Bipolarni tranzistor

Elektronika – 4. predavanje

William B. Shockley (1910-1989)

- Poznat kao “otac” tranzistora

“It has today occurred to me that an amplifier using semiconductors rather than vacuum tubes is in principle possible.”

Walter Houser Brattain (1902-1987)

- Eksperimentalni fizičar koji je također radio s vakuumskim cijevima.
- Priključio se Shockleyju i Bardeenu u istraživanju poluvodiča.

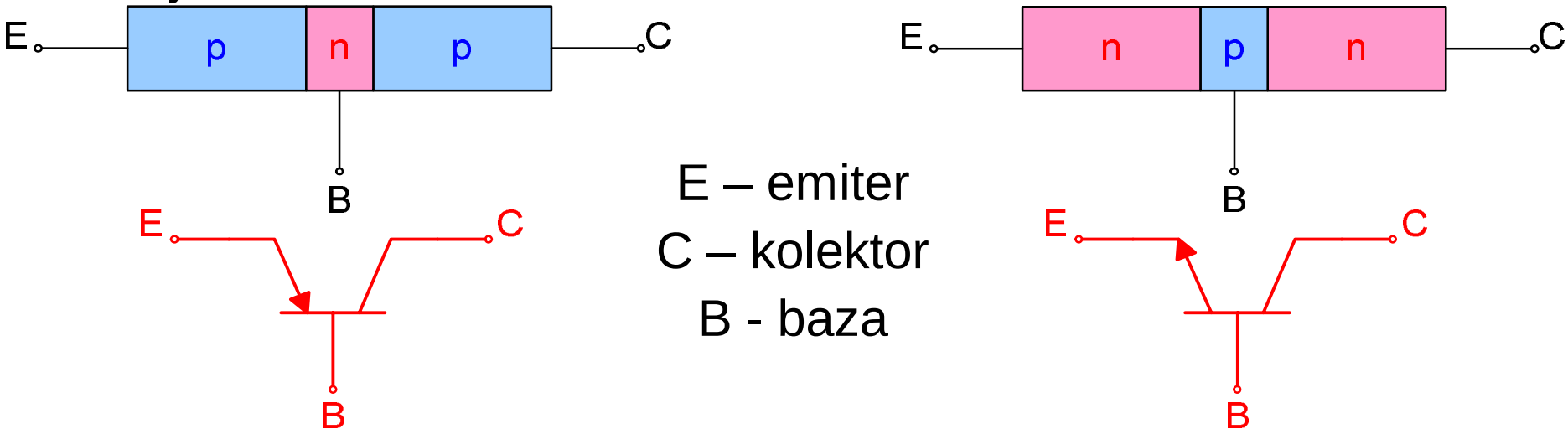
John Bardeen (1908-1991)

- Fizičar, Naval Ordnance Laboratory (1941-1945)
- Teorijski fizičar, Bell Telephone Laboratories (1945-1951)
- Nobelova nagrada za fiziku 1956 i 1972
  - Tranzistor 1956, supervodljivost 1972.

“I knew the transistor was important, but I never foresaw the revolution in electronics it would bring.”

Bipolarni tranzistor

- Naziv tranzistor je nastao kao složenica od dvije engleske riječi: transfer resistor (prenijeti otpor).
- Naziv (pridjev) bipolarni znači da u vođenju sudjeluju oba tipa nosilaca: elektroni i šupljine.
- U stručnoj literaturi u uporabi je skraćenica BJT (bipolar junction transistor): bipolarni spojni tranzistor.
- Ustrojstvo i simbol:

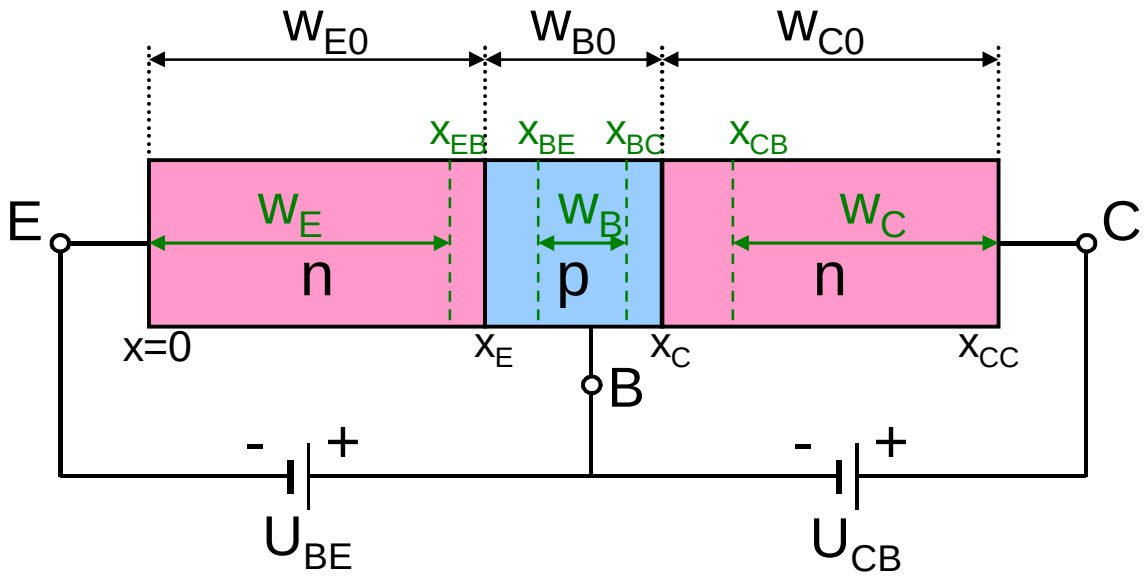


Tranzistorski efekt

- Temelji se na mehanizmu:
  - Injekcije (utiskivanja) nosilaca
  - Tranzita (prijenosa) nosilaca
  - Kolekcije (sakupljanja) nosilaca
- Polarizacija tranzistora i područja rada
  - Spoj emiter-baza je propusno polariziran, a spoj kolektor-baza nepropusno (normalno aktivno područje rada)
  - Spoj emiter-baza i kolektor-baza su propusno polarizirani (područje zasićenja)
  - Spoj emiter-baza i kolektor-baza su nepropusno polarizirani (zaporno područje)
  - Spoj emiter-baza je polariziran nepropusno, a kolektor-baza propusno (inverzno aktivno područje rada)

Normalno polarizirani npn tranzistor

- Definicija područja emitera, baze i kolektora:



w_E – efektivna širina emitera
w_B – efektivna širina baze
w_C – efektivna širina kolektora
w_{E0} – tehnološka širina emitera
w_{B0} – tehnološka širina baze
w_{C0} – tehnološka širina kolektora

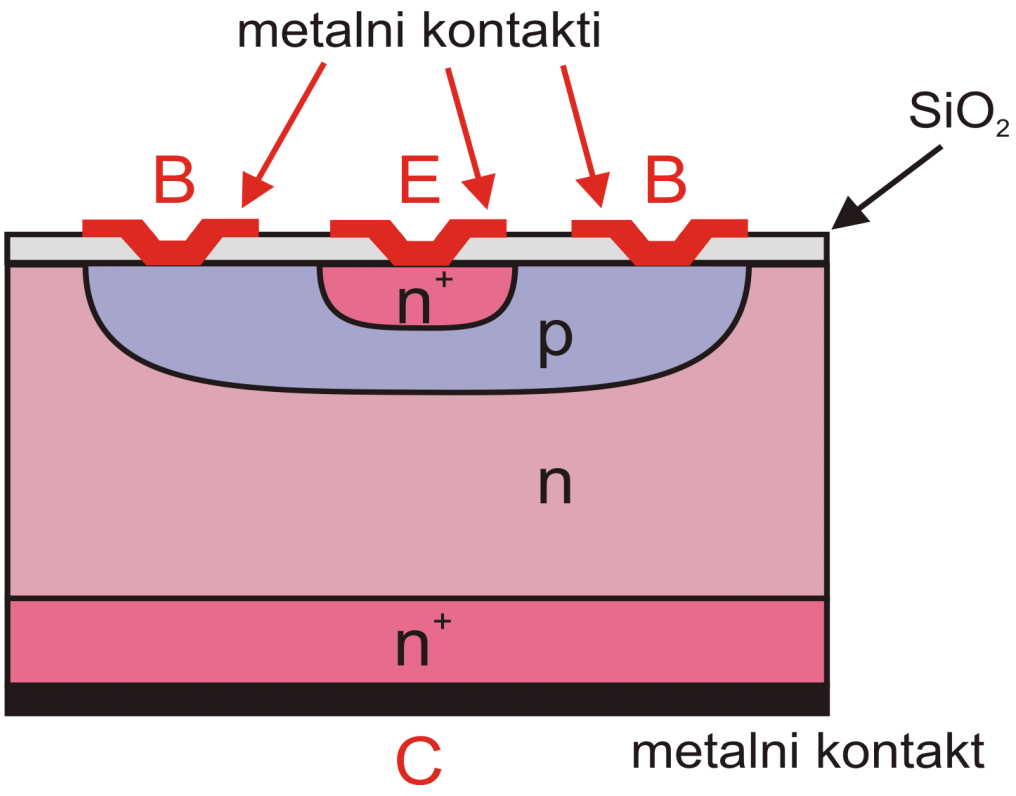
Spoj emiter-baza je propusno polariziran

Spoj kolektor-baza je nepropusno polariziran

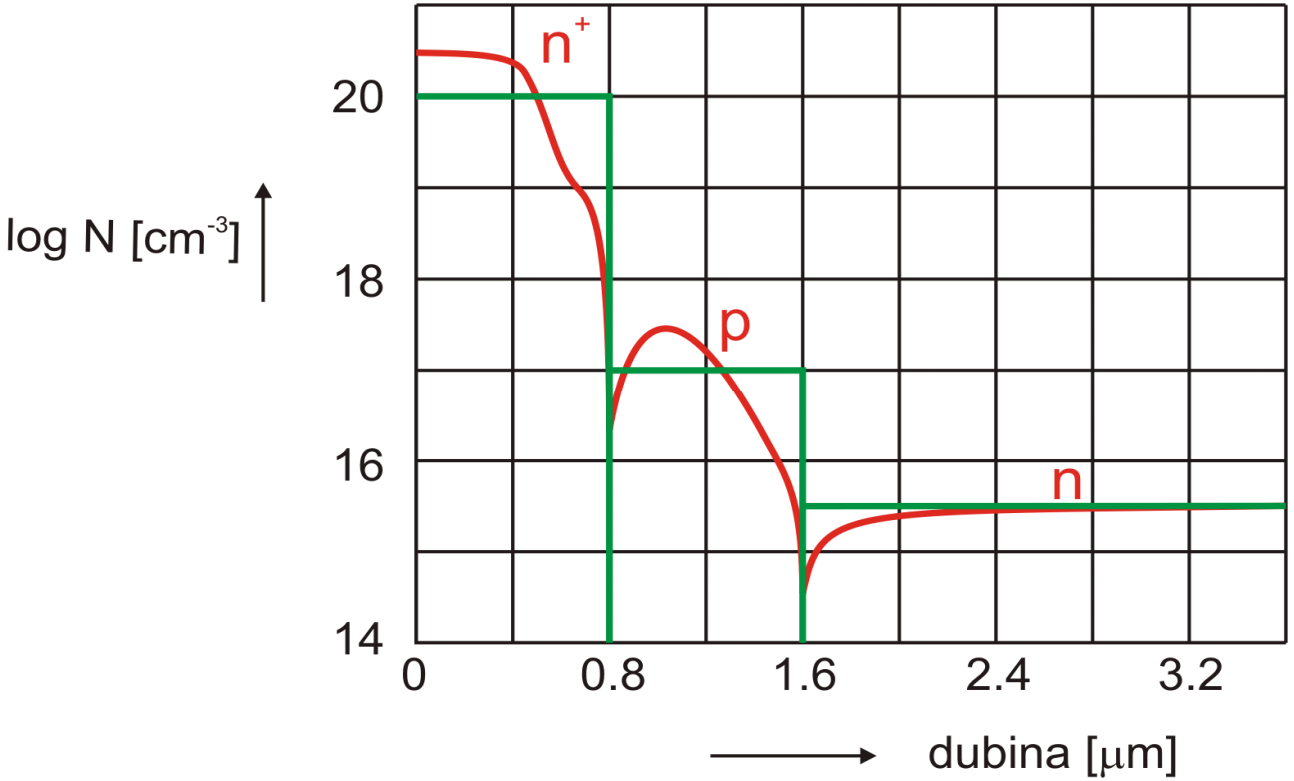
x_{BE}-x_{EB} => osiromašeno područje spoja emiter-baza

x_{CB}-x_{BC} => osiromašeno područje spoja kolektor-baza

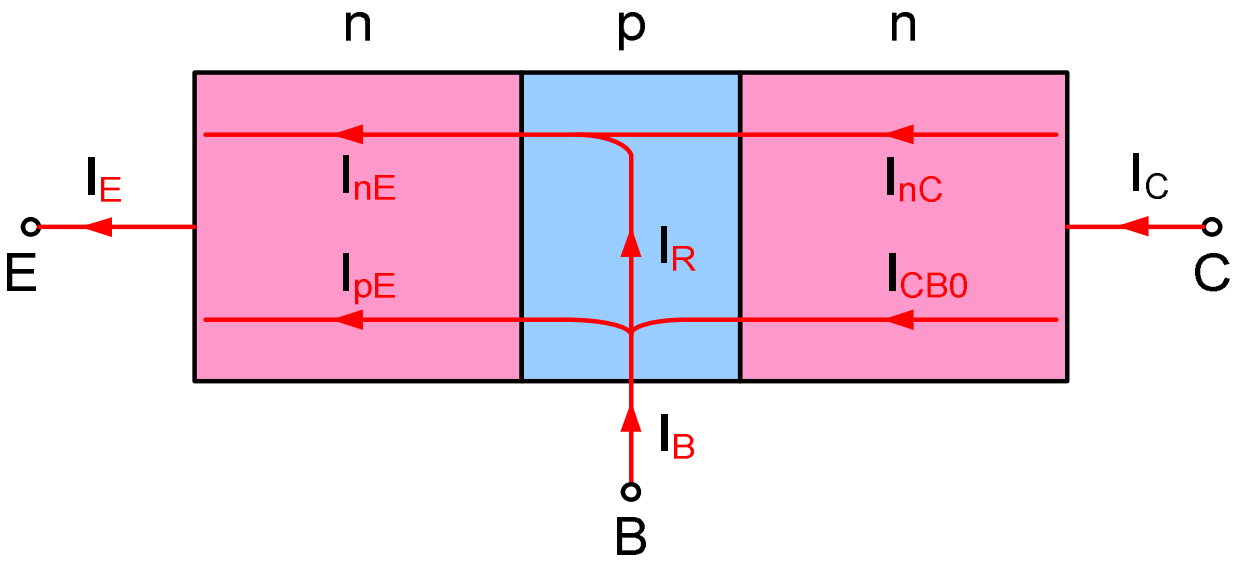
Tehnološka izvedba



- Profil primjesa:
  a) Stvarna raspodjela
  b) Idealizirana raspodjela



Struje normalno polariziranog tranzistora



$$I_E = I_{nE} + I_{pE}$$
$$I_C = I_{nC} + I_{CB0}$$
$$I_R = I_{nE} - I_{nC}$$
$$I_B = I_{pE} + I_R - I_{CB0}$$

$$I_E = I_C + I_B$$

$$I_{nE} = q \cdot S \cdot D_n \cdot \frac{dn_B}{dx}$$

Elektroni injektirani iz emitera u bazu se difuzijom prenose do kolektorskog spojišta!!!

Parametri tranzistora

- Efikasnost (djelotvornost) emitera:

$$\gamma = \frac{I_{nE}}{I_{nE} + I_{pE}} = \frac{I_{nE}}{I_E}$$ (za npn tranzistor)

$$\gamma = \frac{I_{pE}}{I_{nE} + I_{pE}} = \frac{I_{pE}}{I_E}$$ (za pnp tranzistor)

- Prijenosni (transportni) faktor:

$$\beta^* = \frac{I_{nC}}{I_{nE}} = 1 - \frac{I_R}{I_{nE}}$$ (za npn tranzistor)

$$\beta^* = \frac{I_{pC}}{I_{pE}} = 1 - \frac{I_R}{I_{pE}}$$ (za pnp tranzistor)

- Strujno pojačanje:

$$\alpha = \frac{I_{nC}}{I_E} = \frac{I_{nC}}{I_{nE}} \cdot \frac{I_{nE}}{I_E} = \beta^* \cdot \gamma$$ (za npn tranzistor)

$$\alpha = \frac{I_{pC}}{I_E} = \frac{I_{pC}}{I_{pE}} \cdot \frac{I_{pE}}{I_E} = \beta^* \cdot \gamma$$ (za pnp tranzistor)

$$I_C = I_{nC} + I_{CB0} = \alpha \cdot I_E + I_{CB0}$$ $I_C=f(I_E)$

Uvrštavanjem relacije $I_E=I_C+I_B$:

$$I_C = \frac{\alpha}{1-\alpha} \cdot I_B + \frac{I_{CB0}}{1-\alpha} = \beta \cdot I_B + (1+\beta) \cdot I_{CB0}$$

β

Djelotvornost emitera

$$\gamma = \frac{I_{nE}}{I_E} = \frac{I_{nE}}{I_{nE} + I_{pE}} = \frac{1}{1 + \frac{I_{pE}}{I_{nE}}}$$ (npn)

Shockleyjeva jednadžba za struju emitera glasi:

$$I_E = I_{SE}\left[\exp\left(\frac{q \cdot U_{BE}}{k \cdot T}\right) - 1\right]$$

I_{SE} – struja manjinskih nosilaca spoja emiter-baza

$$I_{SE} = q \cdot n_i^2 \cdot S \cdot \left[\frac{D_{nB}}{N_{AB} \cdot L_{nB} \cdot th\left(w_B / L_{nB}\right)} + \frac{D_{pE}}{N_{DE} \cdot L_{pE} \cdot th\left(w_E / L_{pE}\right)}\right]$$

Budući da je $I_E=I_{pE}+I_{nE}$:

$$\gamma = \left[1+\frac{D_{pE}\cdot N_{AB}\cdot L_{nB}\cdot th\left(w_B/L_{nB}\right)}{D_{nB}\cdot N_{DE}\cdot L_{pE}\cdot th\left(w_E/L_{pE}\right)}\right]^{-1}$$

Uz aproksimacije: $w_E/L_{pE}>>1$ i $w_B/L_{nB}<<1$; $th(w_E/L_{pE})\approx 1$ i $th(w_B/L_{nB})\approx w_B/L_{nB}$:

$$\gamma = \left[1+\frac{D_{pE}\cdot N_{AB}\cdot w_B}{D_{nB}\cdot N_{DE}\cdot L_{pE}}\right]^{-1}$$

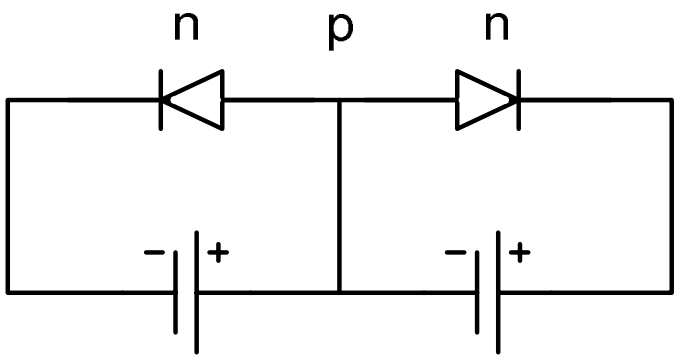
Prijenosni faktor baze tranzistora

$$\beta^* = \frac{I_{nC}}{I_{nE}}$$

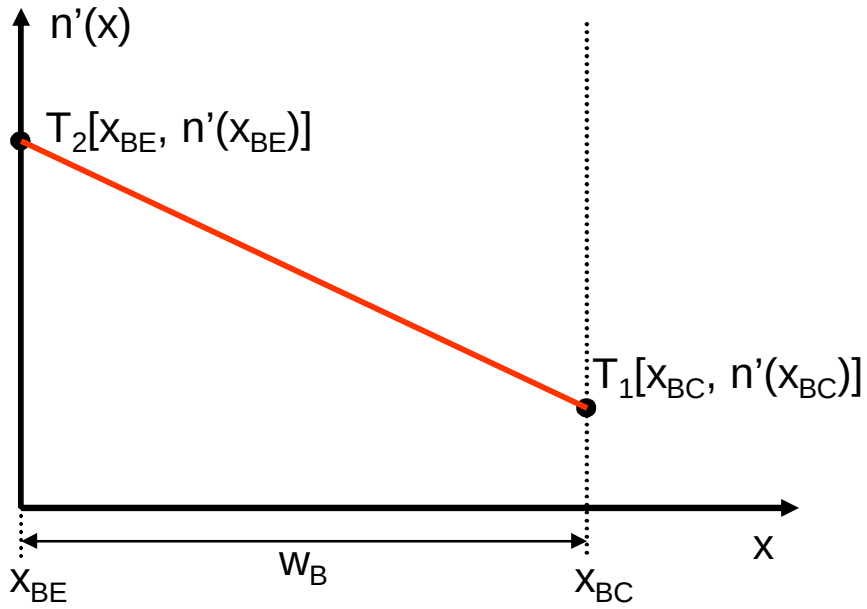
$$\beta^* = \frac{1}{1 + \frac{w_B^2}{2 \cdot L_{nB}^2}} \approx 1 - \frac{1}{2}\left(\frac{w_B}{L_{nB}}\right)^2$$

$w_B << L_{nB}$ **(baza je usko područje)**

Uz uvjet $w_B >> L_{nB}$, $\beta^* \rightarrow 0$, tranzistorski efekt prestaje, a tranzistor se može prikazati s dvije diode:



Vrijeme proleta nosilaca kroz bazu



Linearna raspodjela nosilaca kroz bazu!!!

Jednadžba pravca kroz točke T_1 i T_2:

$$n'(x) - n'(x_{BC}) = \frac{n'(x_{BE}) - n'(x_{BC})}{x_{BE} - x_{BC}}(x - x_{BC})$$

Gustoća difuzijske struje elektrona u bazi:

$$J_{nB} = q \cdot D_{nB} \cdot \frac{dn'(x)}{dx} \approx -q \cdot D_{nB} \frac{n'(x_{BE})}{w_B} = -q \cdot n'(x) \cdot v(x)$$

v(x) => brzina nosilaca kroz bazu

U skladu s definicijom v(x)=dx/dt, vrijeme proleta nosilaca je:

$$t_{pr} = \int_{x_{BE}}^{x_{BC}} \frac{dx}{v(x)}$$

$$v(x) = -\frac{D_{nB}}{w_B} \cdot \frac{n'(x_{BE})}{n'(x)}$$

Uz aproksimaciju $n'(x_{BE}) >> n'(x_{BC}) \approx 0$:

$$n'(x) = \frac{n'(x_{BE})}{-w_B} \cdot (x - x_{BC})$$

Stoga je:

$$v(x) = -\frac{D_{nB}}{x - x_{BC}}$$

$$t_{pr} = -\int_{x_{BE}}^{x_{BC}} \frac{x - x_{BC}}{D_{nB}} dx = \frac{w_B^2}{2D_{nB}}$$

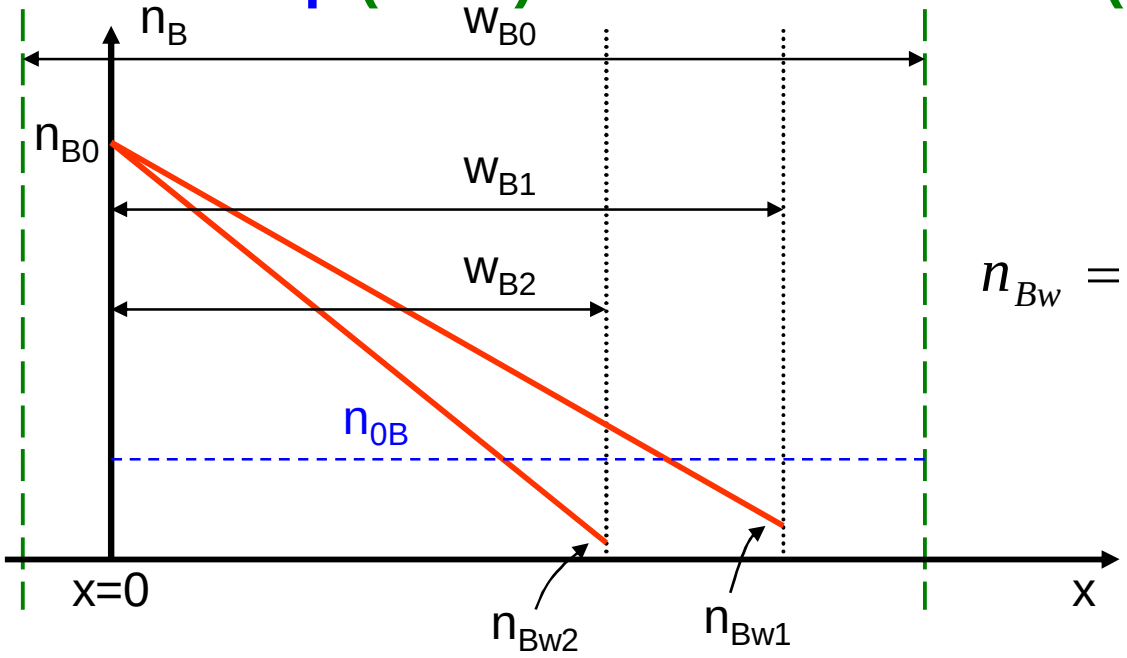
Izraz za vrijeme proleta nosilaca kroz bazu identičan je izrazu izvedenom za usku n stranu pn spoja.

Earlyjev efekt

n (emiter) **p (baza)** **n (kolektor)**

$$n_{B0} = n_{0B} \cdot \exp\left(\frac{U_{BE}}{U_T}\right)$$

$U_{BE}>0$



$$n_{Bw} = n_{0B} \cdot \exp\left(\frac{U_{CB}}{U_T}\right)$$

$U_{CB}<0$

- Povećanjem napona nepropusne polarizacije spoja kolektor-baza, smanjuje se efektivna širina baze (Earlyjev efekt).
- Može nastupiti i naponski proboj (engl. punch-through) pri većim iznosima napona nepropusne polarizacije spoja kolektor-baza.

Ebers-Mollove jednadžbe i model tranzistora

$$I_E = a_{11}\left[\exp\left(\frac{U_{BE}}{U_T}\right)-1\right] + a_{12}\left[\exp\left(\frac{U_{BC}}{U_T}\right)-1\right]$$

$$I_C = a_{21}\left[\exp\left(\frac{U_{BE}}{U_T}\right)-1\right] + a_{22}\left[\exp\left(\frac{U_{BC}}{U_T}\right)-1\right]$$

$$a_{11} = S \cdot q \cdot \left(\frac{D_{nB} \cdot n_{0B}}{w_B} + \frac{D_{pE} \cdot p_{0E}}{L_{pE}}\right)$$

$$a_{22} = S \cdot q \cdot \left(\frac{D_{nB} \cdot n_{0B}}{w_B} + \frac{D_{pC} \cdot p_{0C}}{L_{pC}}\right)$$

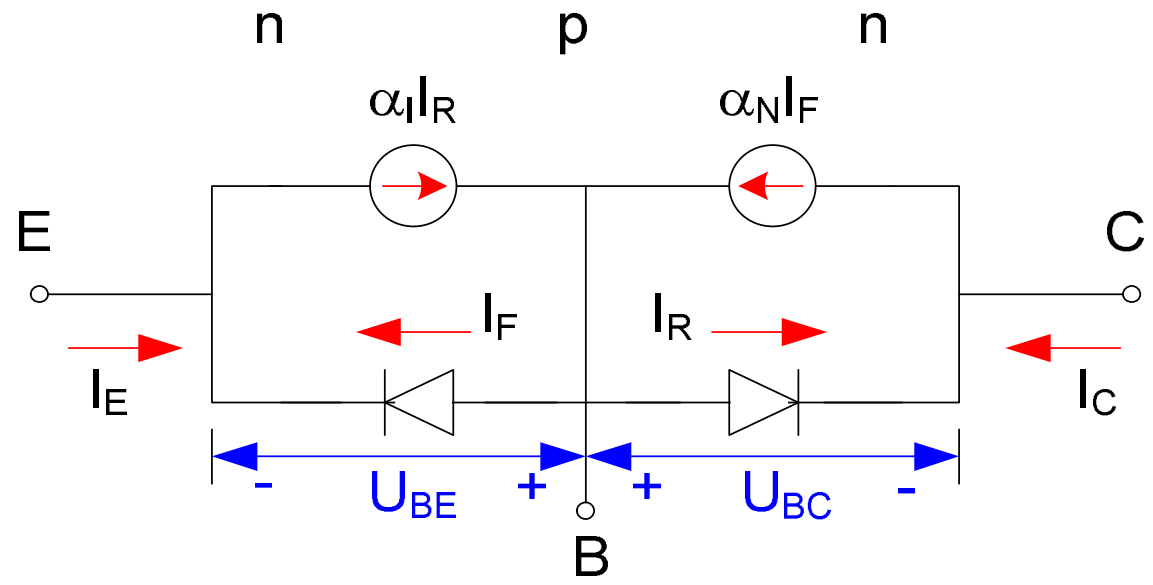
$$a_{12} = a_{21} = -S \cdot q \cdot D_{nB} \cdot \frac{n_{0B}}{w_B}$$

(svojstvo recipročnosti!)

a_{11} jest struja $I_E = I_{ES}$ pri $U_{BC}=0$ i $U_{BE}<0$

a_{22} jest struja $I_C = I_{CS}$ pri $U_{BE}=0$ i $U_{BC}<0$

Injekcijski Ebers-Mollov model



$$I_E - \alpha_I I_R + I_F = 0 \quad (1)$$

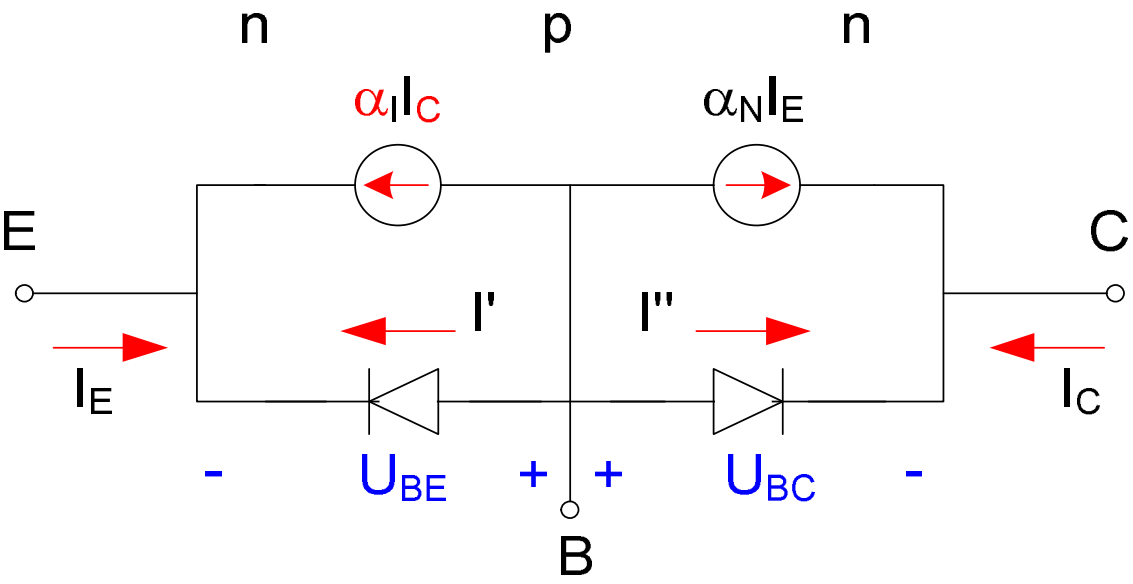
$$I_C - \alpha_N I_F + I_R = 0 \quad (2)$$

$$I_F = I_{ES}\left[\exp\left(\frac{U_{BE}}{U_T}\right) - 1\right] \quad (3)$$

$$I_R = I_{CS}\left[\exp\left(\frac{U_{BC}}{U_T}\right) - 1\right] \quad (4)$$

$$I_E = -I_{ES}\left[\exp\left(\frac{U_{BE}}{U_T}\right) - 1\right] + \alpha_I I_{CS}\left[\exp\left(\frac{U_{BC}}{U_T}\right) - 1\right]$$

$$I_C = \alpha_N I_{ES}\left[\exp\left(\frac{U_{BE}}{U_T}\right) - 1\right] - I_{CS}\left[\exp\left(\frac{U_{BC}}{U_T}\right) - 1\right]$$



$$I_E + \alpha_I I_C + I' = 0$$

$$I_C + \alpha_N I_E + I'' = 0$$

$$I' = I_{EB0}\left[\exp\left(\frac{U_{BE}}{U_T}\right) - 1\right]$$

$$I'' = I_{CB0}\left[\exp\left(\frac{U_{BC}}{U_T}\right) - 1\right]$$

$$I_E = -\frac{I_{EB0}}{1-\alpha_I\alpha_N}\left[\exp\left(\frac{U_{BE}}{U_T}\right) - 1\right] + \frac{\alpha_I I_{CB0}}{1-\alpha_I\alpha_N}\left[\exp\left(\frac{U_{BC}}{U_T}\right) - 1\right]$$

$$I_C = \frac{\alpha_N I_{EB0}}{1-\alpha_I\alpha_N}\left[\exp\left(\frac{U_{BE}}{U_T}\right) - 1\right] - \frac{I_{CB0}}{1-\alpha_I\alpha_N}\left[\exp\left(\frac{U_{BC}}{U_T}\right) - 1\right]$$

$$I_C = \alpha_N I_E + I_{CB0}$$

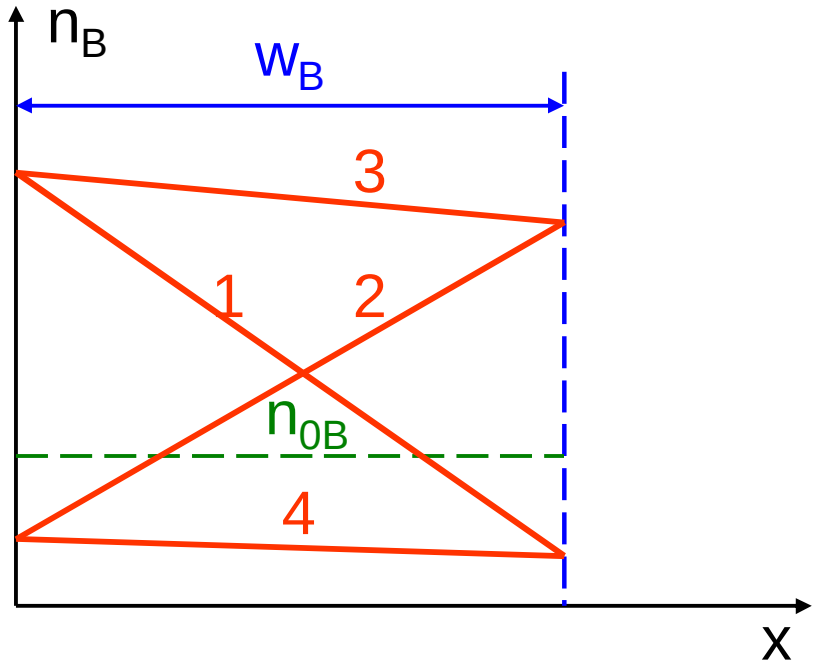
$$I_E = \alpha_I I_C + I_{EB0}$$

$$I_{ES} = \frac{I_{EB0}}{1-\alpha_I\alpha_N} \qquad I_{CS} = \frac{I_{CB0}}{1-\alpha_I\alpha_N}$$

$$I_{CB0} = I_C \quad (uz\ I_E = 0)$$

$$I_{EB0} = I_E \quad (uz\ I_C = 0)$$

Područja rada tranzistora



1 – normalno aktivno područje

2 – inverzno aktivno područje

3 – područje zasićenja

4 – zaporno područje

- Normalno aktivno područje

$U_{BE} >> U_T$, $U_{BC} < 0$

$$I_E = -I_{ES}\left[\exp\left(\frac{U_{BE}}{U_T}\right) - 1\right] - \alpha_I I_{CS} \qquad (1)$$

$$I_C = \alpha_N I_{ES}\left[\exp\left(\frac{U_{BE}}{U_T}\right) - 1\right] + I_{CS} \qquad (2)$$

Iz (1) i (2) slijedi funkcija $I_C = f(I_E)$:

$$I_C = -\alpha_N I_E + \underbrace{I_{CS}\left(1 - \alpha_N \alpha_I\right)}_{I_{CB0}}$$

$$I_C = -\alpha_N I_E + I_{CB0}$$

- Inverzno aktivno područje

$U_{BE}<0$, $U_{BC}>>0$

$$I_E = I_{ES} + \alpha_I I_{CS}\left[\exp\left(\frac{U_{BC}}{U_T}\right) - 1\right] \qquad (1)$$

$$I_C = \alpha_N I_{ES} - I_{CS}\left[\exp\left(\frac{U_{BC}}{U_T}\right) - 1\right] \qquad (2)$$

Iz (1) i (2) slijedi funkcija $I_E=f(I_C)$:

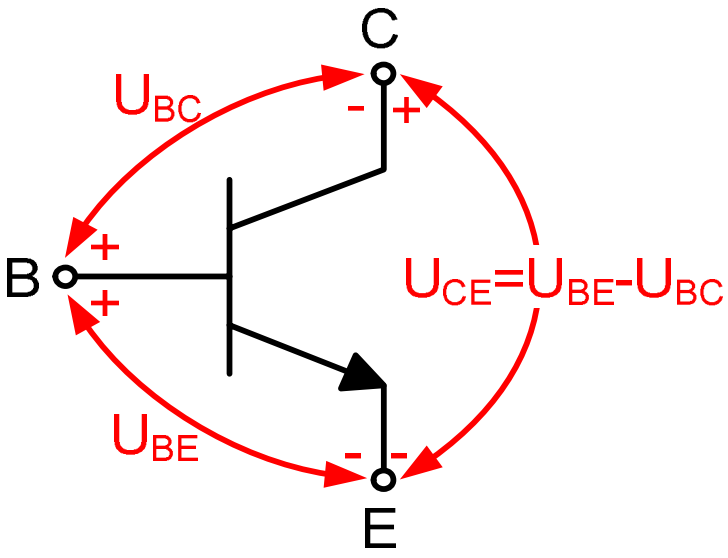
$$I_E = -\alpha_I I_C + I_{EB0}$$

Područje zasićenja

$U_{BE}>0$, $U_{BC}>0$

$$U_{BE} = U_T \cdot \ln \frac{I_E + \alpha_I I_C - I_{EB0}}{-I_{EB0}}$$

$$U_{BC} = U_T \cdot \ln \frac{I_C + \alpha_N I_E - I_{CB0}}{-I_{CB0}}$$



$$U_{CE} = U_T \cdot \ln \frac{\left(I_E + \alpha_I I_C - I_{EB0}\right)\cdot \alpha_N}{\left(I_C + \alpha_N I_E - I_{CB0}\right)\cdot \alpha_I}$$

- Zaporno područje

$U_{BE}<0$, $U_{BC}<0$

$$I_E = \frac{I_{EB0}}{1-\alpha_N\alpha_I}\left(1-\alpha_N\right)$$

$$I_C = \frac{I_{CB0}}{1-\alpha_N\alpha_I}\left(1-\alpha_I\right)$$

Unatoč nepropusnoj polarizaciji kroz oba spojišta teku male struje emitera i kolektora.

Stoga se zaporno područje definira uvjetom: $I_E=0$; $U_{BC}<0$ te je $I_C=I_{CB0}$

Uz ove uvjete iz Ebers-Mollovih jednadžbi dobiva se odgovarajući napon U_{BE}:

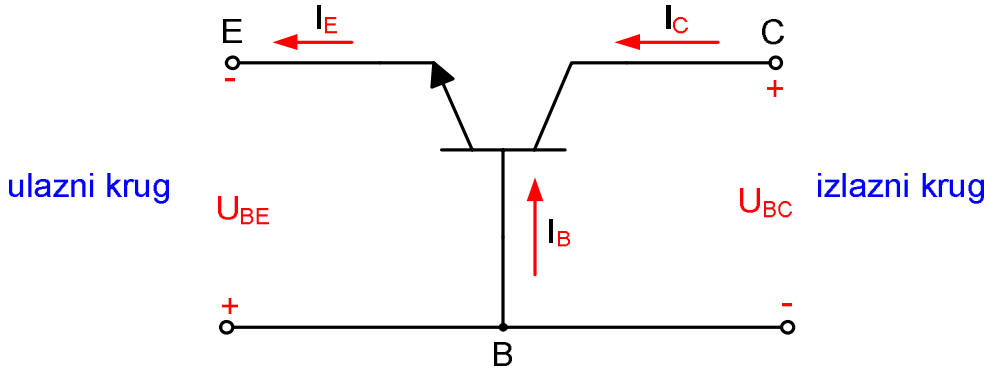
$$U_{BE} = U_T \cdot \ln\left(1-\alpha_N\right)$$

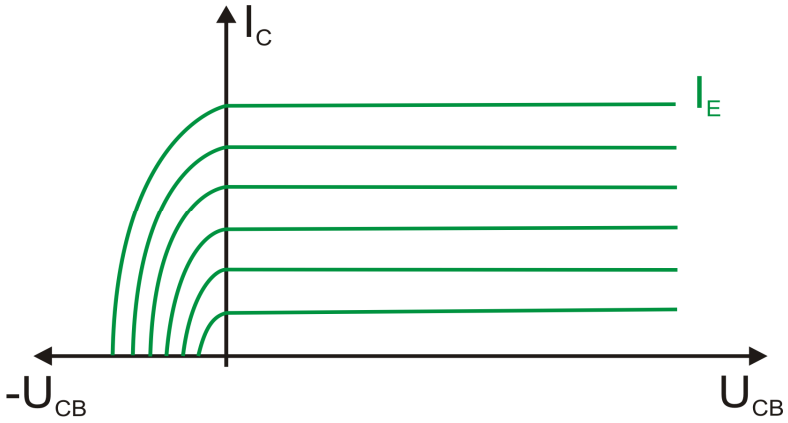
Npr. za $\alpha=0,9$ pri T=300 K

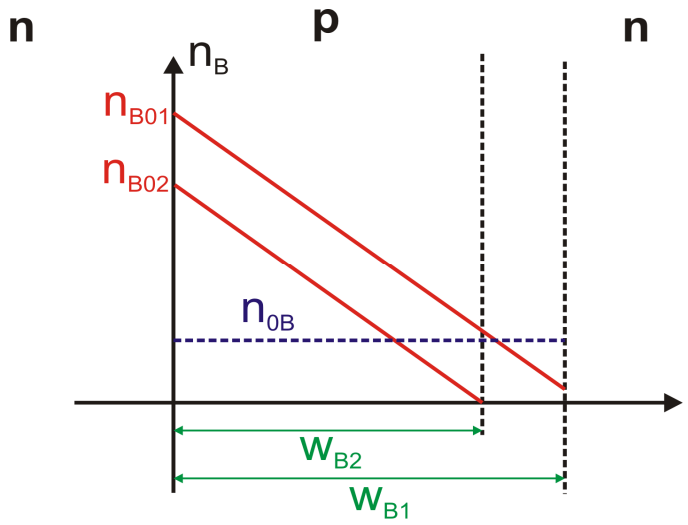
U_{BE}=-59,5 mV

Izlazne karakteristike tranzistora

- Spoj zajedničke baze







$$n_{B0} = n_{0B} \cdot \exp\left(\frac{U_{BE}}{U_T}\right)$$

$$n_{Bw} = n_{0B} \cdot \exp\left(\frac{U_{BC}}{U_T}\right)$$

Spoj zajedničkog emitera