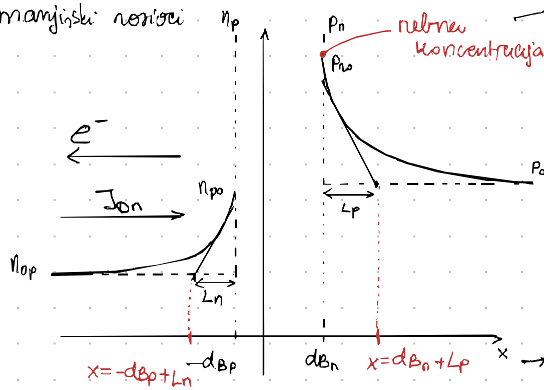
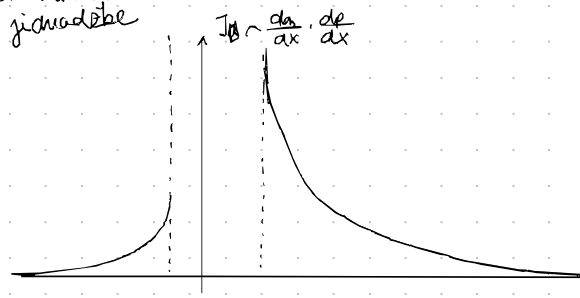
Propusno polarizirani pn spoj

manjinski nosioci



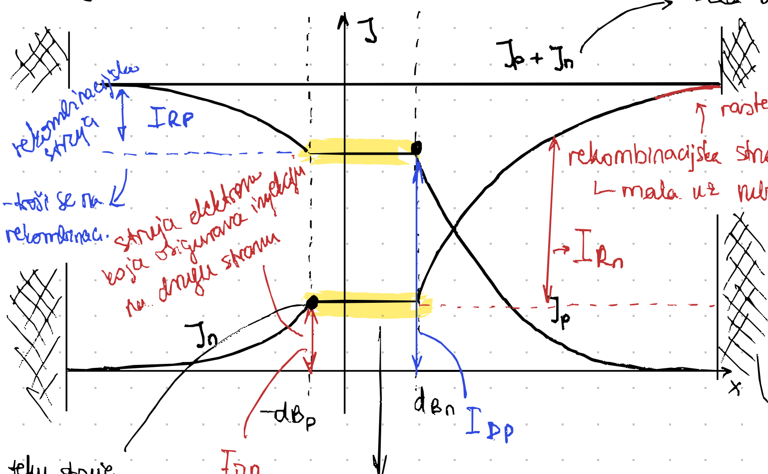
— Boltzmanove jednadžbe



→ dif struje manjinskih nosioca određuju ukupnu struju kroz diodu

* struja ē mora osigurati injekciju sa n na p stranu

Difuzijske struje manjinskih nosilaca



kada u bilokojem trenu spojimo J_p i J_n dobit ćemo da je konstantna kroz strukturu

ta se mjeri

- ukupna struja kroz pn spoj je kontinuirana

↓

jednaka struji na kontaktima

teku struje manjinskih nosioca uz rub osiromašenog područja

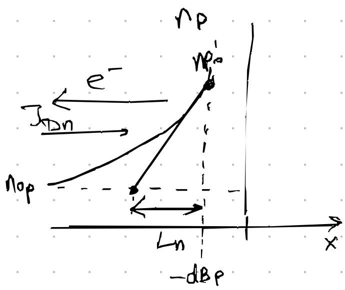
na rubovima osiromašenih područja teče konstantna struja

↳ u tim točkama imamo sve potrebne parametre za računanje difuzijske struje → $I_D = I_{Dn} + I_{Dp}$

→ Zbog rekombinacije dolazi do gradijenta i difuzijske struje

Shockleyeva jednadžba - široke strane

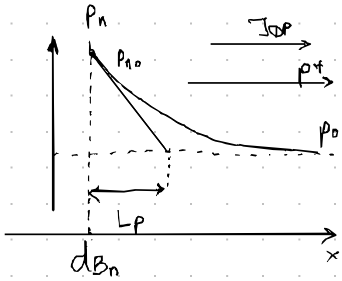
Dif. struje manjinskih nosilaca



$$J_{Dn}(x=-d_{Bp}) = q D_n \frac{dn_p(x)}{dx}\Big|_{-d_{Bp}}$$

$$= q D_n \frac{n_{p0}-n_{0p}}{L_n} = \left\{ n_{p0} = n_{0p}\cdot \exp\left(\frac{U}{U_T}\right)\right\}$$

$$= q D_n \frac{n_{0p}\exp\left(\frac{U}{U_T}\right) - n_{0p}}{L_n} = \frac{q D_n \cdot n_{0p}}{L_n}\left[\exp\left(\frac{U}{U_T}\right)-1\right]$$



$$J_{Dp}(d_{Bn}) = -q D_p \frac{dp_n(x)}{dx}\Big|_{d_{Bn}} = -q D_p \frac{p_{0n}-p_{n0}}{L_p}$$

$$= q D_p\frac{p_{n0}-p_{0n}}{L_p} = \left\{p_{n0} = p_{0n}\exp\frac{U}{U_T}\right\}$$

$$= q\frac{D_p p_{0n}\exp\frac{U}{U_T} - p_{0n}}{L_p} = \frac{q D_p\cdot p_{0n}}{L_p}\left[\exp\left(\frac{U}{U_T}\right)-1\right]$$

$$J = J_{Dn}(-d_{Bp}) + J_{Dp}(d_{Bn}) = \left[\exp\left(\frac{U}{U_T}\right)-1\right]\underbrace{\left(q\frac{D_n n_{0p}}{L_n} - q\frac{D_p p_{0n}}{L_p}\right)}_{J_S}$$

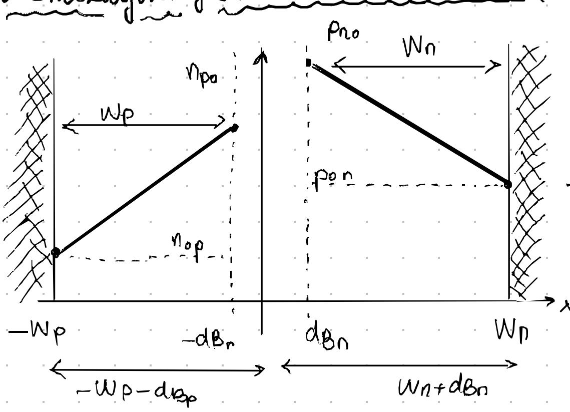
$$\boxed{\Rightarrow J = J_S\left[\exp\left(\frac{U}{U_T}\right)-1\right]}$$

gustoća struje zasićenja

$$J_S = \frac{I_S}{S} \rightarrow I_S = J_S\cdot S$$

$$\rightarrow I_S = S\cdot q\left(\frac{D_n n_{0p}}{L_n} - \frac{D_p p_{0n}}{L_p}\right)$$ struja zasićenja

Shockleyeva jednadžba - uske strane (raspodjela je linearna)



$$J_{Dn}(-d_{Bp}) = q D_n \frac{dn_p(x)}{dx}\Big|_{-d_{Bp}} = q D_n\frac{n_{p0}-n_{0p}}{W_p}$$

radi se o manjinskim nosiocima → e^- na p-strani

zato ide širina p-strane

Boltzman!

$$J_{Dp}(d_{Bn}) = q D_p\frac{dp_n(x)}{dx} = q D_p\frac{p_{n0}-p_{0n}}{W_n}$$

Ukupna struja: $J = J_{Dn}(-d_{Bp}) + J_{Dp}(d_{Bn})$

$$J = q\left[D_n\frac{n_{0p}}{W_p} + D_p\frac{p_{0n}}{W_n}\right]\left(\exp\left(\frac{U}{U_T}\right)-1\right)$$

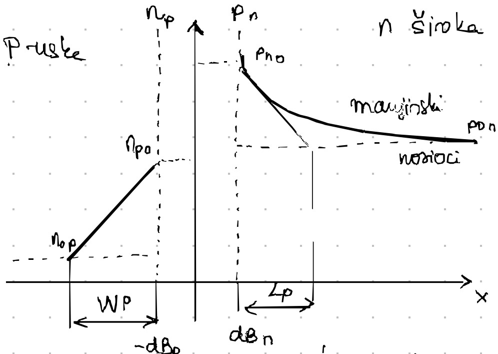
Shockleyeva jednadžba: $J = J_S\left(\exp\left(\frac{U}{U_T}\right)-1\right)$ → $J_S = q\left(D_n\frac{n_{0p}}{W_p} + D_p\frac{p_{0n}}{W_n}\right)$

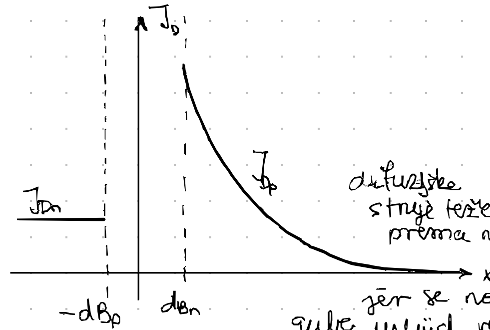
⇒ uska strana: linearno, W

široka strana: eksponencijalna, L

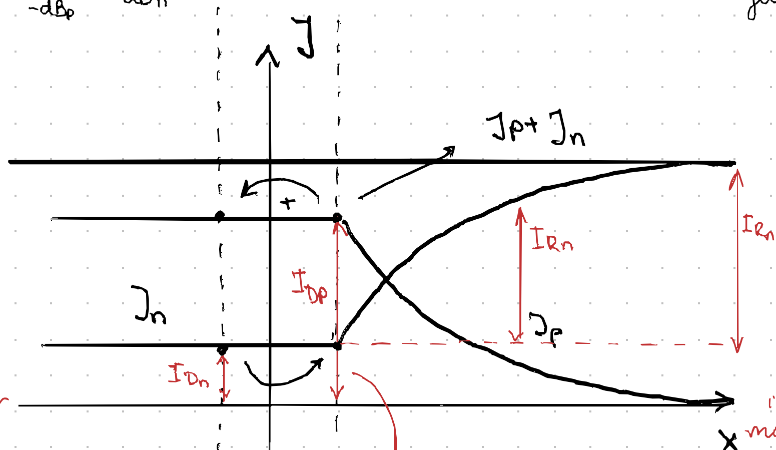
▸ Propusno polarizirani pn-spoj

– uska p-strana
široka n-strana





jer se nosioci gube uslijed rekombinac.



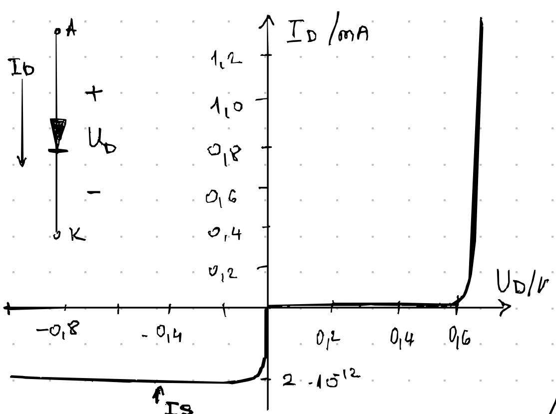
toliko uska da svi e^- završe injektirani na drugu stranu

jedina osigurava injekciju na drugu stranu

da ne bismo izgubili većinske nosioce koji se na n strani troše na rekom

⟵ moramo nadoknaditi te nosioce iz vanjskog kontakta

Strujno naponska karakteristika idealne pn diode



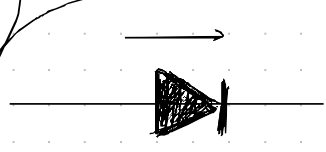
$$I_D = I_S \left[\exp\left(\frac{U}{U_T}\right) - 1 \right] \qquad I_S = J_S \cdot S$$

Propusna polarizacija: $I_D = I_S \exp\left(\frac{U_D}{U_T}\right)$

Zaporna polarizacija: $I_D = -I_S$ (struja zasićenja)

↳ nije simetrična u odnosu na ishodište

$U_D < -3U_T \approx -75\,mV$

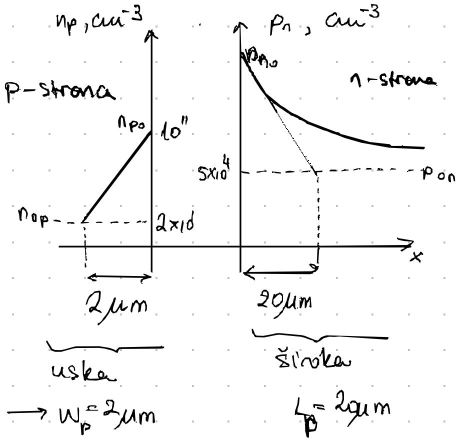


teče samo drift struja manjinskih nosilaca

$I_{Fn} + I_{Fp}$

$U_D > 3U_T$ ⟶ približno vrijedi

Primjer 3.3.



$\mu_n = 400 cm^2/Vs$

$\mu_p = 350 cm^2/Vs$

$S = 0{,}25 mm^2$

$T = 300K$

$n_{op} = 2\times10^1 cm^{-3}$

$n_{po} = 10^{11} cm^{-3}$

$p_{on} = 5\times10^4 cm^{-3}$

$W_p = 2\times10^{-4} cm$

$L_p = 20\times10^{-4} cm$

a) $U_D = ?$

b) struja šupljina --- uz rub osiromašenog područja na n strani

$\hookrightarrow I_{Dp} = ?$

c) sa n na p $\rightarrow I_{Dn} = ?$

d) $I_S = ?$

$* S = 0{,}25 \frac{1}{100} cm^{-2}$

$S = 25\times10^{-4} cm^{-2}$

a)

$$n_{po} = n_{op}\exp\left(\frac{U_D}{U_T}\right) \Rightarrow U_D = U_T\cdot\ln\frac{n_{po}}{n_{op}} = \frac{300}{11600}\cdot\ln\left(\frac{10^{11}}{2\times10^1}\right)$$

$$U_D = 0{,}578 V$$

$$p_{no}? \rightarrow p_{no} = p_{on}\exp\left(\frac{U_D}{U_T}\right) = 5\times10^4\cdot\exp\left(\frac{0{,}578}{\frac{300}{11600}}\right)$$

ili $\frac{p_{no}}{n_{po}} = \frac{p_{on}}{n_{op}} \rightarrow p_{no} = n_{po}\frac{p_{on}}{n_{op}} = 2{,}5\times10^{14} cm^{-3}$

b) $I_{Dp} = ?$

$$* J_{Dp} = q D_p \frac{dp}{dx} \quad dp \rightarrow \Delta p \quad dx \rightarrow \Delta x \qquad D_p = U_T\cdot\mu_p$$

$I_{Dp} = qSD_p$

$$I_{Dp} = q\cdot S\cdot D_p\frac{p_{no}-p_{on}}{L_p} = qS\,U_T\mu_p\frac{p_{no}-p_{on}}{L_p}$$

$$= 1{,}602\times10^{-19}\cdot\frac{300}{11600}\cdot350\cdot\frac{2{,}5\times10^{14}-5\times10^4}{20\times10^{-4}}$$

$$\boxed{I_{Dp} = 453\,\mu A}$$

c) $I_{Dn} = ?$

$$I_{Dn} = qSD_n = qS\,U_T\mu_n\frac{n_{po}-n_{op}}{W_p} = 1{,}602\times10^{-19}\cdot25\times10^{-4}\cdot\frac{300}{11600}\cdot400\frac{10^{11}-20}{2\times10^{-4}}$$

$$\boxed{I_{Dn} = 2{,}07\,\mu A}$$

d) $I_S = ?$

1. način

$$I_D = I_{Dp} + I_{Dn} = \boxed{455{,}07\,\mu A}$$

$$I_D = I_S\left[\exp\left(\frac{U_D}{U_T}\right) - 1\right] \text{ iz (a)} \longrightarrow I_S = \frac{I_D}{\exp\left(\frac{U_D}{U_T}\right)-1} = \boxed{8{,}95\times10^{-14} A}$$

$$\boxed{I_S = 89{,}5\,fA}$$

isto

2. način

manjinski na p

$$I_S = I_{Sn} + I_{Sp} = qS\left[\underbrace{\frac{n_{op}D_n}{W_p}}_{\text{p-strana je uska}} + \underbrace{\frac{p_{on}\cdot D_p}{L_p}}_{\text{široka strana}}\right]$$

manjinski na n strani

svejedno je kako računamo

Primjer 3.4 → ima u skripti

a) $I_D = ?$ $\quad U_D = -5V, -1V, 0.2V, 0.4V, 0.6V$

iz zadatka 3.3 → $I_S = 89{,}5\,fA$

$I_S = -I_D$

U_D / V	-5	-1	0.2	0.4	0.6
I_D / A	$-89{,}5fs$	$-89{,}5fs$	$207pA$	$474nA$	$108mA$

reverzno polariziran

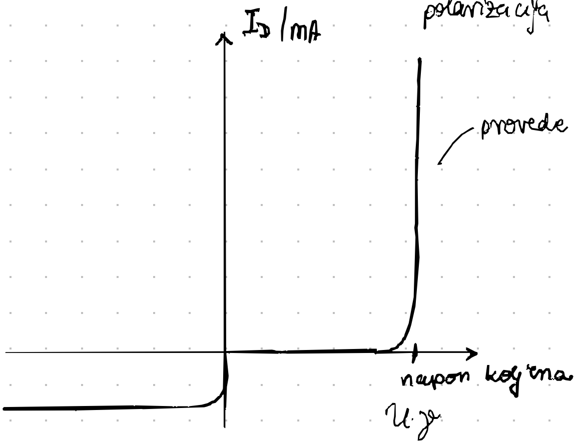
propusna polarizacija

struja exp raste sa naponom

za napone koji su $\leq \approx 75mS$ exp član je zanemariv

$\hookrightarrow I_D = I_S\left[\cancel{\exp\left(\frac{u}{U_T}\right)} - 1\right]$!!

$\rightarrow \underline{I_D = -I_S}$



→ ispod napona koji na dioda praktički ne provodi struju

b) $U_D = ? \rightarrow I_D = 90\%\, I_S \rightarrow I_D = -0.9 I_S$

$$-0.9\cancel{I_S} = \cancel{I_S}\left[\exp\left(\frac{U_D}{U_T}\right) - 1\right]$$

$$-0.9 = \exp\left(\frac{U_D}{U_T}\right) - 1$$

$$\exp\left(\frac{U_D}{U_T}\right) = 0.1$$

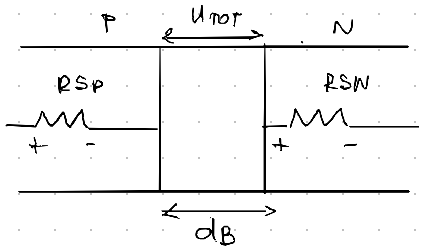
$$\frac{U_D}{U_T} = \ln(0.1) \rightarrow U_D = U_T \cdot \ln(0.1)$$

$$\boxed{U_D = -59{,}6\,mV} \quad > -0.3\,U_T$$

Realna pn dioda – propusna karakteristika

1. – sav napon na osiromašenom područji → jedinu ΔU imamo unutar osiromašenog područja

↳ nema padova napona na kvazineutralnim stranama

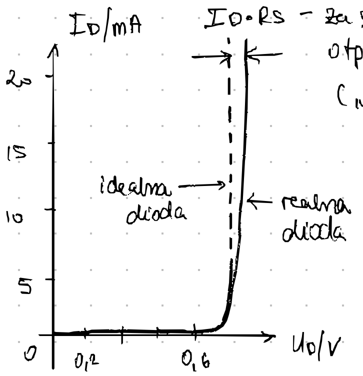


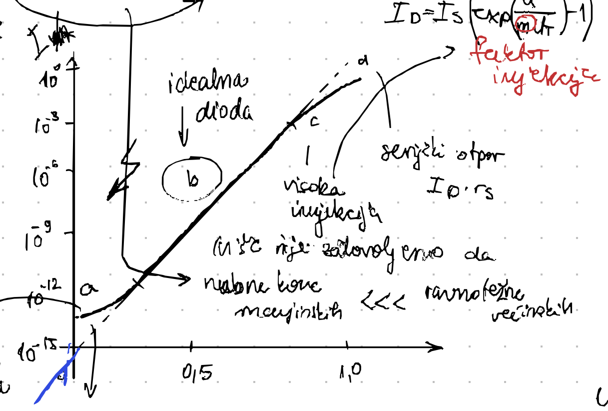
$$\Delta U_D = I_D (R_{SP} + R_{SN}) = I_D \cdot R_S$$

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

2. Nema rekombinacije u osiromašenom području

3. Režim niske injekcije $p_{n0}, n_{p0} << n_{0n}, p_{0p}$





niska injekcija (rekombinacijska struja $I_D \sim \exp\frac{U}{2U_T}$

b - idealna dioda $m \sim 1$

c - visoka injekcija $m > 1 \longrightarrow I_D = I_S\left(\exp\left(\frac{U_D}{mU_T}\right) - 1\right) \Big/ \log$ — zanemareno jer gledamo kad je exp >>> 1

$$\Rightarrow \log(I_D) = \log(I_S) + \log(e)\frac{U_D}{U_T}$$

konstanta — koeficijent

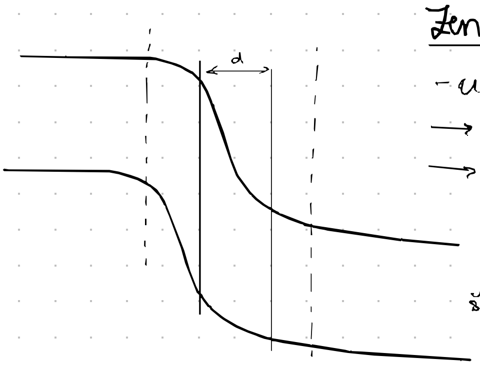
⇒ odsječak na ordinati

Zapornu je Čupertić samo projezio

Proboj

Lavinski proboj – ionizacija atoma poluvodiča u osiromašenom sloju
⟶ za probojne napone $U_B > 8V$

Zenerov (tunelski proboj)
– u diodama s jako dopiranim stranama
⟶ tuneliranje e^- kroz barijeru
⟶ za probojne napone $U_B < 5V$



što je uže, veća je vjerojatnost tuneliranja

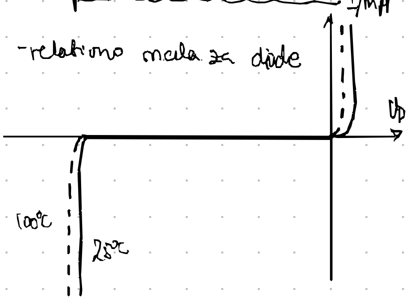
– jako dopirane p i n strane ⟹ jako usko osiromašeno područje

⟹ U_B → ovisi o koncentraciji primjesa slabije dopirane strane pn-spoja

↳ ako imamo veću širinu zabranjenog pojasa → teže izgeneriramo nosioce → teže dođe do proboja

Temperaturna ovisnost

- relativno mala za diode



$$I_S = qS\left(\frac{D_n n_{op}}{L_n} + \frac{D_p p_{on}}{L_n}\right)$$

$$n_{op} = \frac{n_i^2}{p_{op}} \qquad p_{on} = \frac{n_i^2}{n_{on}}$$

$$n_{op} = \frac{n_i^2}{N_A} \qquad p_{on} = \frac{n_i^2}{N_D}$$

$$I_S = qSn_i^2\left(\frac{D_n}{L_n N_A} + \frac{D_p}{L_p N_D}\right)$$

$$\Rightarrow I_S \approx n_i^2$$

- propusna polarizacija $\frac{\Delta U_D}{\Delta T} = 1{,}5$ do $2{,}5\ mV/°C$ $\longrightarrow$ mijenja probojni napon

* proboj:

lavinski $\to U_B/\Delta T > 0$

Zenerov $\to U_B/\Delta T < 0$

najbolje diode $\approx 6V$

Primjer 35.) $T = 25°C$ $\quad U_{D_1} = 0{,}7V$ $\quad I_{D_1} = 2mA$ $\quad m = 1{,}2$

$\Delta U_D = ?$ $\quad I_{D_1} = konst.$ $\quad \Delta T = 5°C$ $\quad \Delta I_S = ?$

$T_1 = 298K$

$T_2 = 293K$

$m > 1 \longrightarrow$ visoka injekcija $\quad I_D = I_S \exp\left(\frac{U_D}{mU_T}\right)$

$$I_S = I_D \exp\left(-\frac{U_D}{mU_T}\right) \longrightarrow \boxed{I_{S1} = 2.75 \times 10^{-13} A = 0{,}275\ pA}$$

$$I_S(T) \approx n_i^2(T)$$

$$n_i(T) = C_1 T^{3/2} \exp\left(-\frac{E_{g0}'}{2ET}\right)$$

$$\frac{I_{S2}}{I_{S1}} = \left(\frac{\cancel{C_1}\, T_1^{3/2} \exp\left(\frac{-E_{g0}'}{2ET_2}\right)}{\cancel{C_1}\, T_2^{3/2} \exp\left(-\frac{E_{g0}'}{2ET_1}\right)}\right)^2$$

$$\frac{I_{S2}}{I_{S1}} = \left(\frac{T_2}{T_1}\right)^3 \exp\left[\frac{E_{g0}'}{k}\left(\frac{1}{T_1} - \frac{1}{T_2}\right)\right] = \left(\frac{303}{298}\right)^3 \exp\left[\frac{1{,}196}{8{,}62 \times 10^{-5}}\left(\frac{1}{298} - \frac{1}{303}\right)\right]$$

$$\frac{I_{S2}}{I_{S1}} = 2.2 \longrightarrow I_{S2} = 2{,}2\, I_{S1}$$ (2,2 puta se povećala I_S)

$$\boxed{I_{S2} = 0{,}61\ pA}$$

$$I_D = I_S \exp\left(\frac{U_D}{mU_T}\right) \longrightarrow \frac{I_{D1}}{I_{S2}} = \exp\left(\frac{U_{D2}}{mU_T}\right) \quad / \ln$$

$$\ln\left(\frac{I_{D1}}{I_{S2}}\right) = \frac{U_{D2}}{mU_T} \longrightarrow U_{D2} = m\, U_{T_2} \cdot \ln\left(\frac{I_{D1}}{I_{S2}}\right)$$

$$\boxed{U_{D2} = 0.687\ V}$$

$$\boxed{\Delta I_S = 0{,}334\ pA}$$

$$\boxed{\Delta U_D = 13\ mV}$$