.
spojna kapacit.

$\underbrace{\qquad}$ $U > 0$, $C_T \to 0$

$\underbrace{\qquad}$ $U < 0$ negat., $g, C_d \to 0$

ZAPOMNI SI!

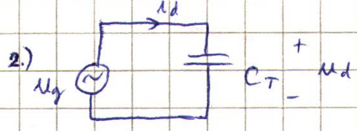
Kako visoka je frekvenca?

$$\omega \cdot \tau_p = 2\pi f \cdot \tau_p = \underline{0{,}06} \quad \begin{cases} \ll 1 & \text{Nizke f.} \\ \gg 1 & \text{visoke f.} \end{cases}$$

$$g_{NF} = \frac{I_D}{U_T} = \underline{\underline{156\ mS}}$$

$$C_{d_{NF}} = \frac{g_{NF} \cdot \tau_p}{2} = \underline{\underline{156\ nF}}$$

2.)



(v zaporni smeri le C_T člen)

$$C_T = \varepsilon \frac{A}{D}$$

del. točka se pojavi v členu D

$$\text{širina } D \doteq x_n = \sqrt{\frac{2\varepsilon}{q} \cdot \frac{N_A}{N_D} \cdot \frac{U_D \mp U_R}{N_A + N_D}} = \underline{\underline{4.4\ \mu m}}$$

enote! ponavadi cm (ostalo pretvori v cm!!)

$$U_{dif} = U_T \ln\left(\frac{N_A N_D}{n_i^2}\right) = \underline{0{,}76\ V}$$

$$\underline{\underline{C_T = 22.7\ pF}}$$

isti postopek bo pri tranzistorjih!

KOLOKVIJ

- Izr. specif. prev. vzorca v temi in pri osvetlitvi!

$N_A = 10^{16}\ cm^{-3}$
$N_D = 5 \cdot 10^{15}\ cm^{-3}$
$\mu_p = 400\ cm^2/Vs$
$\mu_n = 1200\ cm^2/Vs$

σ
a) tema
b) osvetlitev

a) brez osvetlitve

$$p - N_A - n + N_D = 0$$

izhodišče!

zanemarimo ali ne? če ne veš: $p \cdot n = n_i^2$

$$p_o - N_A - \frac{n_i^2}{p} + N_D = 0$$

$$p_o^2 + (N_D - N_A)\, p_o - n_i^2 = 0$$

$$p_o = \frac{N_A - N_D}{2}\left[1 \pm \sqrt{1 + \left(\frac{2 n_i}{N_A - N_D}\right)}\ \right]$$

$$p = 5 \cdot 10^{15}\ cm^{-3} = N_A - N_D$$

$$n = 2 \cdot 10^{4}\ cm^{-3}$$

(lahko bi zanemarili že na začetku)

$$\sigma_o = q\,(p_o \mu_p + n_o \mu_n) = q \cdot p \cdot \mu_p = \underline{\underline{0.32\ \frac{S}{cm}}}$$

p_o – konc. brez osvetlitve

b) osvetlitev

$$\Delta p = \Delta n = 2 \cdot p_o$$

$$\sigma = q\,((p_o + \Delta p)\mu_p + (n_o + \Delta n)\mu_n) = q\,(3 \cdot p_o \cdot \mu_p + 2 \cdot p_o \cdot \mu_n) = \underline{\underline{2.88\ \frac{S}{cm}}}$$

prevodnost se poveča

- Kolikšna je lahko min. vrednost spojne kapac., ki jo izkazuje zaporno pol. dioda, če je njena prebojna trdnost 10^5 V/cm.

$$C_{T_{min}} = \varepsilon \frac{A}{D_{max}}$$!

D_{max} ↳ odvisen od zaporne nap.

max. širino dosežemo v točki preboja!

$E_{BR} = 10^5$ V/cm
$N_A = 10^{18}$ cm^{-3}
$N_D = 10^{16}$ cm^{-3}
$A = 10^{-3}$ cm^2
$C_{T_{min}} = ?$

$$D_{max} \propto U_{R_{max}} = U_{BR}$$
$$D_{max} = x_{n max} + \cancel{x_{p max}} = x_{n max} = \frac{\varepsilon \cdot E_{BR}}{q \cdot N_D} = \underline{6.25 \cdot 10^{-5} cm}$$

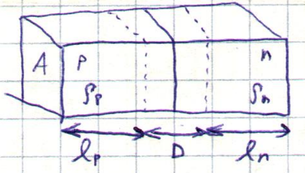
$$C_{T_{min}} = \varepsilon \frac{A}{x_{n max}} = \underline{16\,pF}$$

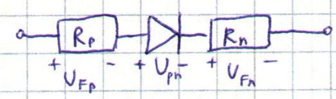
NI NA LISTU!

$$E_{BR} = \frac{q \cdot N_D \cdot x_{n max}}{\varepsilon} = \frac{q \cdot N_A\, x_{p max}}{\varepsilon}$$!!!

- Izr. nap. na zunanjih sponkah diode!

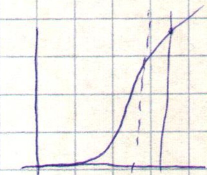
tok preko diod. $I_F = 1mA$
$I_S = 10^{-12}$ A
$l_n = 10^{-2}$ cm
$l_p = 5 \cdot 10^{-2}$ cm
$\rho_n = 0.1$ Ω cm
$\rho_p = 0.04$ Ω cm
$A = 10^{-4}$ cm^2
$U_F = ?$





\+ U_F −

$$I_F = I_S\left(e^{\frac{U_{pn}}{U_T}} - 1\right)$$
$$U_{pn} = U_T \ln\left(\frac{I_F}{I_S} + 1\right)$$
$$\underline{U_{pn} = 0.53\,V}$$



$$\boxed{R_p = \rho_p \cdot \frac{l_p}{A}} = 20\,\Omega$$
$$\boxed{R_n = \rho_n \frac{l_n}{A}} = 10\,\Omega$$

$U_{Fp} = R_p\, I_F = \underline{20 mV}$
$U_{Fn} = R_n\, I_F = \underline{10 mV}$

napet. padca na notr. delih

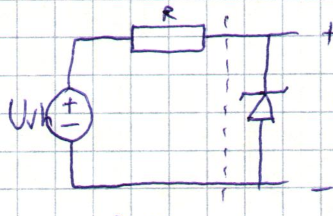
$\underline{U_F = 0.56\,V}$

IZPIT: uporovna premica

- Prebojna dioda

Na izhodu napet. stabil. imamo 5V. Določite vred. upora in izr. spr. izh. nap., če nap. na vhodu niha med 10V in 15V.

$U_{izh} = 5V$
$U_{vh} = 10 \div 15V$
$R = ?$
$\Delta U_{izh} = ?$
$I_{zmax} = 50 mA$
$r_z = 10\,\Omega$

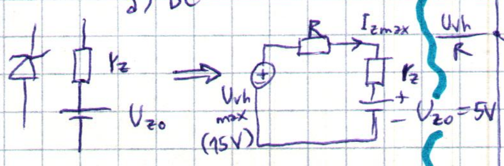


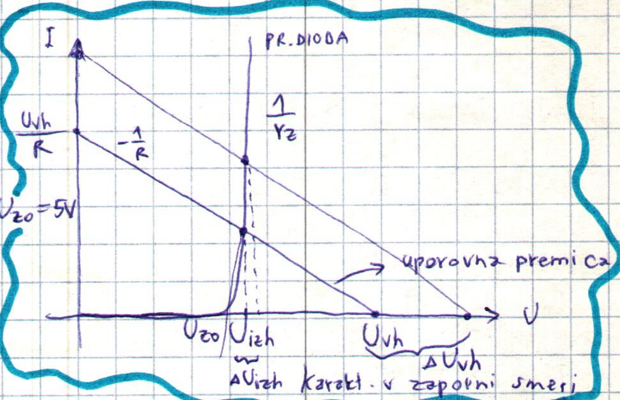
U_{izh} (je bolj stabilna od U_{vh})

Skiciraj princip stabilizacije! IZPIT

a) DC

aproksimiramo





če U_{z0} ni podan, predpost., da je U_{izh}.

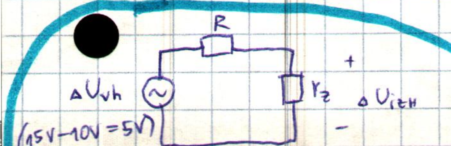
$$I_{zmax} = \frac{U_{vh} - U_{z0}}{R + r_z}$$

$\underline{R = 190\,\Omega}$

velika spr. U_{vh} da majhno ΔU_{izh} (stabilen vir)

če bi bla navpična, bi bil čisto stabilen

b) AC (obdržimo le izmenične) vire in pasiv. elem.



$$\Delta U_{izh} = \frac{r_z}{R + r_z} \Delta U_{vh} = \underline{0{,}24\,V}$$!!!

BIPOLARNI TRANZISTOR

oba tipa nosilcev prispevata k toku — priključki

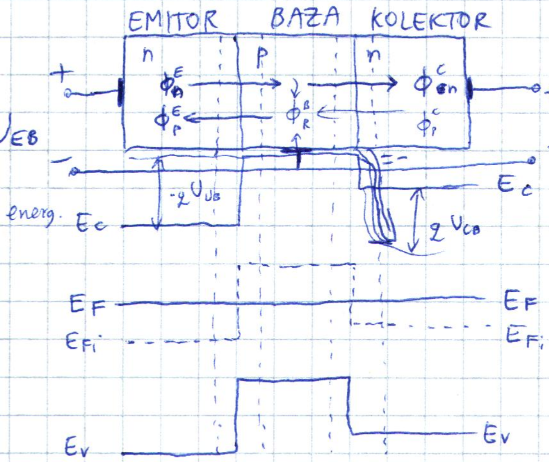


Tabela:

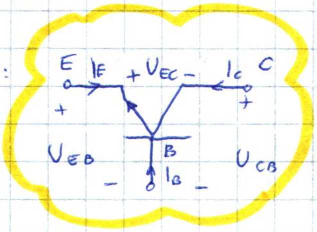
emitorsko bazni spoj

		U_{EB} (EB spoj)	
U_{CB}		$U_{EB} < 0$ PREVODNO	$U_{EB} > 0$ ZAPORNO
	$U_{CB} < 0$ PREVODNO	NASIČENJE	REVERZNO AKTIVNO (R)
kolektorsko bazni (CB spoj)	$U_{CB} > 0$ ZAPORNO	AKTIVNO (F)	ZAPORA

reverse

forward

simbol:



$$U_{EB} - U_{CB} - U_{EC} = 0$$
$$I_B + I_C + I_E = 0$$

AKTIVNO področje delovanja

$$-I_E = I_{en}^E + I_p^E$$
$$I_C = I_{en}^C + I_p^C$$

α v tranz. $\boxed{\alpha_F = \left.\frac{I_C}{-I_E}\right|_{U_{CB}=0}}$

$$I_C = -\alpha_F I_E + I_{CB0}$$ splenzoba za kolektorski tok

↳ v praksi je zelo majhen

$$\boxed{I_C = -\alpha_F I_E}$$

(0.99)

$$I_B + I_C + I_E = 0 \Rightarrow -I_E = I_B + I_C$$

$$I_C = \alpha_F \cdot (I_B + I_C) + I_{CB0}$$
$$I_C = \alpha_F I_B + \alpha_F I_C + I_{CB0}$$
$$I_C - \alpha_F I_C = \alpha_F I_B + I_{CB0}$$
$$I_C = \frac{\alpha_F}{1-\alpha_F} I_B + \frac{I_{CB0}}{1-\alpha_F}$$
$$I_C = \beta_F I_B + \frac{I_{CB0}}{1-\alpha_F}$$
$$\boxed{I_C = \beta_F I_B}$$

$$\boxed{\beta_F = \frac{\alpha_F}{1-\alpha_F}}$$ NAUČI SE!

EBERS - MOLLOV MODEL

za npn - tranzistor

$$\boxed{\begin{aligned}-I_E &= I_{ES}\left(e^{-\frac{U_{EB}}{U_T}}-1\right) - \alpha_R \cdot I_{CS}\left(e^{-\frac{U_{CB}}{U_T}}-1\right)\\ -I_C &= -\alpha_F I_{ES}\left(e^{-\frac{U_{EB}}{U_T}}-1\right) + I_{CS}\left(e^{-\frac{U_{CB}}{U_T}}-1\right)\end{aligned}}$$

poenost. odvisno na katerem področju smo

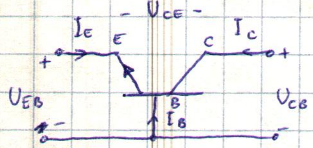
aktivno področje:

$$-I_E = I_{ES}\left(e^{-\frac{U_{EB}}{U_T}}-1\right)$$

$$-I_C = -\alpha_F I_{ES}\left(e^{-\frac{U_{EB}}{U_T}}-1\right) = \alpha_F I_E$$

! če poznamo 2 tokova, 3. izr. iz Kirchhoffa (napetosti -||-)

DC analiza tranzistorja V VEZAVI S SKUPNO BAZO (CB - common base)



Izr. vse veličine in določite območje delovanja tranzistorja! (v praksi bomo lahko zanemarili)

$\alpha_F = 0.99$, $\alpha_R = 0.80$

$I_{ES} = 1\,pA$

$I_{CS} = \dots 1{,}24\,pA$

$I_E = -1\,mA$

$U_{CB} = 5V$

I_C, I_B

U_{EB}, U_{CE}

$$I_{ES}\,\alpha_F = I_{CS}\,\alpha_R$$

$$I_{CS} = I_{ES}\cdot\frac{\alpha_F}{\alpha_R}$$

na listu je ta enačba razbita na člene !

- $I_E = -I_{ES}\left(e^{-\frac{U_{EB}}{U_T}}-1\right) + \alpha_R I_{CS}\left(e^{-\frac{U_{CB}}{U_T}}-1\right)$

$$U_{EB} = -U_T \ln\left(\frac{I_E - \alpha_R I_{CS}\left(e^{-\frac{U_{CB}}{U_T}}-1\right)}{-I_{ES}}+1\right) = \underline{-0.5318\,V}$$

- $I_C = \alpha_F I_{ES}\left(e^{-\frac{U_{EB}}{U_T}}-1\right) - I_{CS}\left(e^{-\frac{U_{CB}}{U_T}}-1\right) = \underline{0{,}99\,mA}$

$$I_E + I_C + I_B = 0$$

$$I_B = -I_E - I_C = \underline{10\,\mu A}$$

$$U_{EB} - U_{CB} + U_{CE} = 0$$

$$U_{CE} = -U_{EB} + U_{CB} = \underline{5{,}5318\,V}$$

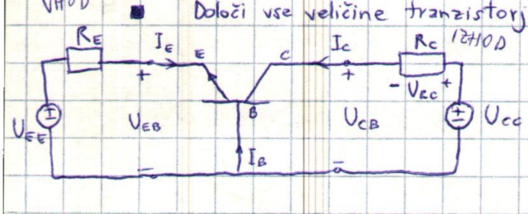
$\boxed{\begin{matrix}U_{EB} < 0\\ U_{CB} > 0\end{matrix}}$ smo v aktivnem področju delovanja

če bi to vedel: $I_E = -I_{ES}\left(e^{-\frac{U_{EB}}{U_T}}-1\right)$

(ostane enačba diode)

$I_C = -\alpha_F I_E$

- Določi vse veličine tranzistorja! $I_E, I_C, I_B, U_{EB}\checkmark, U_{CB}, U_{CE} = ?$



a) stanje delovanja: $U_{EB} = -0{,}7V < 0$ (EB spoj je prevodno polariz.)

$U_{CB} = U_{CC} - R_C I_C > 0$ predpostavimo

vzamemo aktivno obm.

$U_{EE} = -5V$, $U_{CC} = 15V$

$U_{EB} = -0{,}7\,V$,

$R_C = 2k\Omega$, $R_E = 1k\Omega$

$\alpha_F = 0.992$

$\beta_F = \frac{\alpha_F}{1-\alpha_F} = 124$

b) DC analiza

$I_E = -I_{ES}\left(e^{-\frac{U_{EB}}{U_T}}-1\right)$

$I_C = -\alpha_F I_E$

$I_C = \beta_F I_B$

① $U_{EE} - U_{EB} - U_{RE} = 0$

$U_{EE} - U_{EB} - R_E I_E = 0$

$I_E = \frac{U_{EE}-U_{EB}}{R_E} = \underline{-4.3\,mA}$

$\underline{I_C = 4{,}266\,mA}$

$\underline{I_B = 34\,\mu A}$

(II) $U_{CB} - U_{CC} + U_{RC} = 0$

$\quad\;\, -\text{ll}- \quad\;\; + R_C I_C = 0$

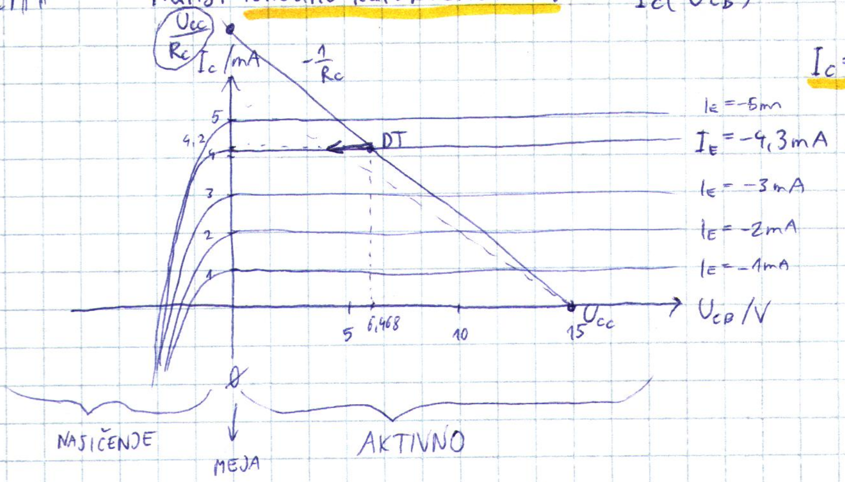
$U_{CB} = U_{CC} - R_C I_C = \underline{6{,}468\,V}$ $\quad$ U_{CB} pozitiven ? ✓ $\rightarrow$ aktivno področje delovanja

$U_{EB} - U_{CB} + U_{CE} = 0$

$U_{CE} = U_{CB} - U_{EB} = \underline{7{,}168\,V}$

IZPIT Nariši izhodno karakteristiko! $\quad I_C(U_{CB})$

$I_C = -\alpha_F I_E$



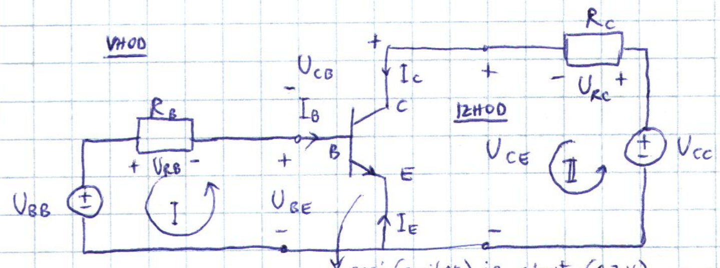
R_C višam, DT leze v levo

meja $\rightarrow$ DT zleze v nasičenje

upor premico vrti

DC ANALIZA, npn, (CE) $\quad$ skupni emitor

$\boxed{\begin{array}{l}\text{AKTIVNO:} \\ I_E = -I_{ES}\left(e^{\frac{U_{BE}}{U_T}} - 1\right) \\ I_C = -\alpha_F I_E \\ I_C = \beta_F I_B\end{array}}$



spoj (emitor) je odprt (0,7V) + predpost., da smo v aktivnem podr.

Določite vse veličine tranzistorja! $\quad$ V katerem podr. delovanja smo?

$U_{BB} = 5V \quad R_B = 100k\Omega$

$U_{CC} = 10V \quad R_C = 1k\Omega$

$U_{BE} = 0{,}7V \quad \beta_F = 100$

(I) $U_{BB} - U_{BE} - U_{RB} = 0$

$U_{BB} - U_{BE} - R_B I_B = 0 \rightarrow I_B = \frac{U_{BB} - U_{BE}}{R_B} = \underline{43\,\mu A}$

$I_C = \beta_F I_B = \underline{4{,}3\,mA}$

generira tok

$I_E = -4{,}343\,mA \quad U_{BE} = 0{,}7V$

$I_C = 4{,}3\,mA \quad U_{CE} = 5{,}7V$

$I_B = 43\,\mu A \quad U_{CB} = 5V$

$I_E + I_C + I_B = 0 \rightarrow I_E = -I_C - I_B = \underline{-4{,}343\,mA}$

(II) $U_{CE} - U_{CC} + U_{RC} = 0$

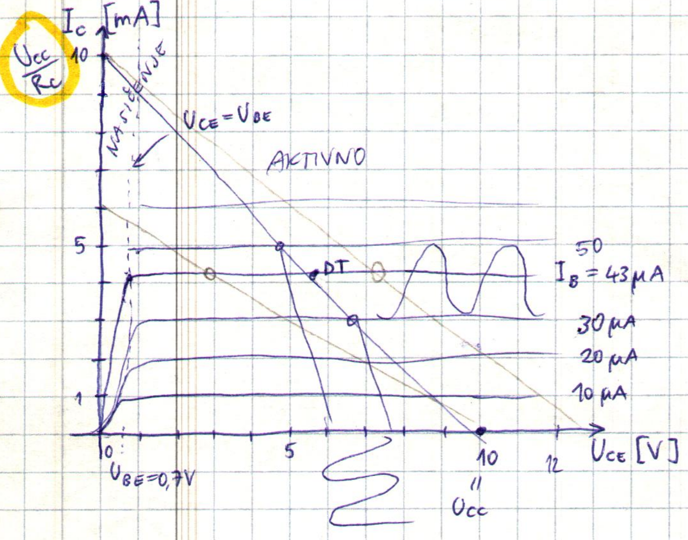
$U_{CE} - U_{CC} + R_C I_C = 0 \Rightarrow U_{CE} = U_{CC} - R_C I_C = 5{,}7V$

$U_{CB} + U_{BE} - U_{CE} = 0 \Rightarrow U_{CB} = U_{CE} - U_{BE} = 5V$

IZHODNO

Narišite izh. karakt., vrišite uporovno premico, označite delovno točko! $\quad$ predpostavka drži

$I_C(U_{CE})$



2 točki U_{cc}, $\frac{U_{cc}}{R_c}$

AKTIVNO: $U_{BE} > 0$
$U_{CB} > 0$

MEJA: $U_{CB} = 0$ meja med akt. in področjem nasičenja
$U_{CE} = U_{BE}$

če upor povečujem, zlezem v nasičenje

AC analiza, npn, CE

s pomočjo nadomestnih inkrementalnih modelov

- DIODA $i = g_{DT}\, u$
  ↳ odvisen od del. točke

- TRANZISTOR

2 tokova izrazimo z 2 napetostima

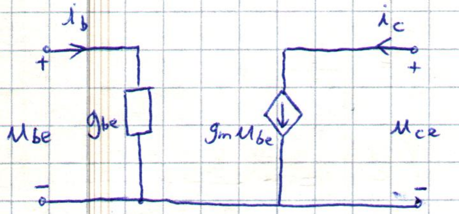
$$\boxed{\begin{aligned} i_b &= g_{11} \cdot u_{be} + g_{12}\, u_{ce} \\ i_c &= g_{21} \cdot u_{be} + g_{22}\, u_{ce} \end{aligned}}$$

(malosignalni)
INKREMENTALNI ČETVEROPOLNI NADOMESTNI MODEL
$= f(DT)$

AKTIVNO področje delovanja:

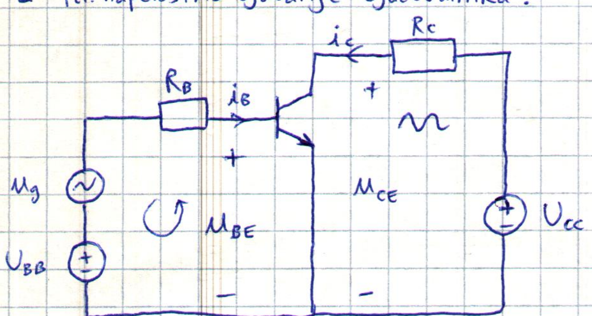
$$\boxed{\begin{aligned} i_b &= g_{11}\, u_{be} = g_{be} \cdot u_{be} \\ i_c &= g_{21}\, u_{be} = g_m \cdot u_{be} \end{aligned}}$$

↳ transkonduktanca



$$g_m = \frac{I_E}{U_T}, \quad g_{be} = \frac{g_m}{\beta_F}$$

Izr. napetostno ojačanje ojačevalnika!

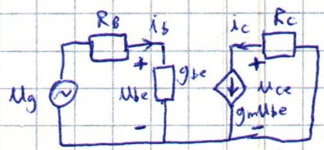


1) DC ANALIZA: $(u_g \to 0)$; $I_C = ?$

$U_{BB} - U_{BE} - R_B I_B = 0 \Rightarrow I_B = \frac{U_{BB} - U_{BE}}{R_B} = 8{,}67\,\mu A$

$I_C = \beta_F I_B = \underline{1.3\,mA}$

2) AC ANALIZA: $\left(\begin{matrix} U_{BB} \to 0 \\ U_{cc} \to 0 \end{matrix}\right.$, TRANZ. nadomestimo z nadom. modelom$\left.\right)$



3.) izračun parametrov

$\boxed{g_m = \frac{I_C}{U_T}} = \underline{50{,}66\ mS}$

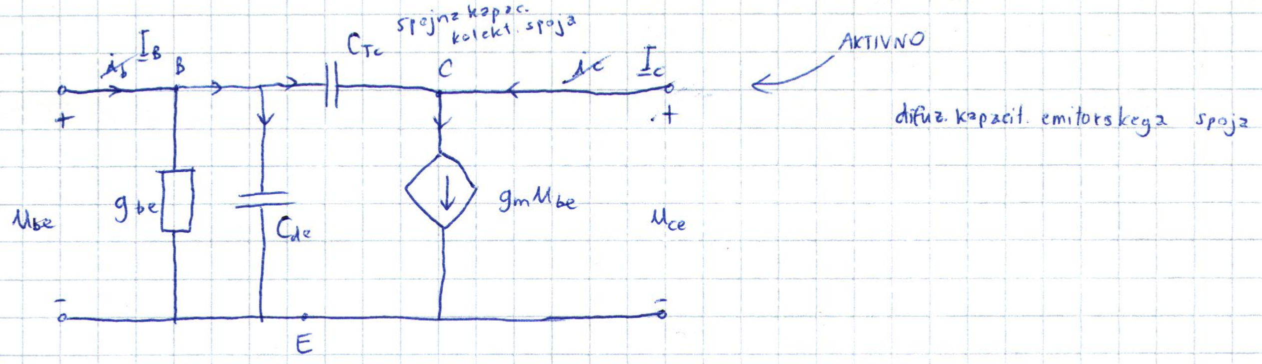
$g_{be} = \frac{g_m}{\beta_F} = \underline{337{,}75\ \mu S}$

4) $\boxed{A_u = \frac{u_{ce}}{u_g}}$ napet. ojačanje

$u_{ce} = -u_{R_C} = -R_C \cdot i_c = -R_C \cdot g_m \cdot u_{be} = -R_C \cdot g_m \cdot \frac{\frac{1}{g_{be}}}{R_B + \frac{1}{g_{be}}} \cdot u_g$

$u_{be} = \frac{r_{be}}{R_B + r_{be}} \cdot u_g$

$A_u = \frac{u_{ce}}{u_g} = -R_C\, g_m \frac{\frac{1}{g_{be}}}{R_B + \frac{1}{g_{be}}} = \underline{\underline{-2{,}94}}$



Določite <u>admitančne parametre</u> pri $f = 10\,MHz$!

$$\underline{I_B} = \underline{Y_{11}} \cdot \underline{U_{BE}} + \underline{Y_{12}} \cdot \underline{U_{CE}}$$

$$\underline{I_c} = \underline{Y_{21}} \cdot \underline{U_{BE}} + \underline{Y_{22}} \cdot \underline{U_{CE}}$$

$$\underline{I_B} = g_{be} \cdot \underline{U_{CE}} + j\omega C_{de} \cdot \underline{U_{BE}} + j\omega C_{Tc}(\underline{U_{BE}} - \underline{U_{CE}}) =$$

$$= \underbrace{(g_{be} + j\omega(C_{de} + C_{Tc}))}_{\underline{Y_{11}}} \underline{U_{BE}} - \underbrace{j\omega C_{Tc}}_{\underline{Y_{12}}} \cdot \underline{U_{CE}}$$

$$\underline{I_c} = g_m \underline{U_{BE}} - j\omega C_{Tc}(\underline{U_{BE}} - \underline{U_{CE}}) =$$

$$= \underbrace{(g_m - j\omega C_{Tc})}_{\underline{Y_{21}}} \underline{U_{BE}} + \underbrace{j\omega C_{Tc}}_{\underline{Y_{22}}} \cdot \underline{U_{CE}}$$

Določite kratkostično tokovno ojačanje !

$f_1 = 10\,MHz$
$\beta_0 = \beta_F(\omega \to 0) = 100$
$g_m = 50\,mS$
$C_{de} = 10\,pF$
$C_{Tc} = 1\,pF$

$\underline{A_i}(f_1)$

$$g_{be} = \frac{g_m}{\beta_0}$$

$$A_i(\omega) = \left.\frac{\text{tok ven iz BJT}}{\text{tok v BJT}}\right|_{U_{CE}\to 0} = \left.\frac{-i_c}{i_b}\right|_{U_{CE}\to 0} =$$

$U_{CE}\to 0$ = kratek stik na izhodu !

$$= -\frac{\underline{Y_{21}}\, u_{be} + \cancel{Y_{22}\, u_{ce}}}{\underline{Y_{11}}\, u_{be} + \cancel{Y_{12}\, u_{ce}}} = -\frac{\underline{Y_{21}}}{\underline{Y_{11}}} = -\frac{g_m - j\omega C_{Tc}}{g_{be} + j\omega(C_{de} + C_{Tc})} =$$

$$= -\frac{\beta_0 g_{be} - j\omega C_{Tc}}{g_{be} + j\omega(C_{de} + C_{Tc})}$$

- $\underline{A_i}(\omega_1) = \underline{-34.3 + j\,47.5} \quad \Longrightarrow \quad |\underline{A_i}(\omega_1)| = \underline{58.6}$
- $\underline{A_i}(\omega = 0) = -\beta_0 = \underline{-100} \quad \Longrightarrow \quad |\underline{A_i}(\omega = 0)| = 100$
- $\underline{A_i}(\omega_\beta) = \dots \quad \Longrightarrow \quad |\underline{A_i}(\omega_\beta)| = \frac{|\underline{A_i}(\omega = 0)|}{\sqrt{2}} = \frac{100}{\sqrt{2}} = \underline{70.7}$
- $\underline{A_i}(\omega_T) = \dots \quad \Longrightarrow \quad |\underline{A_i}(\omega_T)| = \underline{1}$

8. LAB poglej !

JFET TRANZISTOR

Poglej si izhodno karakt.

RIŠI

$I_{DS}(U_{DS})$

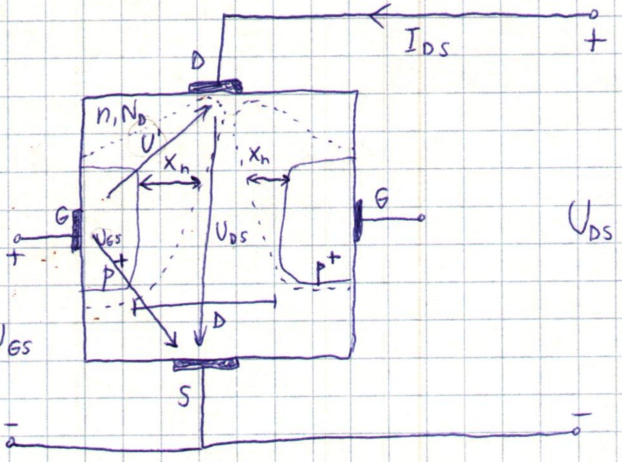
izris, prerez nariši ... (izpit!)

NAUČ JE NARISAT

■ Določite U_{DS} pri kateri se kanal zadrgne pri JFET tr.!

$N_D = 10^{15}\ cm^{-3}$
$D = 4.85\ \mu m$
$\varepsilon_{Si} = 10^{-12}\ As/Vcm$
$U_D = 0.7V$
$U_{GS} = -1V$

$U_{DS,sat} = ?$



širina osir. obm.:

$$X_n = \sqrt{\frac{2\varepsilon_{Si}}{q}\cdot\frac{1}{N_D}(U_D - U')}$$

- točka zadrgnjenja: $D = 2\cdot X_n$; $\underline{U' = U_P}$ pragovna

$$D = 2\sqrt{\frac{2\varepsilon_{Si}}{q}\frac{1}{N_D}(U_D - U_P)}$$

$$\underline{U_P = -4V}$$ — iz tega ven potegnem!

- območja:

$U' < U_P$ NASIČENJE (kanal je zaprt)
$U' > U_P$ LINEARNO (odprt)

- krmiljenje: $U' = U_{GS} - U_{DS}$

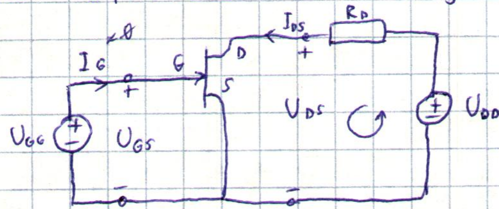
- meja, točka zadrgnjenja: $U_P = U_{GS} - U_{DS,sat}$

$$U_{DS,sat} = \underline{U_{GS} - U_P} = \underline{3V}$$

■ Določite upornost R_D, da se bo JFET tr. nahajal na meji med lin. obm. in obm. nasičenja!

$U_{DD} = 10V$
$U_{GG} = -1V$
$U_P = -3V$
$I_{DSS} = 9mA$

$R_D = ?$



$$\boxed{\begin{array}{lll} U_{DS} > U_{GS} - U_P & \text{NASIČENJE} \\ U_{DS} < U_{GS} - U_P & \text{LINEARNO} \\ U_{DS,sat} = U_{GS} - U_P & - \text{MEJA} \end{array}}$$

!

iz lista: $\boxed{I_{DS} = I_{DSS}\left(1 - \frac{U_{GS}}{U_P}\right)^2}$ velja za obm. nasičenja

$U_{GS} = U_{GG} = \underline{-1V}$

$\underline{I_{DS} = 4mA}$

izhodna zanka: $U_{DS} - U_{DD} + R_D I_{DS} = 0$

meja $U_{DS} = U_{DS,sat} = U_{GS} - U_P = \underline{2V}$

$$R_D = \frac{U_{DD} - U_{DS}}{I_{DS}} = \underline{2k\Omega}$$