# POLPREVODNIŠKA ELEKTRONIKA

# 2 UNI

Zapiski avditornih vaj

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| **Šolsko leto** | 2008/2009 |
| **Izvajalec** | Janez Krč |
| **Avtor dokumenta** | Aljoša Praznik |
| **Skeniranje** | Aljoša Praznik |

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| UREJANJE DOKUMENTA | |
|---|---|
| **VERZIJA** | 01.02 |
| **DATUM** | 01.06.2009 |

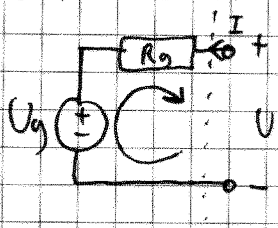
**OPOMBE**

23.02.2009

Janez Krč

Skicirajte zahtevane karakteristike podanih dvopolnih in večpolnih vezij oz. elementov.

a.) $I(U)$




$$\circlearrowleft: -U_g - R_g \cdot I + U = 0$$

$$-R_g \cdot I = U_g - U$$

$$I = -\frac{U_g}{R_g} + \frac{U}{R_g}$$

$$I = U \cdot \frac{1}{R_g} - \frac{U_g}{R_g}$$

$$y = x \cdot k + n$$

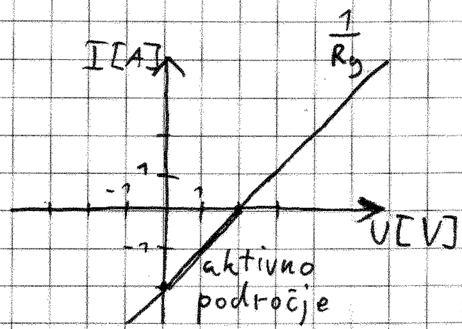
$U_g = 2\,V$
$R_g = 1\,\Omega$

1.) $U = 0$

$$I = -\frac{U_g}{R_g} = -\frac{2\,V}{1\,\Omega} = -2\,A$$

2.) $I = 0$

$$U = U_g = 2\,V$$



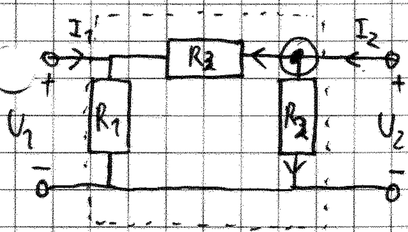

D.N.

1.) $U_g \nearrow$ ?

2.) $R_g \nearrow$ ?

b.) $I_2(U_1, U_2)\Big|_{U_1\text{-parameter}}$

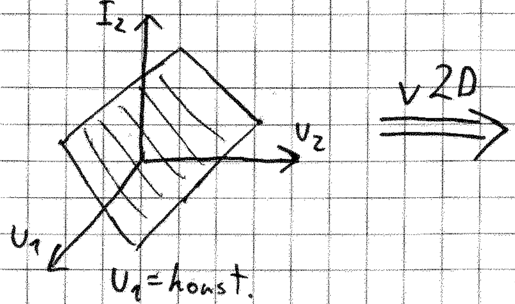
linearen četveropol

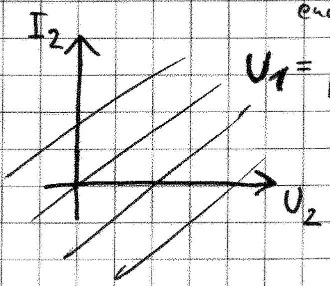


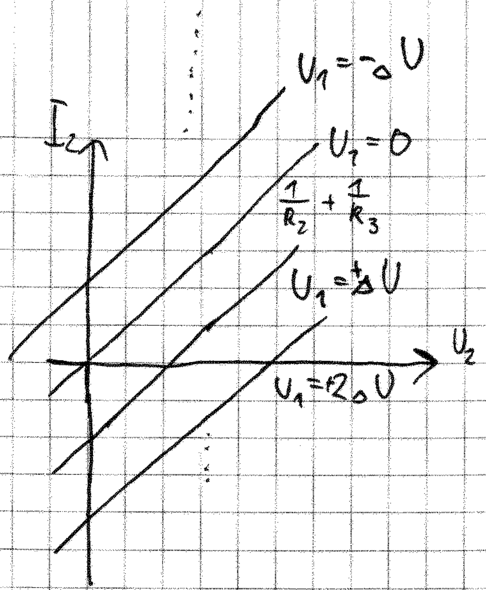

① $$I_2 - \frac{U_2}{R_2} - \frac{U_2 - U_1}{R_3} = 0$$

$$I_2 + U_1 \frac{1}{R_3} - U_2\left(\frac{1}{R_2} + \frac{1}{R_3}\right) = 0$$

$$I_2 = \underbrace{U_1 \cdot \left(-\frac{1}{R_3}\right) + U_2\left(\frac{1}{R_2} + \frac{1}{R_3}\right)}_{\text{enačba ravnine}}$$






c.) $I_C(U_{CB}, I_E)\Big|_{I_E = \text{parameter}}$ $(-10\ mA \ldots\ 0\ mA)$ nelinearen četveropol

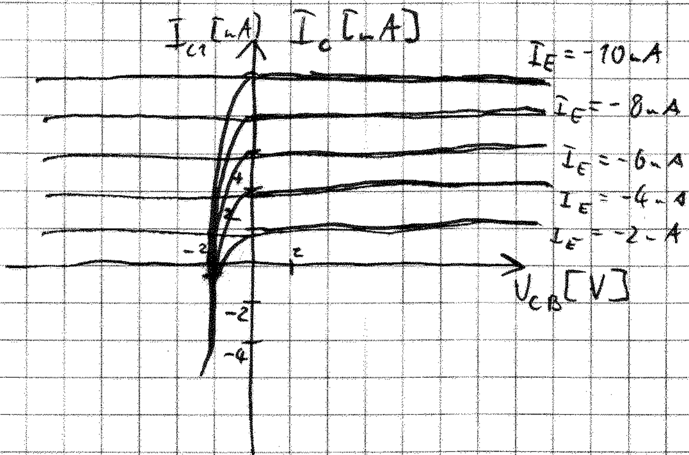
$$I_C = -\alpha_F \cdot I_E - I_{C0}\left(e^{-\frac{U_{CB}}{U_T}} - 1\right)$$ $\alpha_F$ - konstanta

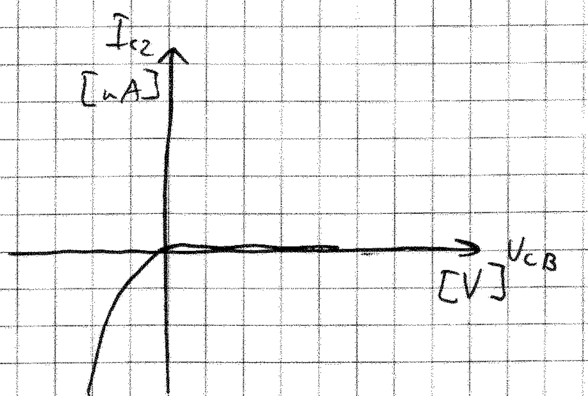
$\alpha_F = 0{,}99$
$I_{C0} = 1\ pA$
$U_T = 25{,}66\ mA$

$$I_C = I_{C1} + I_{C2}$$

$I_{C1} = -\alpha_F \cdot I_E =$

$I_{C2} = -I_{C0}\left(e^{-\frac{U_{CB}}{U_T}} - 1\right)$




grafa $I_{C1}$ in $I_{C2}$ seštejemo

02.03.2009

## Specifična upornost in specifična prevodnost polprevodnikov

$$\sigma = q(\mu_N n + \mu_p p)$$
$\uparrow$ $\frac{S}{cm}$

$\mu_N$ – mobilnost elektronov
$n$ – gostota / koncentracija prostih elektronov
$\mu_p$ – gibljivost vrzeli
$p$ – koncentracija prostih vrzeli

$$\rho = \frac{1}{\sigma} = \frac{1}{q(\mu_n n + \mu_p p)}$$
$\uparrow$ $\Omega cm$

### 1. Čisti, nedopirani, intrinzični polprevodnik

$n_i = p_i$

$$\sigma_i = q(\mu_n n_i + \mu_p p_i) = q\, n_i (\mu_n + \mu_p)$$

$T = 297{,}8\,K$ $\xrightarrow{\text{sobna } T}$ $\sigma_{i_{Si}} = 2{,}91 \cdot 10^{-6}\ \frac{S}{cm}$ , $\rho_{i_{Si}} = \frac{1}{\sigma_{i_{Si}}} = 3{,}44 \cdot 10^{5}\ \Omega cm$

$24{,}8\,°C$
sobna temp.

$Si$ $\uparrow$ silicij

term. ravnovesje (samo temp. vzbujanje): $p \cdot n = n_i^2$

$T = 297{,}8\,K$ $\quad n_{i_{Si}} = 10^{10}\ cm^{-3}$

### 2. dopirani polprevodnik

n-tip

samo $N_D$ – koncentracija donorskih primesi $\quad N_A$ – koncentracija akceptorskih primesi

oz. $N_D > N_A$ $\quad p_n = \frac{n_i^2}{n_n}$

$N_D \gg n_i$ $\quad n_n \gg p_n$

$n_n = N_D - N_A$

$n_n \big|_{N_A \neq \emptyset} = N_D$

$$\sigma_n = q \cdot \mu_n \cdot n_n \qquad \rho_n = \frac{1}{q \cdot \mu_n \cdot n_n}$$

## p-tip

samo $N_A$

oz. $N_A > N_D$

$N_A \gg n_i$

$p_p = N_A - N_D$ $\qquad n_p = \frac{n_i^2}{p_p}$

$p_p \Big|_{N_D=0} = N_A$ $\qquad p_p \gg n_p$

$\sigma_p = q \cdot \mu_p \cdot p_p$ $\qquad \rho_p = \frac{1}{q \cdot \mu_p \cdot p_p}$

Izračunajte koncentracijo dodanih donorskih primesi v n-tipu Silicija.

$\rho_n = 1\ \Omega cm$
$N_A = 2 \cdot 10^{14}\ cm^{-3}$
$(T = 297{,}8\ K)$
$n_i = 10^{10}\ cm^{-3}$
$\mu_n = 1300 \cdot \frac{cm^2}{Vs}$

$N_D = ?$

n-tip
$N_A < N_D$

računamo s cm !!!

$$\rho_n = \frac{1}{q \cdot \mu_n \cdot n_n} \Rightarrow n_n = \frac{1}{q \cdot \mu_n \cdot \rho_n} = 4{,}8 \cdot 10^{15}\ cm^{-3}$$

$n_n = N_D - N_A$

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

Silicij vsebuje primesi fosforja $N_{D_{Fo}}$. Kolikšen naj bo dodatek primesi bora, da bo postal polprevodnik nasprotnega tipa z enako prevodnostjo?

$N_D = 2 \cdot 10^{14}\ cm^{-3}$
$T = 297{,}8\ K$
$n_i = 10^{10}\ cm^{-3}$
$\mu_n = 3\mu_p = 1357\ \frac{cm^2}{Vs}$

$N_A = ?$

n-tip
$N_D$

a.) pred dodajanjem bora

p-tip
$N_D < N_A$

b) po dodajanju primesi bora

$$\sigma_n = \cancel{q} \cdot \underset{3 \cdot \cancel{\mu_p}}{\mu_n} \cdot \underset{N_D}{n_n} \quad \overset{\text{naloga}}{=} \quad \sigma_p = \cancel{q} \cdot \cancel{\mu_p} \cdot \underset{N_A - N_D}{p_p}$$

$$3 N_D = N_A - N_D$$

$$N_A = \overset{1+3}{4} \cdot N_D$$

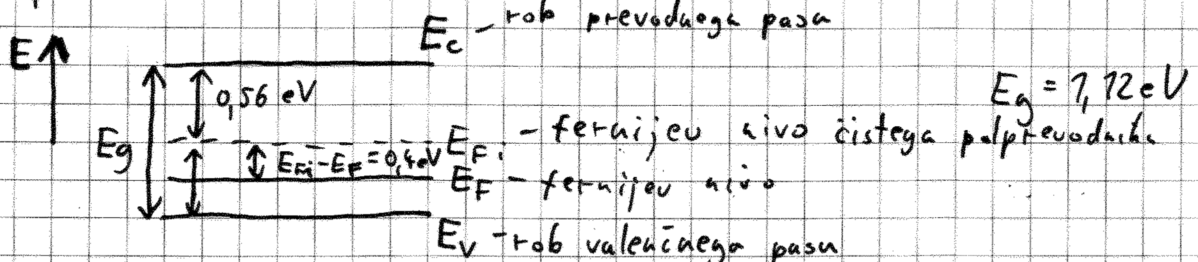
$$N_A = 8 \cdot 10^{14}\ cm^{-3}$$

# Energijski in potencialni nivoji polprevodnika

Narišite sliko energijskih in potencialnih nivojev v siliciju pri sobni temperaturi z dodatkom akceptorskih primesi.

$N_A = 6 \cdot 10^{16}\ cm^{-3}$
$E_G = 1,12\ eV$

p-tip




$E_{Fi} - E_F \longleftrightarrow p_p = N_A$

$$\boxed{p_p = n_i \cdot e^{\left(\frac{E_{Fi} - E_F}{q \cdot U_T}\right)}}$$

eV

1eV

term. nap. $25,66 \cdot 10^{-3}\,V$ $(U_T = k \cdot T)$

Boltzmanova konst.

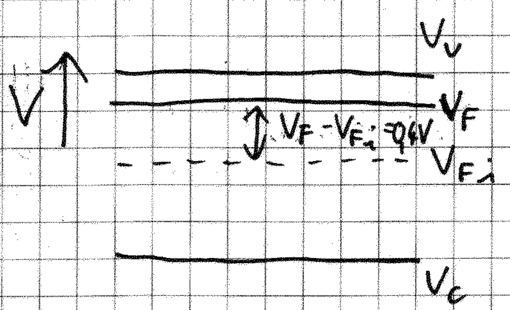
$$\frac{p_p}{n_i} = e^{\left(\frac{E_{Fi} - E_F}{q \cdot U_T}\right)}$$

$$\ln \frac{p_p}{n_i} = \frac{E_{Fi} - E_F}{q \cdot U_T}$$

$$E_{Fi} - E_F = q \cdot U_T \cdot \ln \frac{p_p}{n_i} = 1e \cdot 25,66 \cdot 10^{-3}\,V \cdot \ln \frac{6 \cdot 10^{16}\,cm^{-3}}{10^{10}\,cm^{-3}} = \underline{\underline{0,4\,eV}}$$

$$\boxed{E = -q \cdot V}$$

1eV [V]




$V_F - V_{Fi} \longleftrightarrow p_p$

09.03.2009

V silicijevem vzorcu z danim profilom dopiranja določite potek potencialnih nivojev in električnega polja v strukturi

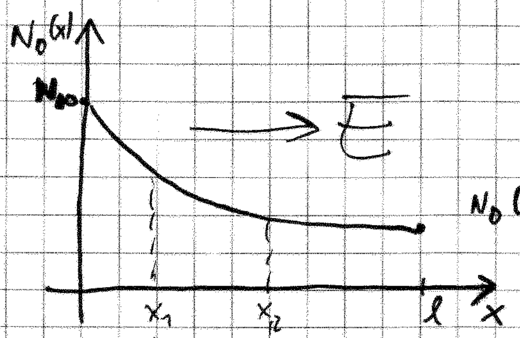
$N_D(x) = N_{D_0} \cdot e^{-\frac{x}{L}}$

$N_{D_0} = 10^{16}\ cm^{-3}$

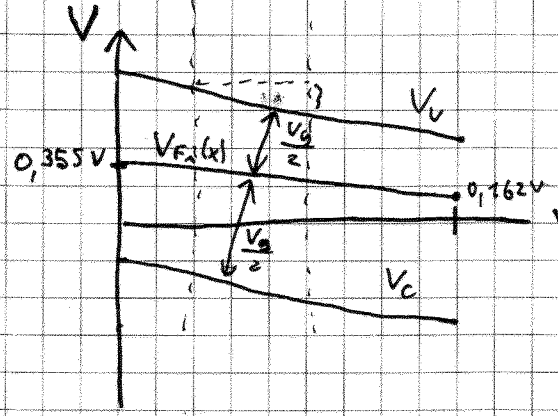
$l = 15\ \mu m$

$L = 2\ \mu m$

$V_g = 1{,}12\ V$




$$N_D(x=l) = 10^{16}\ cm^{-3} \cdot e^{-\frac{15\mu m}{2\mu m}} = 5{,}53 \cdot 10^{12}\ cm^{-3}$$




$V_F$ (term. ravn. $\rightarrow V_F = konst$)

$$N_D(x) = n_n(x)$$

$$\boxed{n_n(x) = n_i \cdot e^{\frac{V_{Fi}(x) - V_F}{U_T}}}$$

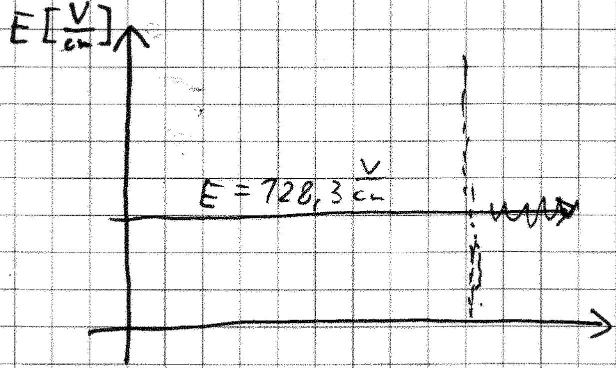
$$\frac{n_n(x)}{n_i} = e^{\frac{V_{Fi}(x) - V_F}{U_T}} \quad / \ln$$

$$\ln \frac{n_n(x)}{n_i} = \frac{V_{Fi}(x) - V_F}{U_T}$$

$$V_{Fi}(x) - V_F = U_T \ln \frac{n_n(x)}{n_i}$$

$$V_{Fi}(x) = V_F + U_T \ln \frac{n_n(x)}{n_i} = V_F + U_T \ln \frac{N_{D0} \cdot e^{-\frac{x}{L}}}{n_i}$$

$$V_{Fi}(x) = V_F + U_T \ln \frac{N_{D0}}{n_i} + U_T \left(-\frac{x}{L}\right)$$




1.) $x = 0$

$$V_{Fi}(x=0) = V_F + 25{,}66 \cdot 10^{-3}\ V \ln \frac{10^{16}}{10^{10}} + 25{,}66 \cdot 10^{-3}\ V \cdot \left(-\frac{0}{2 \cdot 10^{-4}\ cm}\right)$$

$$V_{Fi}(x=0) = V_F + 0{,}355\ V$$

2) $x = l$

$$V_{Fi}(x = 15\cdot 10^{-4}\,cm) = V_F + \ldots = V_F + 0{,}162\ V$$

$$\boxed{E = -\frac{dV}{dx}} = -\frac{dV_{Fi}}{dx} = -\frac{d\left[V_F + U_T \ln\frac{N_{Do}}{n_i} + U_T\left(-\frac{x}{L}\right)\right]}{dx} =$$

$$E = -\left(-\frac{U_T}{L}\right) = \frac{U_T}{L} = 25{,}66\cdot 10^{-3}\,V / 2\cdot 10^{-4}\,cm = 128{,}3\ \frac{V}{cm}$$

2. način za izračun E

$j_n = \emptyset$ term. ravnovesje

$$j_n = q\,\mu_n\,n_n(x)\cdot \underbrace{E(x)}_{\text{D.N.}} + q\,D_n\left(\frac{dn_n(x)}{dx}\right) = 0 \quad ; \quad U_T = \frac{D_N}{\mu_n}$$

Nadaljevanje vaje. Izračunajte potencialno razliko med dvema točkama v vzorcu, v katerih se koncentracija elektronov razlikuje za faktor 10.

$$\frac{n_n(x_1)}{n_n(x_2)} = 10 \qquad V_{Fi}(x_2) - V_{Fi}(x_1)$$

$$V_{Fi}(x) = V_F + U_T \ln\frac{n_n(x)}{n_i}$$

$$V_{Fi}(x_2) - V_{Fi}(x_1) = U_T \ln\frac{n_n(x_2)}{n_i} - U_T \ln\frac{n_n(x_1)}{n_i} = U_T \ln\frac{\frac{n_n(x_2)}{n_i}}{\frac{n_n(x_1)}{n_i}} =$$

$$= U_T \cdot \ln\frac{n_n(x_2)}{n_n(x_1)} = U_T \cdot \ln\frac{1}{10} = \underline{\underline{-0{,}06\ V}}$$

16.03.2009

Za koliko se zmanjša specifična upornost silicijevega vzorca s koncentracijo donorskih primesi $N_D$, če se zaradi osvetlitve poveča koncentracija večinskih in manjšinskih prostih nosilcev za $\Delta n = \Delta p = 8 \cdot 10^{14}\ cm^{-3}$.

$N_D = 10^{15}\ cm^{-3}$

$\mu_n = 3\mu_p$ n-tip

$\mu_p = 460\ cm^2/Vs$

a.) pred osvetlitvijo (term. ravnovesje)

n-tip

$N_D$

$n_{n_0} \gg p_{n_0}$

$n_{n_0} = N_D$

b.) ob osvetlitvi

n-tip

$N_D$

$n_{n_L}$ $p_{n_L}$

$n_{n_L} = \underbrace{n_{n_0}}_{N_D} + \underbrace{\Delta n}_{8\cdot 10^{14}\ cm^{-3}}$

$p_{n_L} = \underbrace{\cancel{p_{n_0}}}_{\text{zanemarimo}} + \underbrace{\Delta p}_{8\cdot 10^{14}\ cm^{-3}}$

$p_{n_0} = \frac{n_i^2}{n_{n_0}}$

$$\rho_{n_0} = \frac{1}{q \cdot \mu_n \cdot n_{n_0}} = \frac{1}{1{,}6 \cdot 10^{-19}\ As \cdot 3 \cdot 460 \frac{cm^2}{Vs} \cdot 10^{15}\ cm^{-3}} = 4{,}53\ \Omega cm$$

$$\rho_{n_L} = \frac{1}{q(\mu_n n_{n_L} + \mu_p p_{n_L})} = 2{,}19\ \Omega cm$$

$\cancel{n_L p_p = n_i^2}$ ne velja

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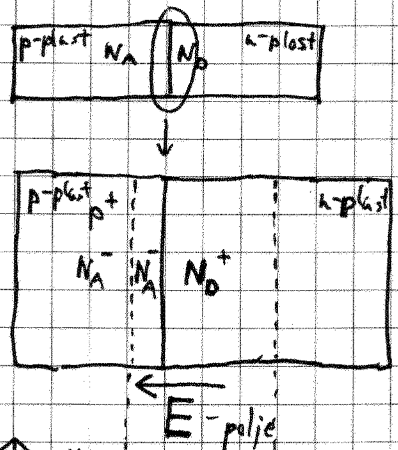
Narišite krajevne poteke koncentracij prostih nosilcev naboja energijskih in potencialnih nivojev stopničastega PN spoja v termičnem ravnovesju ter izračunajte difuzijsko napetost $U_D$.

$p^+$-plast — n-plast — $p^+n$ spoj, ker je več $N_A$.

$N_A = 1{,}3 \cdot 10^{17}\ cm^{-3}$ — $N_D = 5{,}5 \cdot 10^{14}\ cm^{-3}$



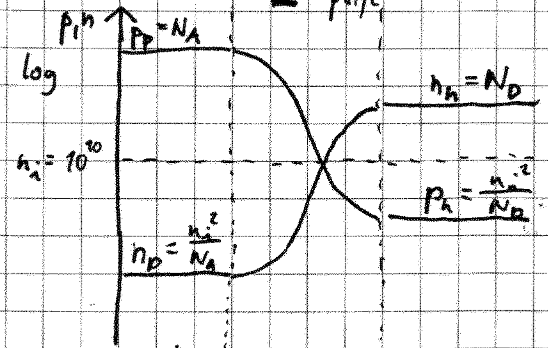

samo v term. ravnovesju

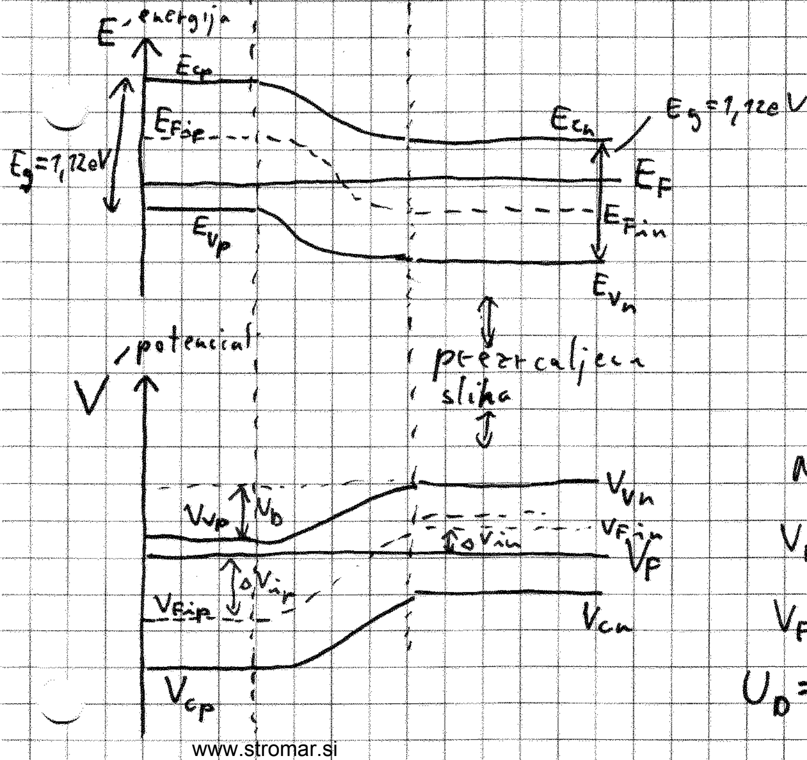
$$n_p = \frac{n_i^2}{p_p}$$

$$n_p \cdot p_p = n_i^2$$

$$\log n_p + \log p_p = 2 \log n_i$$

$$\log n_i = \frac{\log n_p + \log p_p}{2}$$




$$U_D = \underbrace{\Delta V_{Fip}}_{V_F - V_{Fip}} + \underbrace{\Delta V_{Fin}}_{V_{Fin} - V_F}$$

$$\underset{N_A}{p_p} = n_i \cdot e^{\frac{V_F - V_{Fip}}{V_T}} \qquad n_n = n_i \cdot e^{\frac{V_{Fin} - V_F}{U_T}}$$

$$V_F - V_{Fip} = \Delta V_{Fip} = U_T \ln \frac{p_p}{n_i};$$

$$V_{Fin} - V_F = \Delta V_{Fin} = U_T \ln \frac{n_n}{n_i};$$

$$U_D = U_T \left(\ln \frac{p_p}{n_i} + \ln \frac{n_n}{n_i}\right) = \boxed{U_T \ln \frac{p_p \cdot n_n}{n_i^2}} =$$

$$= \boxed{U_T \ln \frac{N_A \cdot N_D}{n_i^2}} = 0{,}7\ V$$

23.03.2009

2. način za izračun $U_D$

$$U_D = \int_{V_{Fi_p}}^{V_{Fi_n}} dV = -\int E \cdot dx = *$$

$$j_p = q\mu_p p \cdot E - q D_p \frac{dp}{dx} = 0 \quad \text{– v term. ravnovesju}$$

$$E = U_T \cdot \frac{1}{p} \cdot \frac{dp}{dx}$$

$$U_T = \frac{D_p}{\mu_p}$$

$$U_D = -\int E \cdot dx = -U_T \int_{p_p}^{p_n} \frac{1}{p}\frac{dp}{\cancel{dx}} \cdot \cancel{dx} = -U_T \ln \frac{p_n}{p_p} = U_T \cdot \ln \frac{p_p}{p_n} = \boxed{U_T \cdot \ln \frac{p_p \cdot n_n}{n_i^2}}$$

$$p_n = \frac{n_i^2}{n_n}$$

Narišite krajevne potece prostorskega naboja $\rho(x)$ in grajenega elek. polja $E(x)$ idealnega stopničastega P-N spoja v term. ravnovesju. Izračunajte širino osiromašenega področja $D = x_p + x_n$.

$\rho(x)$

$E(x)$

$D = x_p + x_n$

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

$N_D = 10^{15}\ cm^{-3}$

$\varepsilon_{Si} = \varepsilon_0 \cdot \varepsilon_{rSi} = 10^{-12} \frac{As}{Vcm}$

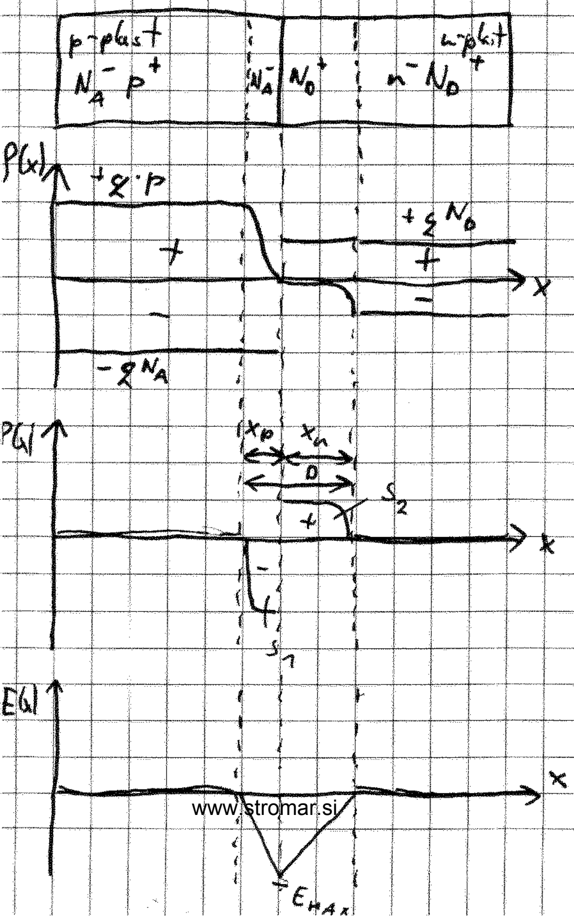
$$\rho = qp - qn - qN_A + qN_D$$

$p = N_A$ nevt. področje

$n = N_D$ nevt. področje

$S_1 = S_2$

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





$$\frac{dE}{dx} = \frac{\rho}{\varepsilon}$$

$$\boxed{E_{MAX} = -\frac{q}{\varepsilon_{Si}} N_A \cdot x_p} = *$$

$$E_{max} = -\frac{q}{\varepsilon_{Si}} N_D x_n$$

0, ker smo v term. ravn.

$$x_n = \sqrt{\frac{2\varepsilon \cdot N_A \,(V_D + U_R)}{q \cdot N_D \,(N_A + N_D)}} \;; \quad N_A \gg N_D$$

$$x_n = \sqrt{\frac{2 \cdot \varepsilon_{Si} U_D}{q \cdot N_D}} \quad ; \quad U_0 = U_T \cdot \ln \frac{N_A \cdot N_D}{n_i^2} = 0{,}77\,V$$

($U_T$: 25,66; $n_i^2$: $10^{20}$)

$$x_n = 10^{-4}\,cm = \underline{\underline{1\,\mu m}}$$

$$x_p = \frac{x_n \cdot N_D}{N_A} = \frac{1\,\mu m \cdot 10^{15}\,cm^{-3}}{10^{18}\,cm^{-3}} = \underline{1\,nm}$$

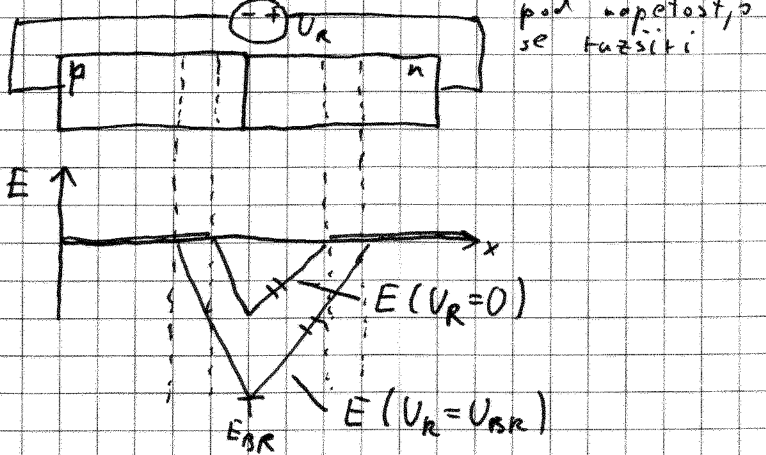
$$D = x_p + x_n \quad ; \quad x_n \gg x_p$$

$$D = \underline{\underline{1\,\mu m}}$$

$$E_{MAX} = * = \underline{\underline{1{,}5 \cdot 10^4 \frac{V}{cm}}}$$

Izračunajte prebojno napetost $U_{BR}$ diode, če je prebojna elek. poljska jakost v siliciju $E_{BR} = 20\,kV/cm$.

$E_{BR} = 200\,\frac{kV}{cm}$
$N_A = 10^{18}\,cm^{-3}$
$N_D = 10^{15}\,cm^{-3}$
$U_0 = 0{,}77\,V$ $\left(U_T \ln \frac{N_A N_D}{n_i^2}\right)$




preboj se zgodi $|E_{MAX}| > E_{BR}$

$$|E_{MAX}| = \frac{q \cdot N_D}{\varepsilon_{Si}} x_n$$

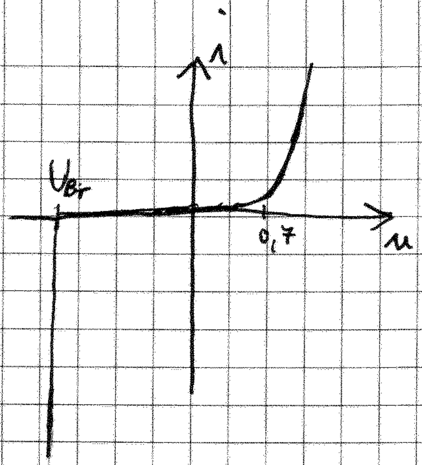
$$\underbrace{E_{MAX_{BR}}}_{E_{BR}} = \frac{q \cdot N_D}{\varepsilon_{Si}} x_n(U_R = U_{BR}) \quad ; \quad x_n(U_R = U_{BR}) = \sqrt{\frac{2\varepsilon_{Si}(U_D + U_R)\cancel{N_A}}{q \cdot N_D \underbrace{\cancel{(N_A + N_D)}}_{N_A}}} \qquad N_A \gg N_D$$

$$\frac{E_{MAX_{BR}} \cdot \varepsilon_{Si}}{q \cdot N_D} = \sqrt{\frac{2 \cdot \varepsilon_{Si} \, (U_D + U_{BR})}{q \cdot N_D}} \quad /^2$$

$$\frac{E_{MAX_{BR}}^2 \cdot \varepsilon_{Si}^{\cancel{2}}}{q^2 N_D^2} = \frac{2\,\cancel{\varepsilon_{Si}}\,(U_0 + U_{BR})}{\cancel{q}\,\cancel{N_D}}$$

$$\frac{E_{MAX_{BR}}^2 \cdot \varepsilon_{Si}}{q \cdot N_D} = 2 \cdot (U_0 + U_{BR}) \quad ; \quad U_{BR} = \frac{E_{MAX_{BR}}^2 \cdot \varepsilon_{Si}}{2 \cdot N_D \cdot q} - U_0 = 125\,V$$

30.03.2009

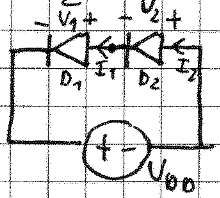



Čezmanjšano $N_D$, večja $U_{Br}$.

Izračunajte napetosti na diodah, ki sta narejeni na povsem enak način le $A_1 = 1,1 \cdot A_2$.

$A_1 = 1,1 A_2$ $\quad \frac{A_1}{A_2} = 1,1$

$U_{DD} = 1V$




$\underline{U_{DD} + U_2 + U_1 = 0}$ $\quad (-U_{DD} = U_2 + U_1)$

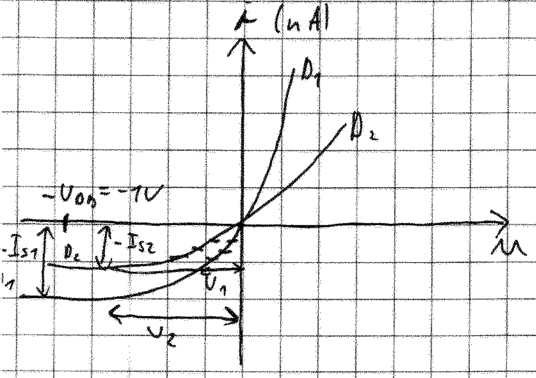
$\underline{I_1 = I_2}$

$\underline{I_1 = I_{s1} (e^{\frac{U_1}{U_T}} - 1)}$ ✓

$(I_2 = I_{s2} (e^{\frac{U_2}{U_T}} - 1))$ $\quad \underline{I_2 = -I_{s2}}$

$$\left.\begin{array}{l} I_{s1} = A_1 \cdot J_{s1} \\ I_{s2} = A_2 \cdot J_{s2} \end{array}\right\} J_{s1} = J_{s2} \text{ ker sta enaki}$$

$$\frac{I_{s1}}{I_{s2}} = \frac{A_1}{A_2} = 1,1$$




$D_2 \rightarrow$ globoko v zapori $\rightarrow I_2 = -I_{s2}$

$D_1 \rightarrow U_1$ blizu 0 V

$$\frac{I_1}{I_2} = \frac{I_{s1}\left(e^{\frac{U_1}{U_T}} - 1\right)}{-I_{s2}}$$

$$1 = -\frac{A_1}{A_2}\left(e^{\frac{U_1}{U_T}} - 1\right) \quad / \cdot \frac{A_2}{A_1}$$

$$\cancel{1 = \frac{A_1}{A_2}}$$

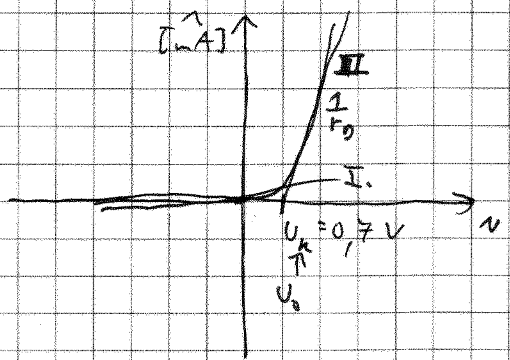
$$\frac{A_2}{A_1} = -e^{\frac{U_1}{U_T}} + 1 \Rightarrow \frac{A_2}{A_1} - 1 = -e^{\frac{U_1}{U_T}} \Rightarrow 1 - \frac{A_2}{A_1} = e^{\frac{U_1}{U_T}} \quad / \ln$$

$$\ln\left(1 - \frac{A_2}{A_1}\right) = \frac{U_1}{U_T}$$

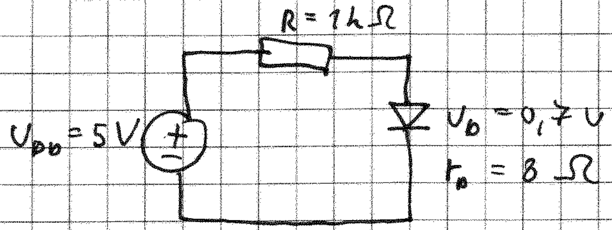
$$U_1 = U_T \ln\left(1 - \frac{A_2}{A_1}\right) = \underline{\underline{-62{,}4\,mV}}$$

$$U_2 = -U_{DD} - U_1 = -1V - (-0{,}0624V) = \underline{\underline{-0{,}9376\,V}}$$

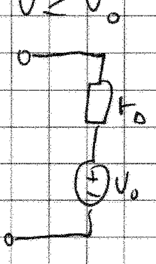
V danem vezju določite tok skozi diodo in napetost na diodi. Karakteristika diode je aproksimirana z dvema linearnima segmentoma.



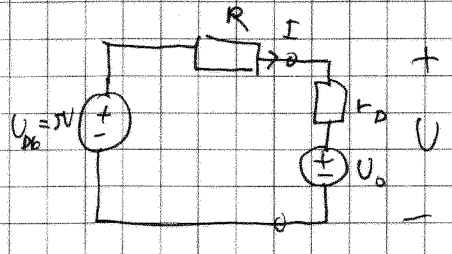

$$I = \begin{cases} 0 & U < U_0 \quad \mathrm{I} \\ \frac{U - U_0}{r_D} & U \geq U_0 \quad \mathrm{II} \end{cases}$$




$U \geq U_0$




$\Rightarrow$




$$I = \frac{U_{DD} - U_0}{R + r_D} = \frac{5V - 0{,}7V}{1000\,\Omega + 8\,\Omega} = 4{,}27\,mA$$

$$U = I \cdot r_D + U_0 = 0{,}734\,V$$

Določite najvišjo dopustno moč obremenitve silicijeve p-n diode.

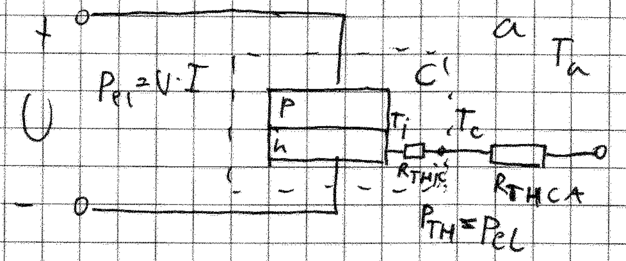
$T_a = 50\,°C$ (temperatura okolice)

$T_{jmax} = 150°C$ (temperatura spoja)

$R_{thjc} = 2{,}5\ \frac{°C}{W}$ (termična upornost med spojem in ohišjem)
j-junction c-case

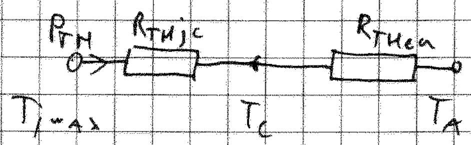
$A_c = 40\,cm^2$

$\delta_{thca} = 2{,}5 \cdot 10^{-3}\ \frac{W}{cm^2\,°C}$ (konstanta toplotne izmenjave med ohišjem in okolico)
c-case a-ambient




termodinamika ← analogija → elektrika

| | |
|---|---|
| $T$ | $V$ |
| $\Delta T$ | $U$ |
| $R_{TH}$ | $R$ |
| $P_{TH}$ | $I$ |




$$P_{THmax} = \frac{T_{jmax} - T_a}{R_{THjc} + R_{THca}} = \quad ; \quad R_{THCA} = \frac{1}{A_c \cdot \delta_{THCA}} = 10\ \frac{°C}{W}$$

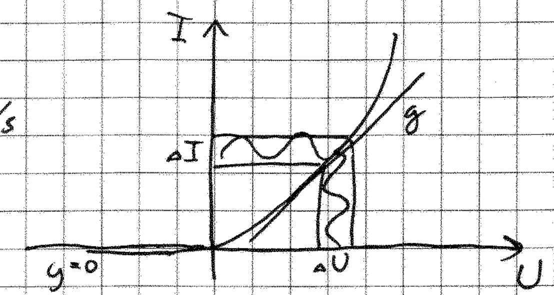
$$= \frac{150°C - 50°C}{2{,}5°C/W + 10°C/W} = \underline{\underline{8W}}$$

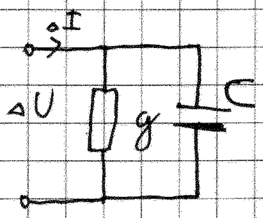
KOLOKVIJ DO PREBOJNE DIODE 06.04.2009

Določite nadomestni vezji diode za majhne harmonične signale.

$N_A = 10^{18}\ cm^{-3}$
$N_D = 7\cdot 10^{14}\ cm^{-3}$
$A = 10^{-3}\ cm^2$
$D_p = 12,5\ cm^2/s$
$\tau_p = 2\ \mu s$
$f = 5\ kHz$

① $U = 0,7\ V$
② $U = -10\ V$




$$g = \frac{\partial I}{\partial U} = \quad ; I = I_s\cdot\left(e^{\frac{U}{U_T}} - 1\right)$$

$$g = \frac{I_s}{U_T}\left(e^{\frac{U}{U_T}}\right) = \frac{1}{U_T}\left(I_s\cdot e^{\frac{U}{U_T}} + I_s - I_s\right) = \frac{1}{U_T}\left(I + I_s\right)$$

① $U = 0,7V$

$$I = A\cdot q\cdot n_i^2\left(\underbrace{\frac{D_p}{L_p N_D}}_{\text{vrzeli } I_p} + \cancel{\frac{D_n}{L_n N_A}}\right)\left(e^{\frac{U}{U_T}} - 1\right) \qquad N_A \gg N_D$$

$P_{no} = \frac{n_i^2}{N_D} = \frac{n_i^2}{n_{no}}$

$I = I_n + I_p$

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

$I = \ldots$

$g = \frac{I + \cancel{I_s}}{U_T}$ zanemarimo

$C_D = \sqrt{\frac{g\cdot\tau_p}{2}}$ / ni žihr ; $N_A \gg N_D$

difuz. kap.

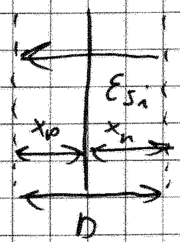
② $U = -10V$

$I = -I_S$

$g = 0$

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

spojna kap.




$$D = \sqrt{\frac{2\varepsilon}{q}\left(\frac{1}{N_A} + \frac{1}{N_D}\right)\left(U_D + U_R\right)}$$ zaporna nap. +10V

$; U_D = (V_F - V_{Fip}) + (V_{Fin} - V_F) = U_T \ln\frac{p}{n_i} + U_T \ln\frac{n}{n_i}$

$\varepsilon = \varepsilon_0\cdot\varepsilon_r = 10^{-12}\ \frac{F}{cm}$

$U_D = U_T \ln\frac{N_A}{n_i} + U_T \ln\frac{N_D}{n_i}$

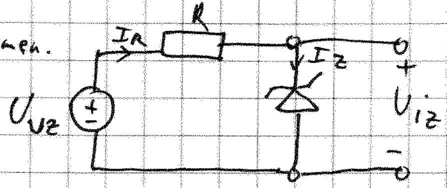
$U = U_T \ln\frac{N_A N_D}{n_i^2}$

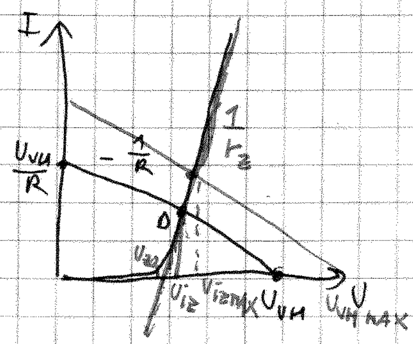
20.04.2009.

V danem nap. stabilizatorja določite upor R tako, da bo pri maksimalni vhodni napetosti tekel čez prebojno diodo ravno maksimalni dopustni tok $I_{zmax}$. Za dano spremembo vhodne napetosti določite spremembo izhodne napetosti stabilizatorja.

$I_{zmax} = 50\,mA$
$U_{vhmax} = 15\,V$
$U_{VH} = 10-15$
$U_{Zo} = 5\,V$
$r_z = 10\,\Omega$

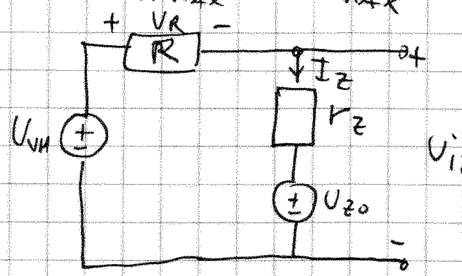
a) brez bremen. upora





$R = ?$

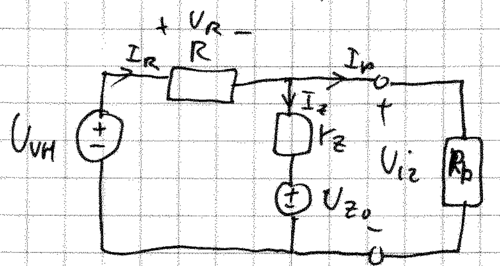
$U_{VHmax} \rightarrow I_{zmax}$



$$R = \frac{U_R}{I_R}\Big|_{I_R = I_Z} = \frac{U_{VHmax} - U_{iz}}{I_{zmax}}\Bigg|_{max} = \frac{U_{vmax} - (I_{zmax} \cdot r_z + U_{zo})}{I_{zmax}} = \frac{15V - (0{,}05A \cdot 10\Omega + 5V)}{0{,}05A} =$$

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

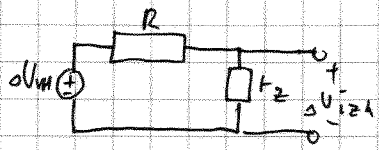
b.) breme $R_b = 470\,\Omega$



$$R = \frac{U_R}{I_R} = \frac{U_{VH} - U_{iz}}{I_z + I_b}\Bigg|_{max} = \frac{U_{vhmax} - (I_{zmax} \cdot r_z + U_{zo})}{I_{zmax} + \frac{U_{iz}}{R_b}} = \underline{\underline{154\,\Omega}}$$

$\Delta U_{izh}$:

a.)



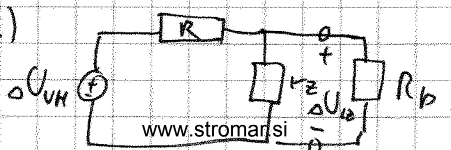
$$\Delta U_{izh} = \frac{r_z}{r_z + R} \cdot \Delta U_{VH} = \underline{\underline{0{,}25V}};$$

$r_z = 10\Omega$, $R = 190\Omega$, $\Delta U_{VH} = 5V$

$$\Delta U_{izh.rel.} = \frac{\Delta U_{izh}}{\Delta U_{VH}} \cdot 100\% = 5\%$$

inkrementalni nadomestni model

b.)

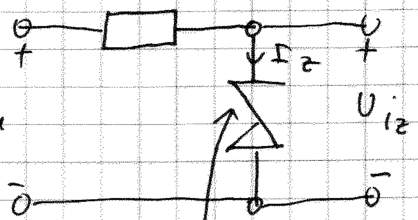


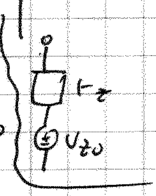
$$\Delta U_{izh} = \frac{r_z \| R_B}{r_z \| R_B + R} \Delta U_{VH} = \underline{\underline{0{,}3V}}$$

$$r_z \| R_B = \frac{r_z \cdot R_B}{r_z + R_B} = 9{,}8\Omega$$

Prebojno diodo z $U_{Z0}=5{,}6\,V$ in $r_Z=5\,\Omega$ želimo uporabiti za stabilizacijo enosmerne napetosti. Določite območje dopustnega spreminjanja vhodne napetosti, če je največji dopustni tok obremenitve diode $I_{Zmax}=10\,mA$ in tok pri katerem dioda še zadovoljivo deluje kot stabilizator $I_{Zmin}=1\,mA$. Določite obseg spreminjanja izhodne napetosti.

$U_{Z0}=5{,}6\,V$
$r_Z=5\,\Omega$
$I_{Zmax}=10\,mA$
$I_{Zmin}=1\,mA$
$R=220\,\Omega$




$$U_{VHmax}=I_{Zmax}\cdot R+I_{Zmax}\cdot r_Z+U_{Z0}$$
$$=I_{Zmax}(R+r_Z)+U_{Z0}$$
$$=\underline{7{,}85\,V}$$

$$U_{VHmin}=I_{Zmin}\cdot R+I_{Zmin}\cdot r_Z+U_{Z0}$$
$$=I_{Zmin}(R+r_Z)+U_{Z0}=5{,}825\,V$$

$$\Delta U_{VH}=U_{VHmax}-U_{VHmin}=2{,}025\,V$$

1.) $\Delta U_{izh}=\dfrac{r_Z}{r_Z+R}\cdot\Delta U_{VH}=$

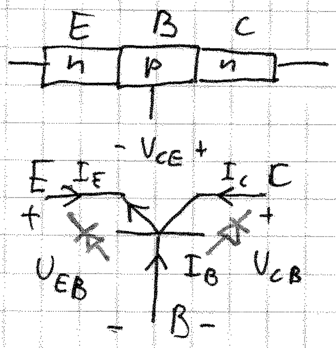
2.) $\Delta U_{izh}=U_{izhmax}-U_{izhmin}=0{,}045\,V$

$U_{izhmax}=r_Z\cdot I_{Zmax}+U_{Z0}=5{,}65\,V$

$U_{izhmin}=r_Z\cdot I_{Zmin}+U_{Z0}=5{,}605\,V$

04.05.2009

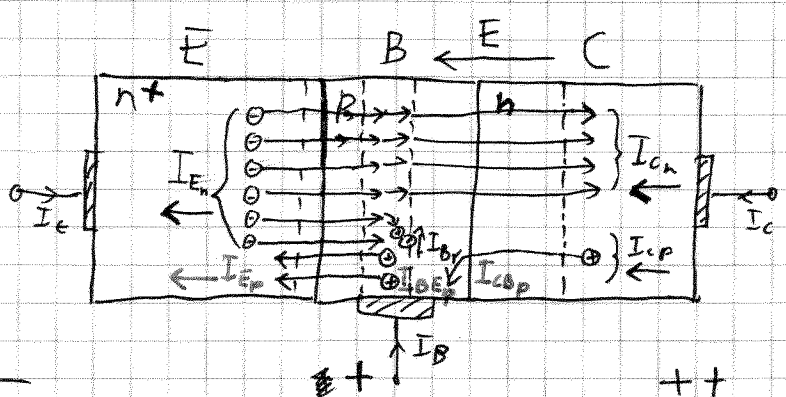
Shematično narišite prerez strukture npn tranzistorja in prikažite pomembnejše komponente tokov v aktivnem področju delovanja. Narišite tudi poteke energijskih nivojev v danem tranzistorju.




aktivno podr.:

npn

EB spoj prevodno $U_{EB}$ negativna
CB spoj zaporno $U_{CB}$ pozitivna





D.N.

— term. ravn.
- - - akt. podr.

$E = -q \cdot V$

Ferm. nivo samo za term. ravn. Za aktivno ne rišemo

Npn tranzistor ima kratko spojen kolektorsko-bazni spoj. Zapišite I(U) karakteristiko tako dobljenega dvopola in jo primerjajte s karakteristiko pn diode.

npn

$N_{DE} = 10^{18}\ cm^{-3}$

$N_{AB} = 10^{16}\ cm^{-3}$

$\tau_n = 3{,}12\ \mu s$

$\mu_n = 1248\ \frac{cm^2}{Vs}$

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

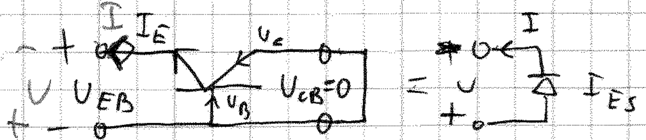
$W = 1\ \mu m$ - debelina baze

$W \ll L_n$ (baza tanka)

pn diodo

n plast = enaki par. kot emitor $N_D = N_{DE}$

p plast = enaki —ll— baza, razen $W$; $N_A = N_{AB}$




1. Ebers-Mollov model

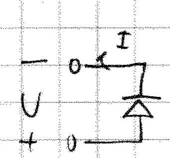
~~pnp~~ npn

$$-I_E = I_{ES}\left(e^{-\frac{U_{EB}}{U_T}} - 1\right) - \alpha_R \cancel{I_{CS}\left(e^{-\frac{U_{CB}}{U_T}} - 1\right)}^{\,=0}$$

$$I = I_{ES}\left(e^{\frac{U}{U_T}} - 1\right) \quad \text{kot dioda}$$

$$I_{ES} \underset{W \ll L_n}{=} A \cdot q \cdot n_i^2 \cdot \left(\cancel{\frac{D_{pE}}{L_{pE} N_{DE}}} + \frac{D_{nB}}{W\, N_{AB}}\right) = 1\,pA; \quad D_{nB} = U_T \cdot \mu_n$$

$N_{DE} \gg N_{AB}$

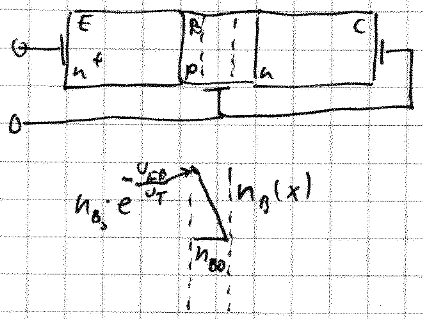


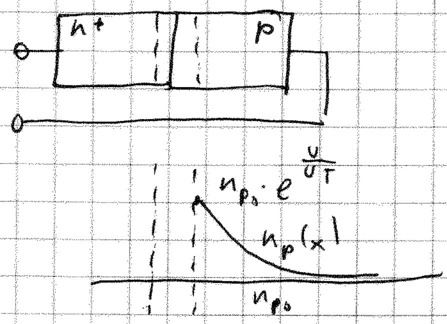

$$I = I_s \cdot \left(e^{\frac{U}{U_T}} - 1\right); \quad I_s = A \cdot q \cdot n_i^2 \cdot \left(\cancel{\frac{D_p}{N_p \cdot N_D}} + \frac{D_n}{L_n \cdot N_A}\right) =$$

$N_D \gg N_A$

$$\frac{I_s}{I_{ES}} = \frac{\cancel{A \cdot q \cdot n_i^2} \cdot \left(\frac{D_n}{L_n \cdot N_A}\right)}{\cancel{A \cdot q \cdot n_i^2} \cdot \left(\frac{D_{nB}}{W \cdot N_{AB}}\right)} = \frac{W}{L_n} = \frac{1\,\mu m}{100\,\mu m} = \frac{1}{100} \qquad I_{ES} = 100\, I_s$$

$$L_n = \sqrt{D_n \cdot \tau_n} = \sqrt{\mu_n \cdot U_T \cdot \tau_n} = 100\,\mu m$$



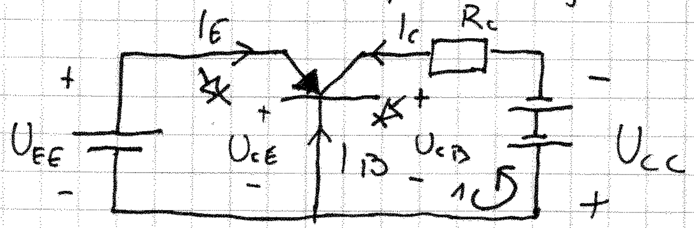




$$j_D \propto \frac{dn}{dx}$$

11.5.09

- Izračunajte, pri kateri napetosti $U_{CC}$ se bo delovna točka tranzistorja nahajala ravno na meji med aktivnim in področjem nasičenja.

$I_E = 1\,mA$
$R_C = 5{,}6\,k\Omega$
$\alpha_F = 0{,}98$




| pnp | EB | CB |
|---|---|---|
| akt. pod. | prev. $U_{EB} > \emptyset$ | zap $U_{CB} < \emptyset$ |
| podr. nas. | prev. $U_{EB} > \emptyset$ | prev $U_{CB} > \emptyset$ |

MEJA $U_{CB} = 0$

1: $U_{CC} + I_C R_C + U_{CB} = 0$

$U_{CC} = -\underset{\text{podan}}{I_C R_C} - \underset{\emptyset}{\cancel{U_{CB}}}$ iščemo $I_C$

2. Ebers-Moll: pnp: $I_C = -\alpha_F I_E + I_{C0}\left(e^{\frac{U_{CB}}{U_T}} - 1\right)$ $U_{CB} = \emptyset$

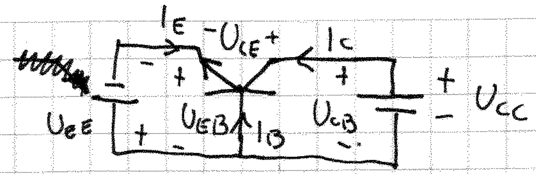
$I_C = -0{,}98 \cdot I_E = -0{,}98\,mA$

$U_{CC} = -(-0{,}98\,mA)\,5{,}6\,k\Omega$

$U_{CC} = 5{,}488\,V$

- Izračunajte napetosti in tokove npn tranzistorja v orientaciji s skupno bazo v aktivnem področju delovanja.

$\beta_F = 99$
$I_{CS} = 1\,pA$
$\alpha_R = 0{,}8$
$I_E = -2\,mA$
$U_{CB} = 2\,V$




$I_B$ $\quad I_C$ $\quad I_E$ ✓ $\quad U_{EB}$ $\quad U_{CE}$ $\quad U_{CB}$ ✓

$I_B + I_C + I_E = 0$

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

1. Ebers Mollov model:

$$\text{pnp: } I_E = \overbrace{I_{ES}\left(e^{\frac{U_{EB}}{U_T}} - 1\right)}^{I_F} - \overbrace{\alpha_R I_{CS}\left(e^{\frac{U_{CB}}{U_T}} - 1\right)}^{I_R}$$

$$\cancel{\text{npn}}\ I_C = -\alpha_F \underbrace{I_{ES}\left(e^{\frac{U_{EB}}{U_T}} - 1\right)} + I_{CS}\left(e^{\frac{U_{CB}}{U_T}} - 1\right)$$

za npn damo negativno. $-I_E$

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

$$I_{ES} = \frac{\alpha_R I_{CS}}{\alpha_F} = * \qquad \boxed{\alpha_F = \frac{\beta_F}{\beta_F + 1}}$$

$\alpha_F = 0{,}99$

$$* = \frac{0{,}8 \cdot 1\,pA}{0{,}99} = 0{,}808\,pA$$

$$-U_{EB} = U_T \ln \frac{-I_E}{I_{ES}} = 0{,}555\,V \rightarrow \boxed{U_{EB} = -0{,}555\,V}$$

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

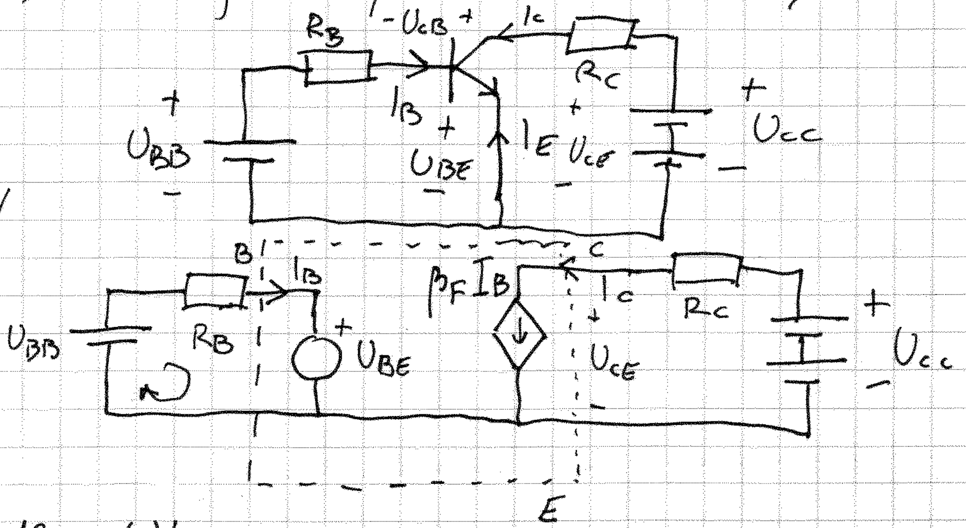
$$= 0{,}555\,V + 2\,V = \boxed{2{,}555 = U_{CE}}$$

$-I_C = -\alpha_F(-I_E) = -0{,}99 \cdot 2mA = -1{,}98\,mA$

$I_B = -I_C - I_E = -1{,}98\,mA + 2\,mA = 0{,}02\,mA$

- Za dano vezje z bipolarnim tranzistorjem določite vrednost upora $R_B$ tako, da bo napetost $U_{CE}$ enaka $U_{CC}/2$. Pri izračunu predpostavite, da je napetost $U_{BE} = 0{,}7V$

$U_{CE} = \frac{U_{CC}}{2}$
$U_{BE} = 0{,}7V$
$\alpha_F = 0{,}99$
$U_{BB} = U_{CC} = 12V$
$R_C = 1k\Omega$




$U_{CE} = \frac{U_{CC}}{2} = \frac{12}{2} = 6V$

$U_{RC} = 6V$

$I_C = U_{RC}/R_C = 6V/1k\Omega = 6\,mA$

$I_B = I_C/\beta_F = 60{,}6\,\mu A$

$\beta_F = \frac{\alpha_F}{1-\alpha_F} = 99$

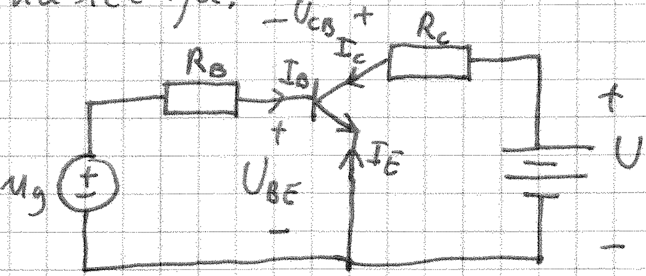
$I_B R_B + U_{BE} - U_{BB} = 0$

$R_B = \frac{U_{BB} - U_{BE}}{I_B} = \frac{12V - 0{,}7V}{0{,}0606\,mA} = 186{,}45\,k\Omega$

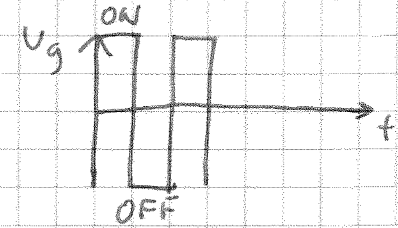
MANJKA 11.05.

18.05.2009

V danem vezju (tranzistor kot stikalo) izračunajte velikost premenske upornosti pri kateri bo tranzistor v sklenjenem stanju (ON) ravno na meji med aktivnim področjem in področjem nasičenja.




$I_B = 30\,\mu A$ (tranz. "ON")
$U_{cc} = 5\,V$
$\beta_F = 99$
$I_{Es} = 10^{-14}\,A$

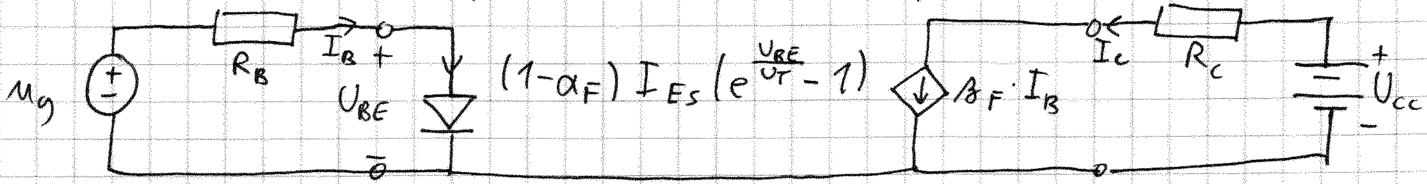



meja akt./nas $\rightarrow$ $U_{CB} = 0$

$$R_C \cdot I_C + U_{CE} - U_{cc} = 0$$

$$R_C = \frac{U_{cc} - U_{CE}}{I_C} = \frac{U_{cc} - (\overset{0}{U_{CB}} + U_{BE})}{I_C} = \frac{U_{cc} - U_{BE}}{I_C} = *$$

Poenostavljen model za npn tr. v akt. področju v orien. s skupnim emitor.




$$I_C = \beta_F\, I_B = 99 \cdot 30\,\mu A \doteq 3\,mA$$

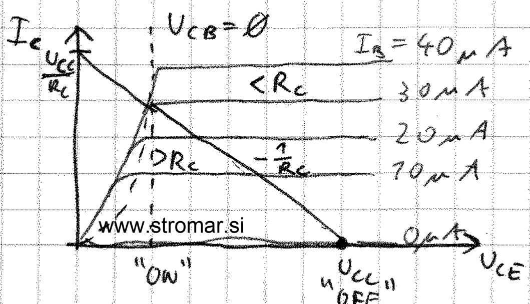
$$I_B = (1-\alpha_F) \cdot I_{ES}\,(e^{\frac{U_{BE}}{U_T}} - 1)$$

$$U_{BE} = U_T \cdot \ln \frac{I_B + (1-\alpha_F) I_{ES}}{(1-\alpha_F) I_{ES}} = 0{,}678\,V \quad ; \quad \alpha_F = \frac{\beta_F}{1+\beta_F} = 0{,}99$$

$$* = \frac{5V - 0{,}678V}{3\,mA} = 1{,}44\,k\Omega \;;$$

del., uporovna premica

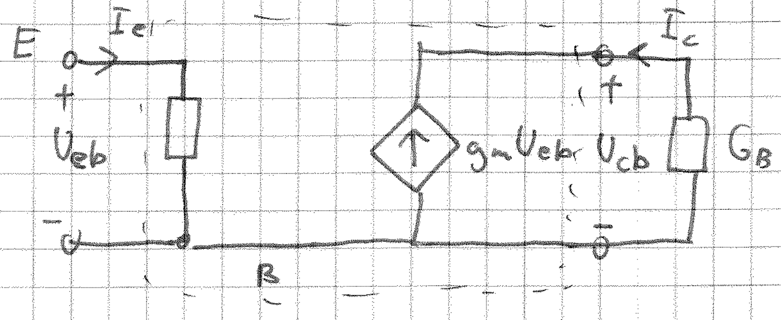
$$I_C = -\frac{1}{R_C} U_{CE} + \frac{U_{cc}}{R_C}$$



Določite enosmerni emitorski tok, da bo napetostno ojačanje ojačevalnika majhnih nizkofrekvenčnih signalov s tranzistorjem v orientaciji s skupno bazo v aktivnem področju enako 200.

NF

$A_u = 200$
$\alpha_{F_{NF}} = \alpha_0 = 0{,}99$
$G_B = 1\,mS\ (1\,k\Omega)$




$$A_u = \frac{U_{cb}}{U_{eb}} = \frac{g_m U_{eb}}{U_{eb} \cdot G_B} = \frac{g_m}{G_B} \quad ; \quad g_e = \frac{I_E}{U_T}$$

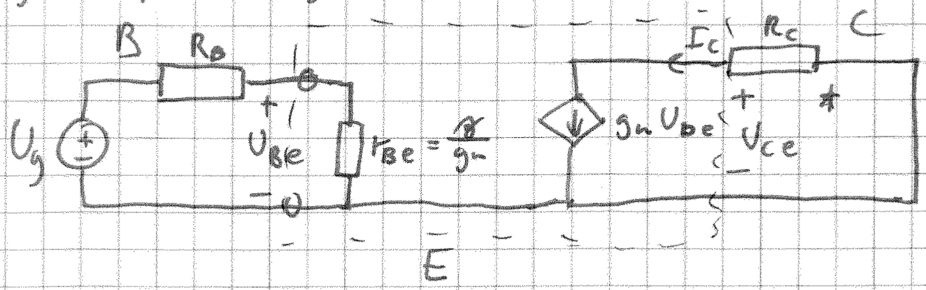
izhod, vhod, enosmerna del točka

$$g_m = \frac{I_c}{U_T} = \alpha_0 \cdot g_e$$

$$A_u = \frac{\overbrace{\alpha_0 \cdot I_E}^{g_m}}{U_T \cdot G_m} \Rightarrow I_E = \frac{A_u \cdot U_T \cdot G_B}{\alpha_0} = \underline{5{,}2\,mA}$$

S pomočjo narisanega inkrementalnega modela bipolarnega tranzistorja izračunajte izhodno napetost $U_{ce}$ pri znani napetosti generatorja majhnih signalov na vhodu

$U_g = 100\,mV$
$I_E = 1\,mA$
$R_B = 4{,}7\,k\Omega$
$\alpha_0 = 0{,}98$
$R_c = 1\,k\Omega$



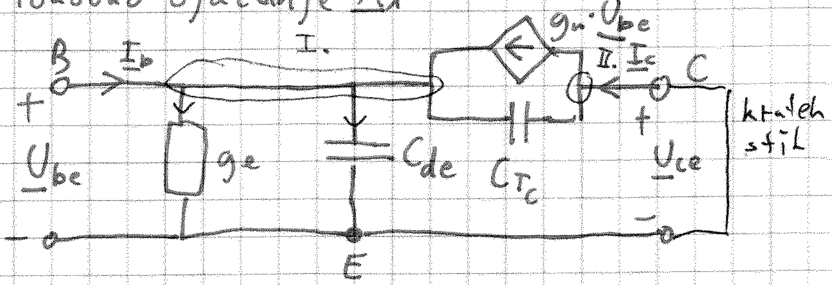

$$\cancel{U_{BE} = \frac{R_{be}}{R_{be}+}} \quad U_{be} = \frac{r_{be}}{r_{be}+R_B} U_g = 21{,}44\,mV$$

$$U_{ce} = -0{,}819\,V$$

25.05.2009

Za bipolarni tranzistor v aktivnem področju in orientaciji s skupnim emitorjem določite admitančne četveropolne parametre $\underline{y}_{ij}$ pri podani frekvenci $\omega = 10^8 \frac{rad}{s}$ (15,9 MHz) in določite kratkostično tokovno ojačanje $\underline{A}_i$

$\omega = 10^8 \frac{rad}{s}$ (15,9 MHz)
$\alpha_F(\omega=0) = \alpha_0 = 0,99$
$g_e = 40\,mS \qquad (g_e = \frac{I_E}{U_T})$
$C_{de} = 100\,pF$
$C_{T_c} = 10\,pF$




$$\underline{I}_b = \underline{y}_{11}\underline{U}_{be} + \underline{y}_{12}\underline{U}_{ce}$$
$$\underline{I}_c = \underline{y}_{21}\underline{U}_{be} + \underline{y}_{22}\underline{U}_{ce}$$

I.: $$\underline{I}_b - \underline{U}_{be}\cdot g_e - \underline{U}_{be}\cdot j\omega C_{de} + g_m\underline{U}_{be} - (\underline{U}_{be} - \underline{U}_{ce})\cdot j\omega C_{T_c} = 0$$
$$\underline{I}_b = \underline{U}_{be}\underbrace{(g_e - g_m + j\omega(C_{de}+C_{T_c}))}_{\underline{y}_{11}} - \underline{U}_{ce}\underbrace{j\omega C_{T_c}}_{\underline{y}_{12}}$$

II.: $$\underline{I}_c - g_m\underline{U}_{be} + (\underline{U}_{be} - \underline{U}_{ce})\,j\omega C_{T_c} = 0$$
$$\underline{I}_c = \underbrace{(g_m - j\omega C_{T_c})}_{\underline{y}_{21}}\underline{U}_{be} + \underbrace{j\omega C_{T_c}}_{\underline{y}_{22}}\underline{U}_{ce}$$

$$g_m = \alpha_0 \cdot g_e = 39,6\,mS$$

$\underline{y}_{11} = 0,4\,mS + j\,11\,mS$

$\underline{y}_{12} = -j\,1\,mS$

$\underline{y}_{21} = 39,6\,mS - j\,1\,mS$

$\underline{y}_{22} = j\,1\,mS$

$$\underline{A}_i = \frac{-\underline{I}_c}{\underline{I}_b} = -\frac{\underline{y}_{21}\underline{U}_{be} + \underline{y}_{22}\overset{=0}{\underline{U}_{ce}}}{\underline{y}_{11}\underline{U}_{be} + \underline{y}_{12}\underline{U}_{ce}} = -\frac{\underline{y}_{21}}{\underline{y}_{11}} = -\frac{\alpha_0 g_e - j\omega C_{T_c}}{(1-\alpha_0)g_e + j\omega(C_{de}+C_{T_c})} =$$

$\omega = 0$: $A_i = -\frac{\alpha_0 g_e}{(1-\alpha_0)\cdot g_e} = -\beta_0 \Rightarrow |A_i| = 99$

$\omega = 10^8\,rad/s$: $\underline{A}_i = -(0,0396 - j\,3,599)$

$|\underline{A}_i| = \sqrt{(\ \ )^2 + (\ \ )^2} \doteq 3,6$

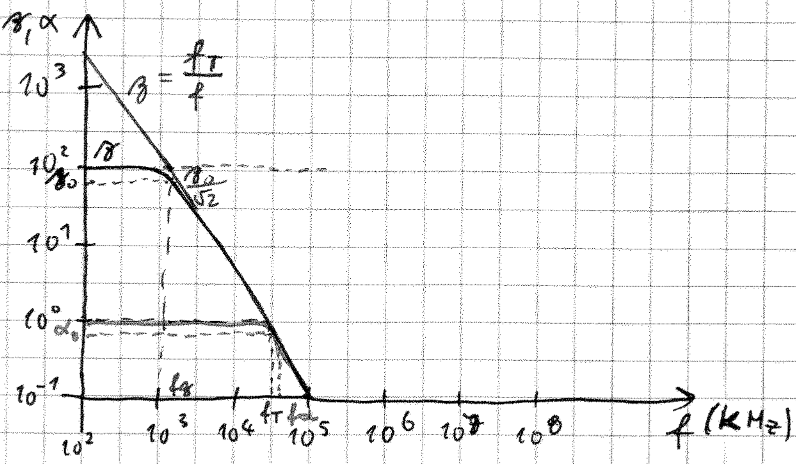
## Frekvenčna karakteristika tokovnega ojačanja

$\underline{\beta}(f)$ – skupni emitor $\quad |\underline{\beta}(f)| = \beta(f)$

$\underline{\alpha}(f)$ – skupna baza $\quad |\underline{\alpha}(f)| = \alpha(f)$

$f_\beta = 1\,MHz \quad \beta(f_\beta) = 70$

$\beta_0, \alpha_0, f_T, f_\alpha = ?$




$$\beta_0 \Rightarrow \beta(f_\beta) = \frac{\beta_0}{\sqrt{2}} \Rightarrow \beta_0 = \sqrt{2} \cdot \beta(f_\beta) = \underline{\underline{99}}$$

$$\alpha_0 = \frac{\beta_0}{1+\beta_0} = 0,99$$

Produkti parov β in f ali α in f, ki predstavljajo točke na premici $\beta = \frac{f_T}{f}$ so enaki po vrednosti.

$$\beta_0 \cdot f_\beta = 1 \cdot f_T$$

$$f_T = \beta_0 \cdot f_\beta = 99 \cdot 1\,MHz = \underline{\underline{99\,MHz}}$$

$\cancel{\alpha_0 \cdot f_\alpha = \alpha_0 f_\alpha}$ $\quad \alpha_0 \cdot f_\alpha = 1 \cdot f_T = \beta_0 f_\beta$

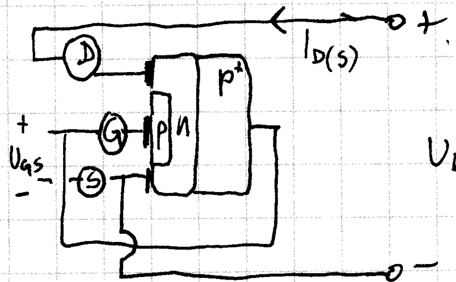
$$f_\alpha = \frac{f_T}{\alpha_0}$$

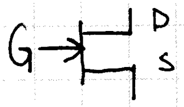
$$f_\alpha = \frac{\beta_0 \cdot f_\beta}{\alpha_0} = \frac{\alpha_0 \cdot f_\beta}{(1-\alpha_0)\alpha_0} = \frac{f_\beta}{1-\alpha_0} = 100\,MHz$$

• Spojni FET: pri kateri napetosti $U_{DS}$ pride do zadrgnitve kanala spojnega FET tranzistorja. Izračunajte tudi največji tok nasičenja $I_{DSS}$.

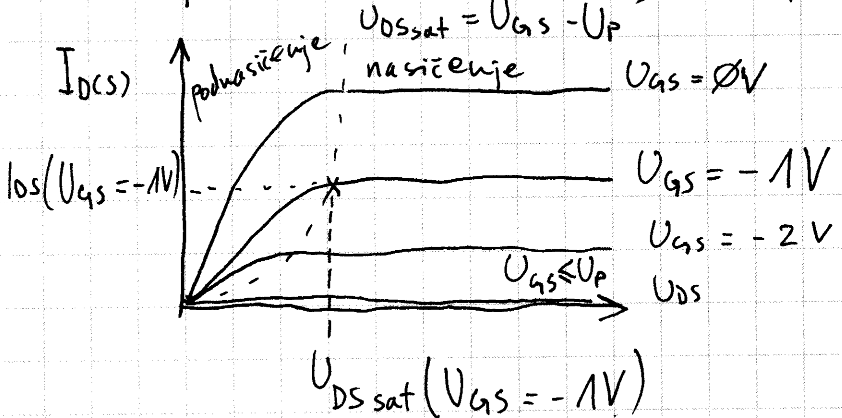
$U_{GS} = -1V$
$\rho_n = 4{,}64\ \Omega cm$
$D = 4{,}85\ \mu m$ debelina kanala
$I_{DS}|_{U_{GS}} = 2{,}25\ \mu A$

$\mu_n = 1345\ cm^2/Vs$
$U_D = 0{,}7\ V$




$U_{DSsat} = U_{GS} - U_P$ → napetost preščipnjenja




$$U_{DSSAT}(U_{GS}=-1V) = -1V - U_P$$

$$U_P = U_D - \frac{q N_D D^2}{8\varepsilon_{Si}} \qquad U_P = -4V$$

$$\rho_N = \frac{1}{q \mu_N N_D} \rightarrow N_D = \frac{1}{\rho_N q_N \mu_N} = 10^{15}/cm^3$$

$$U_{DSAT}(U_{GS}=-1V) = -1V - U_P = \underline{\underline{3V}}$$

$$I_{DS} = I_{DSS}\left(1 - \frac{U_{GS}}{U_P}\right)^2$$

$$I_{DSS} = \frac{I_{DS} \leftarrow 2{,}25\,mA}{\left(1 - \frac{U_{GS}}{U_P}\right)^2} = \boxed{4\,mA}$$

$U_{GS}$: $-1V$ $\quad$ $U_P$: $-4V$

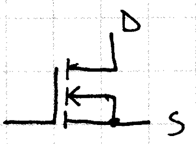
- Za MOS tranzistor z induciranim n kanal in orientaciji s skupnim izvorom določite področje delovanja in diferencialne prevodnostne parametre gij v delovni točki A) $U_{GS} = 3V$ $U_{DS} = 2V$ B) $U_{GS} = 5V$ $U_{DS} = 2V$

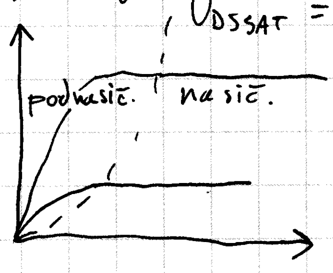
$R_B = 10\,k\Omega$

$\mu_n \cdot C_o = 1\,mA/V^2$

$W/L = 2$

$U_T = 2V$ pragovna napetost




- Če $U_{DS} \geq U_{DSSAT}$, smo v področju nasičenja. Uporabimo enačbo za $I_{DS}$.
- Če $U_{DS} < U_{DSSAT}$, uporabimo enačbo za $I_D$.

A)

$U_{DSSAT} = 3V - 2V = 1V$

$\underset{2V}{U_{DS}} > \underset{1V}{U_{DSSAT}}$ → smo v nasičenju → uporabimo $I_{DS}$ enačbo

$$g_{11} = \frac{\partial I_G}{\partial U_{GS}}\bigg|_{U_{DS}=konst} = \boxed{\emptyset} \qquad I_G = \emptyset$$

$$g_{12} = \frac{\partial I_G}{\partial U_{DS}}\bigg|_{U_{GS}=konst} = \boxed{\emptyset}$$

$$g_{21} = \frac{\partial I_{D(S)}}{\partial U_{GS}}\bigg|_{U_{DS}=konst}$$

$$g_{22} = \frac{\partial I_{D(S)}}{\partial U_{DS}}\bigg|_{U_{GS}=konst}$$

$$I_{DS} = \frac{C_0 W \mu_n}{2L} U_T^2 \left(1 - \frac{U_{GS}}{U_T}\right)^2$$

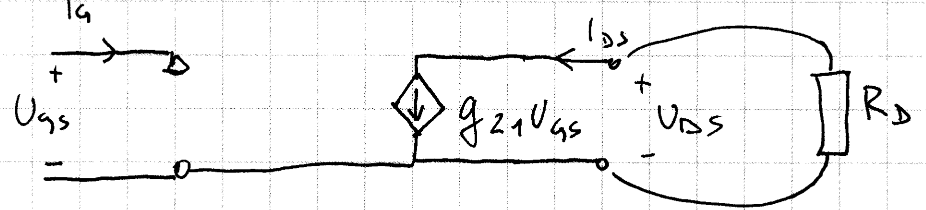
$$I_{DS} = \frac{\mu_n C_0 W}{2L}\left(U_{GS} - U_T\right)^2$$

$$\frac{\partial I_{DS}}{\partial U_{GS}} = \frac{\mu_N C_0 W}{2L} 2(U_{GS} - U_T) = \boxed{2mS}$$

(odvisnost od $I_{DS}$
$\sqrt{2\mu_n C_0 \frac{W}{L} I_{DS}}$ )

$$g_{22} = \boxed{\emptyset} \quad (\text{neodvisen od } U_{DS})$$

ojačanje:




$$A_u = \frac{-g_{21} U_{GS} R_D}{U_{GS}} = \frac{U_{DS}}{U_{GS}} = -g_{21} R_D = \boxed{-20}$$

'30

b) podnasičenje (D.N.)

$$g_{11} = g_{12} = \emptyset$$
$$g_{21} = 4\,mS$$
$$g_{22} = 2\,mS$$

$$I_D = \frac{C_o W \mu_n}{L}\left[(U_{GS} - U_T) U_{DS} - \frac{U_{DS}^2}{2}\right]$$

$U_{GS} = 5V \qquad U_{DS} = 2V$

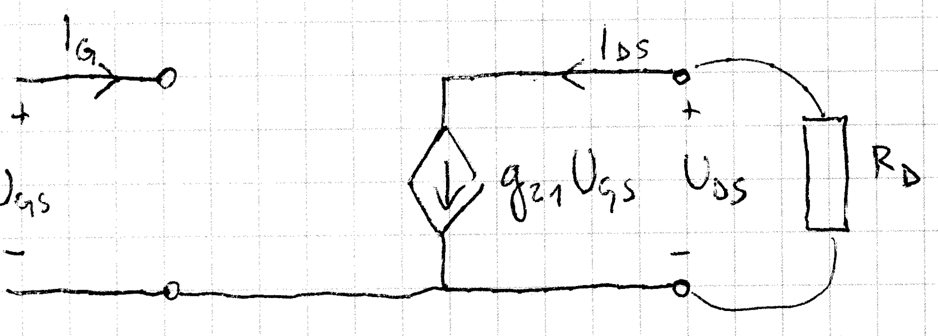
$U_{DSSAT} = U_{GS} - U_T$

$U_{DSSAT} = 5V - 2V = 3V > U_{DS} = 2V \rightarrow$ podnasičenje

$$I_G = \emptyset \rightarrow \quad g_{11} = \partial I_G / \partial U_{GS} = \emptyset$$
$$g_{12} = \partial I_G / \partial U_{DS} = \emptyset$$

$$g_{21} = \frac{\partial I_{D(S)}}{\partial U_{GS}} = \frac{C_o W \mu_n}{L} U_{DS} = 4\,mS$$

$$g_{22} = \frac{\partial I_{D(S)}}{\partial U_{DS}} = \frac{C_o W \mu_n}{L}\left[U_{GS} - U_T - \frac{\cancel{2} U_{DS}}{\cancel{2}}\right] = 2\,mS$$




$$A_u = \frac{U_{DS}}{U_{GS}} = \frac{-g_{21}\cancel{U_{GS}} R_D}{\cancel{U_{GS}}} = -g_{21} R_D = -20$$