1. Pločica je homogeno dopirana 1 tipom primjesa Si

na $T = 450\,K$ $\quad n = 10^{14}\,m^{-3}$

1-1 Kolika je intrizična na ?adanoj

$$n_i = C_1 T^{\frac{3}{2}} \exp\left(-\frac{E_{g0}}{2E_T}\right) = 3{,}07 \cdot 10^{16} \cdot (450)^{\frac{3}{2}} \cdot \exp\left(-\frac{1{,}196 \cdot 11600}{2 \cdot 450}\right)$$

$$= 5{,}92 \cdot 10^{13}\ cm^{-3}$$

SOBNA = $1{,}45 \cdot 10^{10}$

1-2 Tip i koncentraciju primjese dopira

N_x

$n > n_i \rightarrow$ jer su elektroni većinski, dopiran donorima (N-tip)

$$p = \frac{n_i^2}{n} \rightarrow \text{termodinamička ravnoteža}$$

$$p = \frac{(5{,}92 \cdot 10^{13})^2}{10^{14}} = 3{,}5 \cdot 10^{13}\ cm^{-3}$$

$p \cdot n = n_i$

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

Zakon električne neutralnosti

$$p + N_D^+ = n + N_A^- \qquad N_A^- = 0 \rightarrow \text{dopirano samo jednom primjesom}$$

$$N_D^+ = n - p = 10^{14} - 3{,}5 \cdot 10^{13} = 6{,}5 \cdot 10^{13}\ cm^{-3}$$

1-3 Ako u to pločicu dodamo istu koncentraci suprotnog tipa pri-

kolika će biti koncetracija šupljia na $T = 300\,K$

$\Rightarrow$ $N_A \rightarrow$ dodajemo akceptore $\quad N_A = N_D$ bije kompenzirani silicij

vrijedi $n = p = n_i \qquad n_i(300) = 1{,}45 \cdot 10^{10}\ cm^{-3}$ (to se zna = DEAUFOLT)

(kompenzirani = kvazi intrinstični si tj. tako je pola ša)

1-4 KOLIKO ĆE SE POMAKNUTI FERMIJEV NIVO NAKON DRUGOG DOPIRANJA

→ DO SREDINE ZABRANJENOG PODRUČJA

($n = p = n_i$ $E_F = E_{Fi} = \frac{E_G}{2}$ (RADI DOPIRAJ ISTOG KOL ALI DRUGOG TIPA PA REKOMBINACIJOM PADNE DO SREDINE)

1-5 KOLIKI JE OTPOR SI PLOČICE POPREČNOG PRESJEKA

$S = 15\ mm^2$ $\ell = 1\ mm$ ako je spec. vodlj $\sigma = 5\ mS/cm$

$S = 5 \cdot 10^{-2}\ cm^2$ $\ell = 0,1\ cm$

→ SVE U cm

$$R = \rho \frac{\ell}{S} = \frac{1}{\sigma} \frac{\ell}{S} = \frac{1}{5 \cdot 10^{-3}} \cdot \frac{0,1}{5 \cdot 10^{-2}} = 400\ \Omega$$

2 Skokovit PN spoj ima homogeno dopirane strane $N_A = 10^{17}\,cm^{-3}$ $N_D = 10^{15}\,cm^{-3}$ vrijedi da je $W_p = 1\,\mu m \ll L_n = 1 \cdot 10^{-4}\,cm$

! ($W_p \ll L_n$ → USKA P STRANA ZAKLJUČIMO) vrijedi $W_n = 100\,\mu m \gg L_n = 1 \cdot 10^{-2}\,cm$

! ($W_n \gg L_n$ → široka N strana zaključ)

VREMENA ŽIVOTA MANJINSKIH NOSIOCA IZNOSE $\tau_n = 0{,}5\,\mu s$ $\tau_p = 0{,}8\,\mu s$

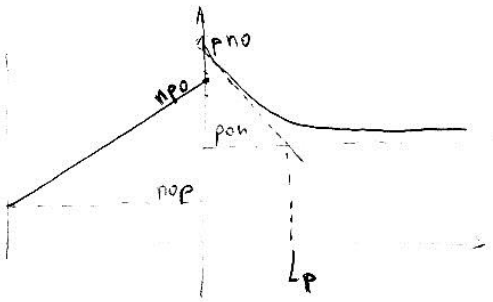
POKRETLJIVOST $\mu_n = 850\ cm^2/Vs$ $\mu_p = 350\ cm^2/Vs$

POVRŠINA PN SPOJA $S = 1\,mm^2 = 1 \cdot 10^{-2}\,cm^2$ $T = 300\,K$

2.1 IZRAČUNATI I_{sn} (elektronska komponenta u reverznoj struji zasićenja)

1. – STRANU
2. – gledamo manjinske nosioce
3. – elektronsku komponentu računamo na p strani
4. – P strana je uska → znamo W_p i W_n → likvarna (ali zadano :)

I_{sn} → na p strani



USKA $W_p \ll L_n$

ŠIROKA $W_n \gg L_p$

W_n i W_p zad L_n i L_p zad

IZ TABLICE $I_{sn} = \int \cdot S \cdot D_n \cdot \frac{n_{op}}{W_p}$ → IZRAČUN $\frac{n_i^2}{N_A}$ $= \int \cdot S \cdot \mu_n U_T \cdot \frac{n_i^2}{N_A} \cdot \frac{1}{W_p}$

($\mu_n U_T$) TU SKRIVENA POKRETLJIVOST

$= 1{,}6 \cdot 10^{-19} \cdot 10^{-2} \cdot 850 \cdot \frac{300}{11600} \cdot \frac{(1{,}45 \cdot 10^{10})^2}{10^{17}} \cdot \frac{1}{10^{-4}} = 7{,}395 \cdot 10^{-13}\,A$

2.2 IZRAČUNATI I_{SP}

- GLEDAMO MANJINSKE NOSIOCE
- n-STRANA → ŠUPLJINE manjinske
- N-STRANA → ŠIROKA !!

I_{SP} → na N strani

IZ ŠALICA FORMULA

$$I_{SP} = q \cdot S \cdot D_p \cdot \frac{p_{on}}{L_p}$$ → računamo na n strani $\frac{n_i^2}{N_D}$

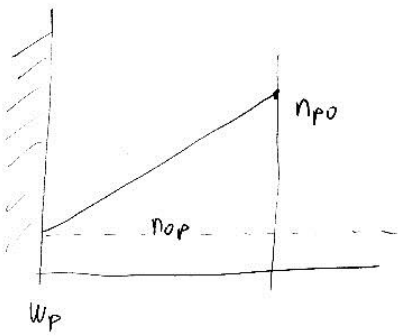
$$= q \cdot S \cdot \frac{n_i^2}{N_D} \cdot \frac{D_p \tau_p}{L_p \cdot \tau_p} = q \cdot S \cdot \frac{n_i^2}{N_D} \cdot \sqrt{\frac{D_p}{\tau_p}} = q \cdot S \cdot \frac{n_i^2}{N_D} \cdot \sqrt{\frac{\mu_p U_T}{\tau_p}}$$

$$= 1{,}6 \cdot 10^{-19} \cdot 10^{-2} \frac{(1{,}45)^2}{10^{15}} \cdot \sqrt{\frac{350 \cdot 300}{11600 \cdot 0{,}8 \cdot 10^{-6}}}$$ τ u sekund.

$$= 1{,}132\ 10^{-12} A$$

2.3 KOLIKI JE NAPON PRIKLJUČENA NA PN SPOJ AKO JE RUBNA KONCENTRACIJA manjinskih elektrona $n_{po} = 1{,}377 \cdot 10^{12}\ cm^{-3}$

$$n_{op} = \frac{n_i^2}{N_A} = \frac{(1{,}45)^2}{10^{17}} = 2{,}1 \cdot 10^{3}\ cm^{3}$$



(propusno polariziran spoj)

rubne koncentracije iz Boltzmann relacija

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

$$U = U_T \ln\left(\frac{n_{po}}{n_{op}}\right) = 300 \frac{1}{11600} \ln\left(\frac{1{,}377 \cdot 10^{12}}{2{,}1 \cdot 10^{3}}\right) = 0{,}525\ V \checkmark$$

2.4

Kolika je pri tome ravnotežna koncentracija manjinskih šupljina

$$p_{on} = \frac{(n_i)^2}{N_D} = \frac{(1{,}45)^2}{10^{15}} = 2{,}5 \cdot 10^5 \ cm^{-3}$$

$$p_{no} = p_{on} \cdot \exp\left(\frac{U}{U_T}\right) \quad (1)$$ možemo riješiti tako da se u (1) uvrsti

$U = 0{,}525$ (ovisi o 2.3)

(provjera)

$$n_{po} = n_{op} \exp\left(\frac{U}{U_T}\right) \quad (2)$$

podijelimo (1) : (2) $\Rightarrow$

$$\frac{p_{no}}{n_{po}} = \frac{p_{on}}{n_{op}} = \frac{\frac{n_i^2}{N_D}}{\frac{n_i^2}{N_A}} = \frac{N_A}{N_D}$$

$$p_{no} = n_{po} \cdot \frac{N_A}{N_D} = 1{,}377 \cdot 10^{12} \ \frac{10^{17}}{10^{15}} = 1{,}377 \cdot 10^{14} \ cm^{-3}$$

2.5 Uz neki napon priključen uz PN spoj, potoče struja $I_D = 10 \ mA$

Kolika je dinamički otpor PN spoja

$$R_D = \frac{1}{\frac{dI_D}{dU_D}}$$

$$I_D = I_S\left(\exp\frac{U_D}{U_T} - 1\right) \approx I_S \exp\frac{U_D}{U_T}$$

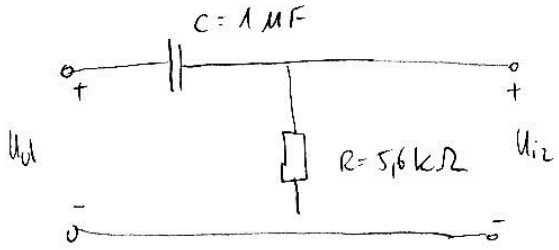
I_S = jako veliko $10^{-12}/10^{-15}$ pa je može zanemariti

$$\boxed{r_d = \frac{U_T}{I_D}} \qquad I_D \gg I_S$$

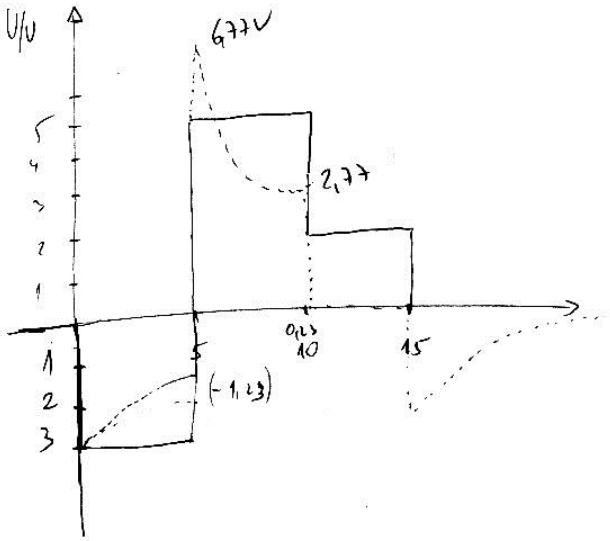
$$R_D = \frac{1}{I_S\left(\exp\frac{U_D}{U_T}\right)\cdot\frac{1}{U_T}} = \frac{U_T}{I_S \exp\frac{U_D}{U_T}} = \frac{U_T}{I_D} = \frac{300}{11600 \cdot 10 \cdot 10^{-3}} = 2{,}59 \ \Omega$$

$\approx I_D$

3 NA SLICI JE ZADAN CR mreža i napon koji je priključen na njen ulaz



$\tau = R \cdot C =$



3.1 skokai ulaznog napona se vide kao skokovi napona na otporniku

- u $t = 0^+$ imamo skok $-3V$

3.1* Izračunati: $u_{iz}(T = 0^+) = -3V$

3-2 $t = 3ms$

$0 < t < 5\ ms$

$$u_{iz}(t) = u_{iz}(0^+) \cdot \exp\left(-\frac{t}{\tau}\right) = -3 \exp\left(-\frac{3}{5,6}\right) = -1,76V$$

prije skoka imam $u_{iz}(5^-) = u_{iz}(0^+) \exp\left(\frac{-5}{5,6}\right) = -1,23V$

poslije skok $u_{iz}(5^+) = u_{iz}(5^-) + \underbrace{8V}_{\text{skok}} = 6,77V$

3-3 koliki je U_0 $t = 9ms$

$5 < t < 10$

$$U_{iz}(t) = U_{iz}(5^+) \cdot \exp\left(-\frac{(t-5)}{\tau}\right)$$ → GLEDAMO ZA $T > 5$

$$U_{iz}(t=9ms) = 6{,}77 \exp\left(-\frac{(9-5)}{5{,}16}\right) \ldots = 3{,}314\,V$$

PRIJE SKOKA $U_{iz}(10^-) = U_{iz}(5^+) \exp\left(-\frac{10-5}{5{,}16}\right) = 2{,}77\,V$

POSLIJE SKOKA $U_{iz}(10^+) = U_{iz}(10^-) - \frac{3V}{\text{skok}} = -0{,}23\,V$

3-4 $T = 12ms$ $10 < t < 15$

$$U(t) = U_{iz}(10^+) \exp\left(-\frac{(t-10)}{\tau}\right)$$

$$U(t=12m) = -0{,}23V \cdot \exp\left(-\frac{(12-10}{5{,}16}\right) = -0{,}16$$

PRIJE SKOKA $U_{iz}(15^-) = U(10^+)\exp\left(\frac{15-10}{\tau}\right) = -0{,}23 \exp\left[-\frac{15-10}{5{,}16}\right] = -0{,}094\,V$

POSLIJE SKOKA $U_{iz}(15^+) = U_{iz}(15^-) - \frac{2V}{\text{skok}} = -2{,}094\,V$

„SKOK" JE ZAPRAVO PROMJENA NAPONA PREMA GRAFU U ODNOSU -/+ trenutak

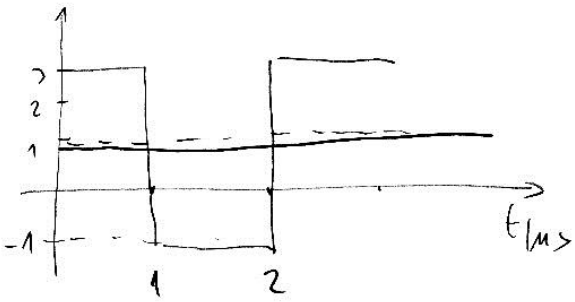
3-5 $T = 21\,ms$ $t > 15$

$$U(t) = U_{iz}(15^+) \exp\left(-\frac{t-15}{\tau}\right)$$ → $t > 15$

$$U_{iz}(t=21) = -2{,}094 \exp\left(-\frac{21-15}{5{,}16}\right) = -0{,}72\,V$$

TEORIJA

(1) ZA RC $R = 1\,M\Omega$ i $C = 1\,\mu F$ ODREDITI STAC STANJE NA IZLAZU AKO JE POBUDA ZADANA



- istosmjerna je 1V srednja vrijednost
- $U_{PP} = 4V$ pomaknuta za 1 V

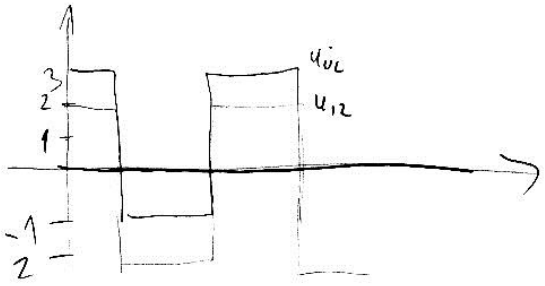
$\tau = R \cdot C = 10^6 \cdot 10^{-6} = 1\,s$

$T = 2\,ms$ → mi ćemo fukiji $\tau >> T$ (pravac po 1)

Što znači da je to skoro ko PRAVAC srednje vrijednosti

(2) AKO R i C zamijene MJESTA kako će BITI IZLAZI

KAPOM U STAC STANJU TJ IMAO CR u



- totprati ulazni napon onjegova sr vrijednost = ϕ

③ Si pločica su $N_D = 10^{15}\ \text{cm}^{-3}$ $T = 300\ K$

Nako što se doda $N_A = 10^{15}$ spec. otpor pločice

1) $\sigma_1 = \rho \cdot \mu_n \cdot n = \rho\, \mu_n N_D$

zato što je $n_i = 1{,}45 \ll N_D$

2) kupon dop $N_{A\,neto} = N_A - N_D = 10^{15}\ \text{cm}^{-3}$

$\sigma_2 = \rho \cdot \mu_p \cdot p = \rho\, \mu_p \cdot N_{A\,neto}$

$n_i \ll N_{A\,neto}$

$$\rho_1 = \frac{1}{\sigma_1} = \frac{1}{\rho \mu_n N_D} \qquad \rho_2 = \frac{1}{\sigma_2} = \frac{1}{\rho \mu_p N_{A\,neto}}$$

$$\frac{\rho_2}{\rho_1} = \frac{\rho \mu_n N_D}{\rho \mu_p N_{A\,neto}} = \frac{\mu_n}{\mu_p} \Rightarrow \mu_n > \mu_p \Rightarrow \rho_2 > \rho_1$$

$N_D = N_{A\,neto}$

OTPOR RASTE ZBOG POKR.

(4) TEOR

Si dopiran s $N_D = 5 \cdot 10^{15}$ i $N_A = 5 \cdot 10^{15}$ $T = 300\,K$

ako $T_2 = 350$ specifična vodljivost pločice

$N_A = N_D \rightarrow$ kompenzirani si $n = p = n_i$

$T = 300 \rightarrow n_i = 1.45 \cdot 10^{-10}$

$$\sigma = \sigma_i = q \cdot n_i (\mu_n + \mu_p) = q (\mu_n \cdot n + \mu_p \cdot p)$$

$T \uparrow \Rightarrow n_i \uparrow$ (eksponencijalno)

$\Rightarrow \mu \downarrow$ (pokretljivost pada ali manje nego što n_i raste)

$T \uparrow \Rightarrow \sigma_i \uparrow \Rightarrow$ spec vodljivost raste

(5) Za Si pn spoj na $T = 350\,K$ s kontaktima

$N_D = N_A = 10^{16}$ i širokim P i N stranama

Vrijedi ... I_{sn} I_{sp} osiromašeno područje se jednako širi na obje strane

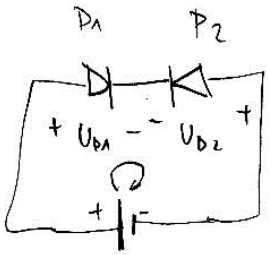
$N_A = N_D$ ✓

$$I_{sn} = q \cdot S \cdot D_n \frac{n_{op}}{L_n} = q \cdot S \, n_{op} \sqrt{\frac{D_n}{\tau_n}}$$

$$I_{sp} = q \cdot S D_p \cdot \frac{p_{on}}{L_p} = q \cdot S \, p_{on} \sqrt{\frac{D_p}{\tau_p}}$$

$$\frac{I_{sn}}{I_{sp}} = \sqrt{\frac{D_n}{D_p}} = \sqrt{\frac{\mu_n}{\mu_p}} \quad \mu_n > \mu_p \quad \boxed{I_{sn} > I_{sn}}$$

6



$U_6 = 8V$

$I_{S1} = 10\,nA$

$I_{S2} = 5\,nA$

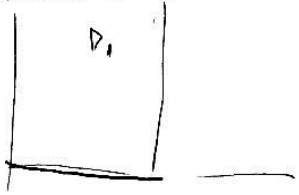
$U_{\gamma 1} = U_{\gamma 2} = 0{,}7\,V$

Ako u sklopu teče I

— po polaritetu priključenog napona se zaključi da je struja $\angle\phi$

$D_1 \rightarrow$ propusno

$D_2 \rightarrow$ nepropusno – ograničava struju



$|U_{D1}| = 0{,}7\,V$

$|U_{D2}| = |0{,}7 - 8|\,V = 7{,}3\,V$ (recurzni)

$\Rightarrow \quad |U_{D2}| > |U_{D1}| \qquad I_{S2} = -5\,nA$

7. (TEOR)

kolika je širina zabranjenog područja pdu kada

iz kojeg je najmanjeg svjetlosne diode i koje ima

biti da svjetli zeleno $\lambda = 0,5\ nm$

→ zaporno i propusno → **PROPUSNO** . jer se rekombinira i pritom se oslobađa energija pa svjetli

1) $\epsilon_g = 1,12\ eV$ (Si → ne može jer svjetli infracrveno)

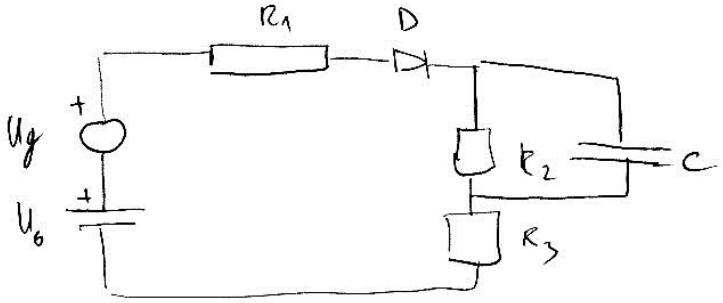
2) $\epsilon_c = 2,48\ eV$

$$\lambda = \frac{1,24}{E} \Rightarrow \quad E = \frac{1,24}{\lambda} = 2,48\ eV$$

8. SKLOP S DIODOM PREMA SLICI ISTOSMJERNI I MALOG ~ napona

ako su $R_1 = 10\ \Omega$ $R_2 = 1\ k\Omega$ $R_3 = 10\ \Omega$

kolike su otpori R_{ST} i R_{din}

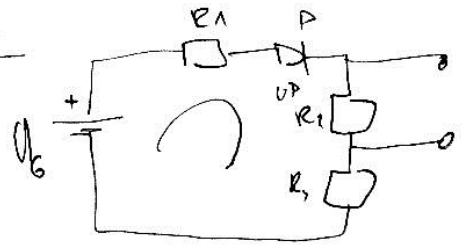


– ako je ~ mali signal (U_g) DIODA SE MOŽE LINEARIZIRATI

STATIKA

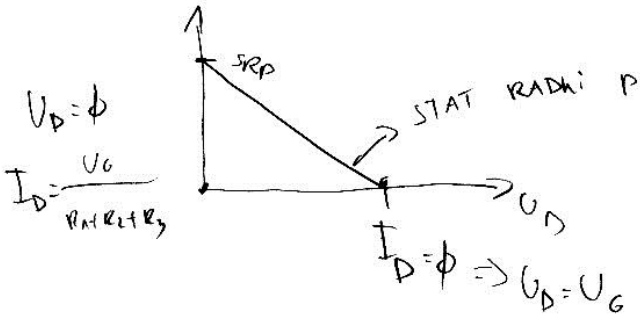
$U_g = 0$ kratko spojen izmj izvor

STAT



U STATICI ODSPAJAMO KONDIĆ!

$$U_G = I_D \cdot (R_1 + R_2 + R_3) + U_D$$



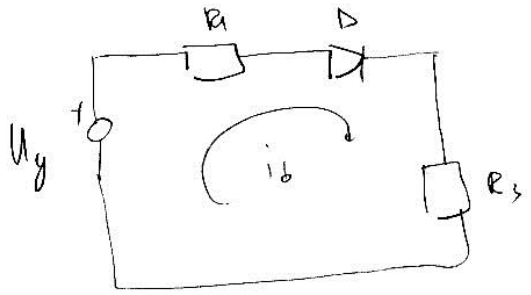
$\left(-\frac{1}{R_{ST}}\right)$

$$\Rightarrow R_{ST} = R_1 + R_2 + R_3 = 1{,}02\ k\Omega = 1020\ \Omega$$

DINAMU

→ SVI KONDENZATORI SU KRATKI SPOJ

→ GASIMO ISTO SMJERNE IZVORE



$$U_g = i_d(R_1 + R_3) + U_d$$

$$i_d = f(U_d)$$

$$i_d = -\frac{U_d}{R_1 + R_3} + \frac{U_g}{R_1 + R_3}$$

(VIDI KMJI 21) STR - PRI 4.424 (4 Maih slike)

sjeku se u RADNOJ TOČKI (STATI DINAMIČKI

$(I_{DQ}\ U_{DQ})$

$$\sim \left(-\frac{1}{R_{din}}\right) \quad R_{din} = R_1 + R_3 = 20\ \Omega$$