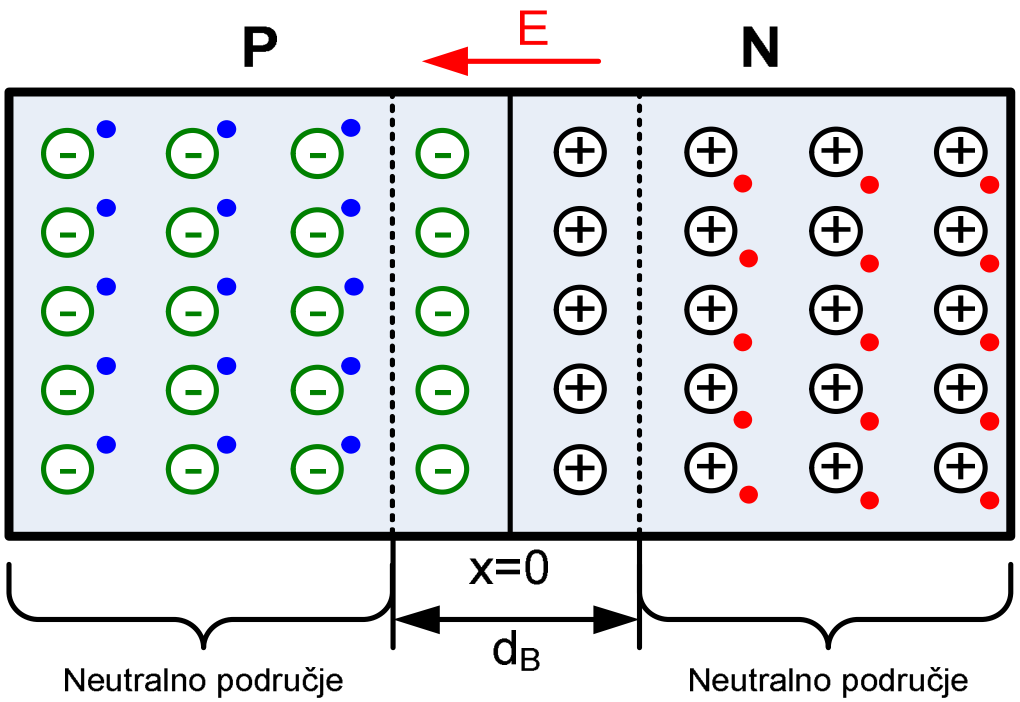
pn spoj

Elektronika – 3. predavanje



• elektroni

• šupljine

⊖ akceptori

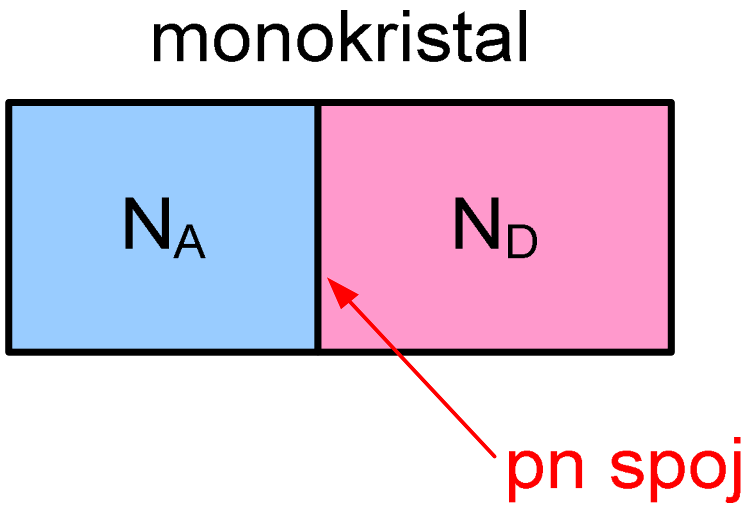
⊕ donori

E - električno polje

d_B - osiromašeno područje

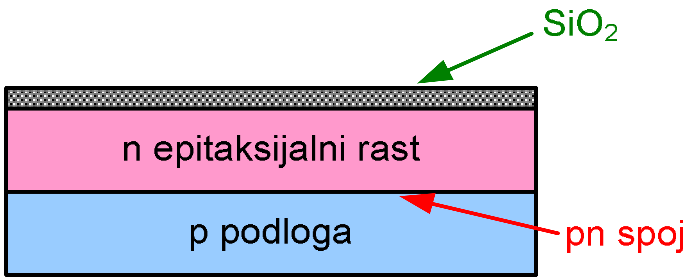
pn spoj

- Prikaz pn spoja

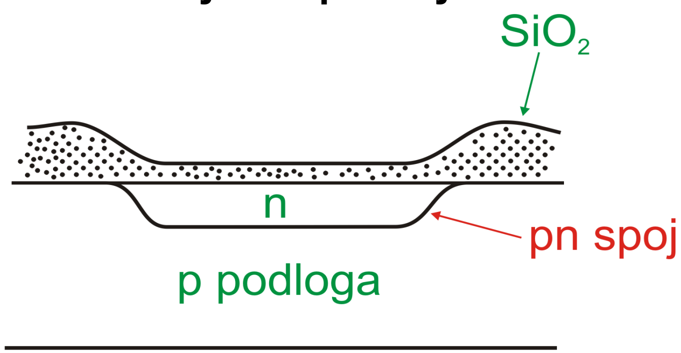


- Tehnološki postupci:
  - Epitaksijalni rast
  - Difuzija primjesa
  - Ionska implantacija

- pn-spoj dobiven epitaksijalnim rastom n-tipa na podlozi p-tipa:



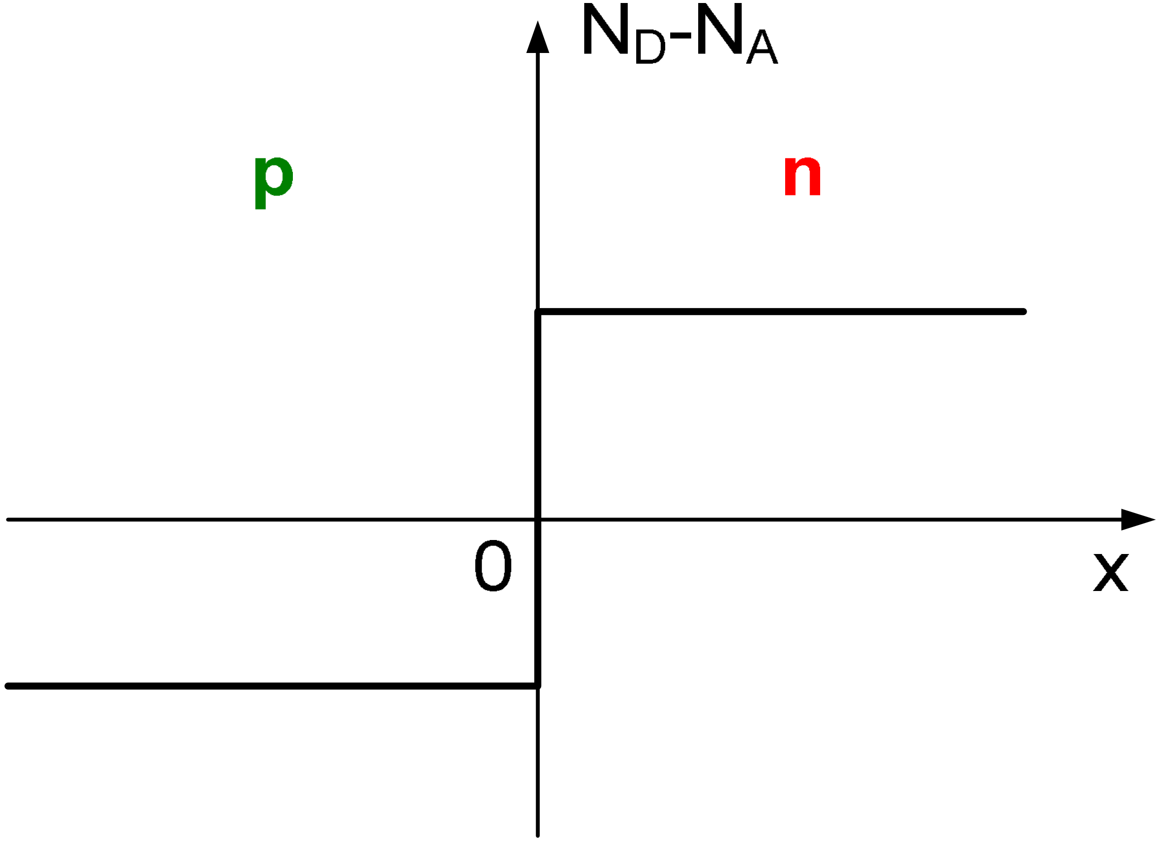
- pn-spoj dobiven difuzijom primjesa:



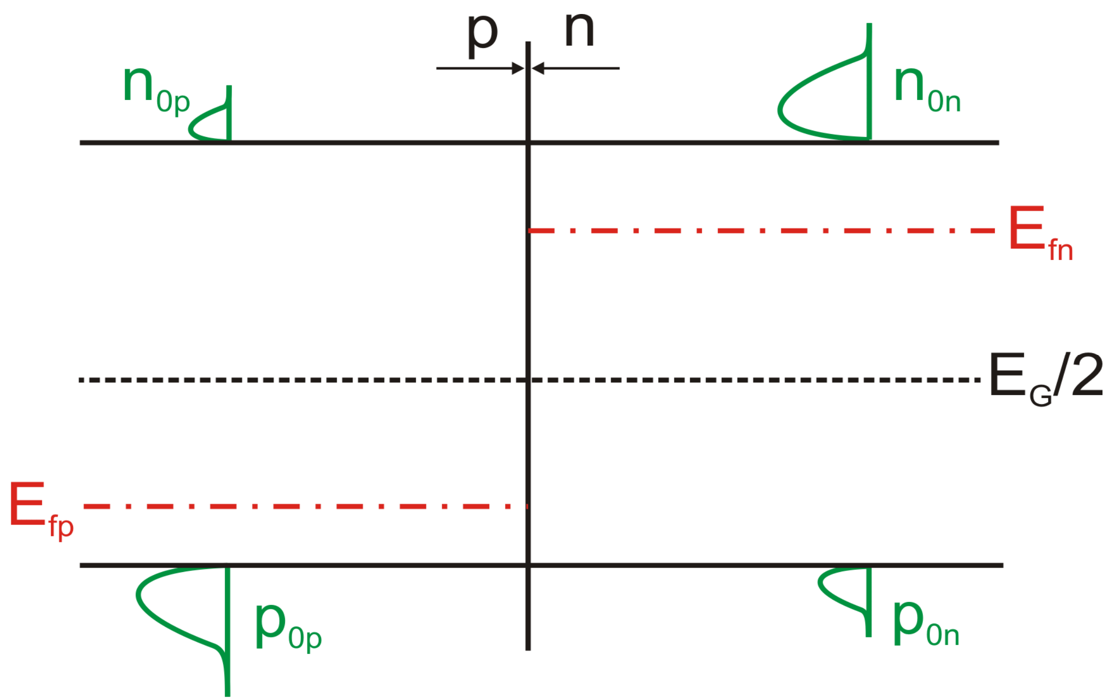
Difuzija primjesa se obavlja na visokoj temperaturi u difuzijskim pećima.

Ionska implantacija je niskotemperaturan tehnološki postupak koji se obavlja uz potencijalnu razliku (~100 kV) pri čemu je omogućeno prodiranje iona kroz površinu čvrstog tijela.

Skokoviti pn prijelaz



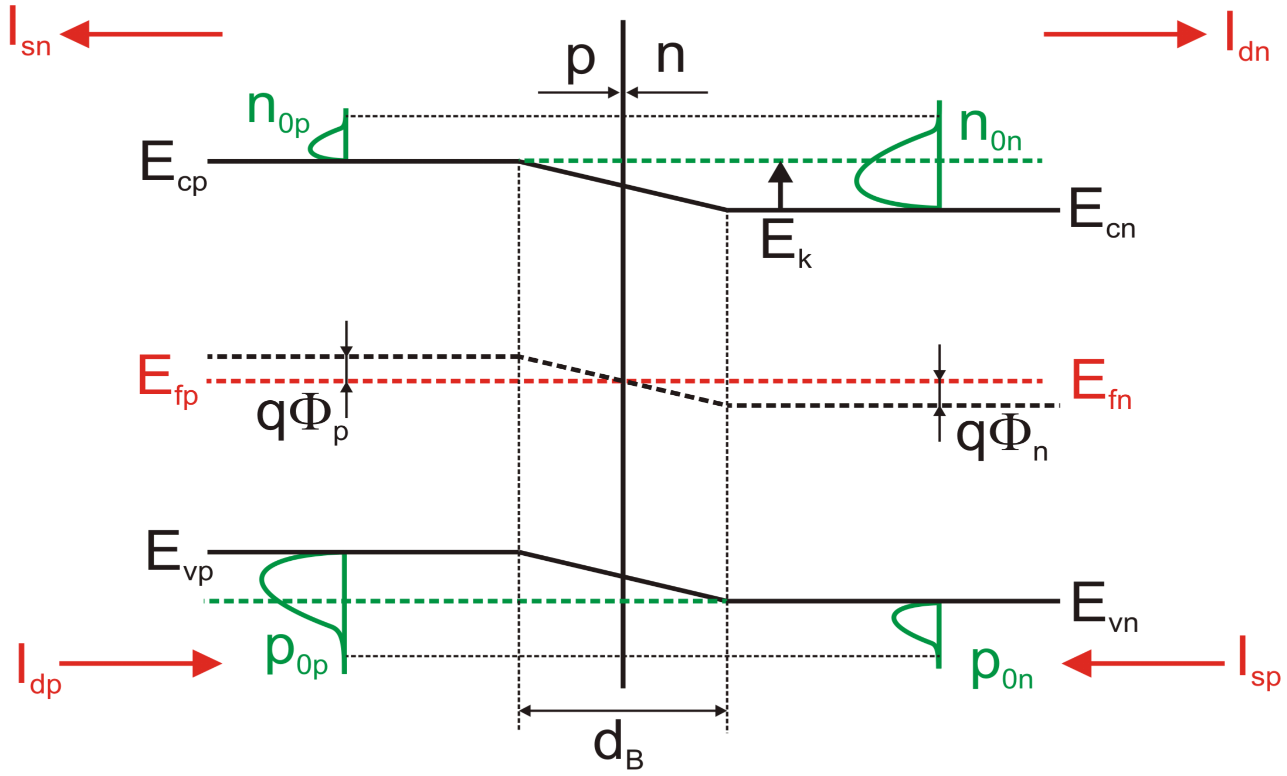
- Zamišljeno neravnotežno stanje pn prijelaza



Ravnotežne koncentracije nosilaca:

- na p strani: n_{0p} (manjinska koncentracija) i p_{0p} (većinska koncentracija)
- na n strani: n_{0n} (većinska koncentracija) i p_{0n} (manjinska koncentracija)

- pn-spoj u ravnoteži:



$$I_{Dn} + I_{Sn} = 0$$

$$I_{Dp} + I_{Sp} = 0$$

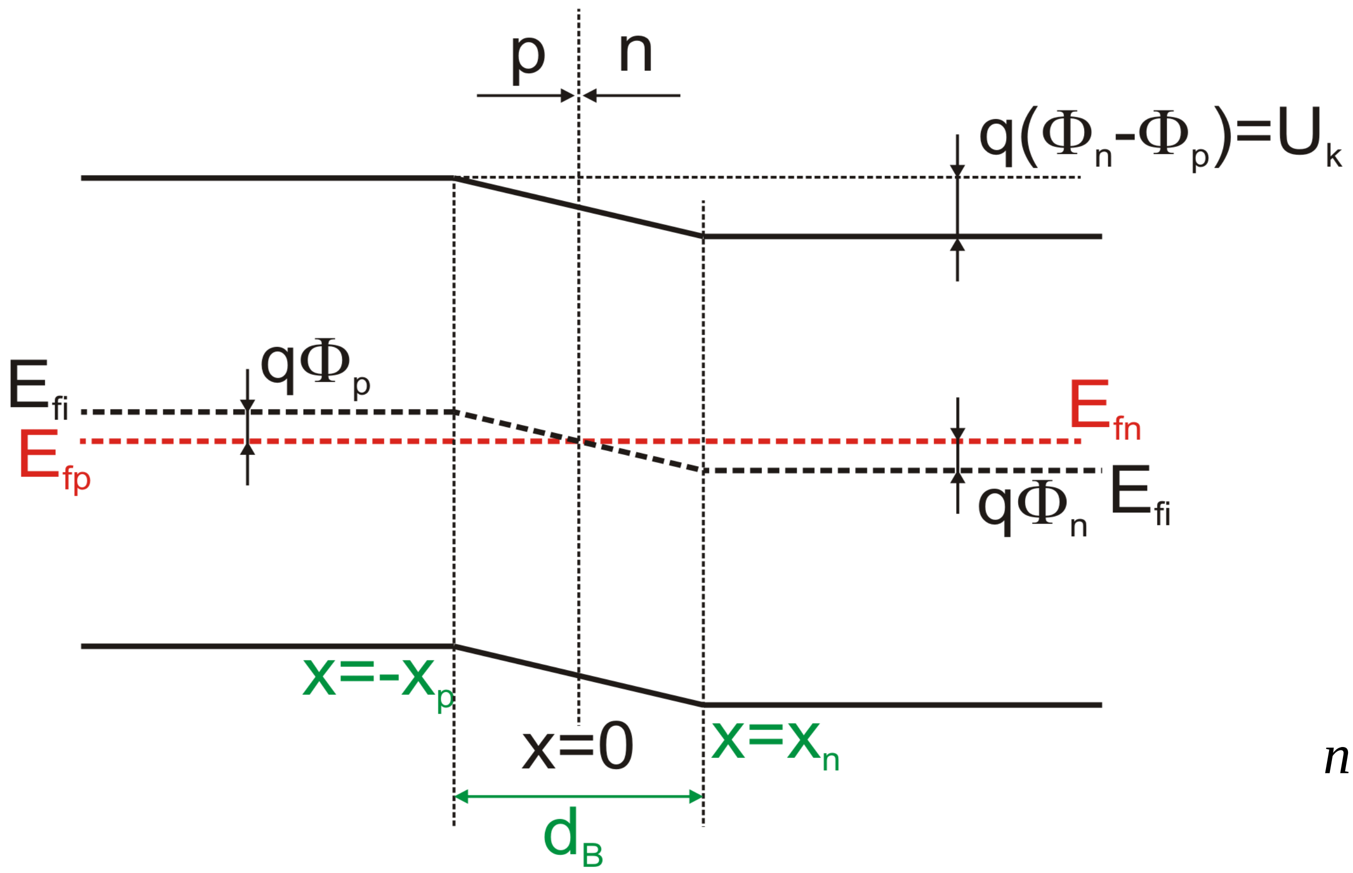
Potencijalna energija na barijeri: $E_k = q \cdot U_k = q \cdot \Phi_n - q \cdot \Phi_p$

Φ – potencijal

d_B – širina osiromašenog područja

Katedra za sunčane ćelije i fotonaponske sustave

Kontaktni potencijal



$$E_k = -q \cdot U_k$$

$$0 = qn_0\mu_n E + qD_n \frac{dn_0}{dx}$$

$$-E = \frac{D_n}{n_0\mu_n} \cdot \frac{dn_0}{dx}$$

$$-E = \frac{d\Phi}{dx} = \frac{k \cdot T}{q \cdot n_0} \cdot \frac{dn_0}{dx}$$

$$\Phi(x_n) - \Phi(-x_p) = \frac{k \cdot T}{q} \ln\left(\frac{n_0(x_n)}{n_0(-x_p)}\right)$$

$$n_0(x_n) \approx N_D \qquad n_0(-x_p) \approx \frac{n_i^2}{N_A}$$

$$U_k = \frac{k \cdot T}{q} \ln\left(\frac{N_A \cdot N_D}{n_i^2}\right)$$

Širina osiromašenog sloja

- Poisson-ova jednadžba

$$-\frac{d^2\Phi}{dx^2}=\frac{\rho(x)}{\varepsilon}$$

ρ(x) – gustoća naboja

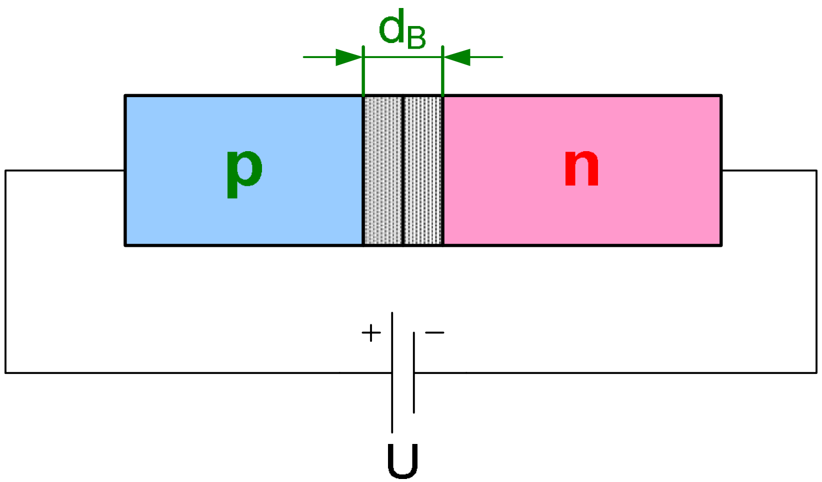
ε – permitivnost (dielektrička konstanta)

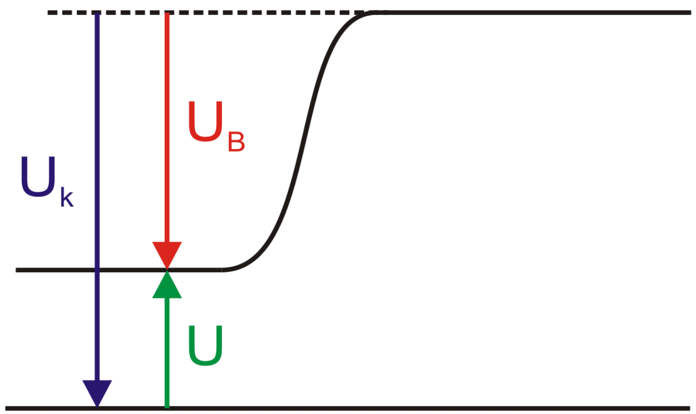
$$x_n=\sqrt{\frac{2\varepsilon U_k}{q}\cdot\frac{N_A}{N_D\cdot(N_A+N_D)}} \qquad x_p=\sqrt{\frac{2\varepsilon U_k}{q}\cdot\frac{N_D}{N_A\cdot(N_A+N_D)}}$$

$$d_B=x_n-(-x_p)=\sqrt{\frac{2\varepsilon U_k}{q}\cdot\frac{(N_A+N_D)}{N_A\cdot N_D}} \qquad N_D\cdot x_n=N_A\cdot x_p$$

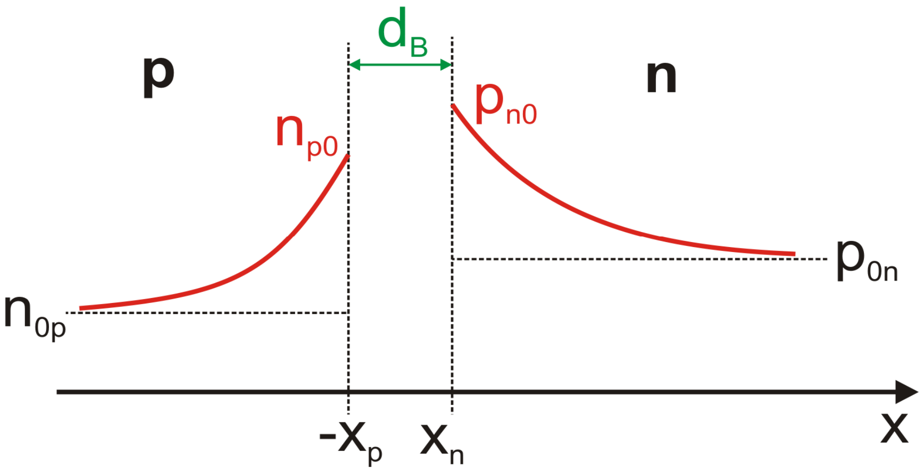
pn spoj s priključenim naponom

- **Propusna polarizacija**



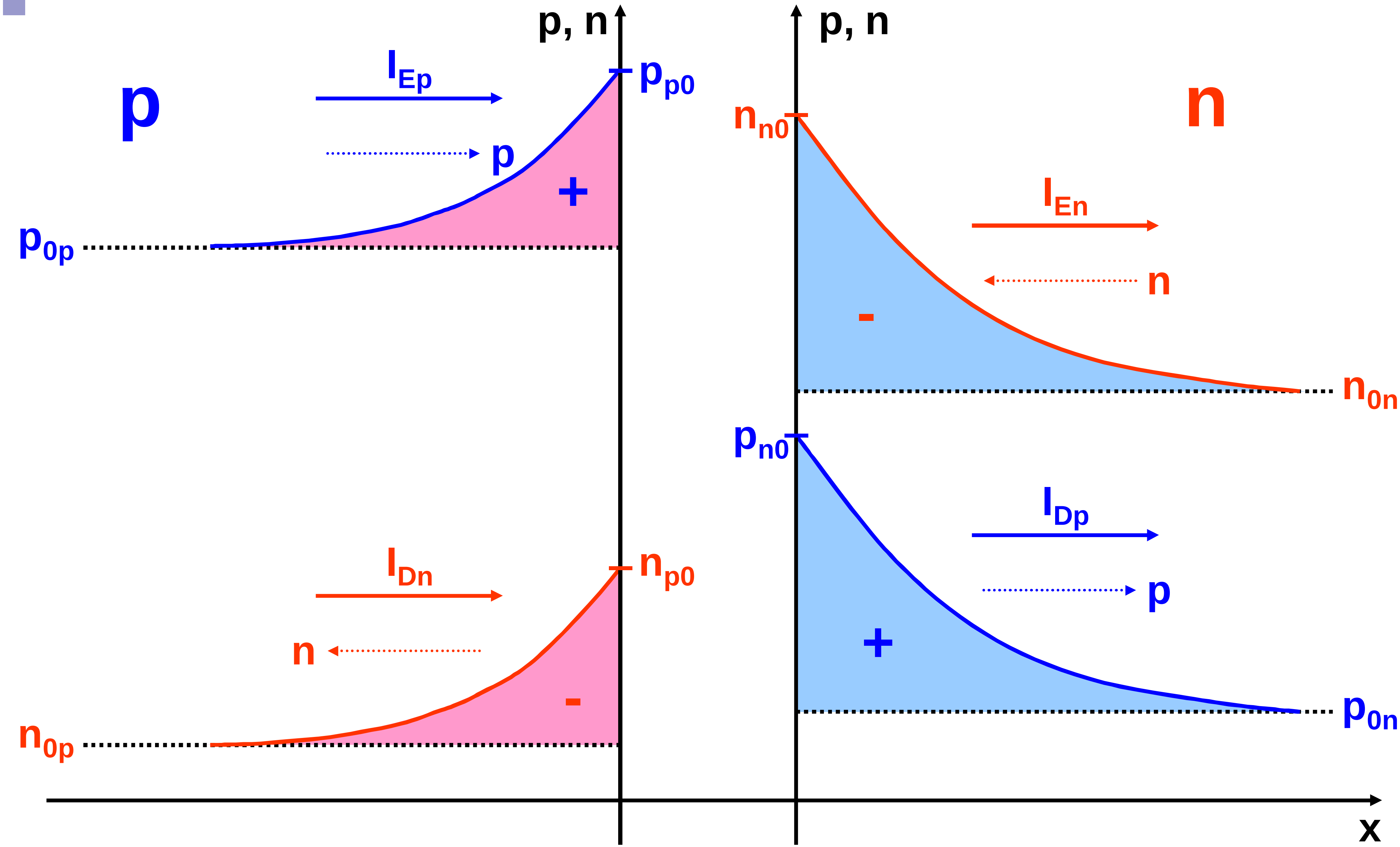


$$U_B = U_k - U$$



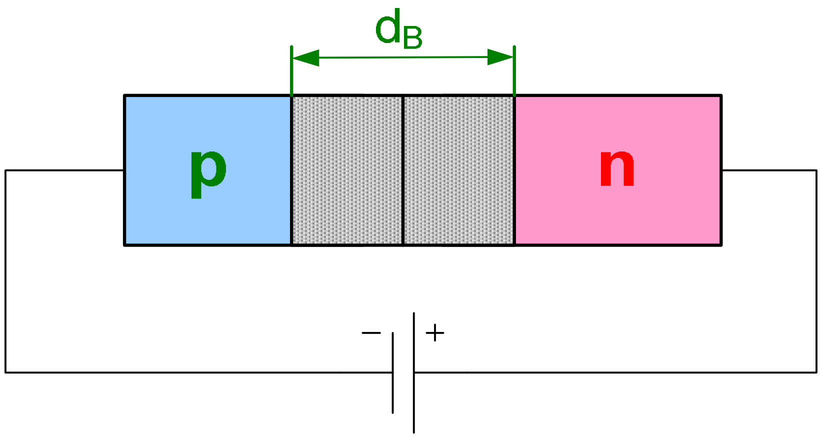
$$n_{p0} = n_{0p} \exp\left(\frac{q}{kT} \cdot U\right)$$

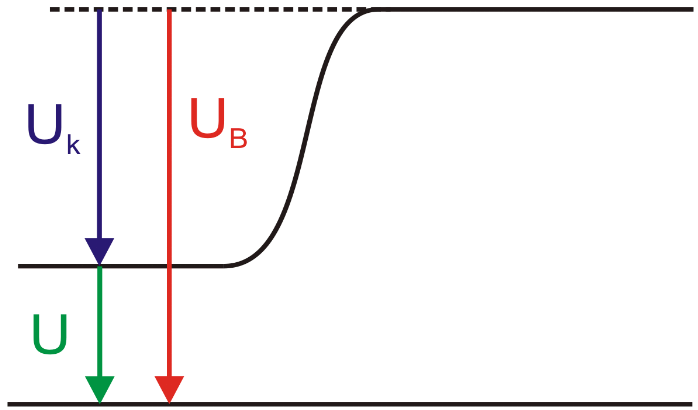
$$p_{n0} = p_{0n} \exp\left(\frac{q}{kT} \cdot U\right)$$



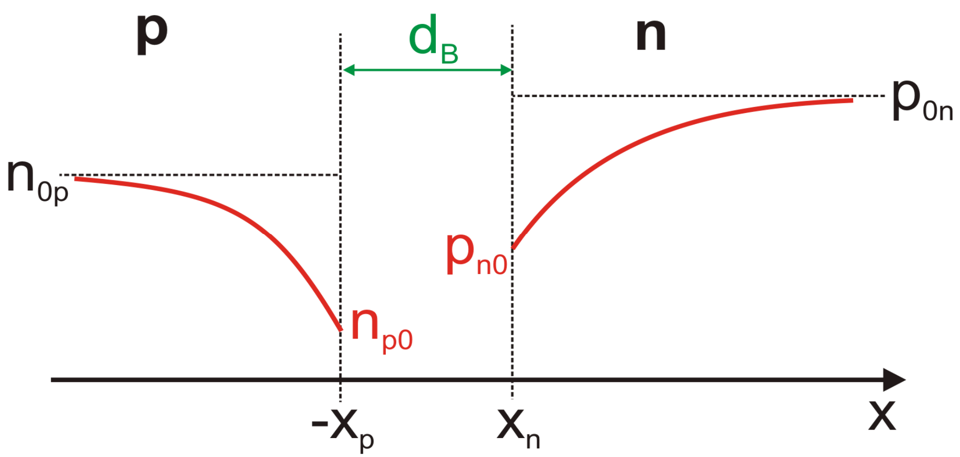
p, n
p
I_{Ep}
p
p_{p0}
+
p_{0p}
I_{Dn}
n
n_{p0}
-
n_{0p}
p, n
n
n_{n0}
I_{En}
n
-
n_{0n}
p_{n0}
I_{Dp}
p
+
p_{0n}
x

Nepropusna polarizacija



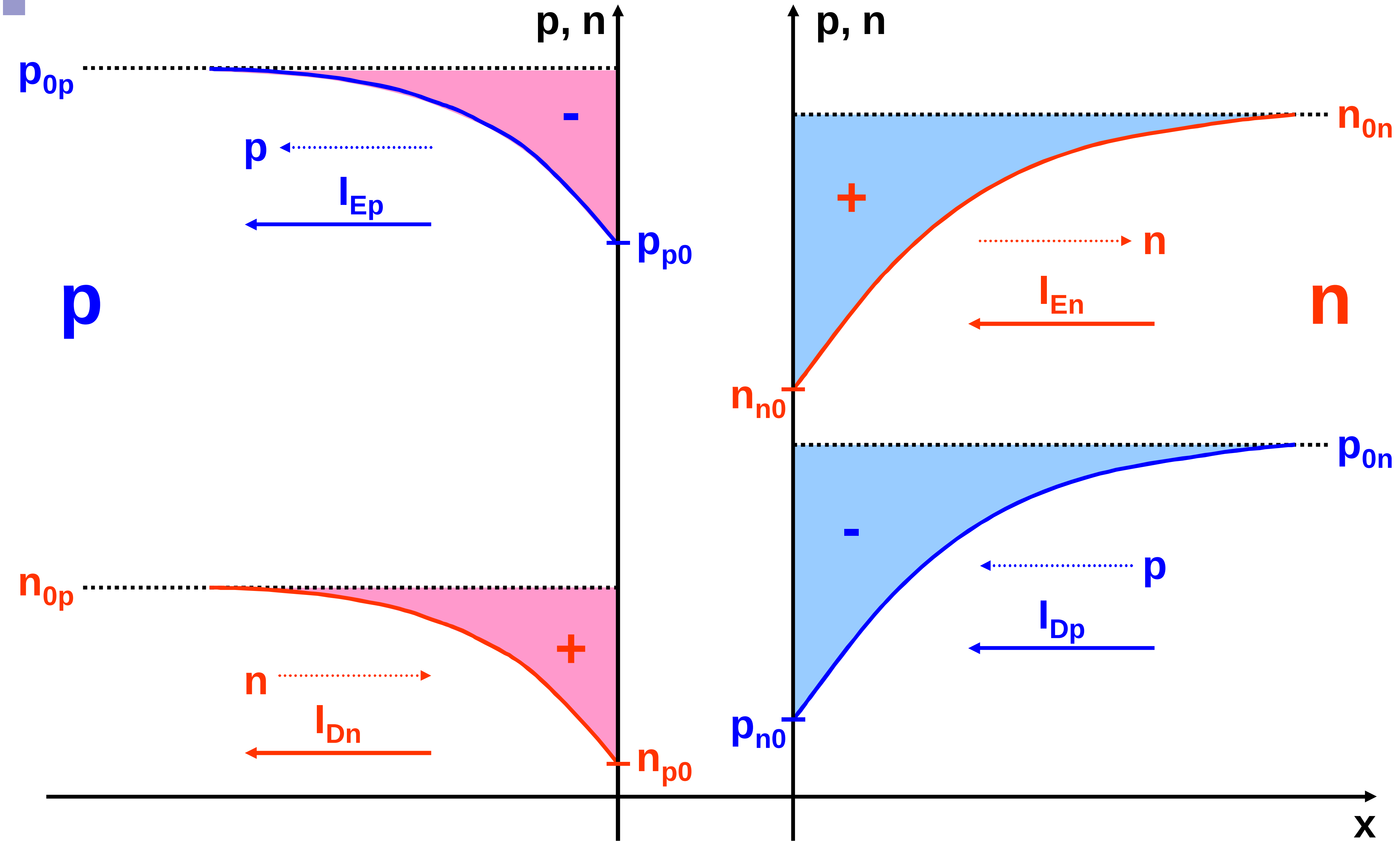


$$U_B = U_k + U$$



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

$$p_{n0} = p_{0n} \exp\left(\frac{q}{kT} \cdot (-U)\right)$$


p, n
p, n
p_{0p}
-
p
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n_{0n}
+
n
I_{En}
n
n_{n0}
p_{0n}
-
p
I_{Dp}
p_{n0}
x

Kapacitet osiromašenog sloja

- (Tranzitni kapacitet, barijerni kapacitet,…)
- Kapacitet po jedinici površine definiran je izrazom:

$$C_T = \frac{dQ}{dU}$$

Q – naboj po jedinici površine

U – narinuti napon

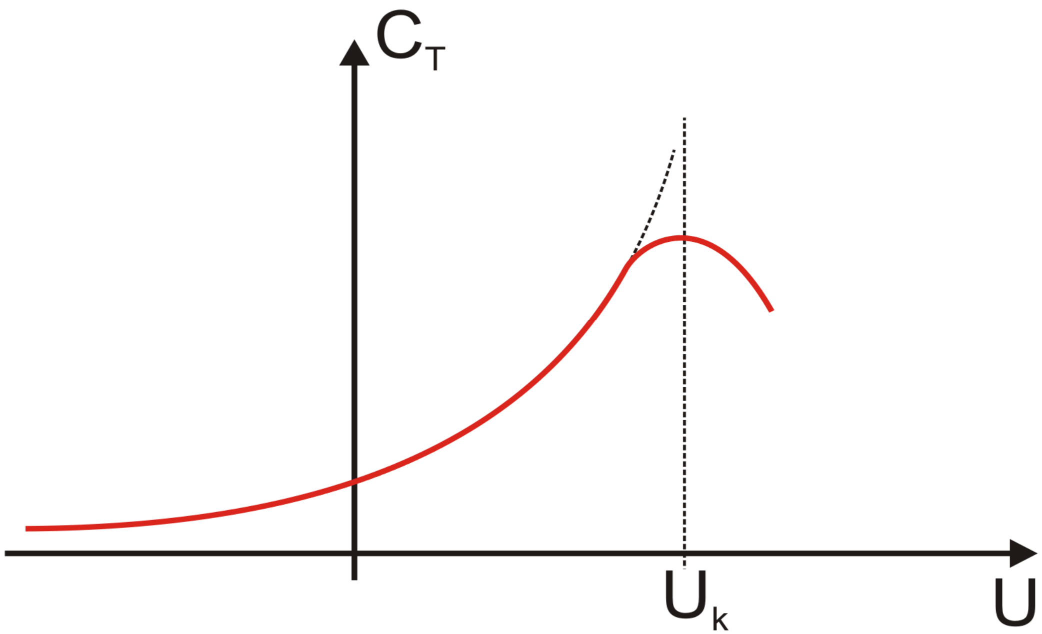
- Na n-strani Q iznosi:

$$Q = q \cdot N_D \cdot x_n$$

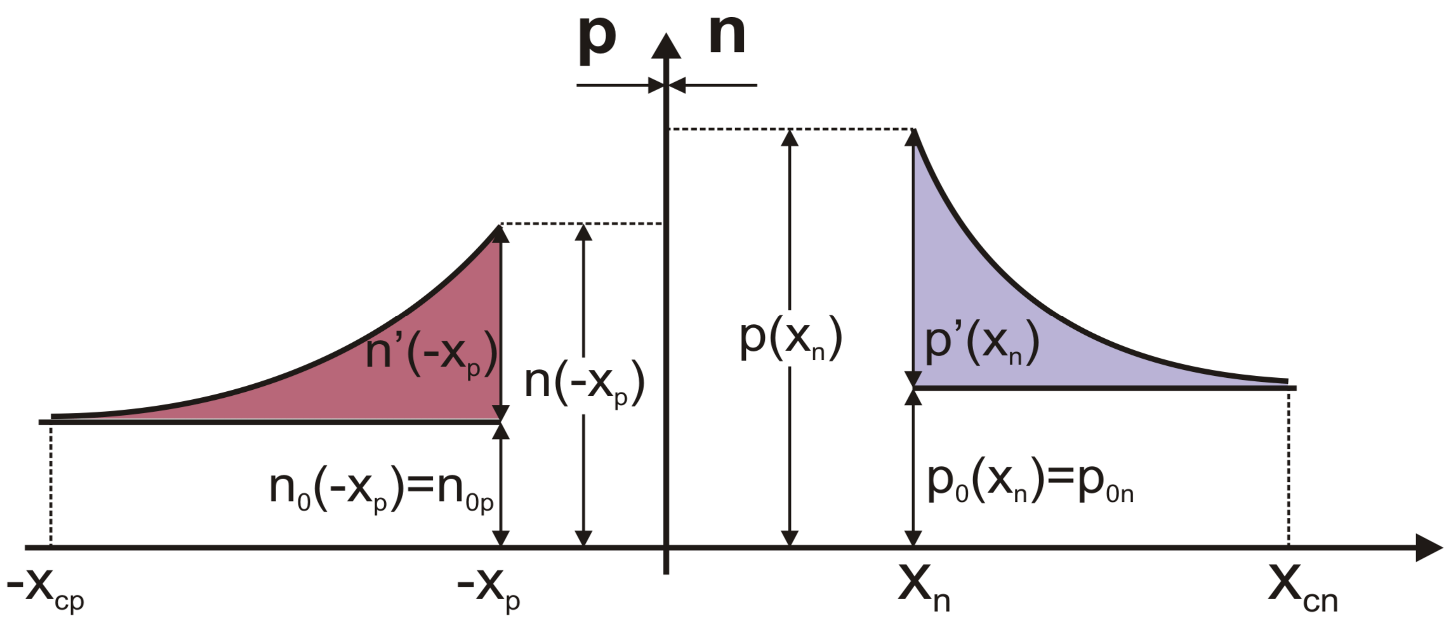
$$x_n = \sqrt{\frac{2 \cdot \varepsilon \cdot (U_k - U)}{q} \cdot \frac{N_A}{N_D \cdot (N_A + N_D)}}$$

$$Q = q \cdot N_D \cdot \sqrt{\frac{2 \cdot \varepsilon}{q} \cdot \frac{N_A}{N_D \cdot (N_A + N_D)} \cdot (U_k - U)}$$

$$C_T = \sqrt{\frac{\varepsilon \cdot q \cdot N_A \cdot N_D}{2 \cdot (U_k - U) \cdot (N_A + N_D)}}$$



Odnos struje i napona pn spoja

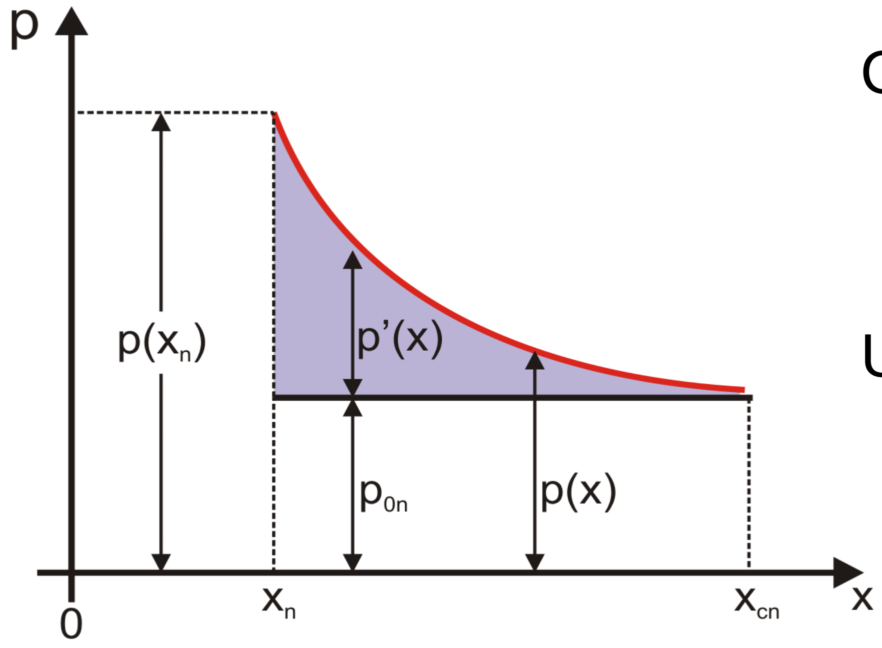


Definicija rubnih vrijednosti gustoće nosilaca naboja:

$$n'(-x_p) = n(-x_p) - n_0(-x_p) = n_0(-x_p)\left[\exp\left(\frac{qU}{kT}\right) - 1\right]$$

$$p'(x_n) = p(x_n) - p_0(x_n) = p_0(x_n)\left[\exp\left(\frac{qU}{kT}\right) - 1\right]$$

Gustoća šupljina na n strani pn spoja



Opće rješenje jednadžbe kontinuiteta glasi:

$$p'(x) = A \cdot \exp\left(\frac{x}{L_p}\right) + B \cdot \exp\left(-\frac{x}{L_p}\right)$$

Uvrštavanjem rubnih uvjeta dobiva se:

$$p'(x_n) = A \cdot \exp\left(\frac{x_n}{L_p}\right) + B \cdot \exp\left(-\frac{x_n}{L_p}\right)$$

$$0 = A \cdot \exp\left(\frac{x_{cn}}{L_p}\right) + B \cdot \exp\left(-\frac{x_{cn}}{L_p}\right)$$

$$p'(x_n) = \frac{p_0(x_n) sh\left(\frac{x_{cn} - x}{L_p}\right)}{sh\left(\frac{x_{cn} - x_n}{L_p}\right)} \cdot \exp\left[\left(\frac{q \cdot U}{k \cdot T}\right) - 1\right]$$

- Gustoća struje šupljina na n strani određena je njenom difuzijskom komponentom:

$$J_p = -q \cdot D_p \frac{dp(x)}{dx} = -q \cdot D_p \frac{dp'(x)}{dx}$$

$$\frac{dp(x)}{dx} = \frac{dp'(x)}{dx}$$

$$J_p(x) = \frac{q \cdot p_0(x) \cdot D_p \cdot ch\left(\frac{x_{cn} - x}{L_p}\right)}{L_p \cdot sh\left(\frac{x_{cn} - x_n}{L_p}\right)} \cdot \left[\exp\left(\frac{q \cdot U}{k \cdot T}\right) - 1\right]$$

- U točki $x=x_n$ gustoća struje iznosi:

$$J_p(x_n)=\frac{q\cdot p_0(x)\cdot D_p}{L_p\cdot th\left(\frac{x_{cn}-x_n}{L_p}\right)}\cdot\left[\exp\left(\frac{q\cdot U}{k\cdot T}\right)-1\right]$$

- Gustoća difuzijske struje elektrona u točki $x=-x_p$ iznosi:

$$J_n(-x_p)=\frac{q\cdot n_0(-x_p)\cdot D_n}{L_n\cdot th\left(\frac{x_{cp}-x_p}{L_n}\right)}\cdot\left[\exp\left(\frac{q\cdot U}{k\cdot T}\right)-1\right]$$

- Ukupna gustoća struje:

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

- Nakon uvođenja supstitucija:

$$\left.\begin{aligned} n_0(-x_p) &= \frac{n_i^2}{N_A} \\ p_0(x_n) &= \frac{n_i^2}{N_D} \end{aligned}\right\} \quad \text{Zakon termodinamičke ravnoteže}$$

$$x_{cp} - x_p = w_p \qquad \text{Efektivna širina p-strane}$$

$$x_{cn} - x_n = w_n \qquad \text{Efektivna širina n-strane}$$

dobiva se izraz:

$$J_n = q \cdot n_i^2 \cdot \left[\frac{D_n}{L_n \cdot N_A \cdot th\left(\frac{w_p}{L_n}\right)} + \frac{D_p}{L_p \cdot N_D \cdot th\left(\frac{w_n}{L_p}\right)} \right] \cdot \left[\exp\left(\frac{q \cdot U}{k \cdot T}\right) - 1 \right]$$

ili u obliku poznatom kao Shockleyjeva jednadžba:

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

gdje je: $I = J \cdot S$

$$U_T = \frac{k \cdot T}{q}$$

$$I_S = q \cdot n_i^2 \cdot S \cdot \left[\frac{D_n}{L_n \cdot N_A \cdot th\left(\frac{w_p}{L_n} \right)} + \frac{D_p}{L_p \cdot N_D \cdot th\left(\frac{w_n}{L_p} \right)} \right]$$

I_S – reverzna struja zasićenja (struja nepropusne polarizacije, struja manjinskih nosilaca)

- Ako su širine neutralnih područja w_p i w_n p i n strane velike u odnosu prema difuzijskim dužinama L_n i L_p (široka n i široka p strana), funkcija tangens hiperbolni može se aproksimirati jedinicom:

$$th\left(\frac{w_p}{L_n}\right) \approx 1 \qquad th\left(\frac{w_n}{L_p}\right) \approx 1$$

a izraz za I_S poprima jednostavniji oblik:

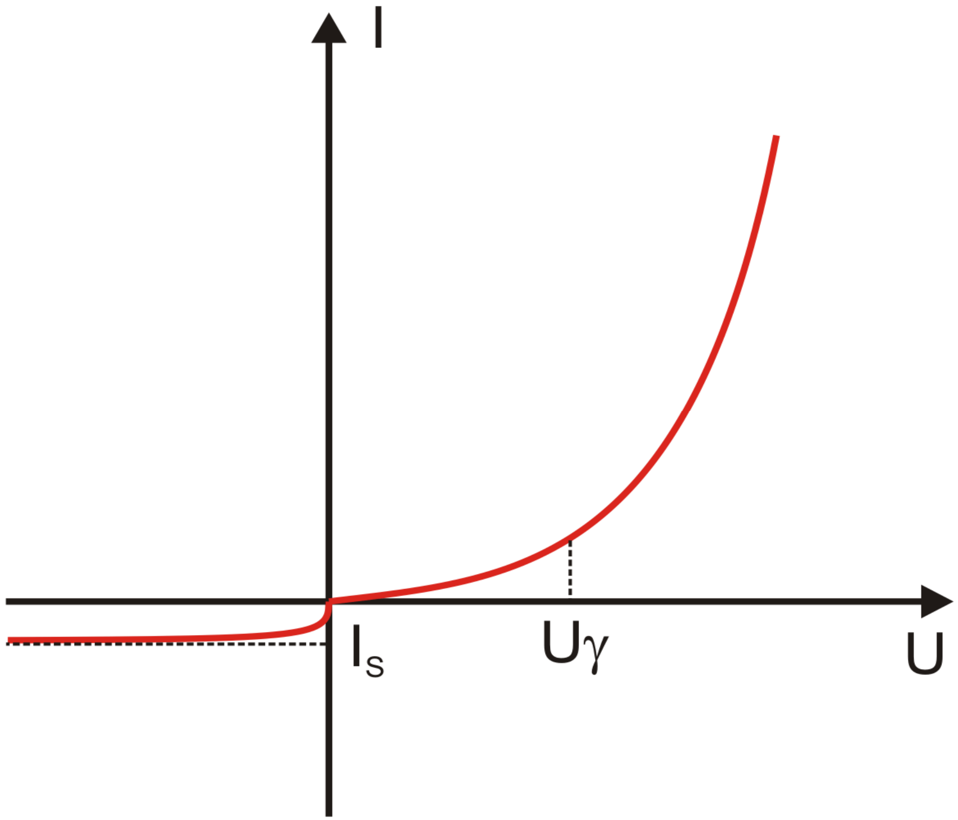
$$I_S = q \cdot n_i^2 \cdot S \cdot \left[\frac{D_n}{L_n \cdot N_A} + \frac{D_p}{L_p \cdot N_D}\right]$$

- Za $w_p << L_n$ i $w_n << L_p$ (uska n i uska p strana) funkcija tangens hiperbolni aproksimira se njenim argumentom:

$$th\left(\frac{w_p}{L_n}\right) \approx \frac{w_p}{L_n} \qquad th\left(\frac{w_n}{L_p}\right) \approx \frac{w_n}{L_p}$$

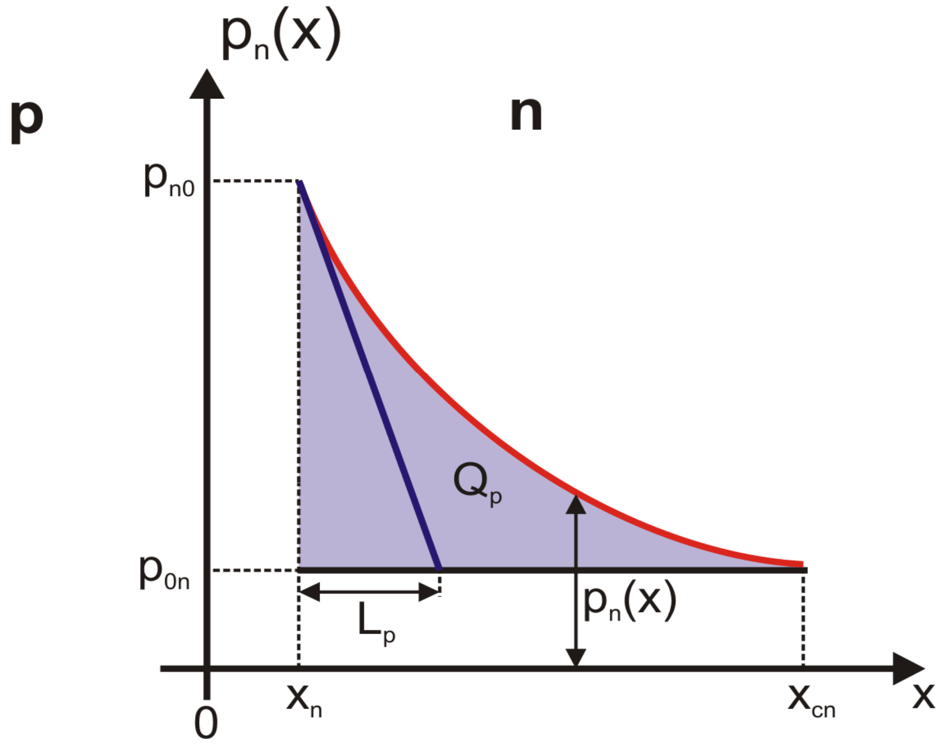
$$I_S = q \cdot n_i^2 \cdot S \cdot \left[\frac{D_n}{w_p \cdot N_A} + \frac{D_p}{w_n \cdot N_D}\right]$$

Strujno-naponska karakteristika



$$I = I_S \left[\exp\left(\frac{U}{m \cdot U_T} \right) - 1 \right]$$

Akumulirani naboj manjinskih nosilaca



$$p_n(x) = p_{0n} + (p_{n0} - p_{0n}) \cdot \exp\left(-\frac{x - x_n}{L_p}\right)$$

$$Q_p = q \cdot S \cdot \int_{x_n}^{x_{cn}} [p_n(x) - p_{0n}]dx$$

$$Q_p = q \cdot S \cdot (p_{n0} - p_{0n}) \cdot \int_{x_n}^{x_{cn}} \exp\left(-\frac{x - x_n}{L_p}\right)dx$$

$$Q_p = q \cdot S \cdot (p_{n0} - p_{0n}) \cdot (-L_p) \cdot \left[\exp\left(-\frac{x_{cn} - x_n}{L_p}\right) - \boxed{\exp\left(-\frac{x_n - x_n}{L_p}\right)}\right] \Rightarrow 1$$

- Za široku n-stranu je: x_{cn}-x_n=w_n>>L_p, stoga je: $\exp\left(-\frac{x_{cn}-x_n}{L_p}\right)\approx 0$

$$Q_p = q\cdot S\cdot\left(p_{n0}-p_{0n}\right)\cdot L_p$$

- Difuzijska struja šupljina:

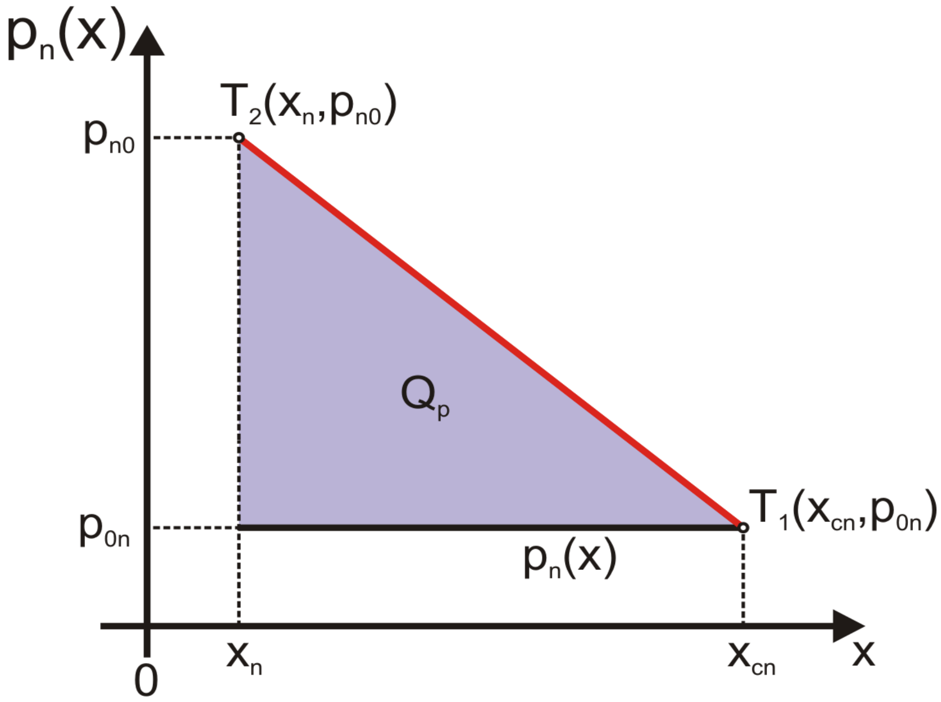
$$I_{dp}\left(x_n\right) = -q\cdot S\cdot D_p\cdot\left.\frac{dp_n(x)}{dx}\right|_{x=x_n}$$

$$I_{dp}\left(x_n\right) = \frac{q\cdot S\cdot D_p}{L_p}\cdot\left(p_{n0}-p_{0n}\right) = \frac{Q_p}{\tau_p}$$

τ_p – vrijeme života šupljina u n-strani

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

Uska n-strana: $x_{cn}-x_n<<L_p$



$$p_n(x)-p_{0n}=\frac{p_{n0}-p_{0n}}{x_{cn}-x_n}(x-x_{cn})$$

$$Q_p=q\cdot S\cdot\int_{x_n}^{x_{cn}}[p_n(x)-p_{0n}]dx$$

$$Q_p=\frac{q\cdot S\cdot w_n}{2}(p_{n0}-p_{0n})$$

Difuzijska struja šupljina: $I_{pd}=-q\cdot S\cdot D_p\dfrac{dp_n(x)}{dx}$ $\quad I_{pd}=q\cdot S\cdot D_p\dfrac{p_{n0}-p_{0n}}{w_n}=\dfrac{Q_p}{t_{pr}}$

gdje je:

t_{pr} – vrijeme proleta šupljine kroz usku n-stranu $\quad t_{pr}=\dfrac{w_n^2}{2\cdot D_p}$

Ovisnost reverzne struje zasićenja o temperaturi

$$I_S = q \cdot S \cdot n_i^2 \cdot \left(\frac{D_p}{L_p \cdot n_{0n}} + \frac{D_n}{L_n \cdot p_{0p}} \right)$$

$$I_S = k' \cdot n_i^2$$

$$\ln I_S = \ln k' + 2 \ln n_i$$

$$\frac{dI_S}{I_S} = 2\frac{dn_i}{n_i} = \left(3 + \frac{E_{G0}}{E_T} \right) \frac{dT}{T}$$

$$n_i = A_1 T^{3/2} \exp\left(-\frac{E_G(T)}{2E_T} \right)$$

$$E_{G0} = E_G(0)$$

$$E_G(T) = a - b \cdot T$$

$$n_i = A_0 T^{3/2} \exp\left(-\frac{E_{G0}}{2kT} \right)$$

$$A_0 = A_1 \exp\left(\frac{b}{2k} \right)$$

$$\ln n_i = \ln A_0 + \frac{3}{2} \ln T - \frac{E_{G0}}{2kT}$$

$$\frac{dn_i}{n_i} = \frac{3}{2}\frac{dT}{T} + \frac{1}{2}\frac{E_{G0}}{kT^2} dT = \frac{1}{2}\left(3 + \frac{E_{G0}}{kT} \right) \frac{dT}{T}$$

Ovisnost struje pn spoja o temperaturi

$$I = I_S\left[\exp\left(\frac{U}{m \cdot U_T}\right) - 1\right]$$

Ako je U >> U_T

$$I = I_S \exp\left(\frac{U}{m \cdot U_T}\right) \approx KT^3 \exp\left(-\frac{E_{G0} - q \cdot U}{m \cdot k \cdot T}\right)$$

$$\frac{dI}{dT} = \left(3 + \frac{E_{G0}}{E_T} - \frac{U}{m \cdot U_T}\right)\frac{I}{T}$$

Ovisnost napona pn spoja o temperaturi

$$U = m\frac{kT}{q}\ln\left(\frac{I}{I_S}\right)$$

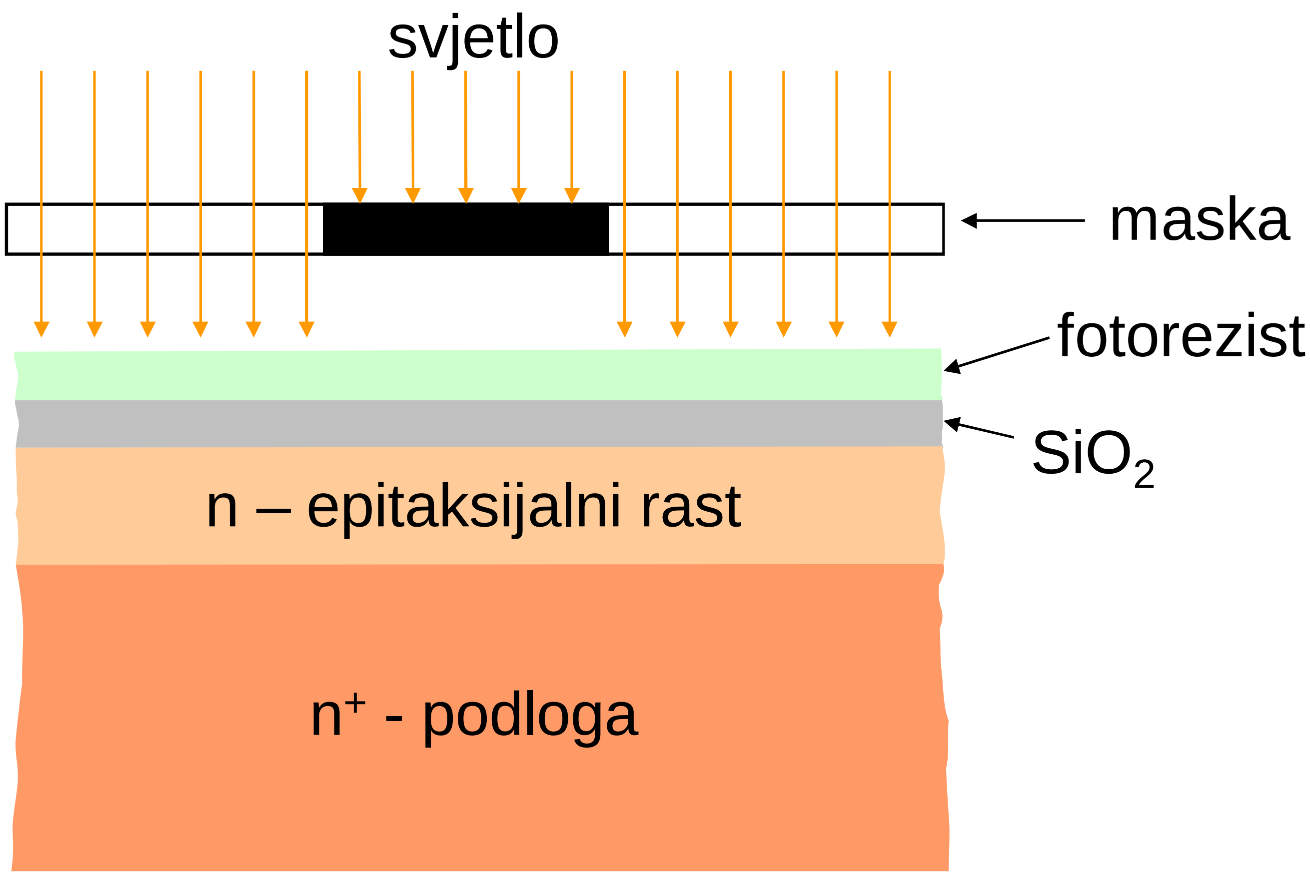
$$\frac{dU}{dt} = \frac{mk}{q}\ln\left(\frac{I}{I_S}\right) + \frac{mkT}{q}\left(-\frac{1}{I_S}\right)\frac{dI_S}{dT}$$

$$\frac{dU}{dt} = -3\left(3 + \frac{E_{G0}}{E_T} - \frac{U}{mU_T}\right)\frac{mU_T}{T}$$

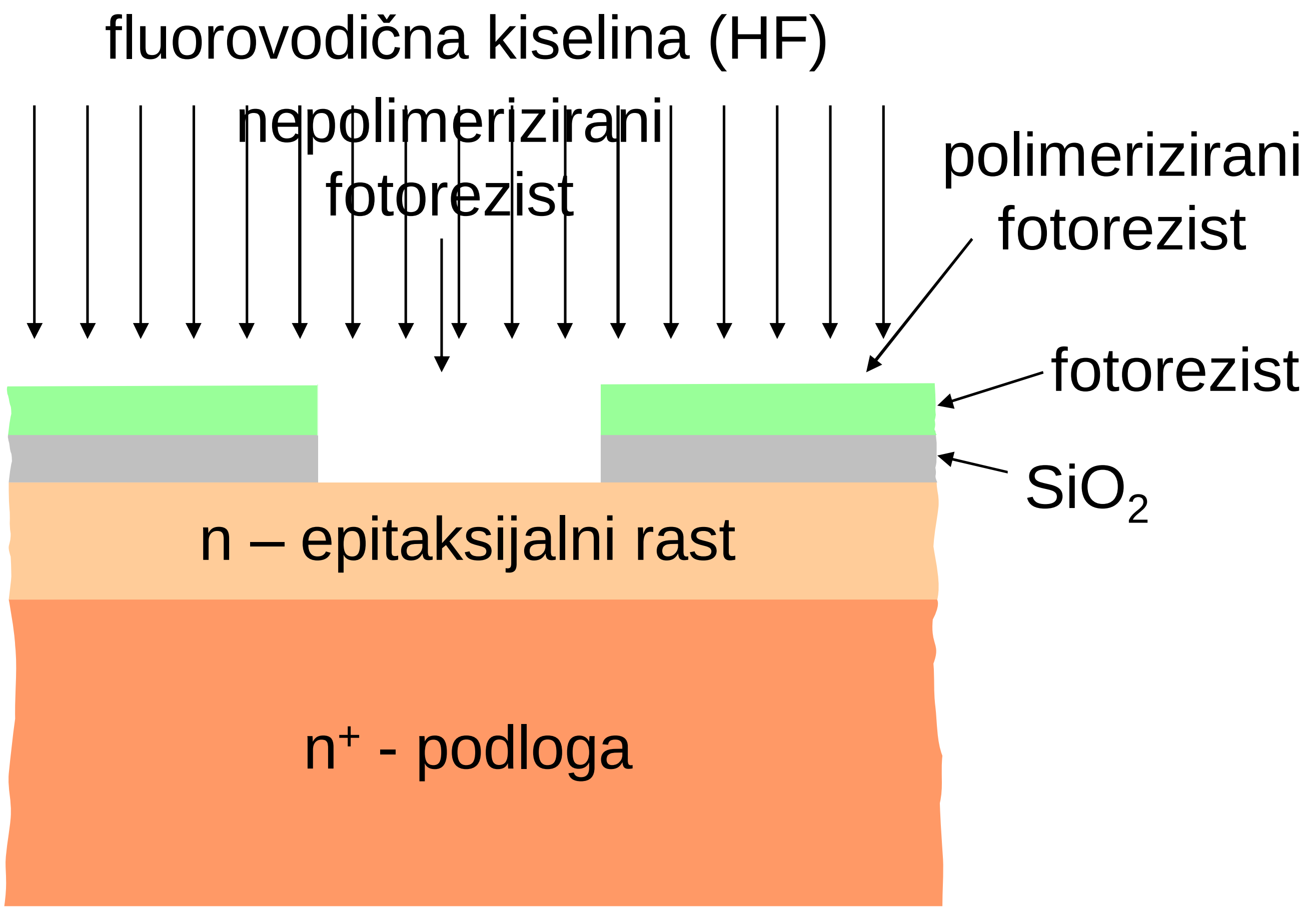
Osnove planarne tehnologije na siliciju

- a) osnovna pločica (n^+ - podloga)
- b) epitaksijalni rast (n – tip)
- c) oksidacija (sloj SiO_2)
- d) fotolitografija (izrada otvora u sloju SiO_2)
- e) difuzija (p – tip)
- f) metalizacija (nanošenje prednjeg i stražnjeg kontakta)

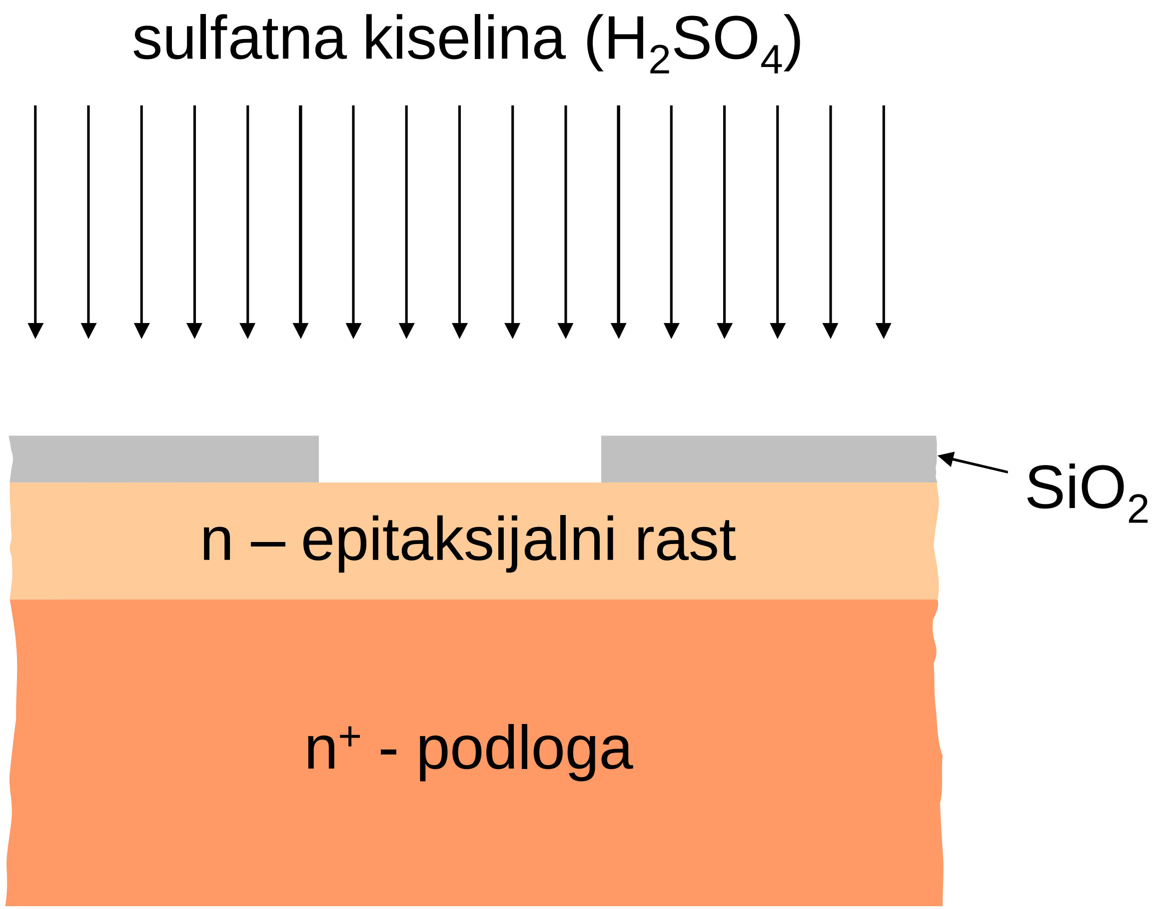
Osnove planarne tehnologije na siliciju



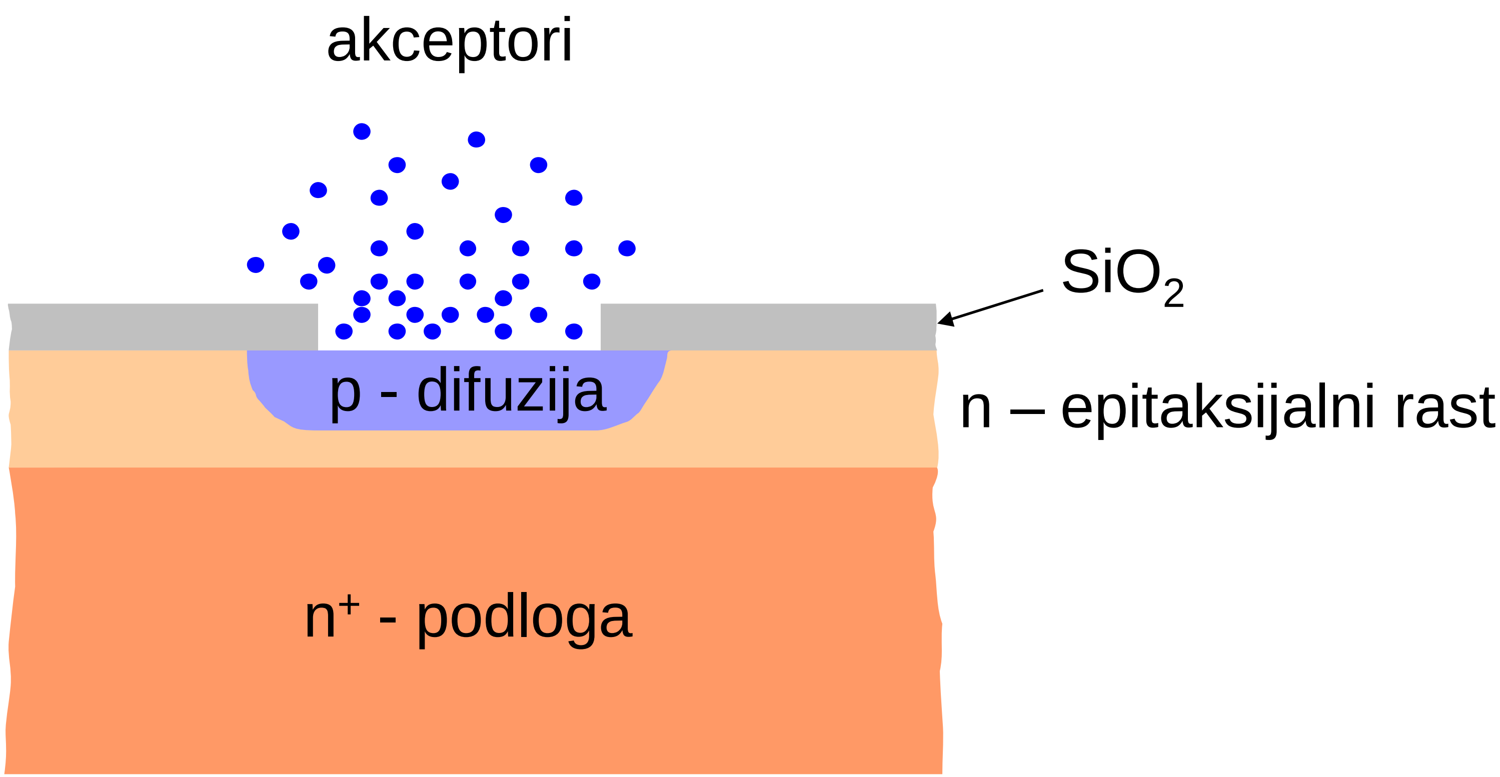
Osnove planarne tehnologije na siliciju



Osnove planarne tehnologije na siliciju



Osnove planarne tehnologije na siliciju



Osnove planarne tehnologije na siliciju