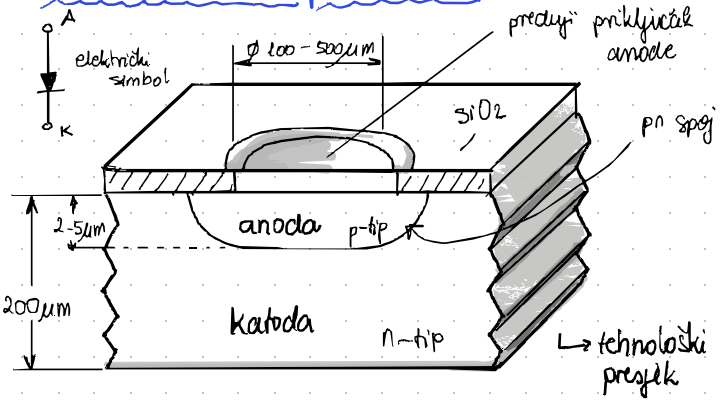
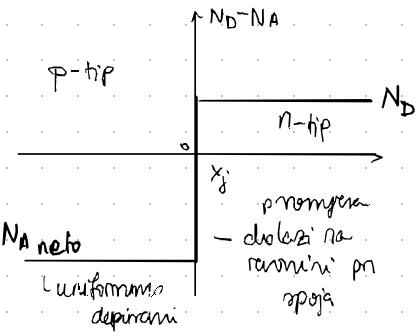
3.1. POLUVODIČKA DIODA

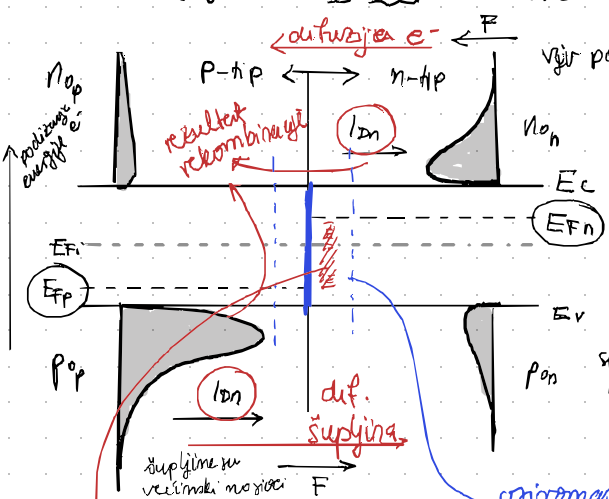
Struktura pn-diode



Skokovita podjela primjese



Energetski dijagram prije uspostavljanja kontakta

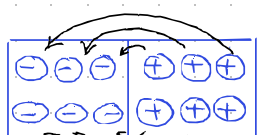


Višak popunjenosti s e^- je veća u n-tipu

E_{Fp}, E_{Fn} → Fermijeve energije

→ donori koji su otpustili e^- u osiromašenom području drže neki poz naboj

→ akceptori imaju višak negativnih naboja

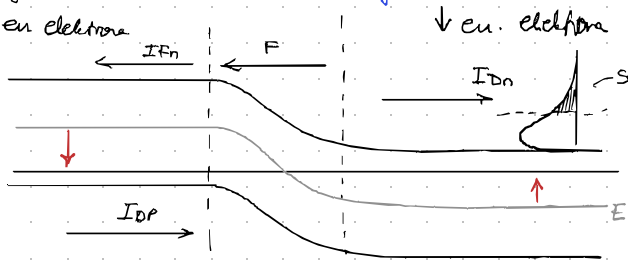


Za neke se može istovariti

→ p - neg. nabijen
↳ na neg. potencijalu od n-strane

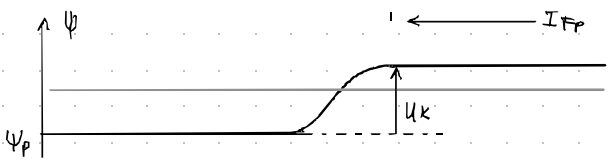
→ neg. potenc
↑ en elektrona

poz. potenc
↓ en. elektrona



— samo onoliki dio ima dovoljno energije za rekombinaciju

E_F → Fermijeve energije su se poklopile isčezljavanjem



U ravnoteži:

$I_n = I_{Dn} - I_{Fn}$

$I_p = I_{Dp} - I_{Fp}$

$I = I_p + I_n =$

Kontaktni potencijal

Prostorni naboj uzrokuje razliku potencijala → kontaktni potencijal U_k

$$E_{Fn} - E_{Fp} = E_T \ln\left(\frac{n_{on}}{n_i}\right) + E_T \ln\left(\frac{p_{op}}{n_i}\right) = E_T \ln\left(\frac{n_{on}}{n_i} \cdot \frac{p_{op}}{n_i}\right)$$

$$U_k = \frac{E_{Fn} - E_{Fp}}{q} = U_T \ln\left(\frac{n_{on}\, p_{op}}{n_i^2}\right)$$

- u ekstrinzičnom temperaturnom području: $U_k = U_T \ln\left(\frac{N_D N_A}{n_i^2}\right)$

$n_{on} = N_D \quad p_{op} = N_A \quad n_i$

$T \uparrow \quad E_{Fn} \to E_{Fi}, \; E_{Fp} \to E_{Fi} \;\Big\} (E_{Fn} - E_{Fp}) \downarrow = U_k$

Primjer 3.1) $N_A = 10^{19}\,cm^{-3}$ p-strana $\quad N_D = 10^{15}\,cm^{-3}$ n-strana $\quad U_k = ? \quad T_1 = 300K \quad T_2 = 350K$

$n_{i_1} = 1{,}45 \times 10^{10}\,cm^{-3}$

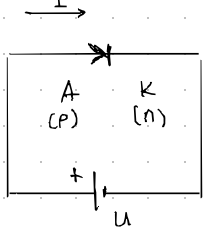
$n_{i_2} = C_1 T^{3/2} \exp\left(-\frac{E_{g1}}{2E_T}\right) = 4{,}96 \times 10^{11}\,cm^{-3}$

$U_k = U_T \ln\left(\frac{N_D N_A}{n_i^2}\right)$

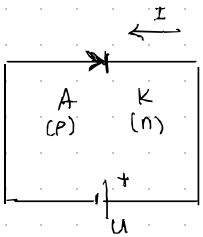
$T_1 = 300K \to U_{k_1} = \frac{300}{11600} \ln\left(\frac{10^{15} \cdot 10^{19}}{(1{,}45 \times 10^{10})^2}\right) = 0{,}695V$

$T_2 = 350K \to U_{k_2} = \frac{350}{11600} \ln\left(\frac{10^{15} \cdot 10^{19}}{(4{,}96 \times 10^{11})^2}\right) = 0{,}598V$

Polarizacija pn-spoja – priključak vanjskog napona

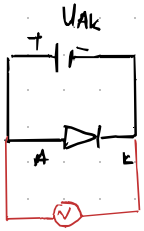


$U_{AK} = U > 0$



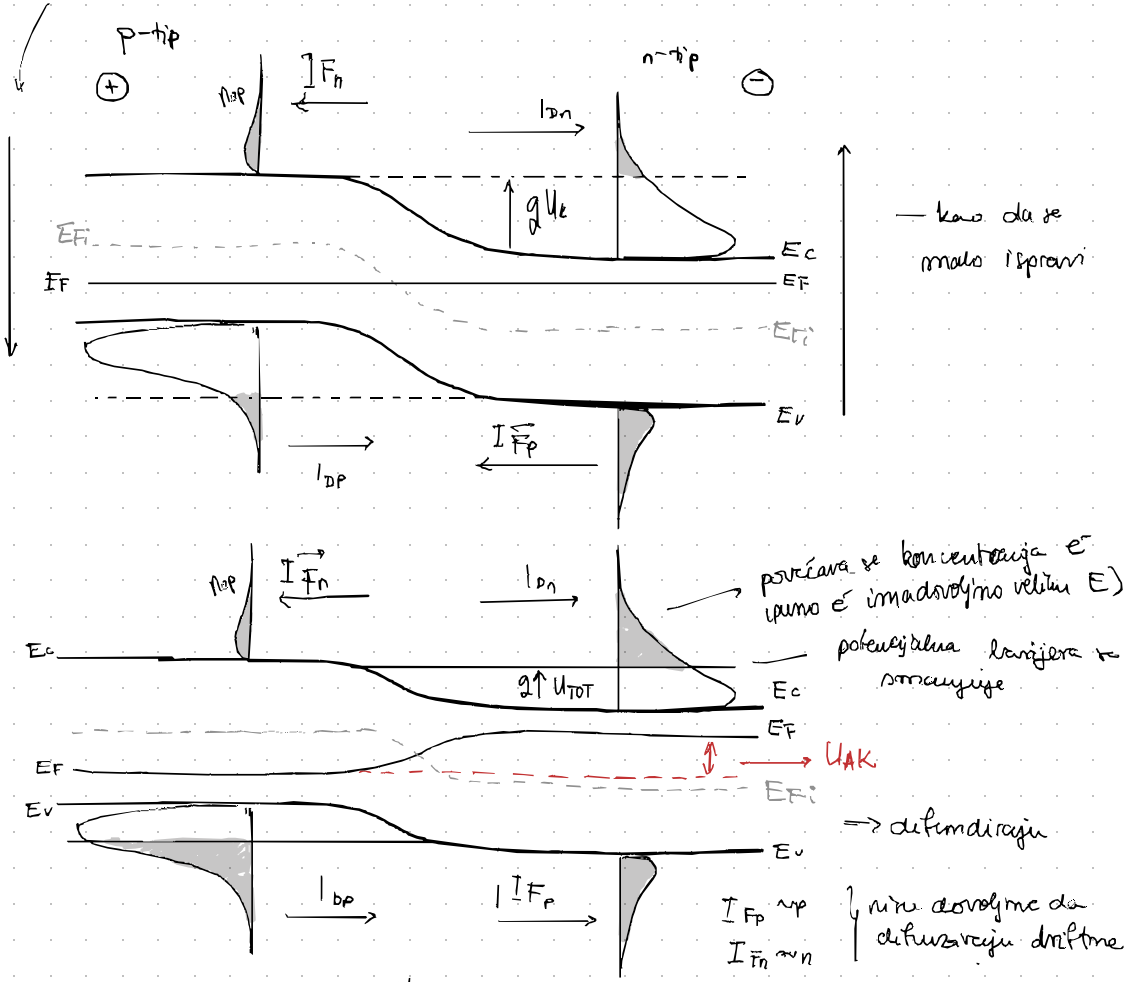
$U_{AK} = -U < 0$

Propusna polarizacija ⇒



– između A i K spojimo pozitivan U

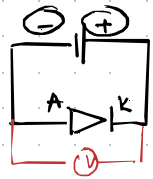
- pozitivnim potencijalom spuštamo energije za e⁻

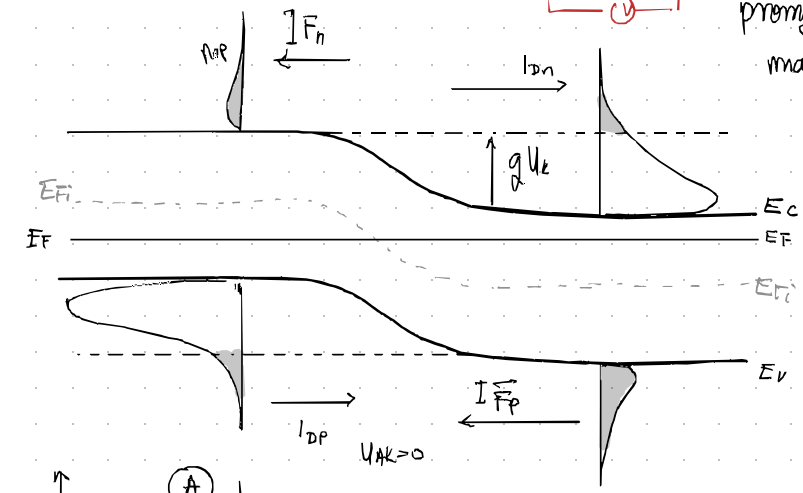


$I_n = I_{Dn} - I_{Fn} \approx I_{Dn}$ $\quad U_{AK} > 0$

$I_p = I_{Dp} - I_{Fp} \approx I_{Dp} \Longrightarrow I = I_n + I_p \approx I_D + I_{Dp}$ PROPUSNA POLARIZACIJA

Zaporna polarizacija





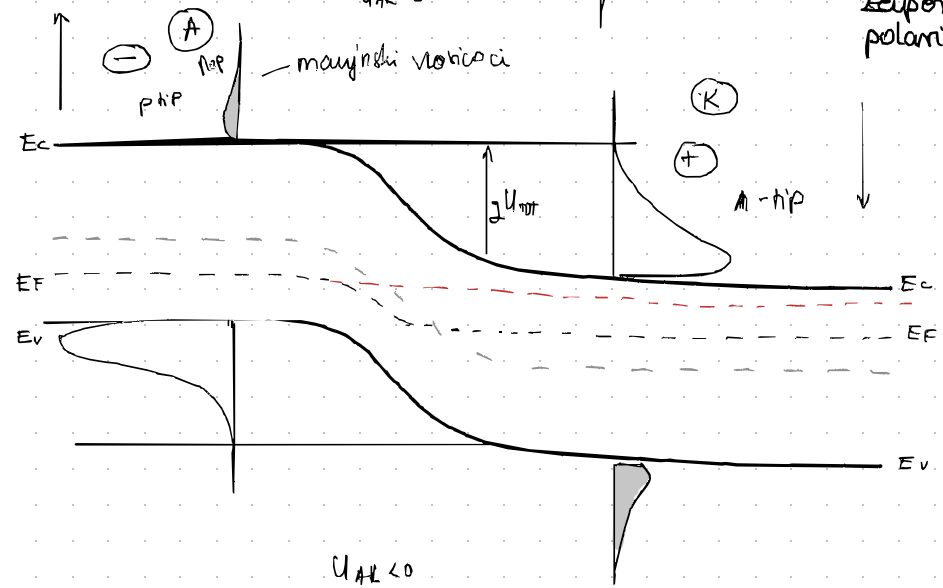
promjenom U_{AK} struja je mala i ne mijenja se

$$I_n = I_{Dn} - I_{Fn} \approx -I_{Fn}$$

$$I_p = I_{Dp} - I_{Fp} \approx -I_{Fp}$$

$$I = I_n + I_p \approx -I_{Fp} - I_{Fn}$$

→ male struje – zaporna ili reverzna polarizacija lide u suprotnom smjeru



Osiromašeni sloj

- raspodjele el. polja $F(x)$ i potencijala $\psi(x)$

Gaussov

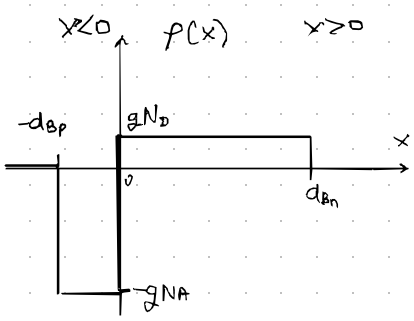
Poissonova jednadžba $\frac{d^2\psi}{dx^2} = -\frac{dF}{dx} = -\frac{f(x)}{\varepsilon}$ $\quad \varepsilon = \varepsilon_0 \varepsilon_r'$, $\varepsilon_{Si}' = 11{,}7$

Prostorni naboj

$$f(x) = \begin{cases} -qN_A^- & \text{za } -d_{Bp} \le x < 0 \\ qN_D^+ & \text{za } 0 < x \le d_{Bp} \end{cases}$$

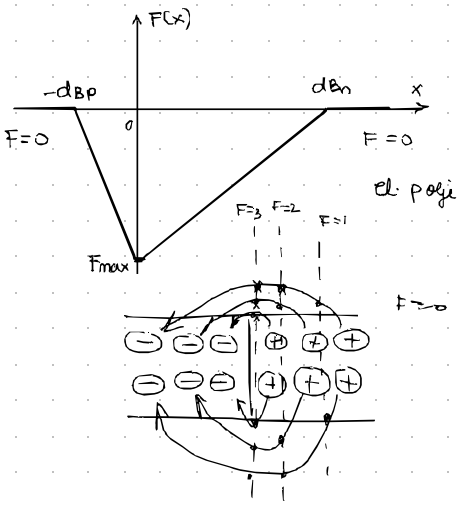
(d_{Bp} i d_{Bn} su granice osiromašenog sloja na p i n strani)

Osiromašeni sloj - raspodjele



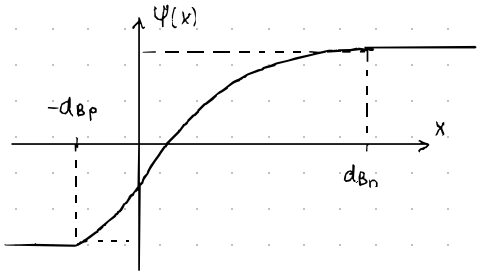
$$\rho(x) = \begin{cases} -qN_A & za \quad -d_{Bp} \le x < 0 \\ qN_D & za \quad 0 < x \le d_{Bn} \end{cases}$$

prostorni naboj $\int$ $-\frac{dF(x)}{dx}$



$$F(x) = \begin{cases} -q\frac{N_A}{\varepsilon}(x + d_{Bp}) & za \quad -d_{Bp} \le x \le 0 \\ \frac{qN_D}{\varepsilon}(x - d_{Bn}) & za \quad 0 \le x \le d_{Bn} \end{cases}$$

$\frac{d\psi}{dx}$ $\int$



$$\psi(x) = \begin{cases} \psi_p + \frac{qN_A}{2\varepsilon}(x + d_{Bp})^2, & -d_{Bp} \le x \le 0 \\ \psi_p - \frac{qN_D}{2\varepsilon}(x - d_{Bn})^2, & 0 \le x \le d_{Bn} \end{cases}$$

↳ moramo integrirati čiju el. polja

→ Raspodjela el. polja

① integ uz rubne uvjete $F(-d_{Bp}) = F(d_{Bn}) = 0$

$$F(x) = \begin{cases} -\frac{qN_A}{\varepsilon}(x + d_{Bp}), & -d_{Bp} \le x \le 0 \\ \frac{qN_D}{\varepsilon}(x - d_{Bn}) & 0 \le x \le d_{Bn} \end{cases}$$

(pozicija na granici pn spoja)

- za $x = 0 \rightarrow$ postiže se max iznos el. polja

$$F(0_-) = F(0_+)$$

$$-\frac{qN_A}{\varepsilon} d_{Bp} = -\frac{qN_D}{\varepsilon} d_{Bn}$$

$\Rightarrow F_{max}$

Neutralnost osiromašenog područja

$\rightarrow qN_A d_{Bp} = qN_D d_{Bn}$

bez obzira počnemo li s desnog ili s lijevog kraja

ukupna širina osiromašenog područja: $d_B = d_{Bp} + d_{Bn}$

$\Rightarrow$ širine p- i n- strana

$$d_{Bp} = d_B \frac{N_D}{N_A + N_D} \quad \downarrow \quad d_{Bp} = d_B \frac{1}{1 + \frac{N_A}{N_D}}$$

$$d_{Bn} = d_B \frac{N_A}{N_A + N_D} \quad \downarrow \quad d_{Bn} = d_B \frac{1}{1 + \frac{N_D}{N_A}}$$

$N_A >> N_D \Rightarrow d_{Bp} \approx 0$, $d_{Bn} \approx d_B$

Osiromašeno područje se širi na slabije dopiranu stranu

→ Raspodjela potencijala

(2) Integracija Poissonove jednadžbe uz rubne uvjete $\psi(-d_{Bp}) = \psi_p$, $\psi(d_{Bn}) = \psi_n$

$$\psi(x) = \begin{cases} \psi_p + \frac{qN_A}{2\varepsilon}(x + d_{Bp})^2 & \text{za } -d_{Bp} \le x \le 0 \\ \psi_n - \frac{qN_D}{2\varepsilon}(x - d_{Bn})^2 & \text{za } 0 \le x \le d_{Bn} \end{cases}$$

→ Za $x=0$ → potencijal mora biti kontinuirana funkcija

$$\psi(0_-) = \psi_p + \frac{qN_A}{2\varepsilon} d_{Bp}^2 = \psi(0_+) = \psi_n - \frac{qN_D}{2\varepsilon} d_{Bn}^2 = \psi_0$$

⇒ potencijal se mijenja samo u osiromašenom području

Ukupna širina osiromaš.: uvrstimo d_{Bp} i d_{Bn}

$$\Rightarrow d_B = \sqrt{\frac{2\varepsilon}{q}\frac{N_A + N_D}{N_A N_D} U_{TOT}} = \sqrt{\frac{2\varepsilon}{q}\left(\frac{1}{N_A} + \frac{1}{N_D}\right) U_{TOT}} = d_B$$

$U_{TOT} = \psi_n - \psi_p$

$U_{TOT} = U_k - U_{AK}$

→ kada je pn spoj u ravnoteži: $U_{TOT} = U_k$

—||— nije u ravnoteži: $U_{TOT} = U_k - U_{AK}$

Max el. polje: $F_{max} = -\frac{2U_{TOT}}{d_B}$

Primjer 3.2) $N_A = 10^{17}\,cm^{-3}$ na p strani $T = 300K$

$N_D = 10^{15}\,cm^{-3}$ na n strani

U_{AK} ↓

$U_1 = 0V$

$U_2 = 0{,}5V$

$U_3 = -5V$

$d_B = ?$ $F_{max} = ?$

$$d_B = \sqrt{\frac{2\varepsilon}{q}\left(\frac{1}{N_A} + \frac{1}{N_D}\right)(U_k - U_{AK})}$$

$\varepsilon = \varepsilon_0 \cdot \varepsilon_{r,Si}$

$\varepsilon_0 = 8{,}854 \times 10^{-14}\,\frac{F}{cm}$

$\varepsilon_{r,Si} = 11{,}7$

$$d_B = \sqrt{\frac{2 \cdot 8{,}854\times10^{-14} \cdot 11{,}7}{1{,}602\times10^{-19}}\left(\frac{1}{10^{17}} + \frac{1}{10^{15}}\right)(U_k - U_{AK})} \quad (1)$$

$$U_k = U_T \ln\left(\frac{N_{AP}\,P_{OP}}{n_i^2}\right) = U_T \ln\left(\frac{N_D \cdot N_A}{(n_i)^2}\right) = 0{,}695\,V \quad (2)$$

$$d_{Bp} = d_B \frac{N_A}{N_D + N_A} \quad (3) \qquad d_{Bn} = d_B \frac{N_A}{N_D + N_A} \quad (4) \qquad F_{max} = -\frac{2(U_k - U_{AK})}{d_B} \quad (5)$$

$U_{AK} = U_1 = 0V$ → $d_{B_1} = 0{,}953\,\mu m$ ($d_B \sim \sqrt{U_{TOT}}$)	jači dop. strana: $d_{Bp_1} = 9{,}44\times10^{-3}\,\mu m$	dominantno se širi na slabije dop. str.: $d_{Bn_1} = 0{,}944\,\mu m$	$F_{max_1} = -11{,}6k\,\frac{V}{cm}$
$U_{AK} = U_2 = 0{,}5V$ → $d_{B_2} = 0{,}505\,\mu m$ smanjenje U_{TOT} → smanjenje osiromaš. područja	$d_{Bp_2} = 5\times10^{-3}\,\mu m$	$d_{Bn_2} = 0{,}5\,\mu m$	$U_{TOT}\downarrow \rightarrow F_{max}\downarrow$ $F_{max_2} = -7{,}72k\,\frac{V}{cm}$ $d_B \sim U_{TOT}$ $F_{max} \sim \sqrt{U_{TOT}}$
$U_{AK} = U_3 = -5V$ reverzni napon → $d_{B_3} = 2{,}73\,\mu m$	$d_{Bp_3} = 0{,}027\,\mu m$	$d_{Bn_3} = 2{,}7\,\mu m$	$F_{max_3} = -41{,}7k\,\frac{V}{cm}$

U_{TOT} raste → $d_B\uparrow$