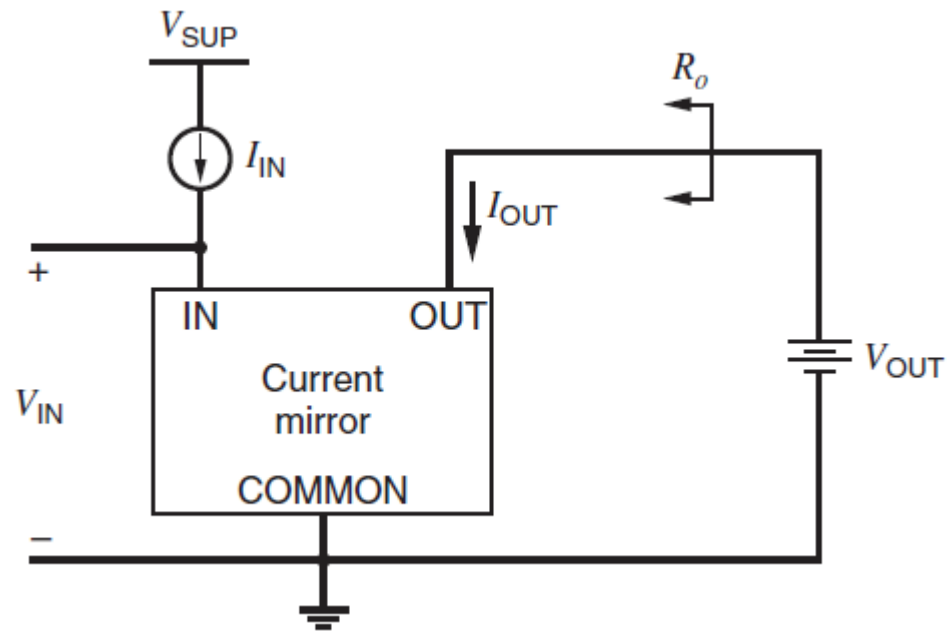


# Osnove elektronike

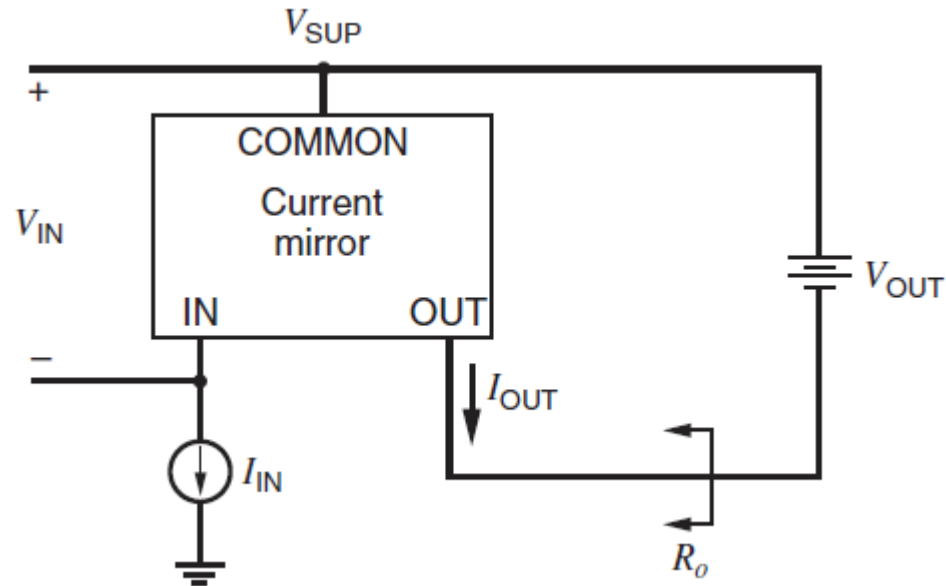
## III semestar

### **STRUJNI IZVORI**

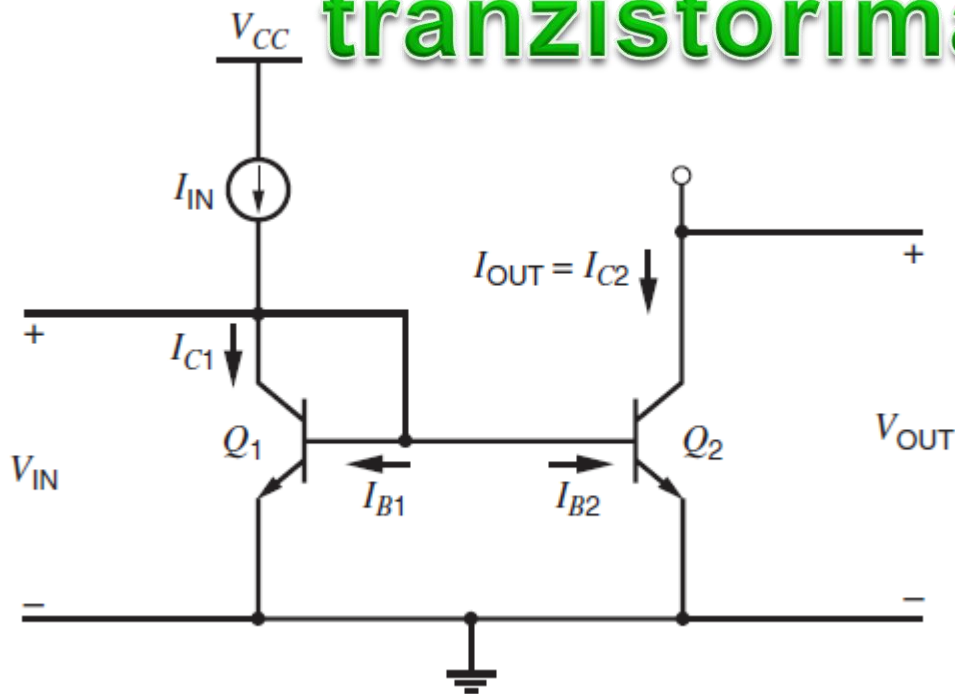
# Strujni izvor referenciran u odnosu na masu



# Strujni izvor referenciran u odnosu na napon napajanja



# Prost strujni izvor sa bipolarnim tranzistorima (BT-ima)



$$V_{BE2} = V_T \ln \frac{I_{C2}}{I_{S2}} = V_{BE1} = V_T \ln \frac{I_{C1}}{I_{S1}}$$

$$V_T = kT/q$$

$$I_{C2} = \frac{I_{S2}}{I_{S1}} I_{C1}$$

$$I_{IN} - I_{C1} - \frac{I_{C1}}{\beta_F} - \frac{I_{C2}}{\beta_F} = 0$$

Za identične tranzistore:

$$I_{S2} = I_{S1}$$

$$I_{OUT} = I_{C2} = I_{C1} = \frac{I_{IN}}{1 + \frac{2}{\beta_F}}$$

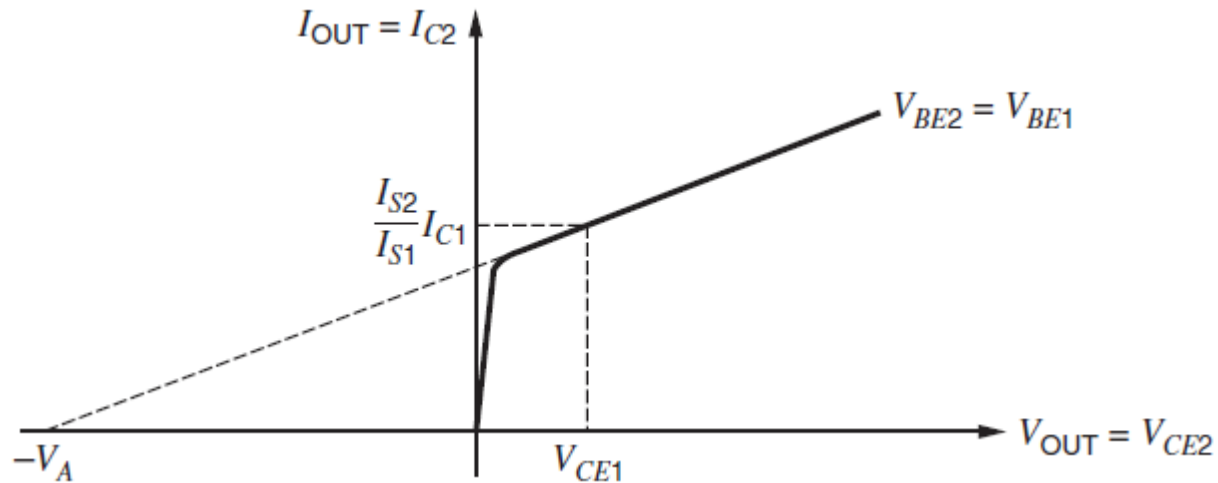
$$I_{OUT} = I_{C1} \simeq I_{IN}$$

Za različite tranzistore:

$$I_{OUT} = \frac{I_{S2}}{I_{S1}} I_{C1} = \left( \frac{I_{S2}}{I_{S1}} I_{IN} \right) \left( \frac{1}{1 + \frac{1 + (I_{S2}/I_{S1})}{\beta_F}} \right)$$

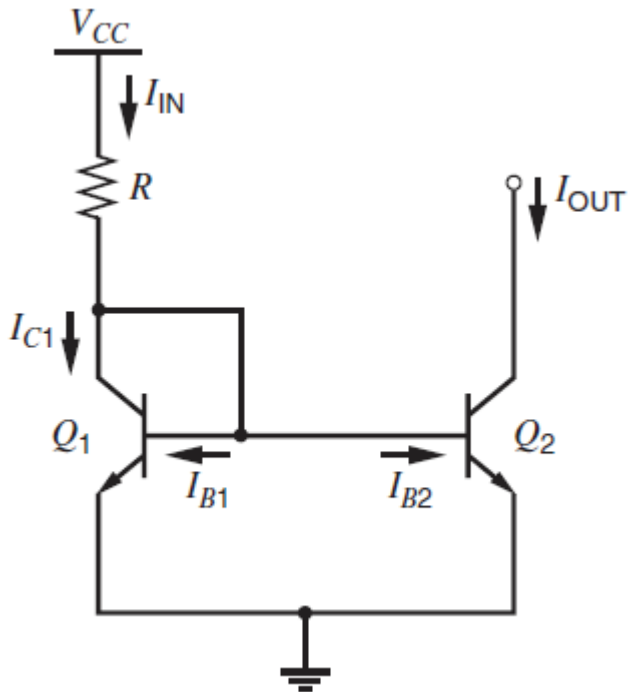
# Prost strujni izvor sa BT-ima

$$R_o = r_{o2} = \frac{V_A}{I_{C2}}$$



$$I_{OUT} = \frac{I_{S2}}{I_{S1}} I_{C1} \left( 1 + \frac{V_{CE2} - V_{CE1}}{V_A} \right) = \frac{\frac{I_{S2}}{I_{S1}} I_{IN} \left( 1 + \frac{V_{CE2} - V_{CE1}}{V_A} \right)}{1 + \frac{1 + (I_{S2}/I_{S1})}{\beta_F}}$$

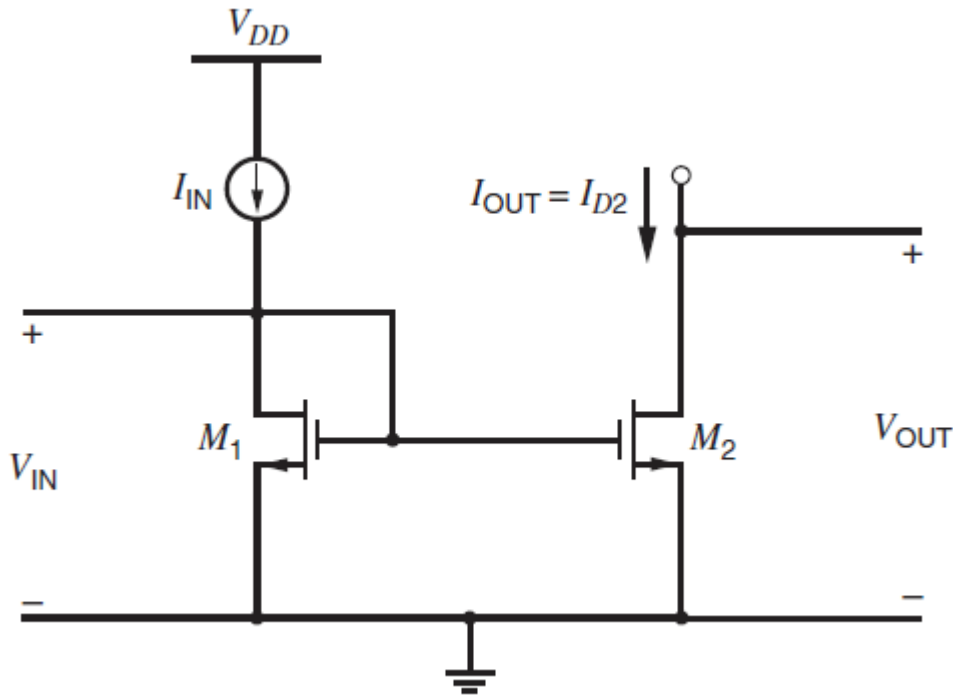
# Prost strujni izvor sa otpornikom za zadavanje referentne struje i identičnim BT-ima



$$I_{IN} = \frac{V_{CC} - V_{BE1}}{R}$$

$$I_{OUT} = I_{C2} = I_{C1} = \frac{I_{IN}}{1 + \frac{2}{\beta_F}}$$

# Prost strujni izvor sa MOSFET-ima



$$V_{GS1} = V_{GS2}$$

$$V_{GS1} = V_T + \sqrt{\frac{2I_{D1}}{B}}$$

$$V_{GS1} = V_T + \sqrt{\frac{2I_{D1}}{\mu_n C_{ox} (W/L)_1}}$$

$$V_{GS2} = V_T + \sqrt{\frac{2I_{D2}}{B}}$$

$$V_{GS2} = V_T + \sqrt{\frac{2I_{D2}}{\mu_n C_{ox} (W/L)_2}}$$

Za identične tranzistore:

$$(W/L)_2 = (W/L)_1$$

$$I_{OUT} = I_{D2} = I_{D1}$$

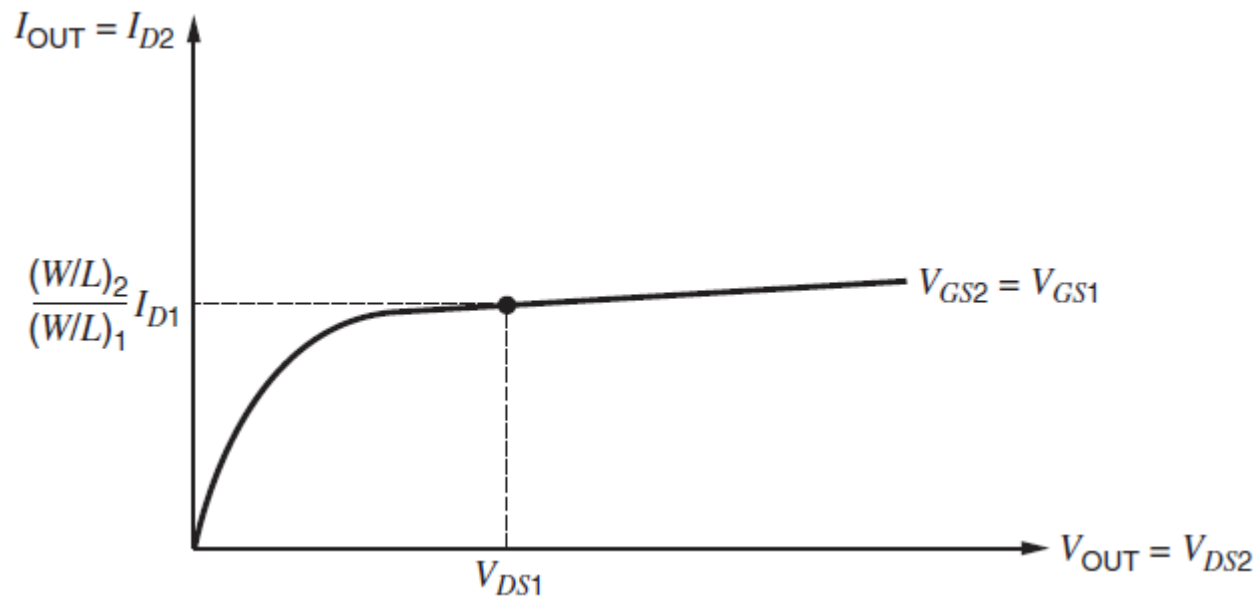
$$I_{OUT} = I_{D1} = I_{IN}$$

Za različite tranzistore:

$$I_{OUT} = \frac{(W/L)_2}{(W/L)_1} I_{D1} = \frac{(W/L)_2}{(W/L)_1} I_{IN}$$

# Prost strujni izvor sa MOSFET-ima

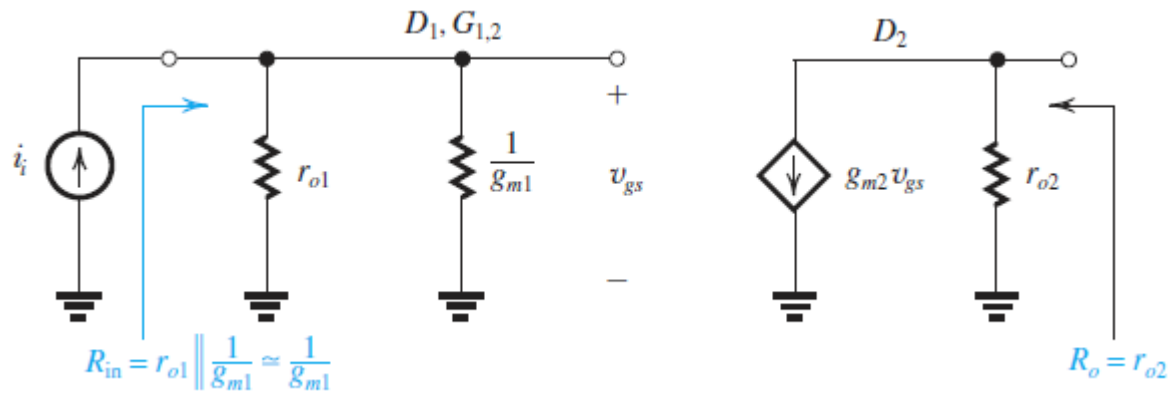
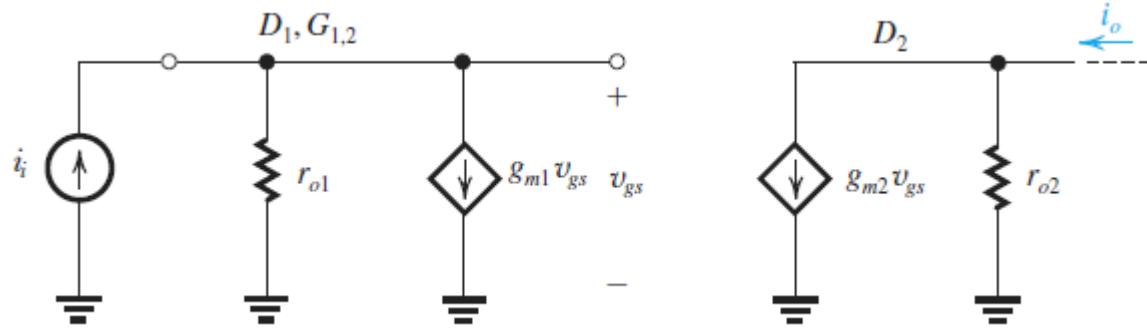
$$R_o = r_{o2} = \frac{V_A}{I_{D2}} = \frac{1}{\lambda I_{D2}}$$



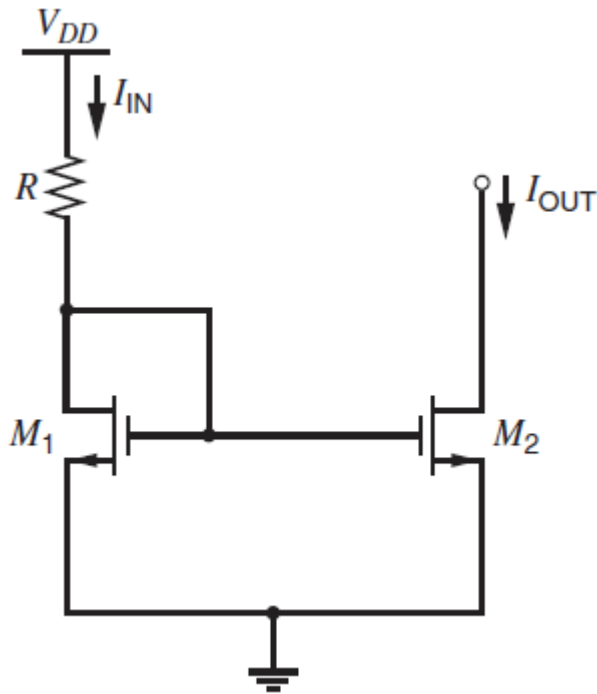
$$I_{OUT} = \frac{(W/L)_2}{(W/L)_1} I_{IN} \left( 1 + \frac{V_{DS2} - V_{DS1}}{V_A} \right)$$



# Prost strujni izvor sa MOSFET-ima



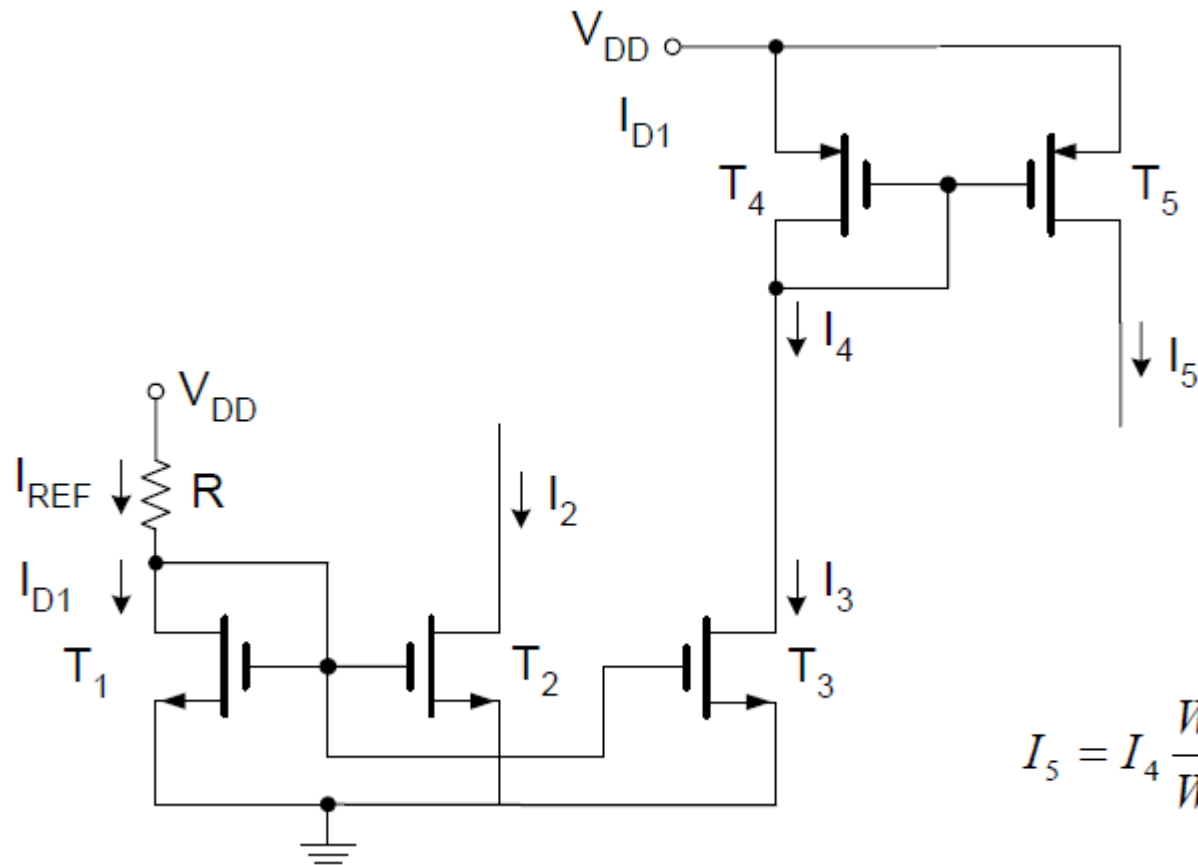
# Prost strujni izvor sa otpornikom za zadavanje referentne struje i identičnim MOSFET-ima



$$I_{IN} = \frac{V_{DD} - V_{GS1}}{R}$$

$$I_{OUT} = I_{D1} = I_{IN}$$

# Kombinovani strujni izvori sa MOSFET-ima



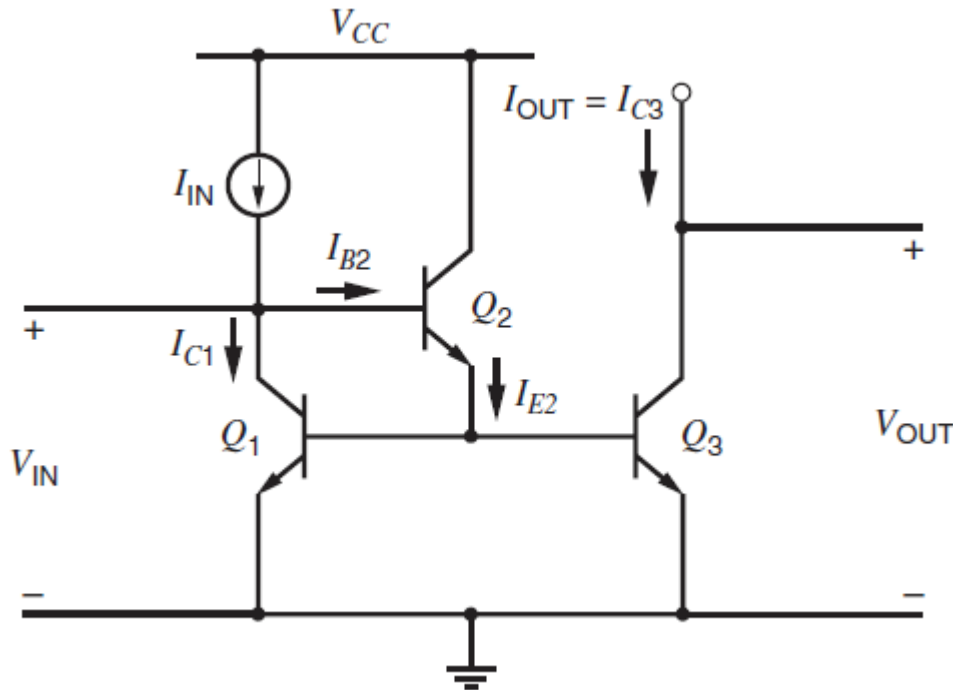
$$I_{REF} = \frac{V_{DD} - V_D}{R}$$

$$I_2 = I_{REF} \frac{W_2/L_2}{W_1/L_1}$$

$$I_3 = I_{REF} \frac{W_3/L_3}{W_1/L_1} = I_4$$

$$I_5 = I_4 \frac{W_5/L_5}{W_4/L_4} = I_{REF} \frac{W_3/L_3}{W_1/L_1} \frac{W_5/L_5}{W_4/L_4}$$

# Poboljšani strujni izvor sa BT-ima



$$V_{IN} = V_{BE1(on)} + V_{BE2(on)}$$

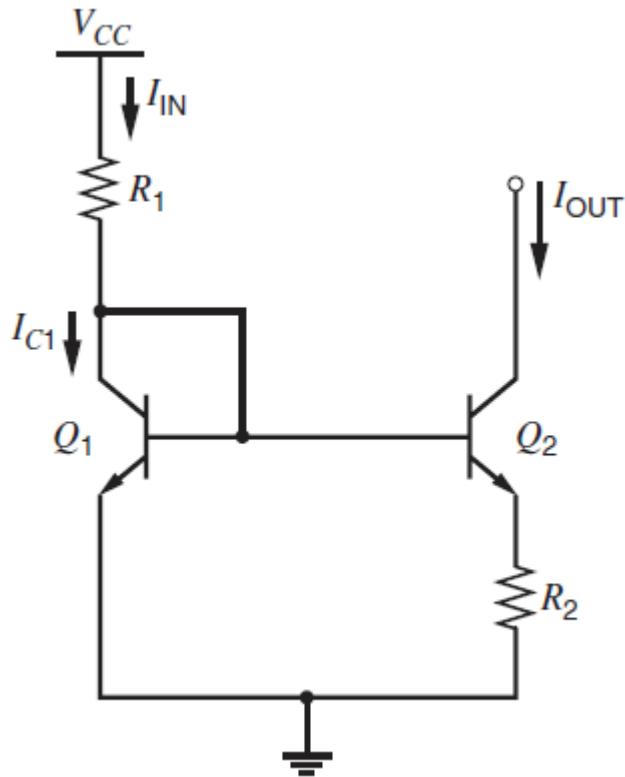
$$I_{B2} = \frac{I_{E2}}{\beta_F + 1} = \frac{2}{\beta_F(\beta_F + 1)} I_{C1}$$

$$I_{IN} - I_{C1} - \frac{2}{\beta_F(\beta_F + 1)} I_{C1} = 0$$

$$I_{OUT} = I_{C3} = \frac{I_{IN}}{1 + \frac{2}{\beta_F(\beta_F + 1)}} \simeq I_{IN} \left( 1 - \frac{2}{\beta_F(\beta_F + 1)} \right)$$

Odnos izlazne i ulazne struje je obrnuto proporcionalan kvadratu strujnog pojačanja, tako da mnogo manje zavisi od temperature.

# Widlar-ov strujni izvor sa BT-ima ( $I_{OUT}$ se zadaje, $R_1$ se izračunava)



$$V_{BE1} - V_{BE2} - \frac{\beta_F + 1}{\beta_F} I_{OUT} R_2 = 0$$

$$V_T \ln \frac{I_{C1}}{I_{S1}} - V_T \ln \frac{I_{OUT}}{I_{S2}} - \frac{\beta_F + 1}{\beta_F} I_{OUT} R_2 = 0$$

$$\beta_F \rightarrow \infty$$

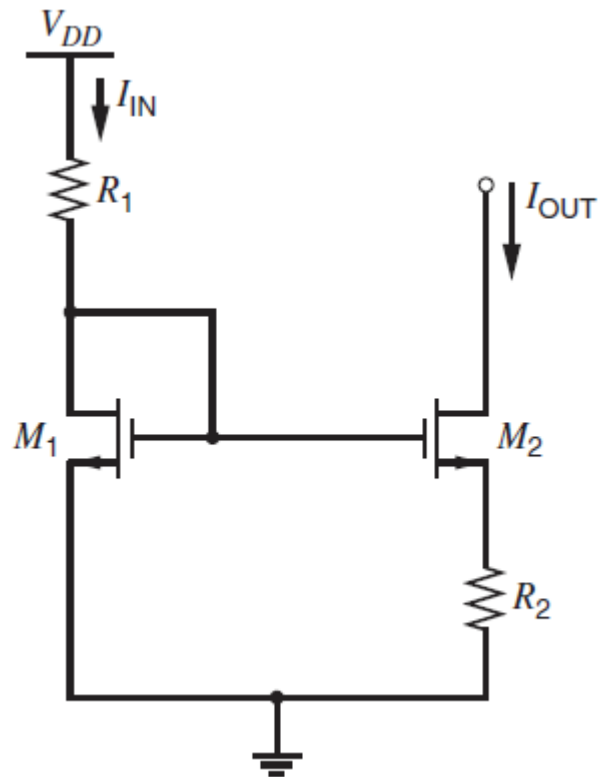
$$V_T \ln \frac{I_{IN}}{I_{S1}} - V_T \ln \frac{I_{OUT}}{I_{S2}} - I_{OUT} R_2 = 0$$

$$V_T \ln \frac{I_{IN}}{I_{OUT}} = I_{OUT} R_2$$

$$I_{IN} = I_{OUT} e^{\frac{I_{OUT} R_2}{V_T}}$$

$$R_1 = \frac{V_{CC} - V_{BE1}}{I_{IN}}$$

# Widlar-ov strujni izvor sa MOS



$$I_{D1} = I_{IN} = \frac{V_{DD} - V_{GS1}}{R}$$

$$I_{D2} = I_{OUT}$$

$$V_{GS1} = V_{GS2} + R_2 I_{D2}$$

$$V_{GS1} = V_T + \sqrt{\frac{2I_{D1}}{B_1}} = V_T + \sqrt{\frac{2I_{D1}}{\mu_n C_{ox} (W/L)_1}}$$

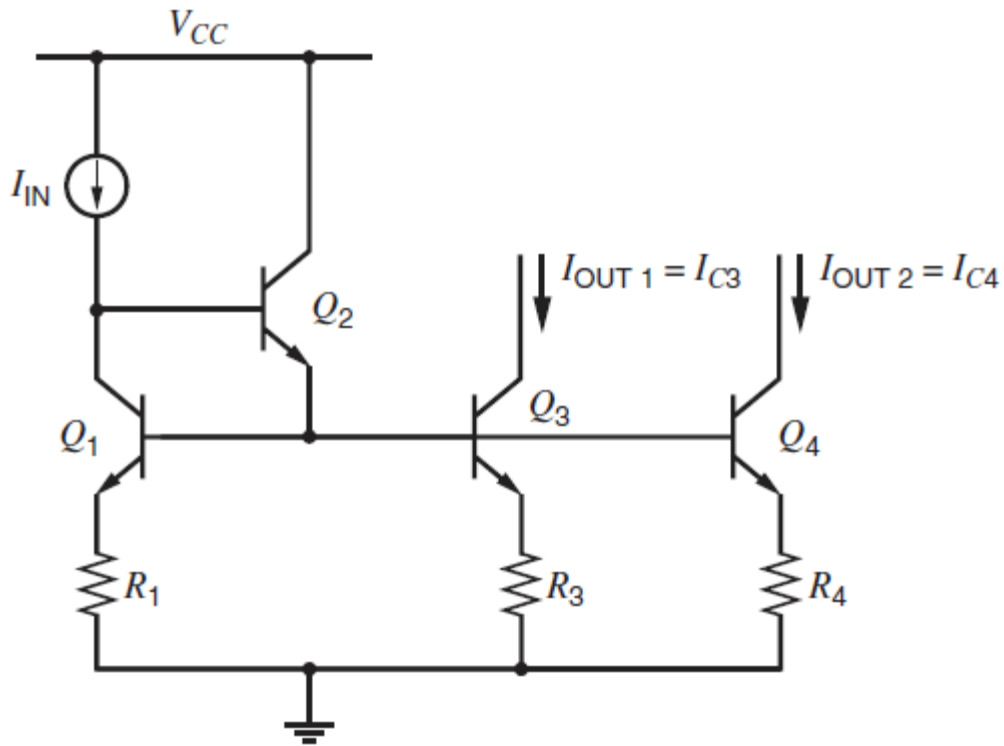
$$V_{GS2} = V_T + \sqrt{\frac{2I_{D2}}{B_2}} = V_T + \sqrt{\frac{2I_{D2}}{\mu_n C_{ox} (W/L)_2}}$$

$$V_T + \sqrt{\frac{2I_{D1}}{B_1}} = V_T + \sqrt{\frac{2I_{D2}}{B_2}} + R_2 I_{D2}$$

$$\sqrt{\frac{2I_{D1}}{B_1}} = \sqrt{\frac{2I_{D2}}{B_2}} + R_2 I_{D2}$$

$$I_{D1} = \frac{B_1}{2} \left( \sqrt{\frac{2I_{D2}}{B_2}} + R_2 I_{D2} \right)^2$$

# Widlar-ov višestruki strujni izvor sa poboljšanim strujnim ogledalom



Izlazna otpornost je:

$$R_o \simeq r_o(1 + g_m R_E)$$

$$R_o \simeq r_{o3} \left( 1 + \frac{I_{C3} R_3}{V_T} \right)$$

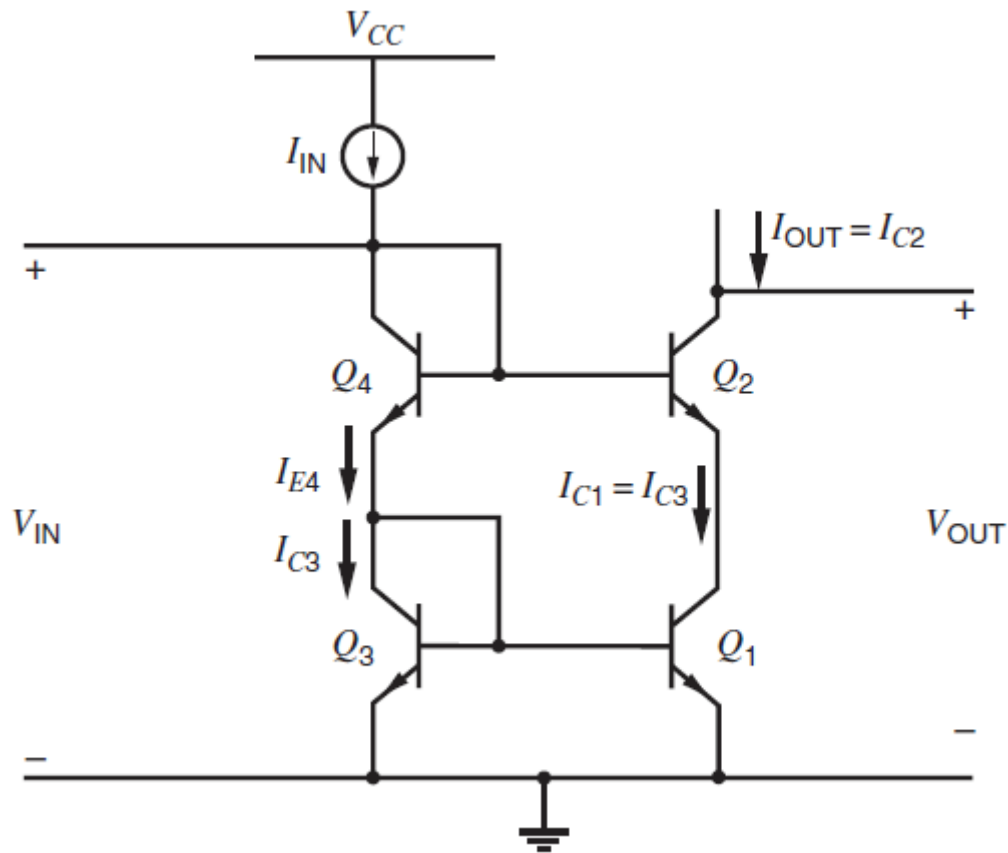
Primer:

$$I_{S4} = 2I_{S1}$$

$$I_{OUT1} = I_{IN}$$

$$I_{OUT2} = 2I_{IN}$$

# Kaskodni strujni izvor sa BT-ima



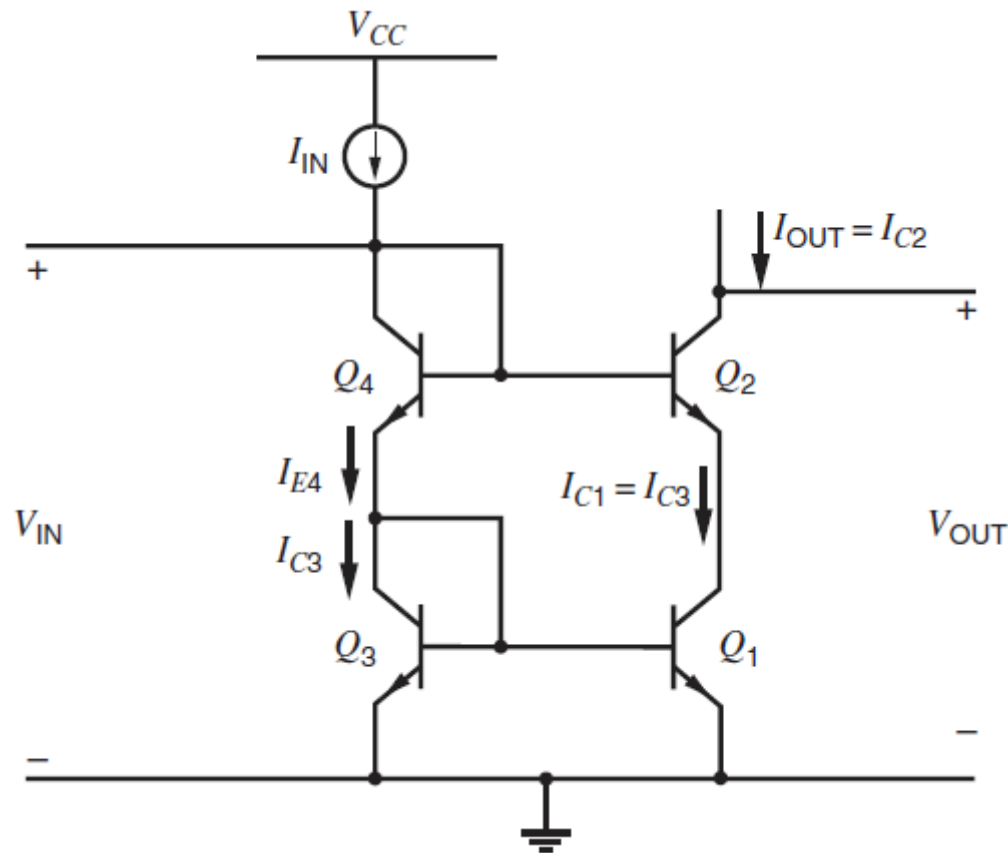
$$V_{IN} = V_{BE3} + V_{BE4} = 2V_{BE(on)}$$

$$R_o \simeq \frac{\beta_0 r_{o2}}{2}$$

$$V_{OUT(min)} = V_{CE1} + V_{CE2(sat)} \simeq V_{BE(on)} + V_{CE2(sat)}$$



# Kaskodni strujni izvor sa BT-ima



$$I_{E4} = I_{C3} + \frac{2I_{C3}}{\beta_F}$$

$$I_{IN} = I_{E4} + \frac{I_{C2}}{\beta_F}$$

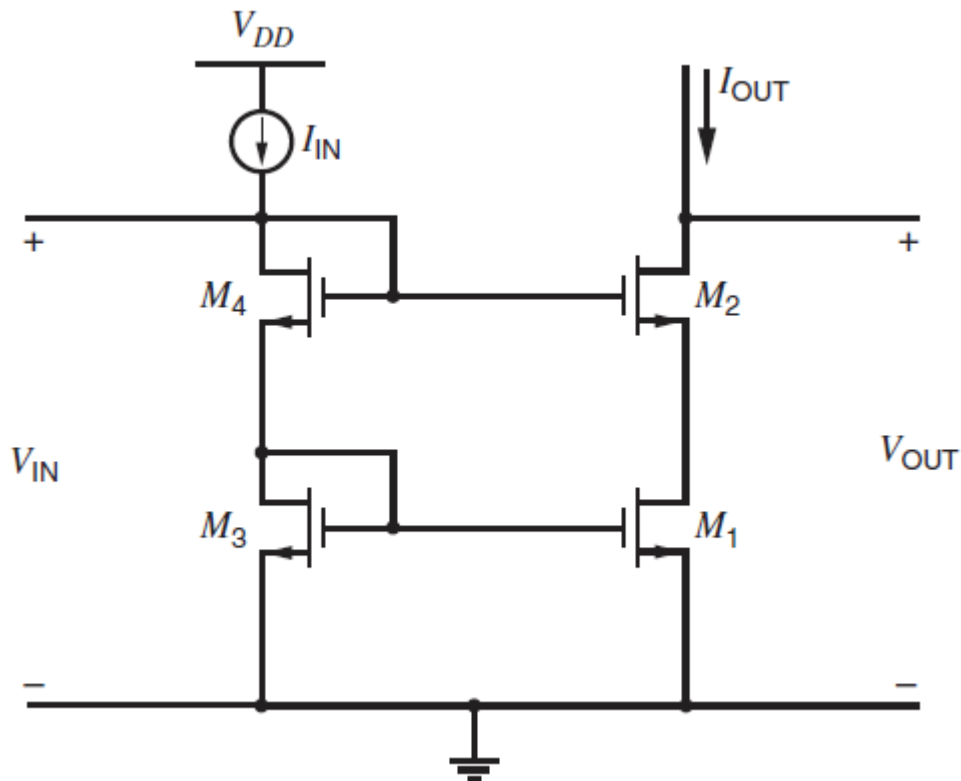
$$I_{C2} = \frac{\beta_F}{\beta_F + 1} I_{C3}$$

$$I_{IN} = I_{C3} + \frac{2I_{C3}}{\beta_F} + \frac{I_{C3}}{\beta_F + 1}$$

$$I_{OUT} = I_{C2} = \left( \frac{\beta_F}{\beta_F + 1} \right) \left( \frac{I_{IN}}{1 + \frac{2}{\beta_F} + \frac{1}{\beta_F + 1}} \right)$$

$$I_{OUT} = I_{IN} \left( 1 - \frac{4\beta_F + 2}{\beta_F^2 + 4\beta_F + 2} \right)$$

# Kaskodni strujni izvor sa MOSFET-ima

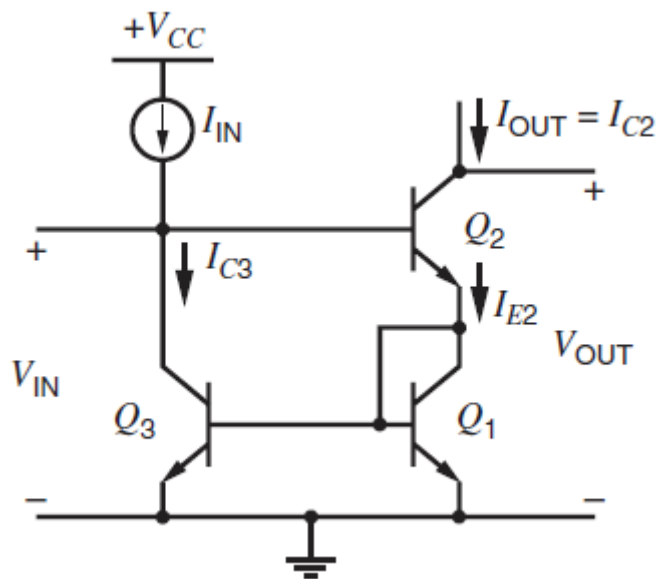


$$V_{IN} = V_{GS3} + V_{GS4}$$

$$R_{o2} = r_{o2}(1 + g_{m2}r_{o1}) + r_{o1}$$

$$R_o = r_{o3}[1 + g_{m3}R_{o2}] + R_{o2}$$

# Wilsonov strujni izvor sa BT-ima



$$V_{IN} = V_{CE3} = V_{BE1} + V_{BE2} = 2V_{BE(on)}$$

$$V_{OUT(min)} = V_{CE1} + V_{CE2(sat)} = V_{BE(on)} + V_{CE2(sat)}$$

$$I_{E2} = I_{C1} + I_{B1} + I_{B3} = I_{C1} \left( 1 + \frac{1}{\beta_F} \right) + \frac{I_{C3}}{\beta_F}$$

$$I_{C3} = I_{C1}$$

$$I_{E2} = I_{C1} \left( 1 + \frac{2}{\beta_F} \right)$$

$$I_{C2} = -I_{E2} \left( \frac{\beta_F}{1 + \beta_F} \right) = I_{C1} \left( 1 + \frac{2}{\beta_F} \right) \left( \frac{\beta_F}{1 + \beta_F} \right)$$

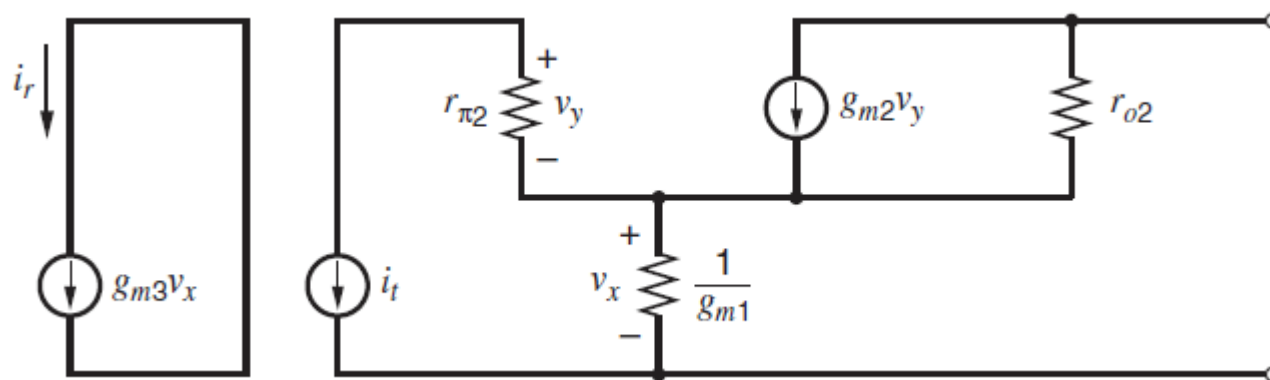
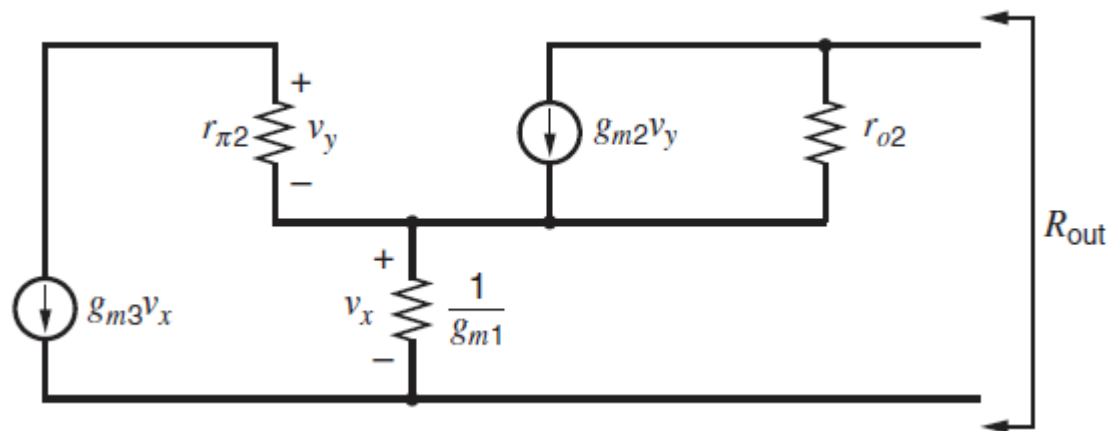
$$I_{C1} = I_{C2} \left[ \frac{1}{\left( 1 + \frac{2}{\beta_F} \right) \left( \frac{\beta_F}{1 + \beta_F} \right)} \right]$$

$$I_{C3} = I_{IN} - \frac{I_{C2}}{\beta_F}$$

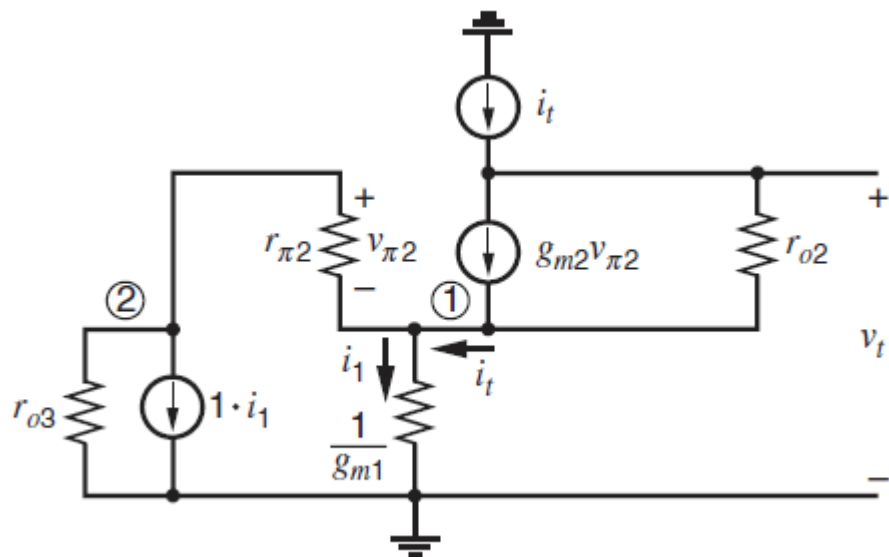
$$I_{OUT} = I_{C2} = I_{IN} \left( 1 - \frac{2}{\beta_F^2 + 2\beta_F + 2} \right) = \frac{I_{IN}}{1 + \frac{2}{\beta_F(\beta_F + 2)}}$$

Odnos izlazne i ulazne struje je obrnuto proporcionalan kvadratu strujnog pojačanja, tako da mnogo manje zavisi od temperature.

# Wilsonov strujni izvor sa BT-ima



# Wilsonov strujni izvor sa BT-ima



Tranzistori Q1 i Q3 formiraju prosto strujno ogledalo sa ekvivalentnom otpornošću:

$$(1/g_{m1}) || r_{\pi 1} || r_{\pi 3} || r_{o1} \approx 1/g_{m1}$$

$$g_{m1}r_{\pi 1} \gg 1 \quad g_{m1}r_{\pi 3} \gg 1 \quad g_{m1}r_{o1} \gg 1$$

Tranzistor Q3 se predstavlja:

$$g_{m3}v_{\pi 3} || r_{o3}$$

$$(g_{m3}/g_{m1})(i_1) = 1(i_1)$$

$$\frac{v_{\pi 2}}{r_{\pi 2}} + i_1 + \frac{\frac{i_1}{g_{m1}} + v_{\pi 2}}{r_{o3}} = 0$$

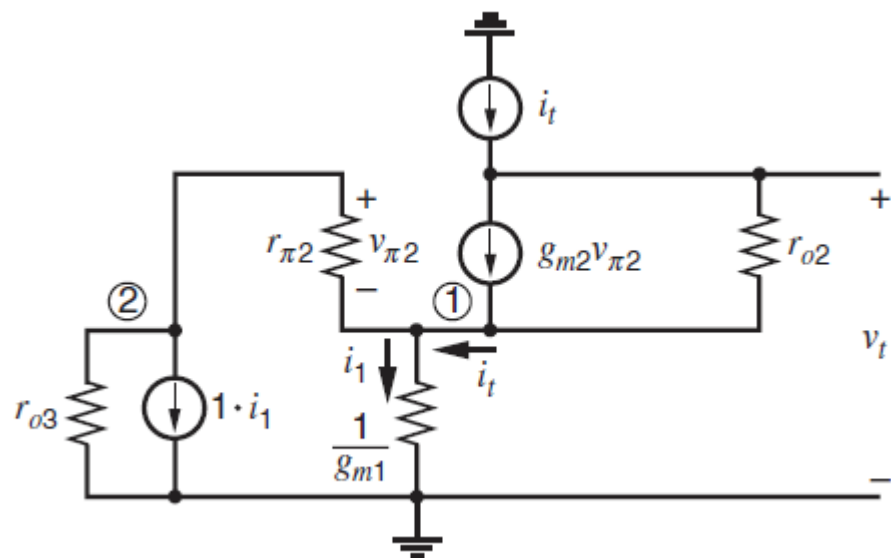
$$i_t = i_1 - \frac{v_{\pi 2}}{r_{\pi 2}}$$

$$v_{\pi 3} = v_{\pi 1} \simeq i_1/g_{m1}$$

$$v_t = \frac{i_1}{g_{m1}} + (i_t - g_{m2}v_{\pi 2})r_{o2}$$

$$v_{\pi 2} = -i_1 r_{\pi 2} \left( \frac{1 + \frac{1}{g_{m1}r_{o3}}}{1 + \frac{r_{\pi 2}}{r_{o3}}} \right)$$

# Wilsonov strujni izvor sa BT-ima



$$i_1 = \frac{i_t}{1 + \left( \frac{1 + \frac{1}{g_{m 1} r_{o 3}}}{1 + \frac{r_{\pi 2}}{r_{o 3}}} \right)}$$

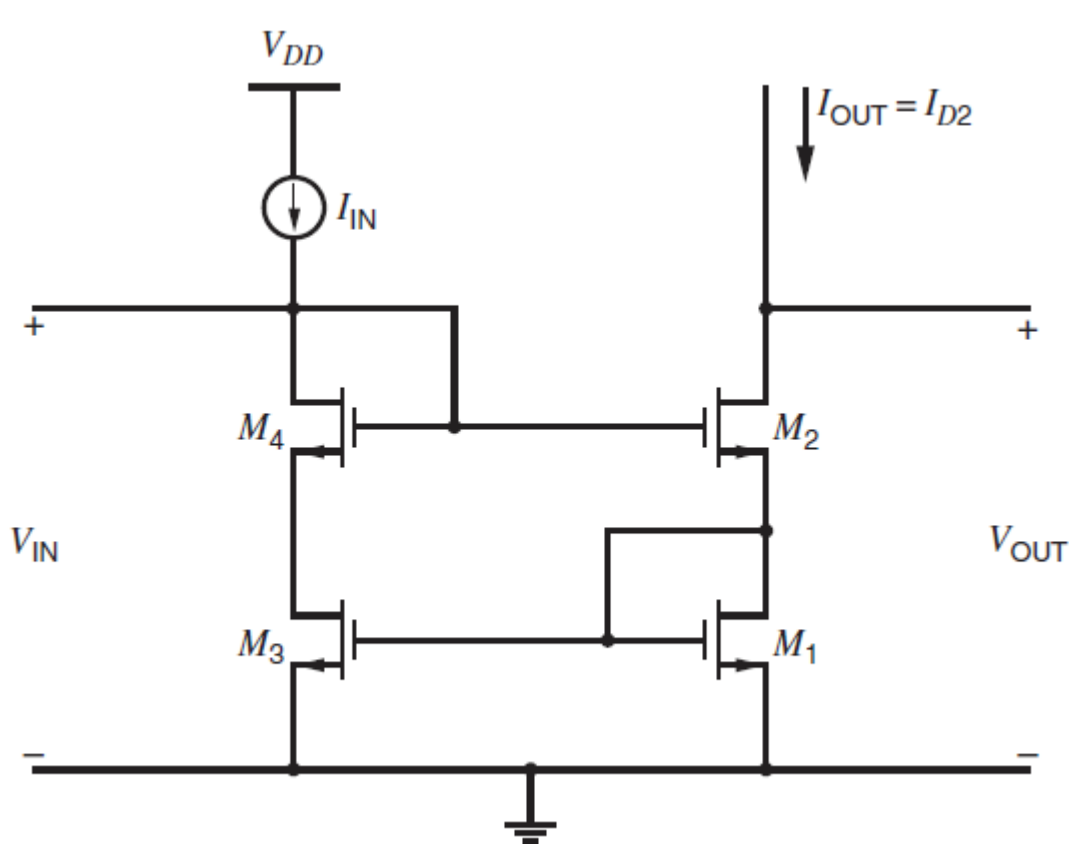
$$v_{\pi 2} = -i_t r_{\pi 2} \left( \frac{1 + \frac{1}{g_{m 1} r_{o 3}}}{2 + \frac{r_{\pi 2}}{r_{o 3}} + \frac{1}{g_{m 1} r_{o 3}}} \right)$$

$$R_o = \frac{v_t}{i_t} = \frac{1}{g_{m 1} \left[ 1 + \left( \frac{1 + \frac{1}{g_{m 1} r_{o 3}}}{1 + \frac{r_{\pi 2}}{r_{o 3}}} \right) \right]} + r_{o 2} + \frac{g_{m 2} r_{\pi 2} r_{o 2} \left( 1 + \frac{1}{g_{m 1} r_{o 3}} \right)}{2 + \frac{r_{\pi 2}}{r_{o 3}} + \frac{1}{g_{m 1} r_{o 3}}}$$

$$R_o = \frac{1}{g_{m 1} (2)} + r_{o 2} + \frac{g_{m 2} r_{\pi 2} r_{o 2}}{2} \simeq \frac{\beta_0 r_{o 2}}{2}$$

$$r_{o 3} \rightarrow \infty$$

# Wilsonov strujni izvor sa MOSFET-ima



$$V_{IN} = V_{GS1} + V_{GS2}$$

$$R_o = \frac{1}{g_{m1}} + r_{o2} + g_{m2}r_{o2} \left( 1 + \frac{1}{g_{m1}r_{o3}} \right) r_{o3} \simeq (1 + g_{m2}r_{o3})r_{o2}$$

# Osnove elektronike

## III semestar

### **STRUJNI IZVORI**