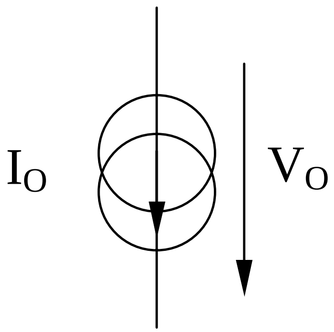
# Capitolul 3

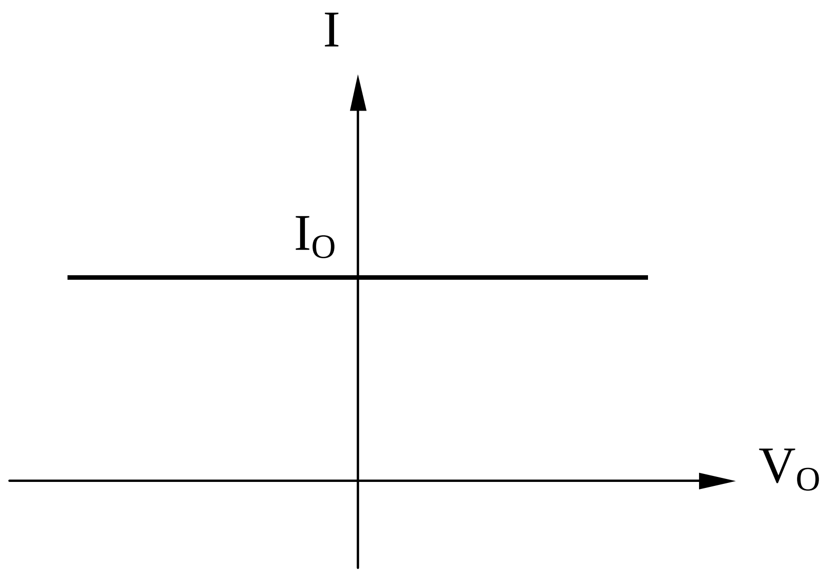
# Surse de curent si surse de tensiune

## 3.1. Surse de curent

# 3.1. Surse de curent

## 3.1.1. Introducere




**Parametri:**

• Curentul de iesire $I_O$ [A]

• Rezistenta de iesire [Ω]

$$R_O = \left.\frac{dV_O}{dI_O}\right|_{V_{CC},T=ct.}$$

- Tensiunea minima de iesire [V]

- Coeficientul de temperatura [A/K]

$$TC_{I_O} = \left.\frac{dI_O}{dT}\right|_{R_L, V_{CC} = ct.}$$

- Coeficientul relativ de temperatura [1/K]

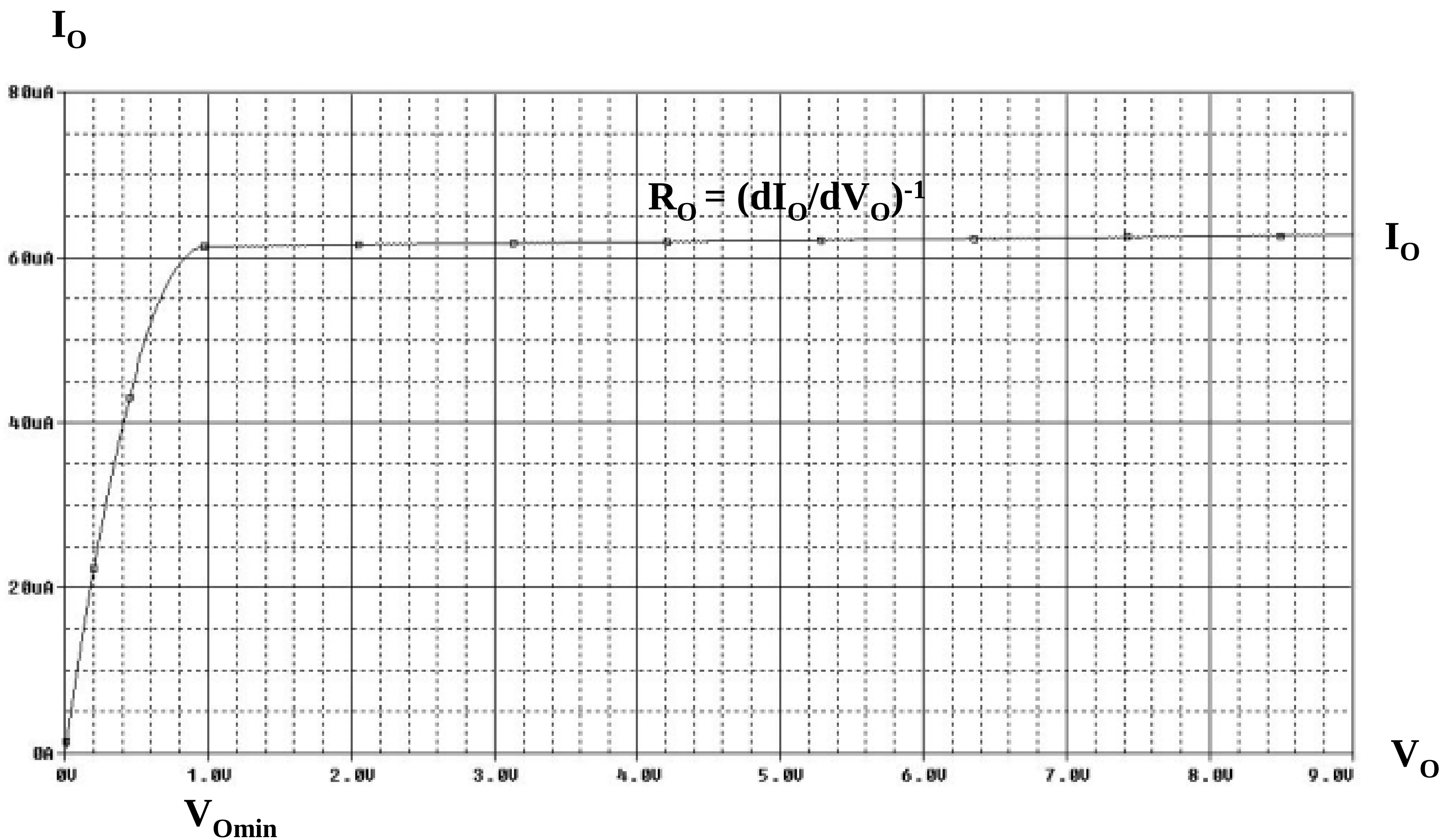
$$RTC_{I_O} = \left.\frac{1}{I_O}\frac{dI_O}{dT}\right|_{R_L, V_{CC} = ct.}$$

- Factorul de rejectie al tensiunii de alimentare (Power Supply Rejection Ratio) [A/V]

$$PSRR = \left.\frac{dI_O}{dV_{CC}}\right|_{R_L, T = ct.}$$

- Sensibilitatea curentului de iesire in raport cu variatiile tensiunii de alimentare [-]

$$S_{V_{CC}}^{I_O} = \left.\frac{dI_O / I_O}{dV_{CC} / V_{CC}}\right|_{R_L, T = ct.} = \left.\frac{V_{CC}}{I_O}\frac{dI_O}{dV_{CC}}\right|_{R_L, T = ct.}$$




Caracteristica de iesire a unei surse de curent

## Clasificare

I. Surse de curent elementare

- complexitate redusa
- performante modeste

II. Surse de curent cascod

- rezistenta de iesire mare
- tensiune minima de iesire mare
- tensiune minima de alimentare mare

III. Surse de curent cu autopolarizare

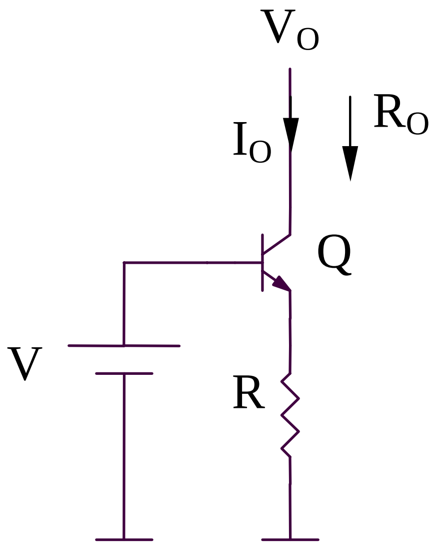
- dependenta redusa $I_O$ ($V_{CC}$)
- necesita circuit de pornire

IV. Surse de curent compensate cu temperatura

- dependenta redusa de temperatura
- complexitare ridicata

## 3.1.2. Surse de curent elementare

### Sursa de curent bipolara cu un tranzistor

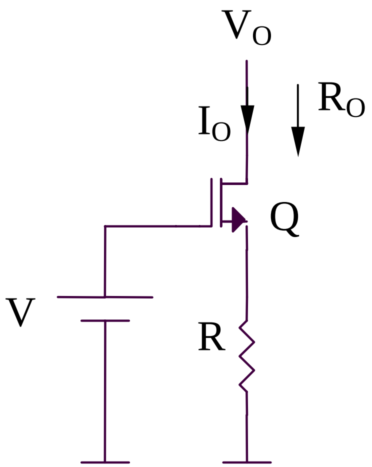



$$I_O = \frac{V - V_{BE}}{R}$$

$$R_O = r_o\left(1 + \frac{\beta R}{r_\pi + R}\right)$$

$$V_{O\min} = V - V_{BE} + V_{CEsat}$$

# Sursa de curent MOS cu un tranzistor



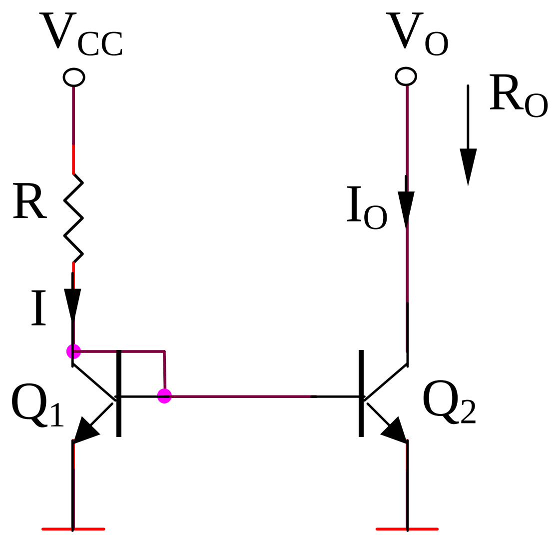

$$\left.\begin{aligned} V &= V_{GS} + I_O R \\ I_O &= \frac{K}{2}\left(V_{GS} - V_T\right)^2 \end{aligned}\right\} \Rightarrow V = V_{GS} + \frac{KR}{2}\left(V_{GS} - V_T\right)^2$$

$$\Rightarrow V_{GS}\left(> V_T\right) \Rightarrow I_O$$

$$R_O = r_{ds}\left(1 + g_m R\right)$$

$$V_{O\min} = V - V_{GS} + \left(V_{GS} - V_T\right) = V - V_T$$

# Oglinda de curent bipolara




## Curent de iesire

$$I = \frac{V_{CC} - V_{BE}}{R} \cong I_{S1} \exp\left(\frac{V_{BE1}}{V_{th}}\right)$$

$$I_O \cong I_{S2} \exp\left(\frac{V_{BE2}}{V_{th}}\right)$$

$$V_{BE1} = V_{BE2}$$

$$\Rightarrow \quad \frac{I_O}{I} \cong \frac{I_{S2}}{I_{S1}} \quad \Rightarrow \quad I_O \cong \frac{V_{CC} - V_{BE}}{R} \frac{I_{S2}}{I_{S1}}$$

**Rezistenta de iesire**

$$R_O = r_o = \frac{V_A}{I_{C2}} = \frac{V_A}{I_O}$$

**Tensiune minima de iesire**

$$V_{O\min} = V_{CE2sat}.$$

**Efect Early**

$$I = \frac{V_{CC} - V_{BE}}{R} = I_{S1}\exp\left(\frac{V_{BE1}}{V_{th}}\right)\left(1 + \frac{V_{CE1}}{V_A}\right)$$

$$I_O = I_{S2}\exp\left(\frac{V_{BE2}}{V_{th}}\right)\left(1 + \frac{V_{CE2}}{V_A}\right)$$

$$\frac{I_O}{I} = \frac{I_{S2}}{I_{S1}}\frac{1 + \frac{V_{CE1}}{V_A}}{1 + \frac{V_{CE2}}{V_A}} = \frac{I_{S2}}{I_{S1}}\frac{1 + \frac{V_{BE1}}{V_A}}{1 + \frac{V_O}{V_A}}$$

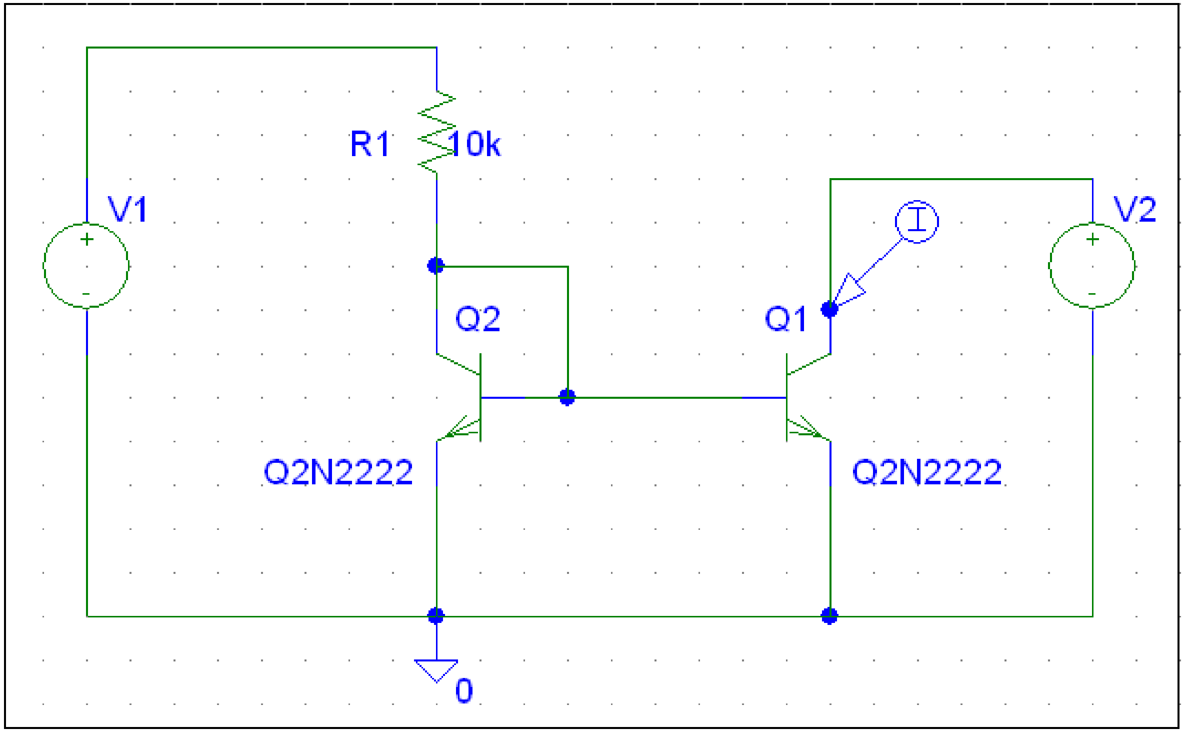
**Influenta β**

$$\frac{I_O}{I} = \frac{\beta I_B}{\beta I_B + 2I_B} = \frac{\beta}{\beta + 2}$$

# SIMULARI pentru oglinda de curent bipolara
# Caracteristica de iesire

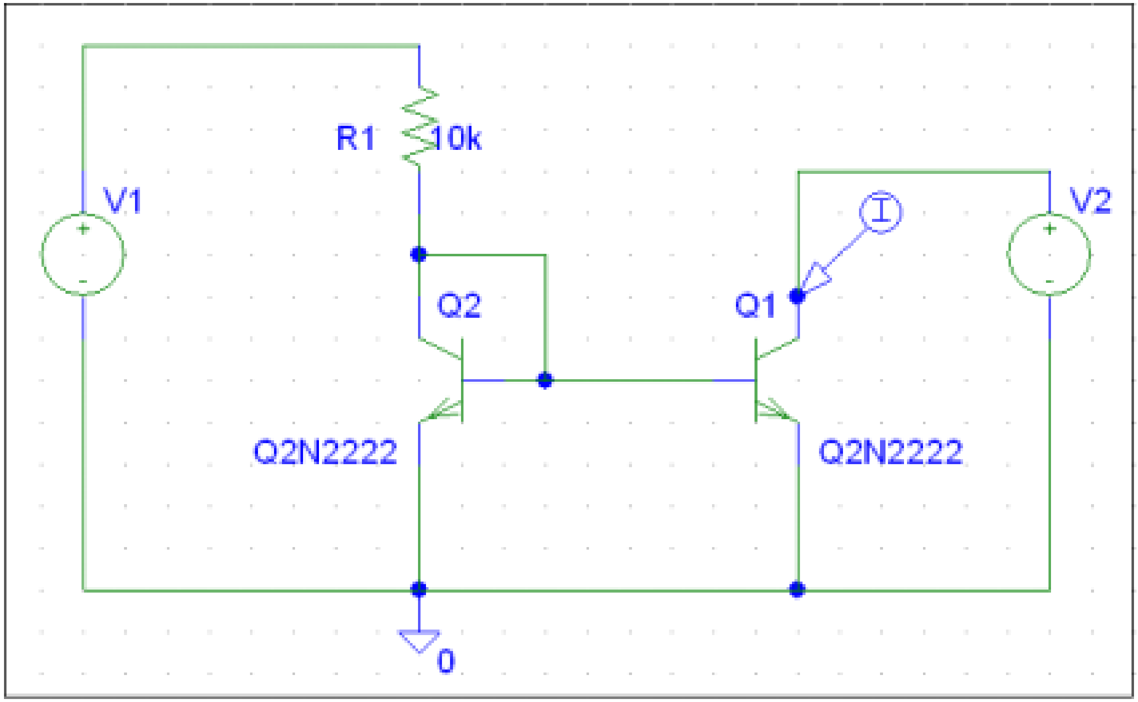
# SIMULARI pentru oglinda de curent bipolara
# Caracteristica de iesire

## SIM 3.1: $I_{C1}$ (V2)



# SIMULARI pentru oglinda de curent bipolara
# Caracteristica de iesire

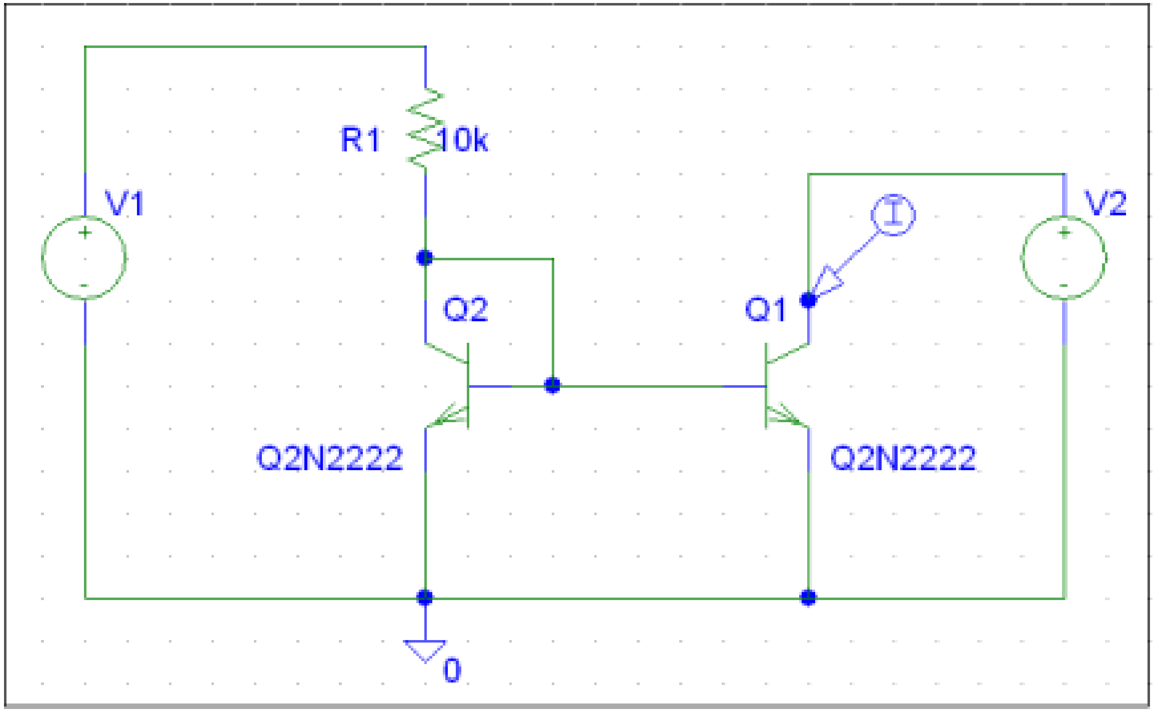
## SIM 3.2: $I_{C1}$ (V2), $V_{A1}$ - parametru



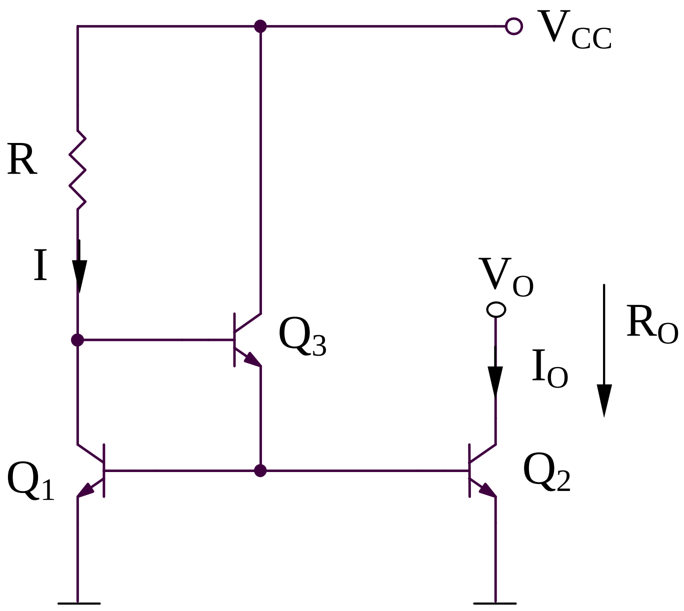
# SIMULARI pentru oglinda de curent bipolara
# Dependenta curentului de iesire de tensiunea de alimentare

# SIMULARI pentru oglinda de curent bipolara
# Dependenta curentului de iesire de tensiunea de alimentare

## SIM 3.3: $I_{C1}$ (V1)



# Sursa de curent cu reducerea efectului β (1)




**Curent de iesire**

$$I_O \cong I = \frac{V_{CC} - 2V_{BE}}{R}$$

**Rezistenta de iesire**

$$R_O = r_o = \frac{V_A}{I_{C2}} = \frac{V_A}{I_O}$$

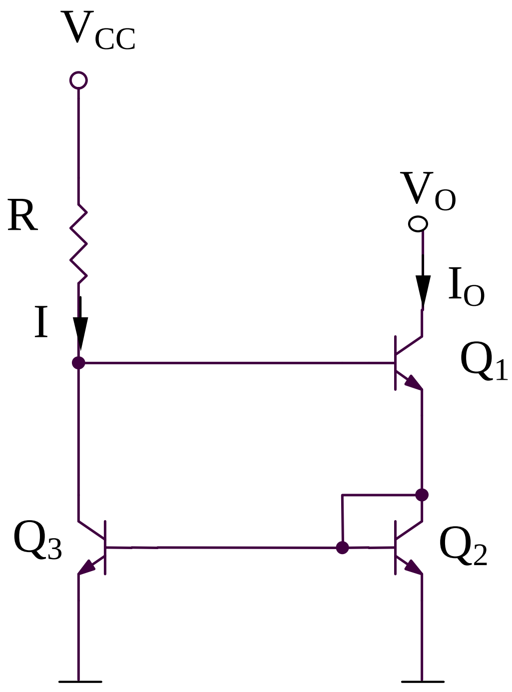
**Tensiune minima de iesire**

$$V_{O\min} = V_{CE2sat}.$$

**Influenta β**

$$\frac{I_O}{I} = \frac{\beta I_B}{\beta I_B + \frac{2I_B}{\beta + 1}} = \frac{1}{1 + \frac{2}{\beta^2 + \beta}} \cong 1$$

# Sursa de curent cu reducerea efectului β (2)




**Curent de iesire**

$$I_O \cong I = \frac{V_{CC} - 2V_{BE}}{R}$$

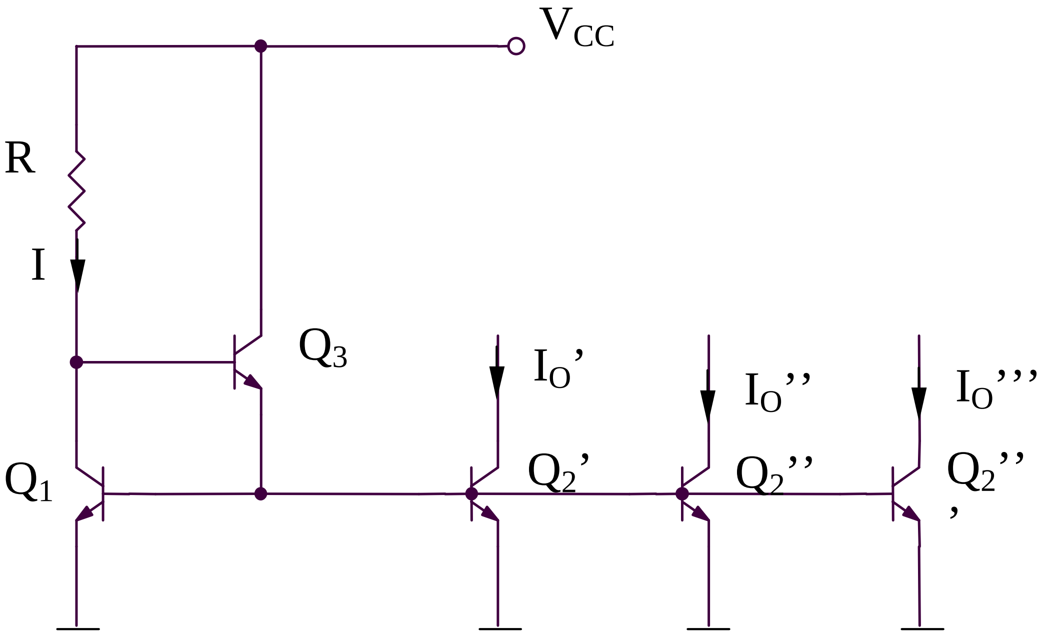
**Tensiune minima de iesire**

$$V_{O\min} = V_{BE2} + V_{CE1sat}.$$

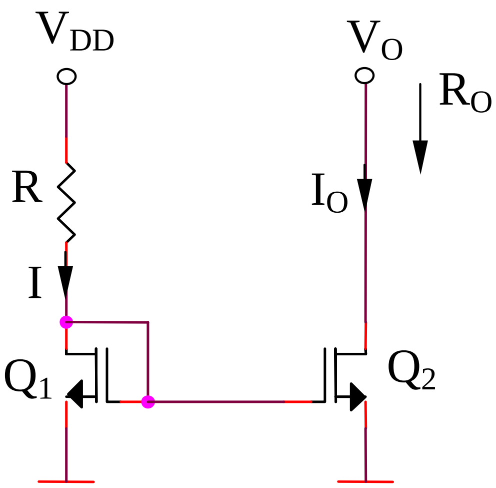
**Influenta β**

$$\frac{I_O}{I} = \frac{\frac{\beta(\beta+2)}{\beta+1} I_B}{\beta I_B + \frac{\beta+2}{\beta+1} I_B} = \frac{1}{1 + \frac{2}{\beta^2 + 2\beta}} \cong 1$$

# Sursa de curent multipla



# Oglinda de curent MOS




**Curentul de iesire**

$$\left.\begin{aligned} V_{DD} &= I_O R + V_{GS1} \\ I_O &= \frac{K}{2}\left(V_{GS1} - V_T\right)^2 \end{aligned}\right\} \Rightarrow V_{DD} = \frac{KR}{2}\left(V_{GS1} - V_T\right)^2 + V_{GS1} \Rightarrow$$

$$\Rightarrow \left(V_{GS1}\right)_{1,2} = V_T - \frac{1}{KR} \pm \frac{1}{KR}\sqrt{1 + 2KR(V_{DD} - V_T)}$$

$V_{GS}$ trebuie sa fie mai mare decat $V_T$:

$$V_{GS1} = V_T - \frac{1}{KR} + \frac{1}{KR}\sqrt{1 + 2KR\left(V_{DD} - V_T\right)}$$

$$\Rightarrow I_O = \frac{1}{KR^2}\left[1 + KR\left(V_{DD} - V_T\right) - \sqrt{1 + 2KR\left(V_{DD} - V_T\right)}\right]$$

**Rezistenta de iesire**

$$R_O = r_{ds2} = \frac{1}{\lambda I_O}$$

**Tensiunea minima de iesire**

$$V_{O\min} = V_{DS2sat} = V_{GS2} - V_T = \sqrt{\frac{2I_O}{K}}$$

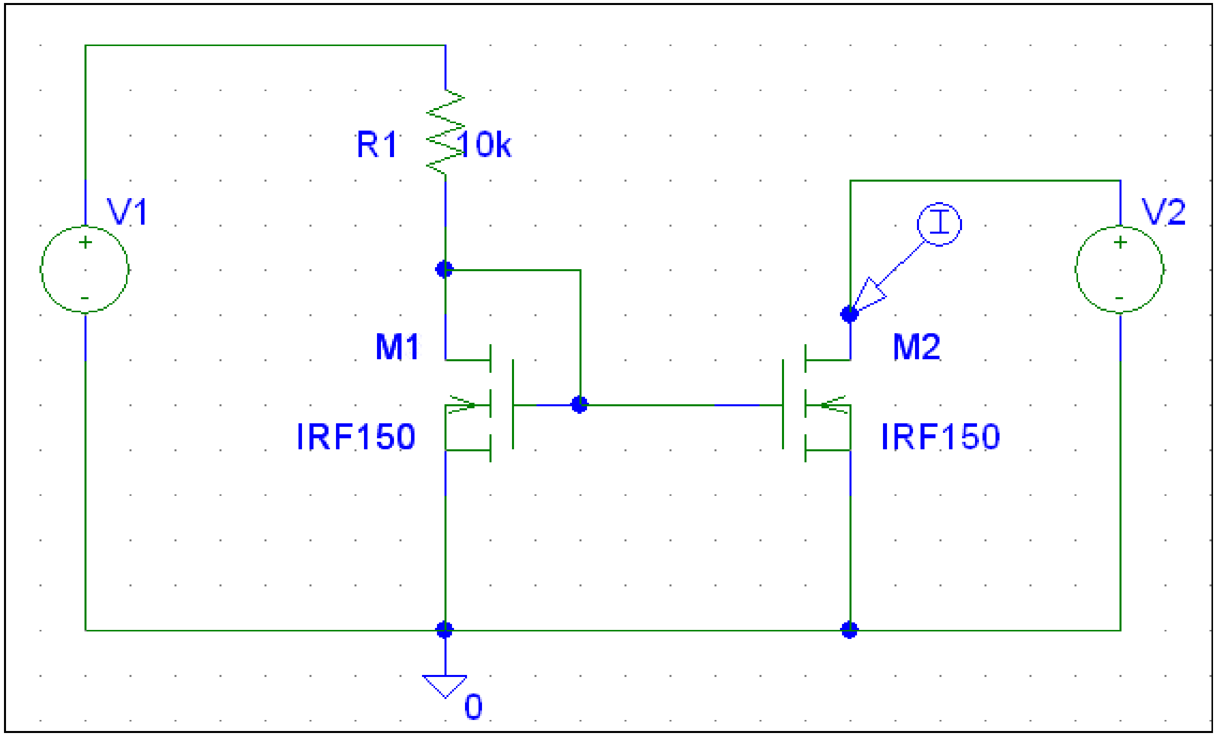
**Efectul de modulare a lungimii canalului**

$$\frac{I_O}{I} = \frac{\frac{K}{2}(V_{GS2} - V_T)^2(1 + \lambda V_{DS2})}{\frac{K}{2}(V_{GS1} - V_T)^2(1 + \lambda V_{DS1})} = \frac{1 + \lambda V_{DS2}}{1 + \lambda V_{DS1}} = \frac{1 + \lambda V_O}{1 + \lambda V_{GS1}}$$

# **SIMULARI pentru oglinda de curent CMOS**
# **Caracteristica de iesire**

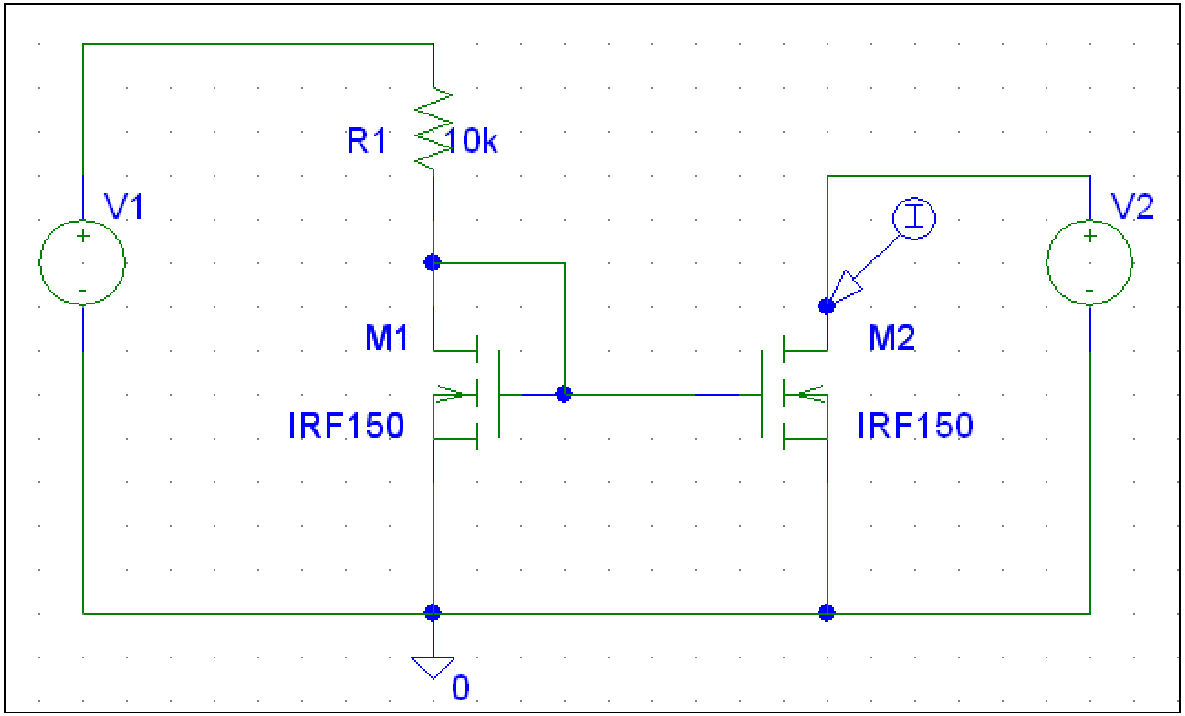
# SIMULARI pentru oglinda de curent CMOS
# Caracteristica de iesire

## SIM 3.4: $I_{D2}$ (V2)



# SIMULARI pentru oglinda de curent CMOS
# Caracteristica de iesire

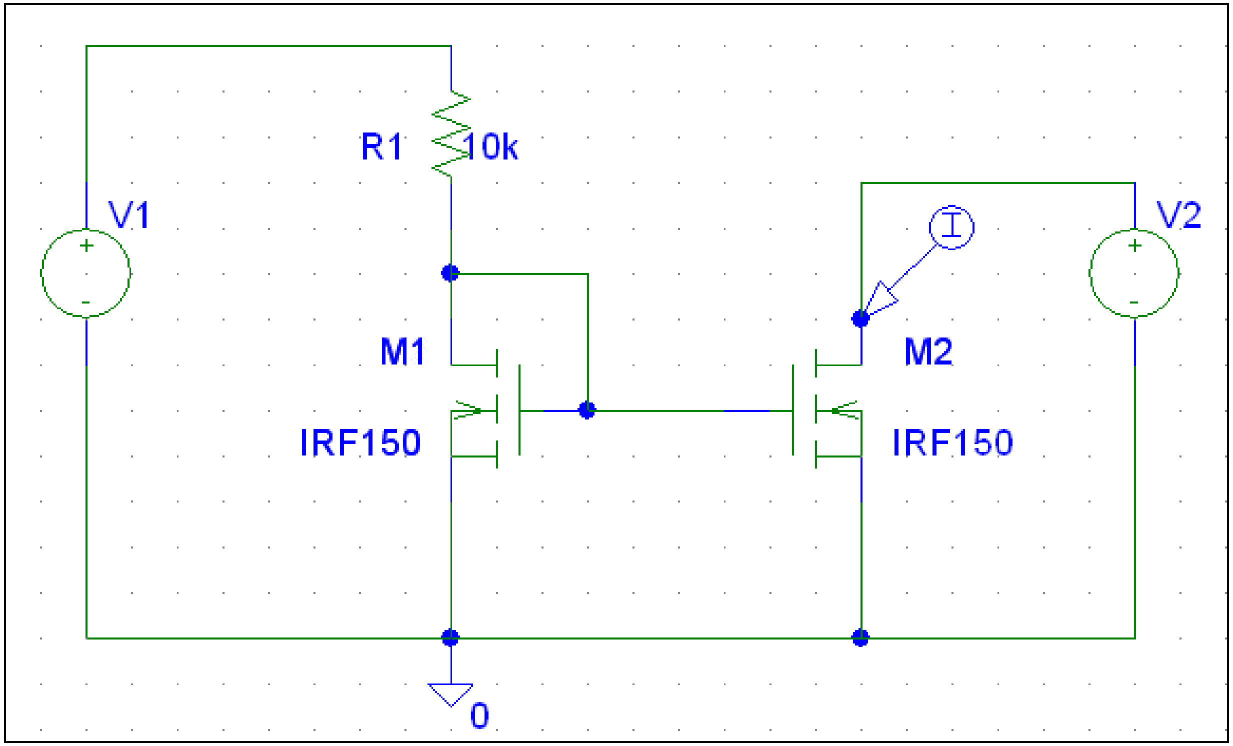
## SIM 3.5: $I_{D2}$ (V2), $r_{ds2}$ - parametru



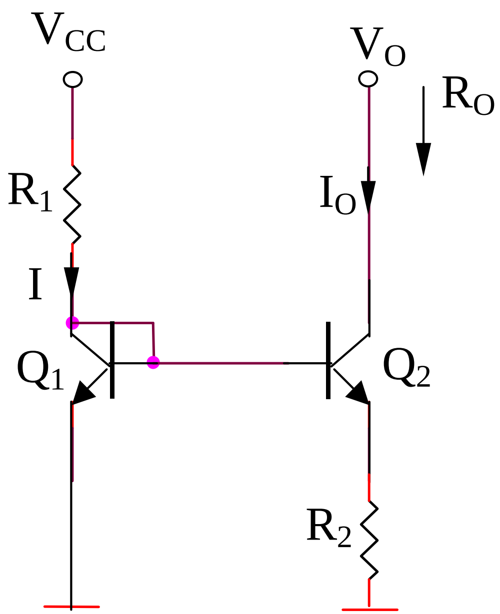
## **SIMULARI pentru oglinda de curent CMOS**
## **Dependenta curentului de iesire de tensiunea de alimentare**

# SIMULARI pentru oglinda de curent CMOS
# Dependenta curentului de iesire de tensiunea de alimentare

## SIM 3.6: $I_{D2}$ (V1)



# Sursa de curent Widlar bipolara




## Curentul de iesire

$$I = \frac{V_{CC} - V_{BE}}{R_1}$$

$$I_O = \frac{V_{BE1} - V_{BE2}}{R_2} = \frac{V_{th}\ln\left(\frac{I}{I_S}\right) - V_{th}\ln\left(\frac{I_O}{I_S}\right)}{R_2}$$

$$I_O = \frac{V_{th}}{R_2}\ln\left(\frac{I}{I_O}\right) = \frac{V_{th}}{R_2}\ln\left(\frac{V_{CC} - V_{BE}}{R_1 I_O}\right)$$

## Tensiunea minima de iesire

$$V_{O\min} = V_{CE2sat.} + I_O R_2$$

## Rezistenta de iesire

$$R_O = r_o\left(1 + \frac{\beta R_2}{r_{\pi 2} + R_2 + (1/g_{m1})//R_1}\right) = \frac{V_A}{I_O}\left(1 + \frac{\beta R_2}{r_{\pi 2} + R_2 + (1/g_{m1})//R_1}\right)$$

**PSRR**

$$\frac{dI_O}{dV_{CC}} = \frac{d}{dV_{CC}}\left[\frac{V_{th}}{R_2}\ln\left(\frac{V_{CC}-V_{BE}}{R_1 I_O}\right)\right]$$

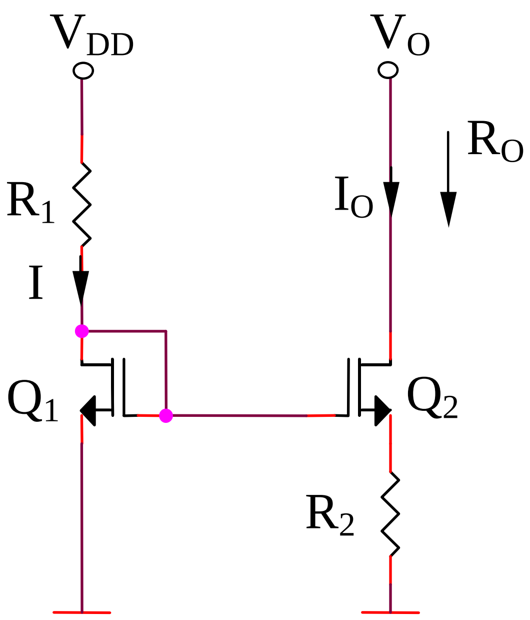
$$\frac{dI_O}{dV_{CC}} = \frac{V_{th}}{R_2}\frac{R_1 I_O}{V_{CC}-V_{BE}}\frac{R_1 I_O-(V_{CC}-V_{BE})R_1\frac{dI_O}{dV_{CC}}}{(R_1 I_O)^2}$$

$$\frac{dI_O}{dV_{CC}} = \frac{\frac{1}{R_2}\frac{V_{th}}{V_{CC}-V_{BE}}}{1+\frac{V_{th}}{R_2 I_O}}$$

**Sensibilitatea curentului de iesire in raport cu variatiile tensiunii de alimentare**

$$S_{V_{CC}}^{I_O} = \frac{V_{CC}}{I_O}\frac{dI_O}{dV_{CC}} = \frac{1}{1+\frac{R_2 I_O}{V_{th}}} = \frac{1}{1+\ln\left(\frac{V_{CC}-V_{BE}}{R_1 I_O}\right)}$$

# Sursa de curent MOS




## Curentul de iesire

$$V_{GS1} = V_T - \frac{1}{KR_1} + \frac{1}{KR_1}\sqrt{1 + 2KR_1(V_{DD} - V_T)}$$

$$V_{GS1} = V_{GS2} + I_O R_2 = V_{GS2} + \frac{KR_2}{2}(V_{GS2} - V_T)^2$$

$$(V_{GS2} > V_T)$$

$$I_O = \frac{K}{2}(V_{GS2} - V_T)^2 (1 + \lambda V_{DS2})$$

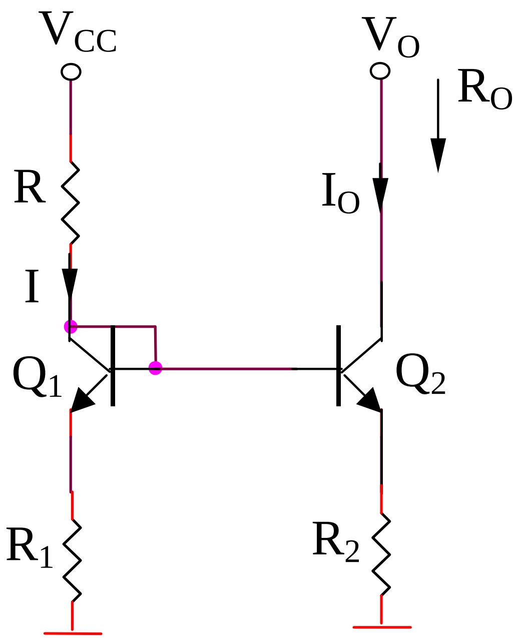
## Tensiunea minima de iesire

$$V_{O\min} = V_{DS2sat} + I_O R_2 = \sqrt{\frac{2I_O}{K}} + I_O R_2$$

## Rezistenta de iesire

$$R_O = r_{ds2}(1 + g_{m2} R_2)$$

# Sursa de curent standard




## Curentul de iesire

$$v_{BE1} + R_1 I = v_{BE2} + R_2 I_O$$

$$I_O = \frac{1}{R_2}\left(R_1 I + v_{BE1} - v_{BE2}\right)$$

$$\frac{I_O}{I} = \frac{R_1}{R_2} + \frac{V_{th}}{R_2 I}\ln\left(\frac{I}{I_O}\frac{I_{S2}}{I_{S1}}\right)$$

Se poate determina $I/I_O$ deoarece:

$$I = \frac{V_{CC} - v_{BE}}{R + R_1}$$

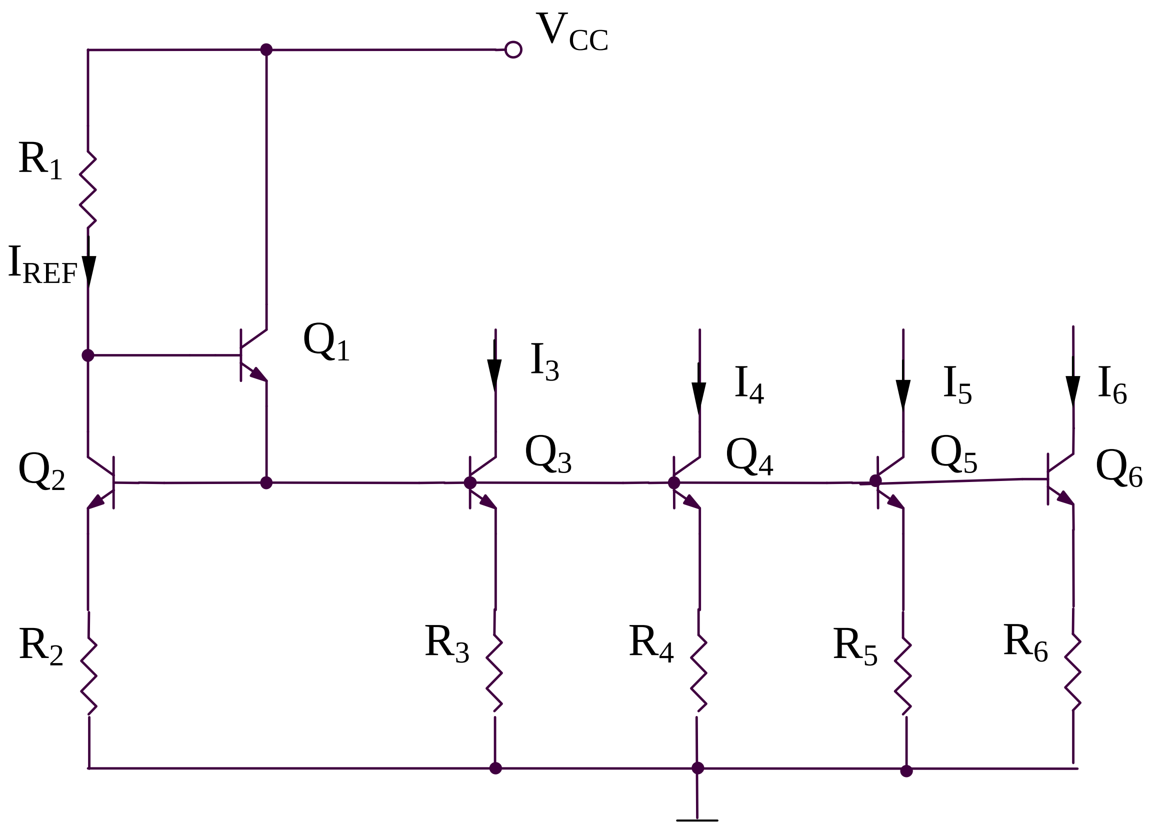
Daca $R_1 I \gg v_{BE1} - v_{BE2}$:

$$\frac{I_O}{I} = \frac{R_1}{R_2}$$

## Rezistenta de iesire

$$R_O = r_{o2}\left(1 + \frac{\beta R_2}{R_2 + r_{\pi 2} + R // (1/g_{m1} + R_1)}\right)$$

# Sursa de curent standard cu iesire multipla




Daca ariile tranzistoarelor sunt alese in asa fel incat densitatile de curent sa fie egale, atunci tensiunile baza-emitor vor fi egale.

$$v_{BE2} - v_{BE3} = V_{th}\ln\left(\frac{I_{REF}}{I_3}\frac{I_{S3}}{I_{S2}}\right) = V_{th}\ln\left(\frac{jA_2}{jA_3}\frac{A_3}{A_2}\right) = 0$$

Deci:

$$v_{BE2} = \ldots = v_{BE6}$$

si:

$$I_3 R_3 = I_4 R_4 = I_5 R_5 = I_6 R_6 = I_{REF} R_2$$

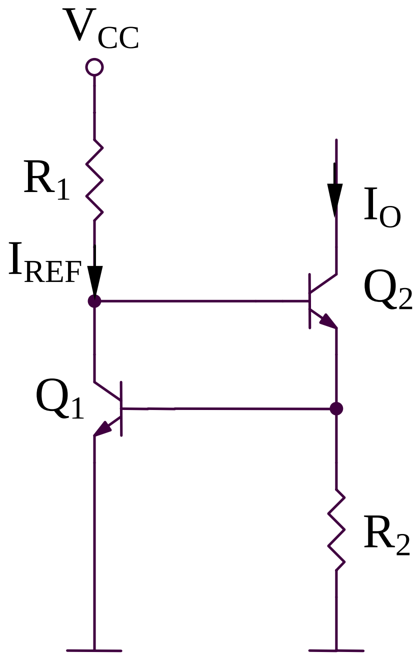
Cei patru curenti de iesire au expresiile:

$$I_3 = I_{REF}\frac{R_2}{R_3};\ \ldots\ ; I_6 = I_{REF}\frac{R_2}{R_6}$$

unde:

$$I_{REF} = \frac{V_{CC} - 2v_{BE}}{R_1 + R_2}$$

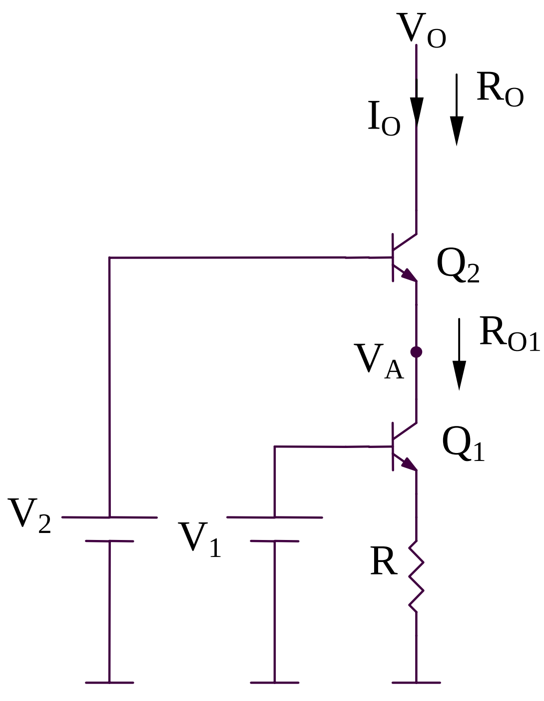
# Sursa de curent utilizand ca referinta tensiunea baza-emitor




$$I_O = \frac{v_{BE1}}{R_2} = \frac{V_{th}}{R_2} \ln \frac{V_{CC} - 2v_{BE}}{R_1 I_S}$$

# 3.1.3. Surse de curent cascod

## Sursa de curent cascod bipolara (1)




**Curentul de iesire**

$$I_O = \frac{V_1 - V_{BE1}}{R}$$

**Rezistenta de iesire**

$$R_O = r_{o2}\left(1 + \frac{\beta R_{O1}}{r_{\pi 2} + R_{O1}}\right) \cong \beta r_{O2}$$

$$R_{O1} = r_{o1}\left(1 + \frac{\beta R}{r_{\pi 1} + R}\right) >> r_{\pi 2}$$

**Tensiune minima de iesire**

$$V_{O\min} = V_A + V_{CE2sat} = V_2 - V_{BE2} + V_{CE2sat}$$

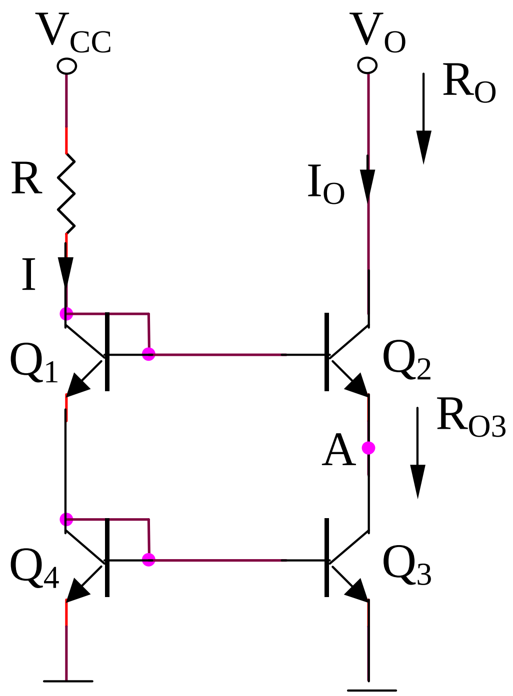
Este necesar ca:

$$V_{CE1} > V_{CE1sat} \Leftrightarrow$$

$$\Leftrightarrow (V_2 - V_{BE2}) - (V_1 - V_{BE1}) > V_{CE1sat} \Leftrightarrow$$

$$\Leftrightarrow V_2 - V_1 > V_{CE1sat}$$

# Sursa de curent cascod bipolara (2)




**Curentul de iesire**

$$I_O = I = \frac{V_{CC} - 2v_{BE}}{R}$$

**Rezistenta de iesire**

$$R_O = r_{o2}\left(1 + \beta \frac{R_{O3}}{r_{\pi 2} + R_{O3} + R//(2/g_{m1})}\right)$$

$$R_{O3} = r_{o3} >> r_{\pi 2}, R//(2/g_{m1})$$

Deci:

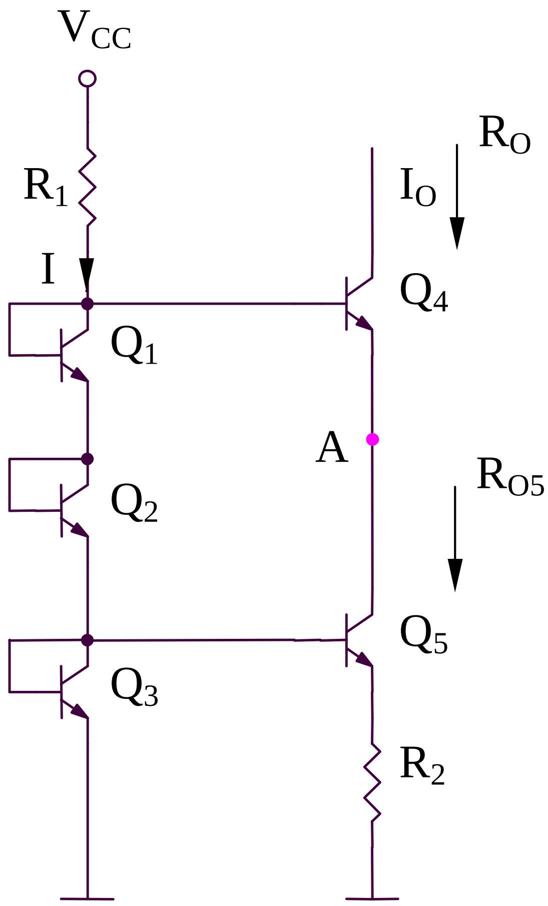
$$R_O \cong \beta r_{o2}$$

**Tensiunea minima de iesire**

$$V_{O\min} = V_A + V_{CE2sat}$$

$$V_A = v_{BE1} + v_{BE4} - v_{BE2} = v_{BE}$$

# Sursa de curent cascod bipolara(3)




**Curentul de iesire**

$$I_O = \frac{v_{BE3} - v_{BE5}}{R_2} = \frac{V_{th}}{R_2}\ln\left(\frac{I}{I_O}\right)$$

$$I = \frac{V_{CC} - 3v_{BE}}{R_1}$$

**Rezistenta de iesire**

$$R_O = r_{o4}\left(1 + \beta\frac{R_{O5}}{r_{\pi 4} + R_{O5} + R_1 // (3/g_{m1})}\right)$$

$$R_{O5} \cong r_{o5}\left(1 + \frac{\beta R_2}{r_{\pi 5} + R_2 + 1/g_{m3}}\right)$$

$$R_{O5} >> r_{\pi 4}, R_1 // (3/g_{m1})$$

Deci:

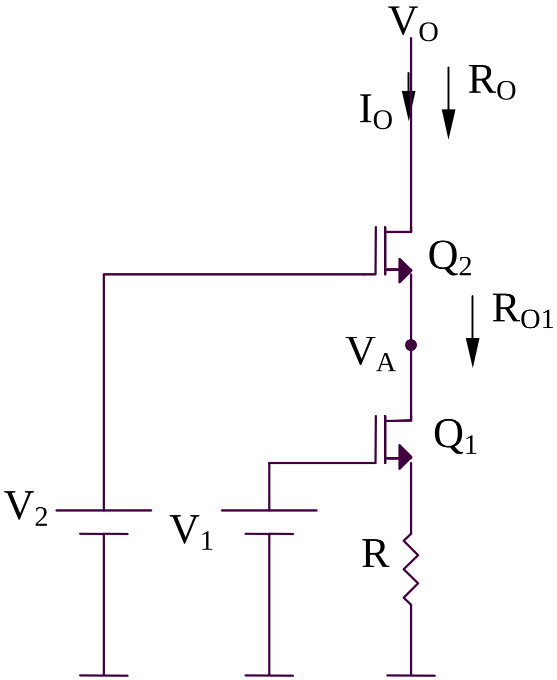
$$R_O \cong \beta r_{o4}$$

**Tensiunea minima de iesire**

$$V_{O\min} = V_A + V_{CE4sat}$$

$$V_A = 2v_{BE}$$

# Sursa de curent cascod MOS (1)




## Curentul de iesire

$$\left.\begin{array}{l} V_1 = V_{GS1} + I_O R \\ I_O = \frac{K}{2}\left(V_{GS1} - V_T\right)^2 \end{array}\right\} \Rightarrow V_1 = V_{GS1} + \frac{KR}{2}\left(V_{GS1} - V_T\right)^2$$

$$\Rightarrow V_{GS1}\left(> V_T\right) \Rightarrow I_O$$

## Rezistenta de iesire

$$R_O = r_{ds2}\left(1 + g_m R_{O1}\right) \cong g_m r_{ds}^2$$

$$R_{O1} = r_{ds1}\left(1 + g_m R\right)$$

## Tensiunea minima de iesire

$$V_{O\,min} = V_2 - V_{GS2} + \left(V_{GS2} - V_T\right) = V_2 - V_T$$

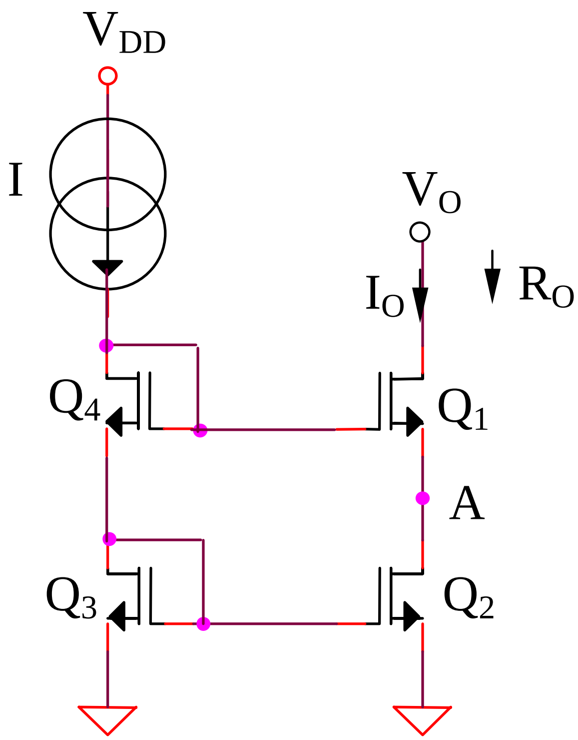
Este necesar ca:

$$V_{DS1} > V_{DS1sat} \Leftrightarrow$$

$$\Leftrightarrow \left(V_2 - V_{GS2}\right) - \left(V_1 - V_{GS1}\right) > V_{DS1sat} \Leftrightarrow$$

$$\Leftrightarrow V_2 - V_1 > V_{DS1sat} = V_{GS} - V_T = \sqrt{\frac{2I_O}{K}}$$

# Sursa de curent cascod MOS (2)




**Curentul de iesire**

$$\frac{I_O}{I} = \frac{1+\lambda V_{DS2}}{1+\lambda V_{DS3}}$$

**Rezistenta de iesire**

$$R_O = r_{ds1}\left(1+g_{m1}r_{ds2}\right) \cong g_m r_{ds}^2$$

**Tensiunea minima de iesire**

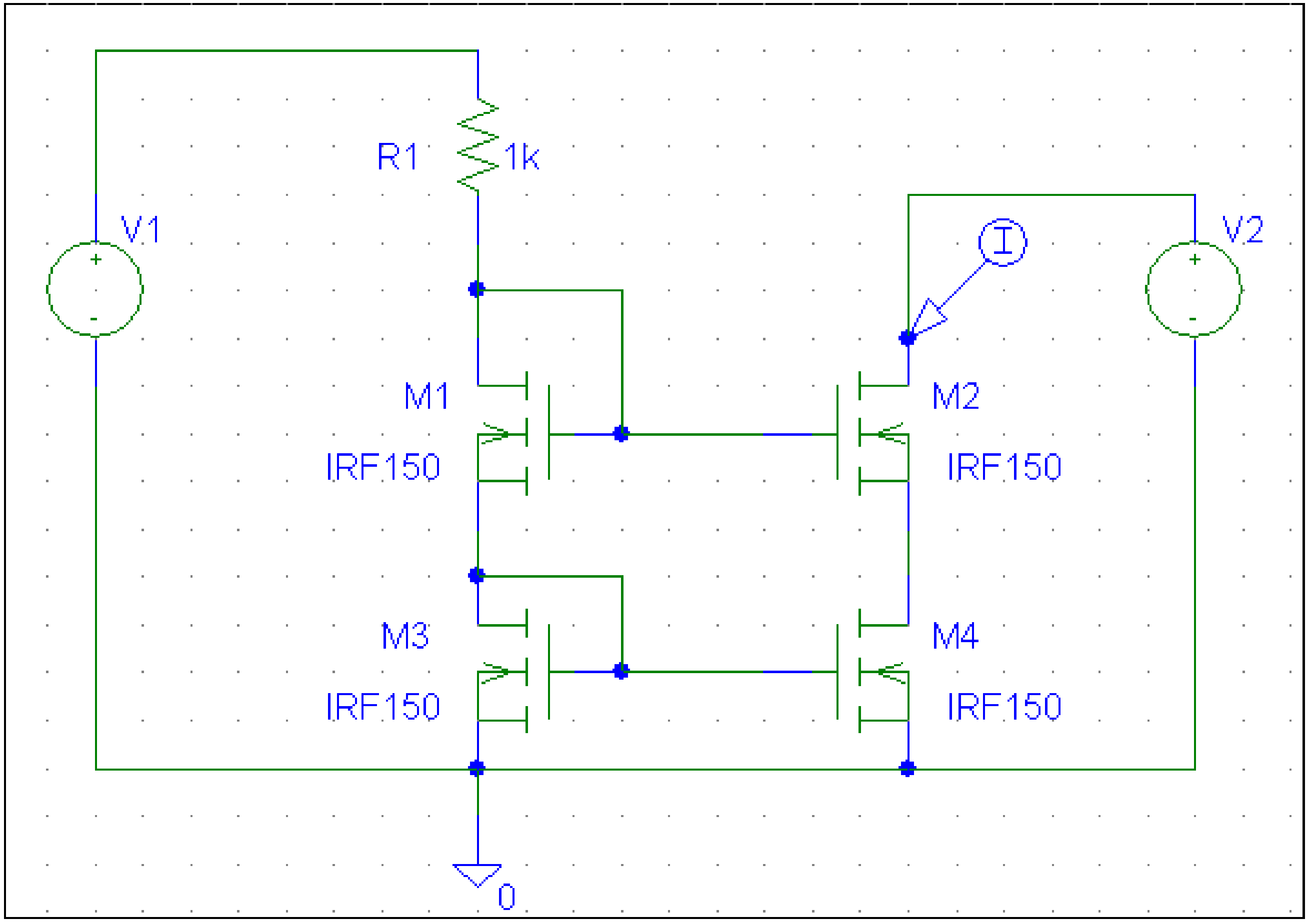
$$V_{O\min} = V_A + V_{DS1sat} = V_{GS} + \left(V_{GS} - V_T\right)$$

$$V_{O\min} = 2V_{GS} - V_T \cong V_T + 2\sqrt{\frac{2I}{K}}$$

# SIMULARI pentru oglinda de curent CMOS cascod
# Caracteristica de iesire

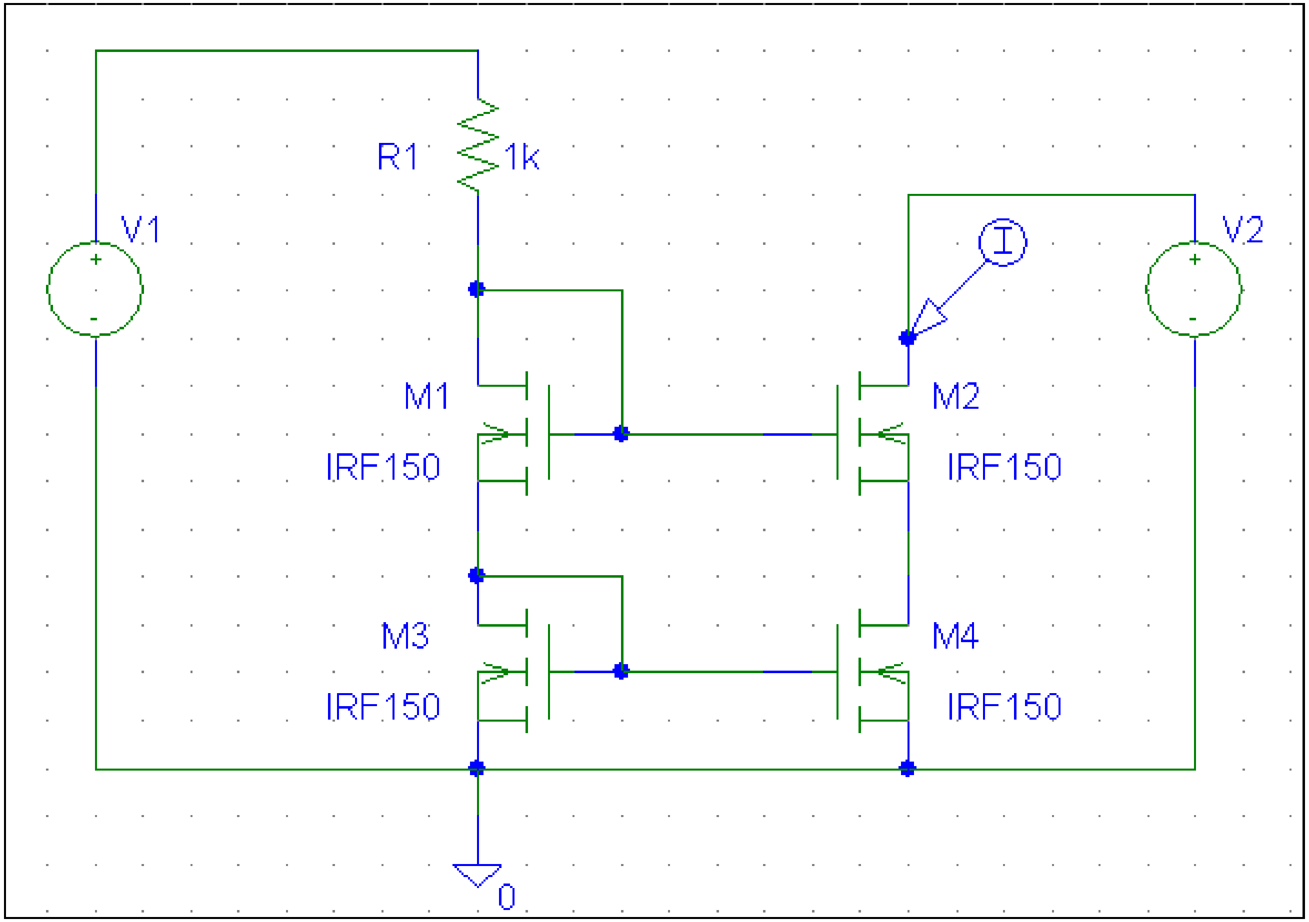
# SIMULARI pentru oglinda de curent CMOS cascod
# Caracteristica de iesire

## SIM 3.7: $I_{D2}$ (V2)



# SIMULARI pentru oglinda de curent CMOS cascod
# Caracteristica de iesire

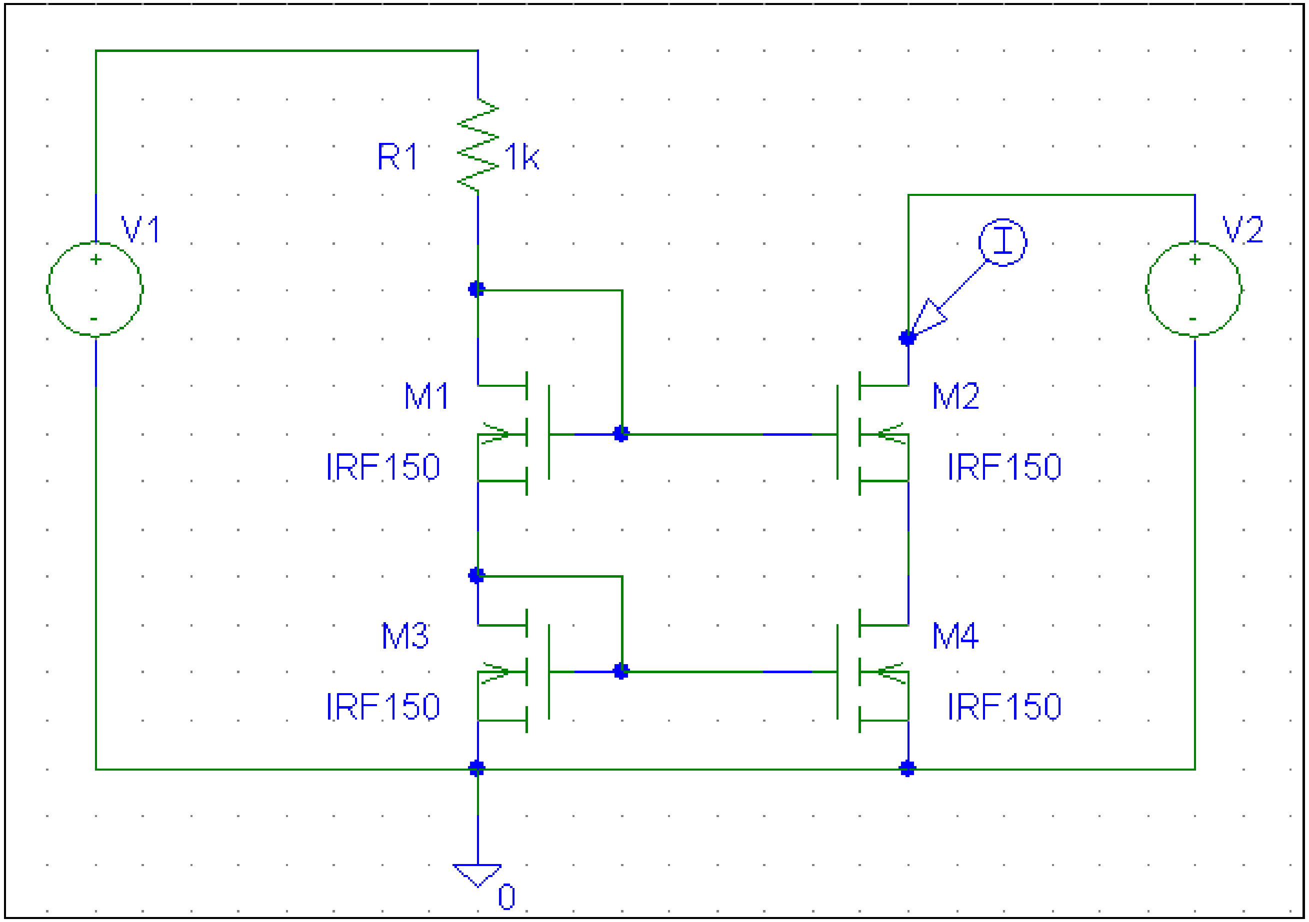
## SIM 3.8: $I_{D2}$ (V2), $r_{ds2}$, $r_{ds4}$ - parametri



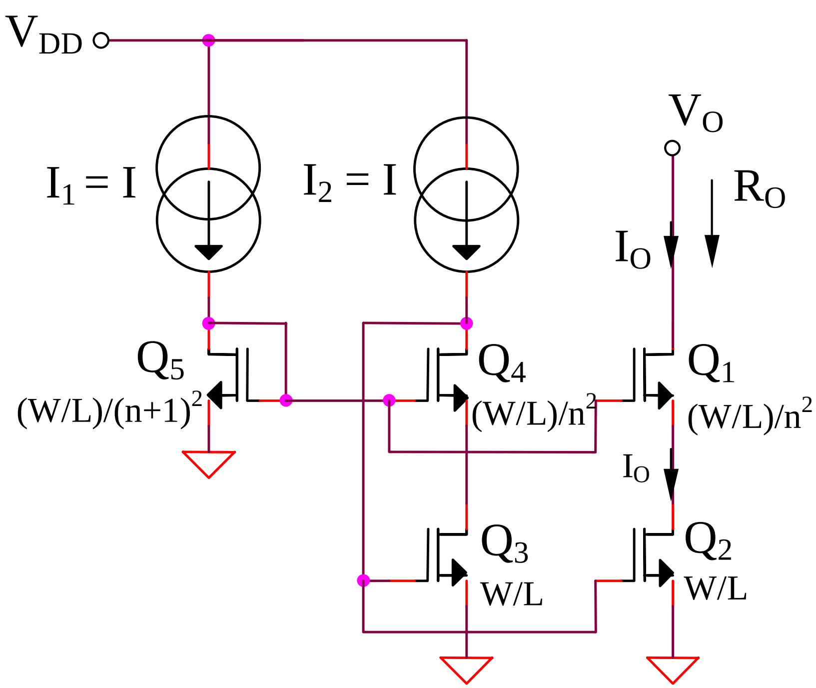
## **SIMULARI pentru oglinda de curent CMOS cascod**
## **Dependenta curentului de iesire de tensiunea de alimentare**

# SIMULARI pentru oglinda de curent CMOS cascod
# Dependenta curentului de iesire de tensiunea de alimentare

## SIM 3.9: $I_{D2}$ (V1)



# Sursa de curent cascod MOS (3)




**Curentul de iesire**

$$I_O = I$$

**Rezistenta de iesire**

$$R_0 = r_{ds1}\left(1 + g_{m1} r_{ds2}\right) \cong g_m r_{ds}^2$$

**Tensiunea minima de iesire**

$$\left.\begin{aligned} I &= \frac{K'}{2}\frac{W/L}{(n+1)^2}\left(V_{GS5} - V_T\right)^2 \\ I &= \frac{K'}{2}\frac{W/L}{n^2}\left(V_{GS1(4)} - V_T\right)^2 \\ I &= \frac{K'}{2}(W/L)\left(V_{GS2(3)} - V_T\right)^2 \end{aligned}\right\} \Rightarrow$$

$$\Rightarrow \begin{cases} V_{GS5} - V_T = (n+1)(V_{GS2(3)} - V_T) \\ V_{GS1(4)} - V_T = n(V_{GS2(3)} - V_T) \end{cases}$$

Tensiunea drena-sursa a tranzistorului $Q_2$ este:

$$V_{DS2} = V_{GS5} - V_{GS1} = (V_{GS5} - V_T) - (V_{GS1} - V_T) = V_{GS2} - V_T = V_{DS2sat}$$

Deci, $Q_2$ este polarizat la limita de saturatie. Rezulta:

$$V_{O\min} = V_{DS1sat} + V_{DS2} = (n+1)(V_{GS2} - V_T) = (n+1)\sqrt{\frac{2I}{K}}$$

## 3.1.4. Surse de curent cu autopolarizare

### Oglinda de curent

$$I_O = \frac{V_{CC} - v_{BE}}{R}$$

$$S_{V_{CC}}^{I_O} = \frac{V_{CC}}{I_O}\frac{\partial I_O}{\partial V_{CC}} \cong 1$$

### Sursa de curent Widlar bipolara

$$I_O = \frac{V_{th}}{R_2}\ln\frac{I}{I_O}$$

$$\frac{\partial I_O}{\partial V_{CC}} = \frac{V_{th}}{R_2}\frac{I_O}{I}\left(\frac{1}{I_O}\frac{\partial I}{\partial V_{CC}} - \frac{I}{I_O^2}\frac{\partial I_O}{\partial V_{CC}}\right)$$

$$\frac{\partial I_O}{\partial V_{CC}} = \frac{\dfrac{V_{th}}{IR_2}}{1 + \dfrac{V_{th}}{R_2 I_O}}\frac{\partial I}{\partial V_{CC}}$$

$$S_{V_{CC}}^{I_O} = \frac{V_{CC}}{I_O}\frac{\partial I_O}{\partial V_{CC}} = \frac{V_{CC}}{I}\frac{1}{1 + \dfrac{R_2 I_O}{V_{th}}}\frac{\partial I}{\partial V_{CC}} \cong \frac{1}{1 + \dfrac{R_2 I_O}{V_{th}}}$$

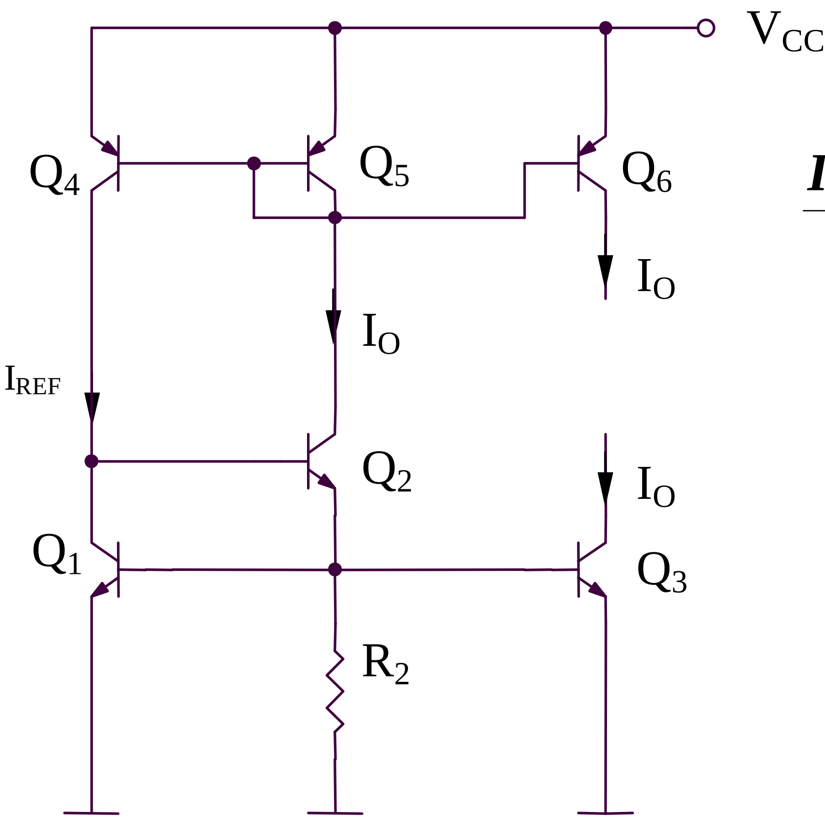
# Sursa de curent utilizand ca referinta tensiunea baza-emitor

$$I_O = \frac{V_{th}}{R_2} \ln \frac{V_{CC} - 2v_{BE}}{R_1 I_S}$$

$$\frac{\partial I_O}{\partial V_{CC}} \cong \frac{V_{th}}{R_2} \frac{R_1 I_S}{V_{CC} - 2v_{BE}} \frac{1}{R_1 I_S}$$

$$S_{V_{CC}}^{I_O} \cong \frac{V_{th}}{v_{BE}} \cong 4\%$$

# Sursa de curent cu autopolarizare utilizand ca referinta tensiunea baza-emitor




$$\left.\begin{aligned} I_O &= \frac{v_{BE1}}{R_2} = \frac{V_{th}}{R_2}\ln\frac{I_{REF}}{I_S} \\ \frac{I_{REF}}{I_O} &= \frac{1+\frac{V_{CC}-2v_{BE}}{V_A}}{1+\frac{v_{BE}}{V_A}} \cong 1+\frac{V_{CC}-2v_{BE}}{V_A} \end{aligned}\right\} \Rightarrow$$

$$\Rightarrow I_O = \frac{V_{th}}{R_2}\ln\frac{I_O}{I_S} + \frac{V_{th}}{R_2}\ln\left(1+\frac{V_{CC}-2v_{BE}}{V_A}\right)$$

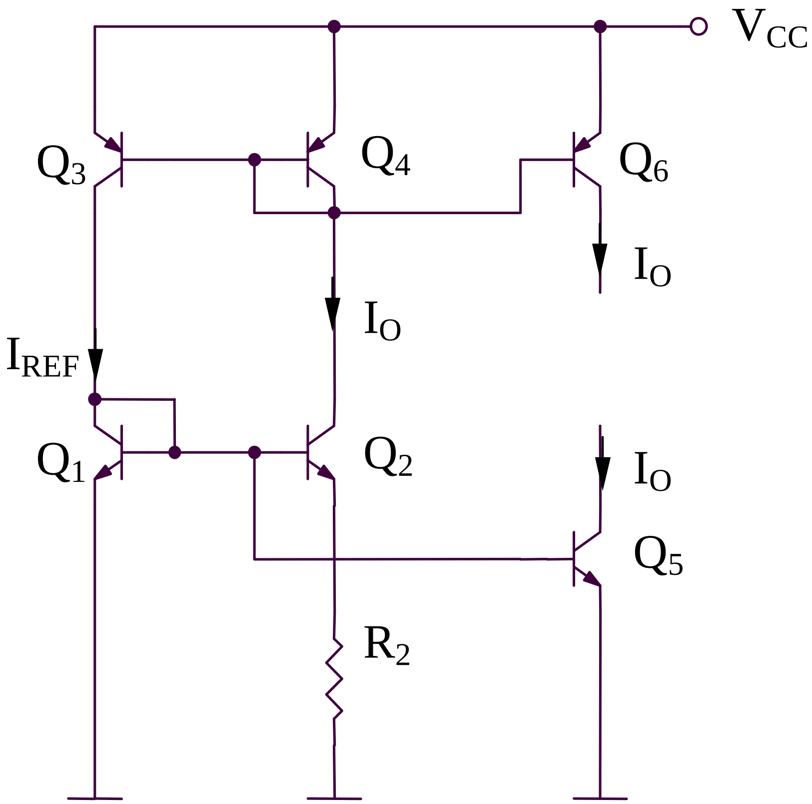
Derivand:

$$\frac{\partial I_O}{\partial V_{CC}} = \frac{V_{th}}{R_2(V_A+V_{CC})}$$

rezulta:

$$S_{V_{CC}}^{I_O} \cong \frac{V_{th}}{v_{BE}}\frac{1}{1+\frac{V_A}{V_{CC}}}$$

# Sursa de curent Widlar cu autopolarizare



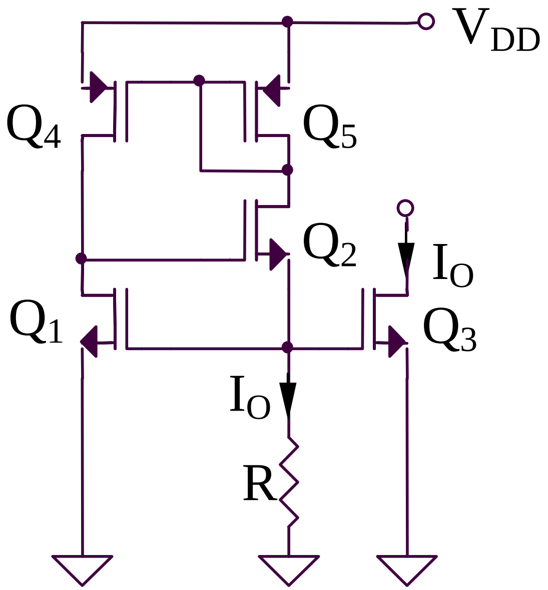

$$I_O = \frac{v_{BE1} - v_{BE2}}{R_2}$$

$$I_O = \frac{V_{th}}{R_2}\ln\left(\frac{I_{REF}}{I_O}\right) + \frac{V_{th}}{R_2}\ln\left(\frac{I_{S2}}{I_{S1}}\right)$$

$$I_O \cong \frac{V_{th}}{R_2}\ln\left(1 + \frac{V_{CC}}{V_A}\right) + \frac{V_{th}}{R_2}\ln\left(\frac{I_{S2}}{I_{S1}}\right)$$

$$S_{V_{CC}}^{I_O} \cong \frac{V_{CC}}{V_A}\frac{1}{\ln\left(\frac{I_{S2}}{I_{S1}}\right)}$$

# Sursa de curent MOS cu autopolarizare (1)




**Curentul de iesire**

$$I_O = \frac{V_{GS}}{R} = \frac{K}{2}\left(V_{GS} - V_T\right)^2$$

$$\frac{KR}{2}V_{GS}^2 - \left(1 + KRV_T\right)V_{GS} + \frac{KR}{2}V_T^2 = 0$$

Rezolvand ecuatia pentru $V_{GS}$ rezulta:

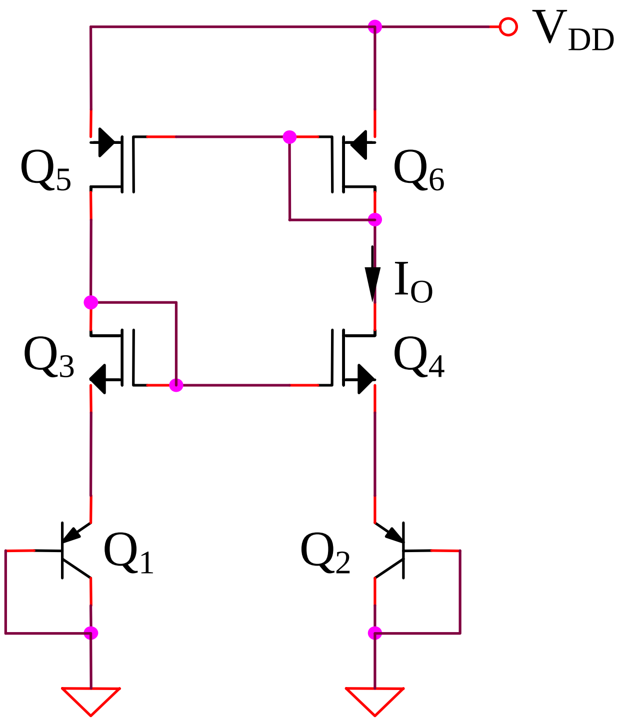
$$V_{GS1,2} = V_T + \frac{1}{KR} \pm \frac{\sqrt{2KRV_T + 1}}{KR}$$

$$V_{GS} = V_T + \frac{1}{KR} + \frac{\sqrt{2KRV_T + 1}}{KR}$$

Deci:

$$I_O = \frac{1}{KR^2}\left(1 + KRV_T + \sqrt{1 + 2KRV_T}\right)$$

# Sursa de curent MOS cu autopolarizare (2)




**Curentul de iesire**

$$V_T + \sqrt{\frac{2I_O}{4K}} + V_{th}\, ln\left(\frac{I_O}{I_S}\right) =$$

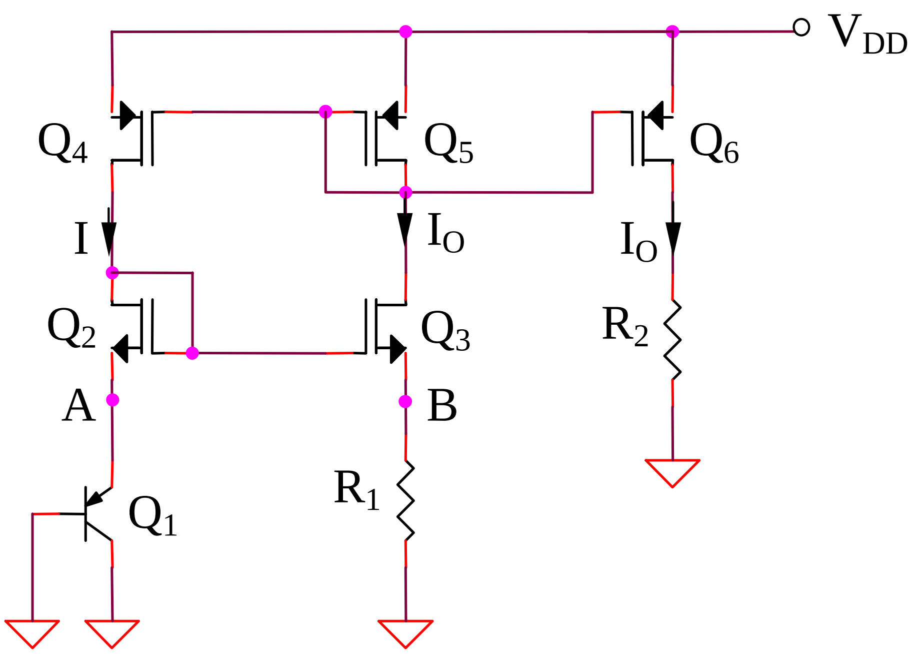
$$= V_T + \sqrt{\frac{2I_O}{K}} + V_{th}\, ln\left(\frac{I_O}{10 I_S}\right)$$

Rezulta:

$$I_O = 2K\left[V_{th}\, ln(10)\right]^2$$

$$V_{th} = \frac{kT}{q}$$ - tensiunea termica

# Sursa de curent MOS cu autopolarizare (3)




**Curentul de iesire**

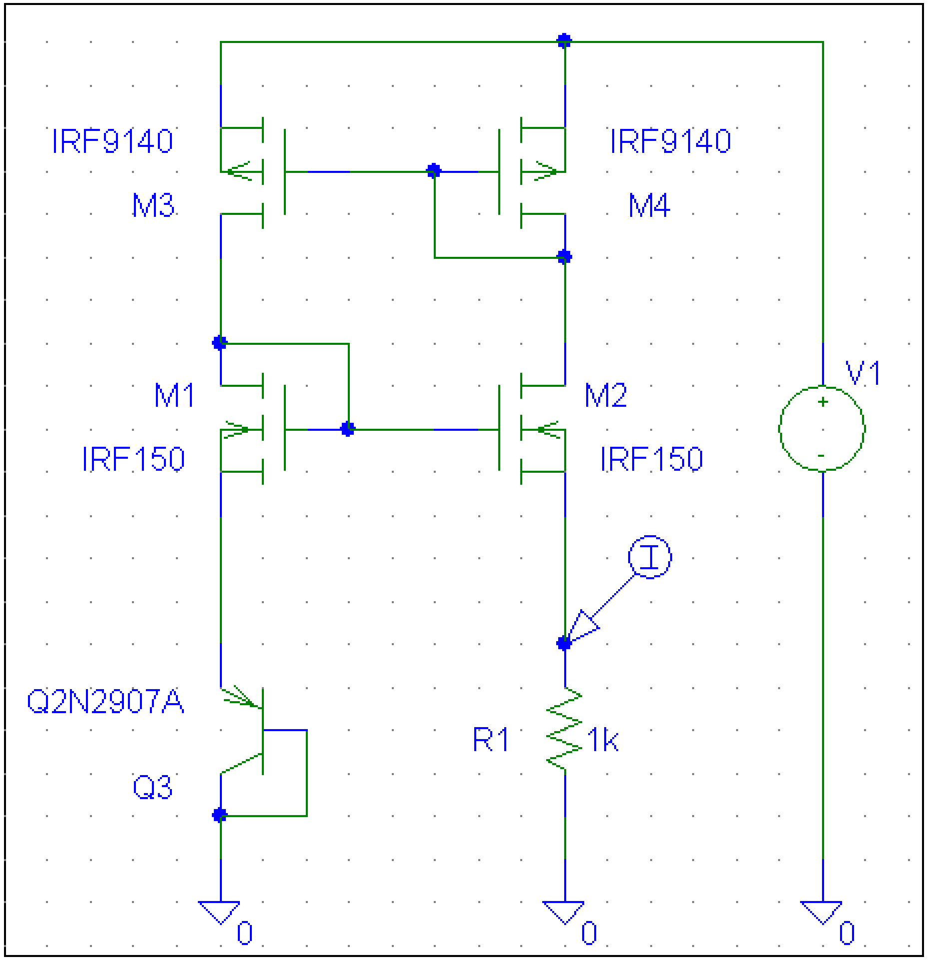
Pentru tranzistoare MOS identice, $V_A = V_B$, deci:

$$I_O = \frac{V_{EB1}}{R_1}$$

# SIMULARI pentru sursa de curent MOS cu autopolarizare (3)
## Dependenta curentului de iesire de tensiunea de alimentare

# SIMULARI pentru sursa de curent MOS cu autopolarizare (3)
# Dependenta curentului de iesire de tensiunea de alimentare

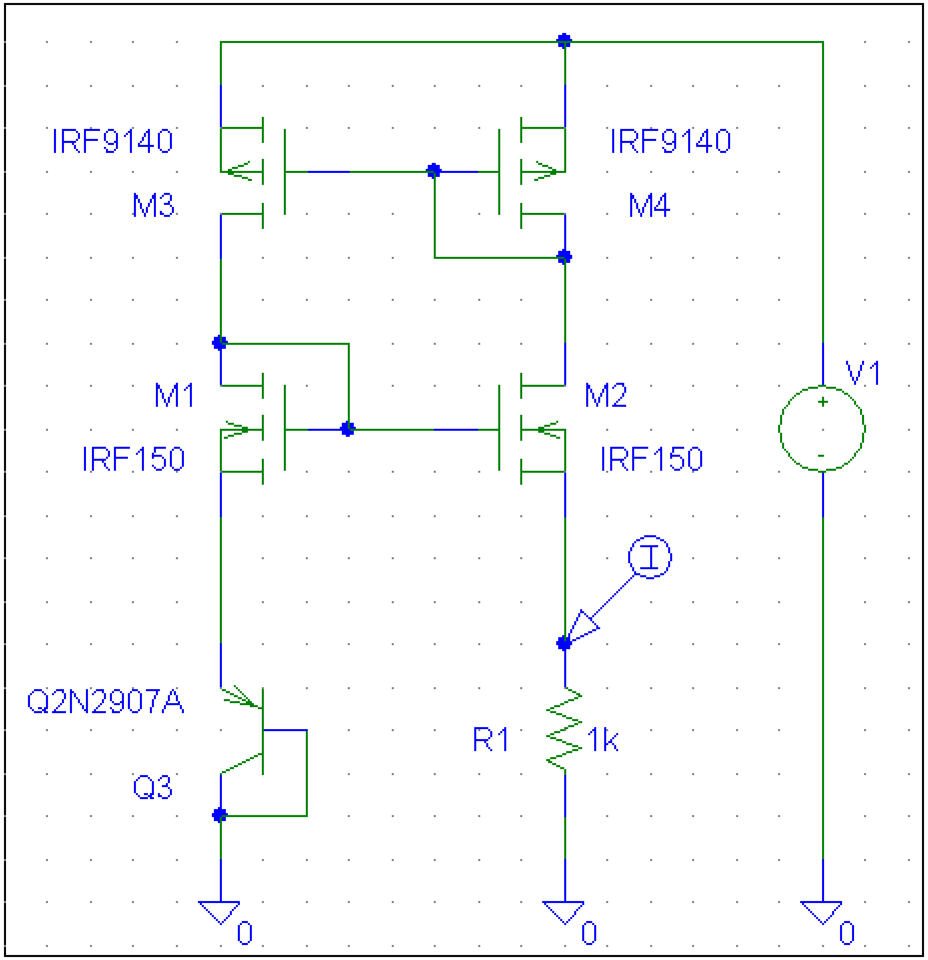
## SIM 3.10: $I_{D2}$ (V1)



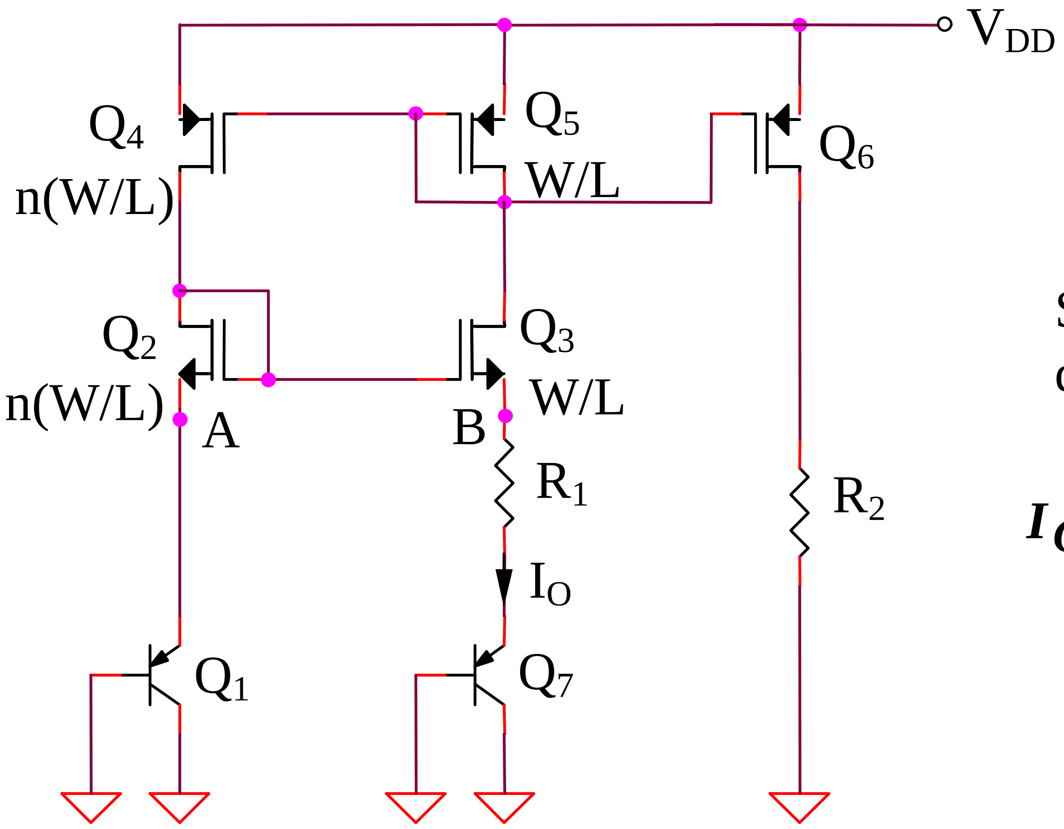
# <u>SIMULARI pentru sursa de curent MOS cu autopolarizare (3)</u>
# <u>Dependenta curentului de iesire de temperatura</u>

# SIMULARI pentru sursa de curent MOS cu autopolarizare (3) Dependenta curentului de iesire de temperatura

## SIM 3.11: $I_{D2}$ (t)



# Sursa de curent MOS cu autopolarizare (4)




**Curentul de iesire**

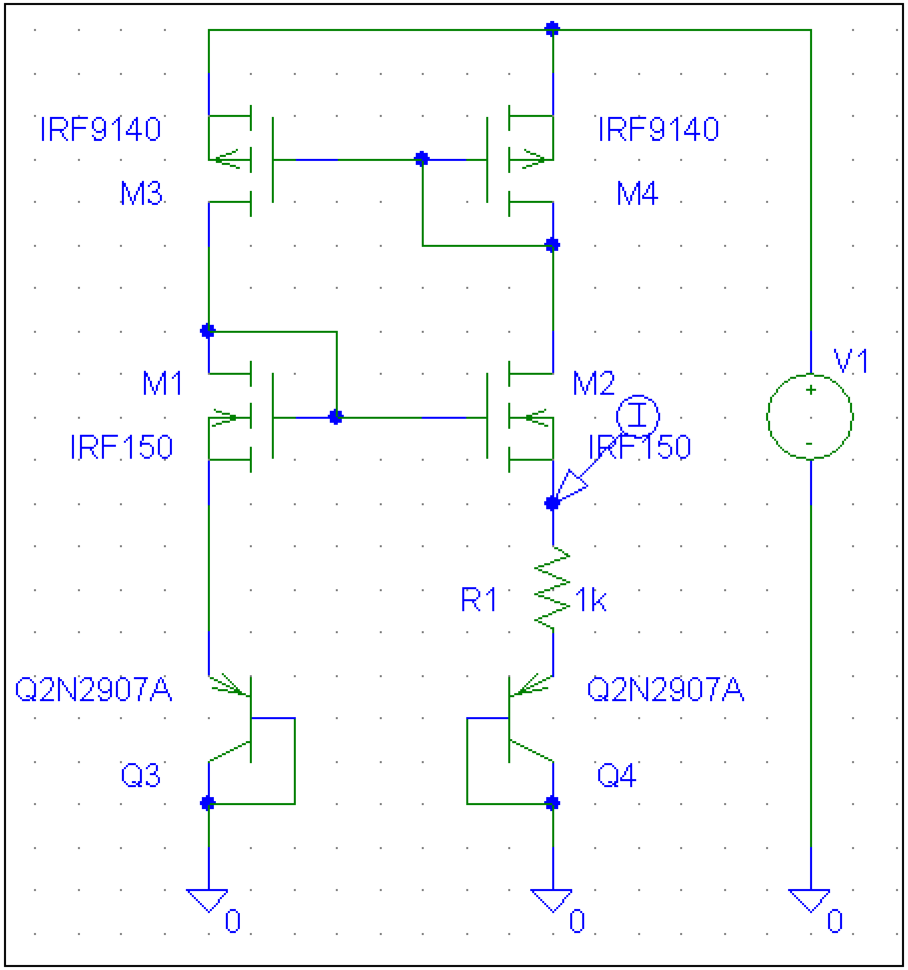
Se poate demostra ca $V_A = V_B$, deci:

$$I_O = \frac{|V_{BE1}| - |V_{BE7}|}{R_1} = \frac{V_{th}}{R_1} ln(n)$$

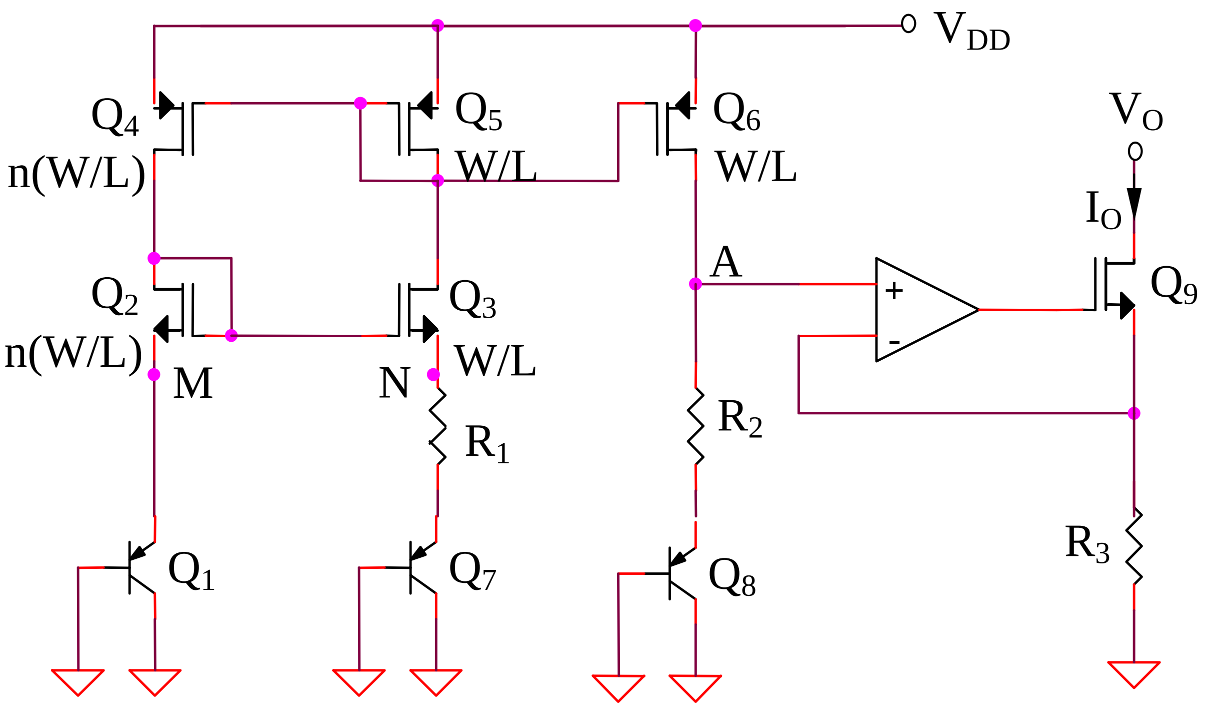
# <u>SIMULARI pentru sursa de curent MOS cu autopolarizare (4)</u>
# <u>Dependenta curentului de iesire de temperatura</u>

# SIMULARI pentru sursa de curent MOS cu autopolarizare (4)
# Dependenta curentului de iesire de temperatura

## SIM 3.12: $I_{D2}$ (t)



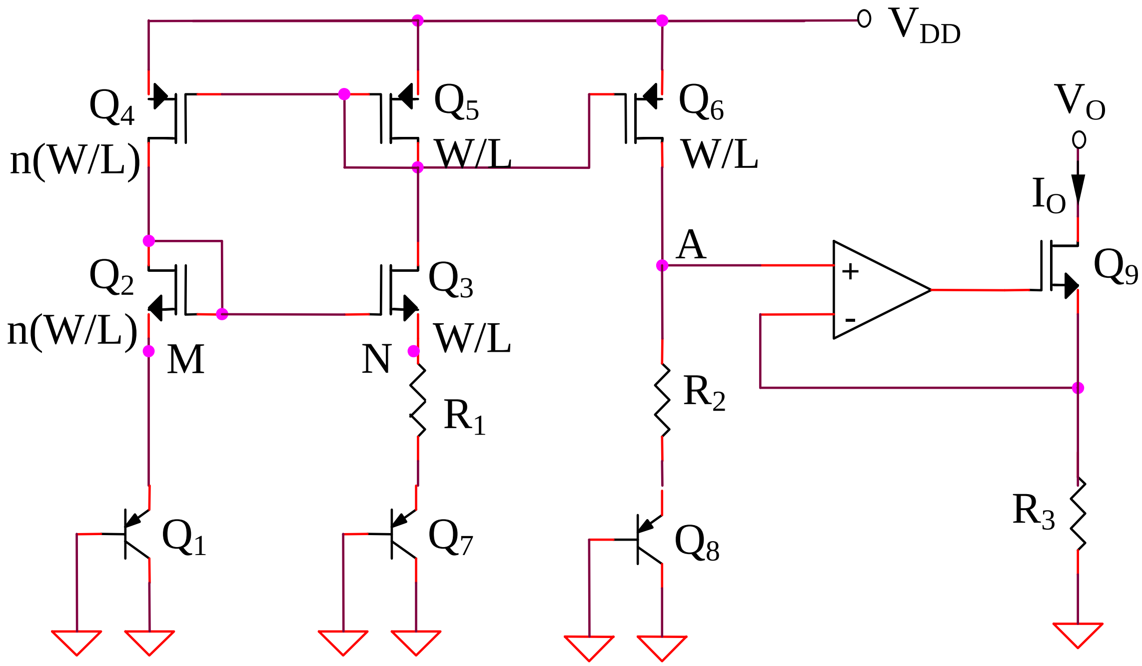
# Sursa de curent MOS cu autopolarizare (5)




$$\left.\begin{array}{l} V_{GS2} = V_{GS3} \\ V_{R_2} = R_2 \dfrac{V_{EB1} - V_{EB7}}{R_1} = \dfrac{R_2}{R_1} V_{th} \ln(n) \end{array}\right\} \Rightarrow I_O(T) = \frac{I}{R_3}\left[\frac{R_2}{R_1} V_{th} \ln(n) + V_{EB8}(T)\right]$$

$$V_{EB}(T) = A + BT + CT \ln\left(\frac{T}{T_O}\right)$$

# Sursa de curent MOS cu autopolarizare (5) – cont.




$$\Rightarrow I_O(T) = \frac{I}{R_3}\left[\frac{R_2}{R_1}\frac{kT}{q}\ln(n) + A + BT + CT\ln\left(\frac{T}{T_O}\right)\right]$$

Conditia de corectie liniara a caracteristicii poate fi scrisa astfel:

$$B + \frac{R_2}{R_1}\frac{k}{q}\ln(n) = 0$$

Rezulta:

$$I_O(T) = \frac{I}{R_3}\left[A + CT\ln\left(\frac{T}{T_O}\right)\right]$$

# 3.2. Surse de tensiune

# 3.2. Surse de tensiune

## 3.2.1. Clasificare

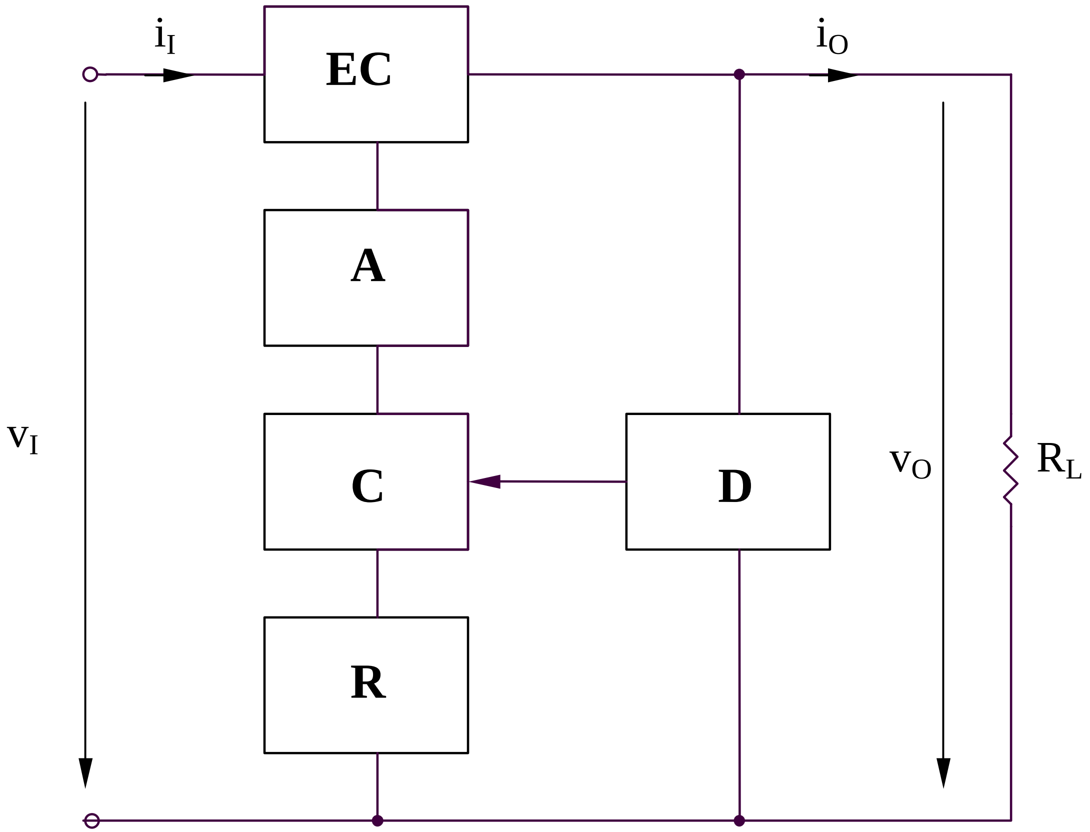
I. Surse de tensiune elementare
- complexitate redusa
- performante modeste

II. Surse de tensiune cu reactie
- rezistenta de iesire redusa
- complexitate medie

III. Surse de tensiune compensate cu temperatura
- dependenta redusa de temperatura a tensiunii de iesire
- complexitate ridicata

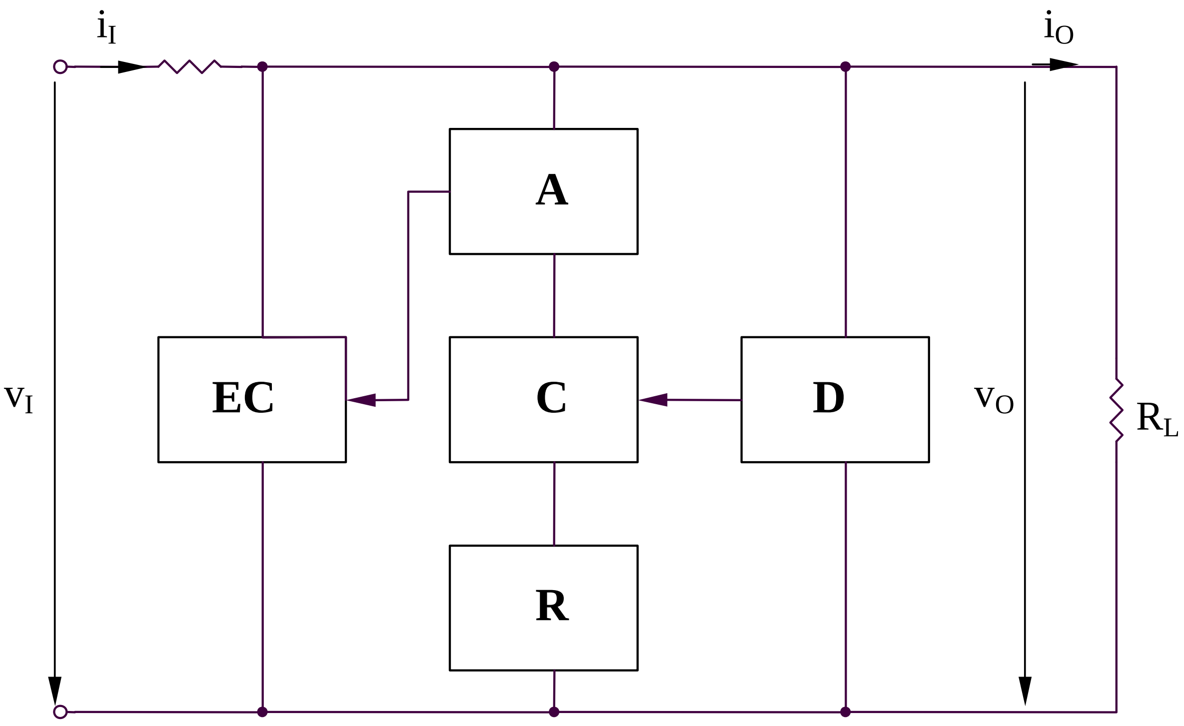
# 3.2.2. Surse de tensiune cu reactie

## Surse de tensiune cu stabilizare serie (schema bloc)



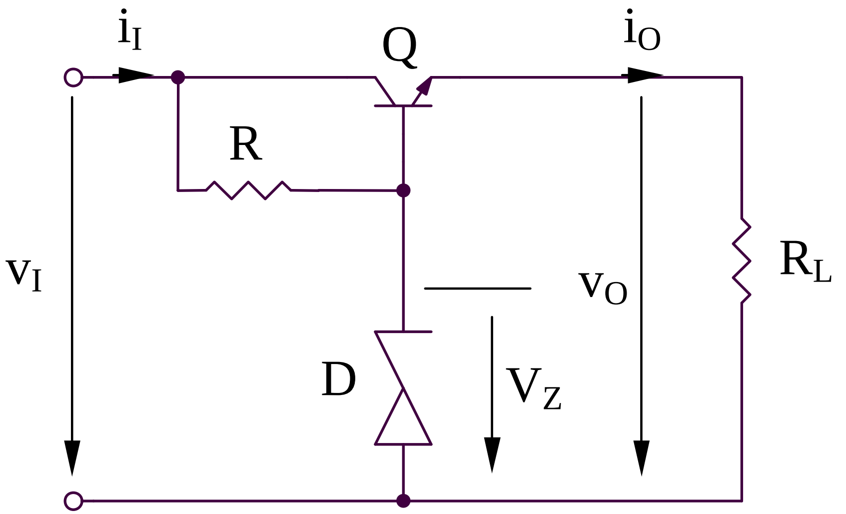

D = bloc de divizare
C = bloc de comparare
R = circuit de referinta
A = amplificator
EC = element de control

# Surse de tensiune cu stabilizare paralel (schema bloc)

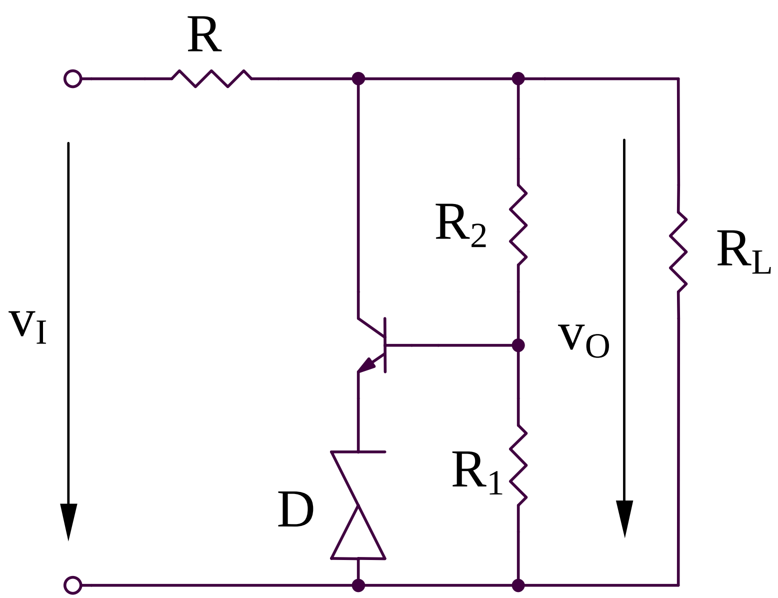



D = bloc de divizare
C = bloc de comparare
R = circuit de referinta
A = amplificator
EC = element de control

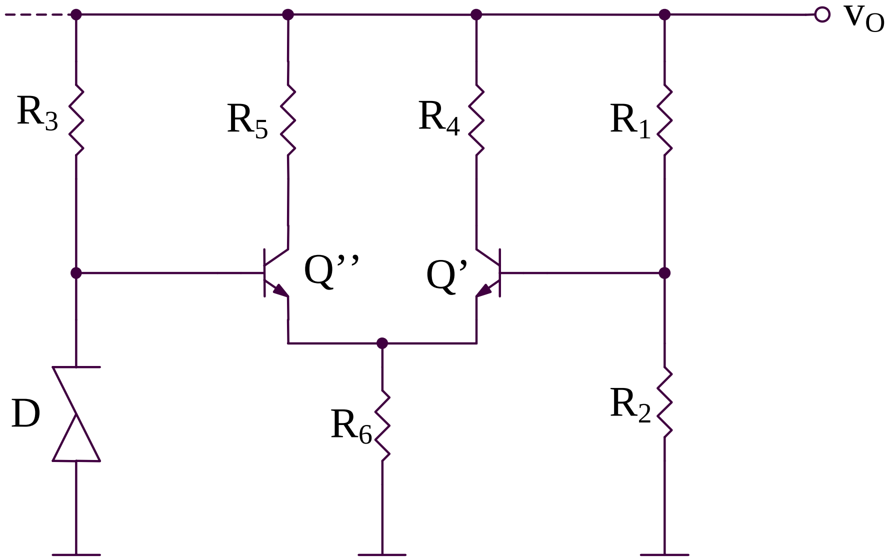
# Exemple de surse de tensiune



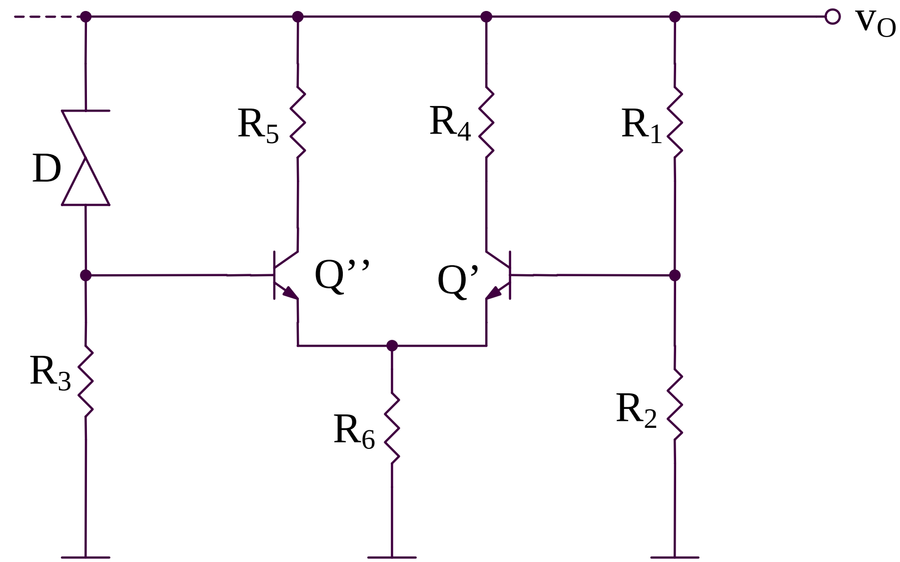

$$v_O = V_Z - V_{BE}$$



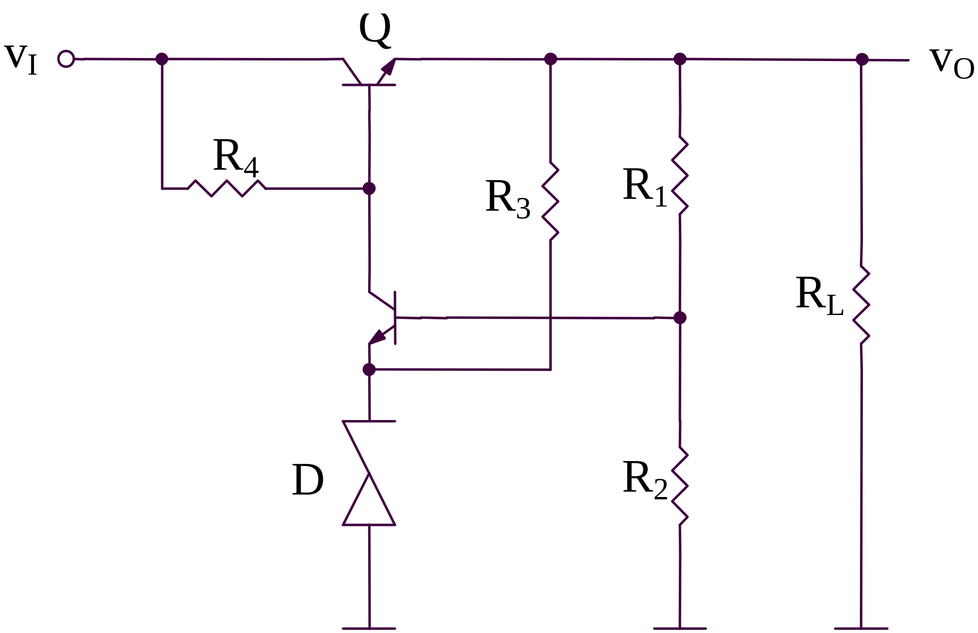

$$v_O = (V_{BE} + V_Z)\left(1 + \frac{R_2}{R_1}\right) > V_Z$$



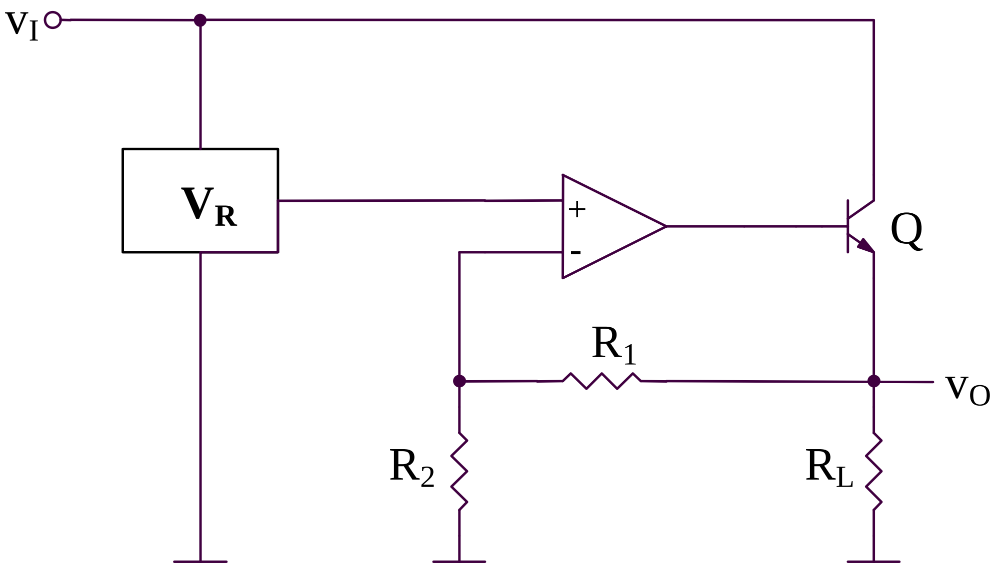

$$v_O = V_Z\left(1 + \frac{R_1}{R_2}\right)$$




$$v_O = V_Z\left(1 + \frac{R_2}{R_1}\right)$$

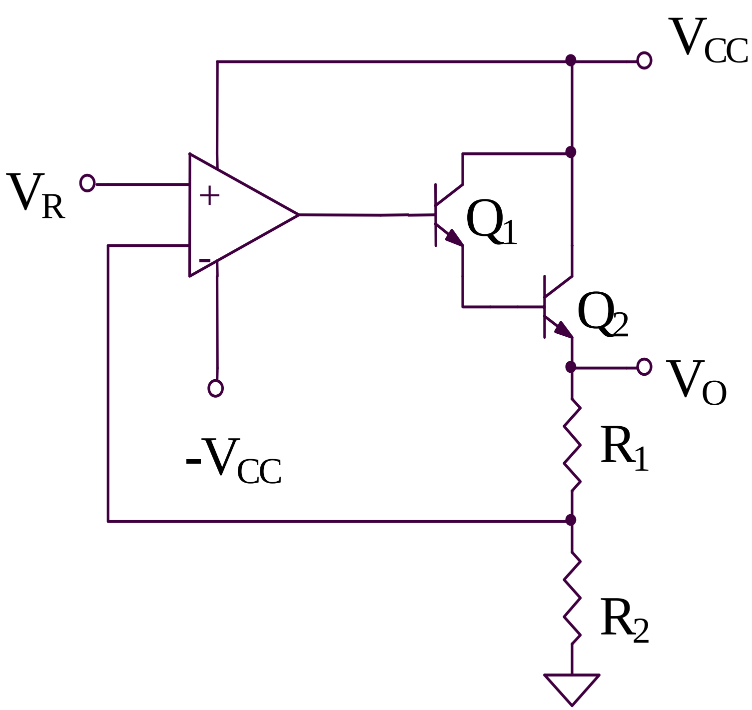



$$v_O = \left(V_Z + V_{BE}'\right)\left(1 + \frac{R_1}{R_2}\right)$$



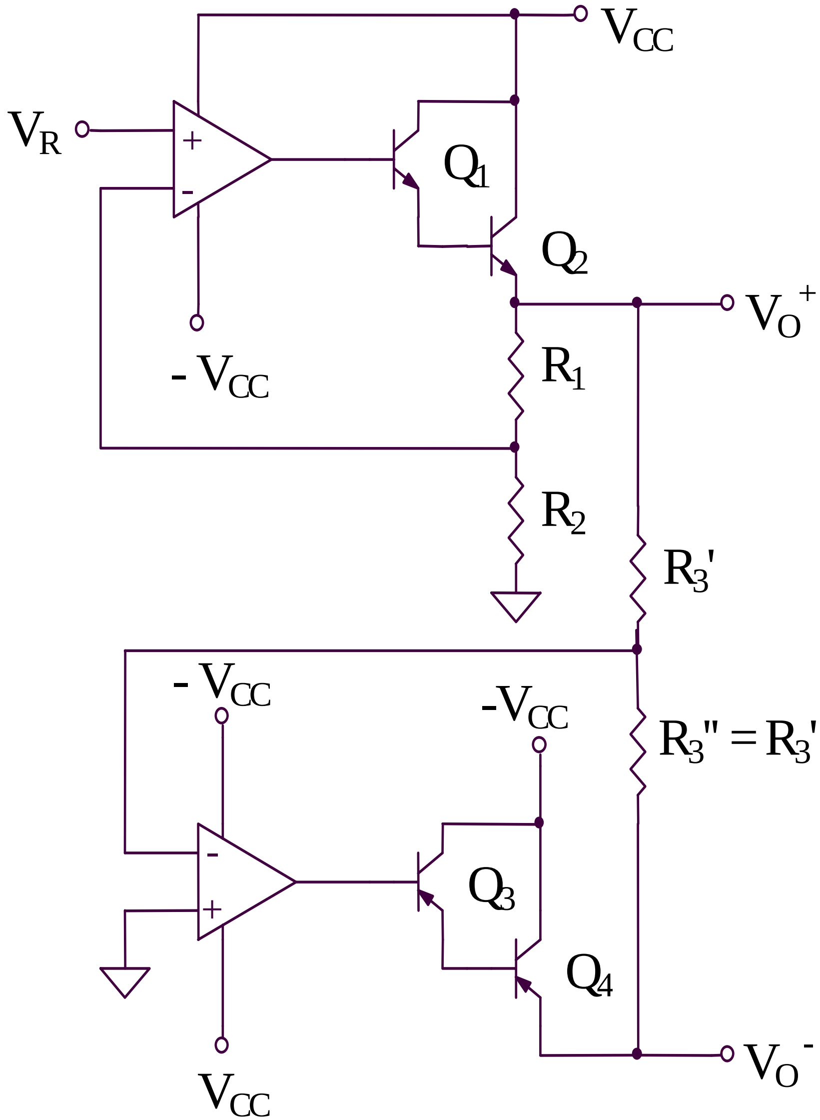

$$V_R = V_O \frac{R_2}{R_1 + R_2}$$

$$V_O = V_R\left(1 + \frac{R_1}{R_2}\right)$$




$$V_R = V_O \frac{R_2}{R_1 + R_2}$$

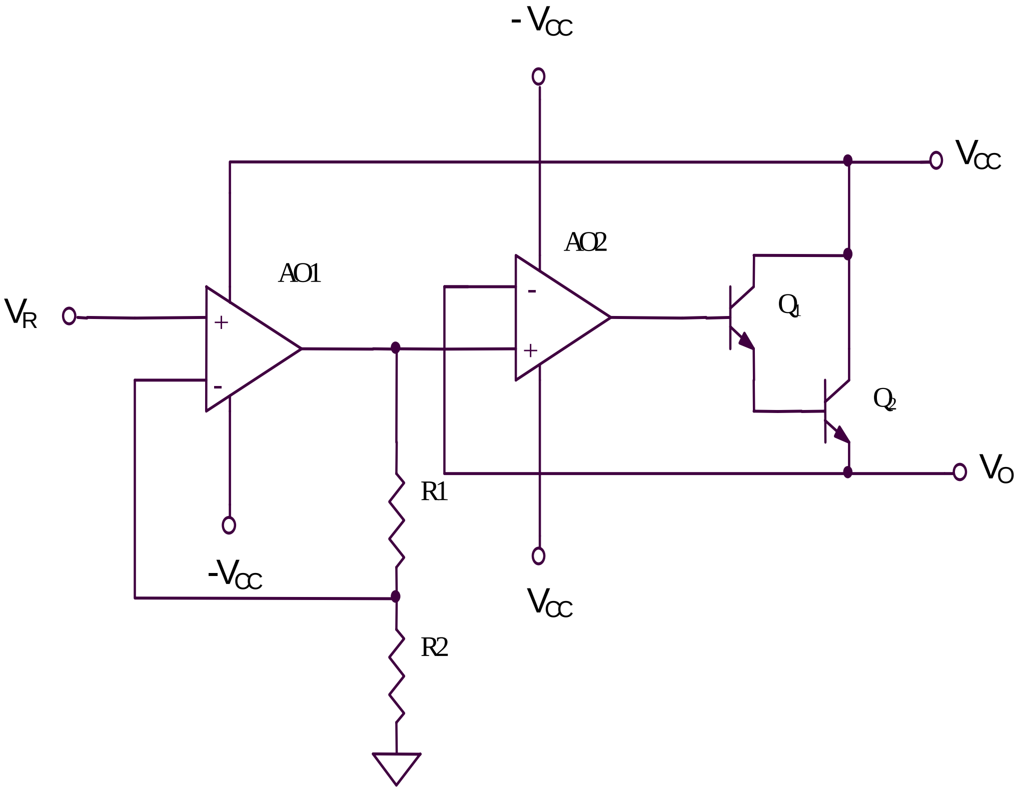
$$V_O = V_R\left(1 + \frac{R_1}{R_2}\right)$$




$$V_R = V_O^+ \frac{R_2}{R_1 + R_2}$$

$$V_O^+ = V_R \left(1 + \frac{R_1}{R_2}\right)$$

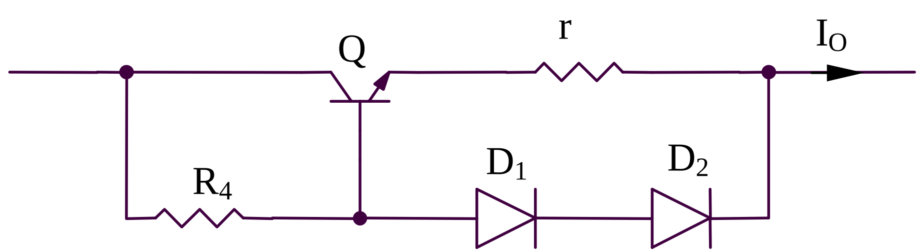
$$\frac{V_O^+}{R_3'} = -\frac{V_O^-}{R_3''} \Rightarrow V_O^- = -V_O^+$$



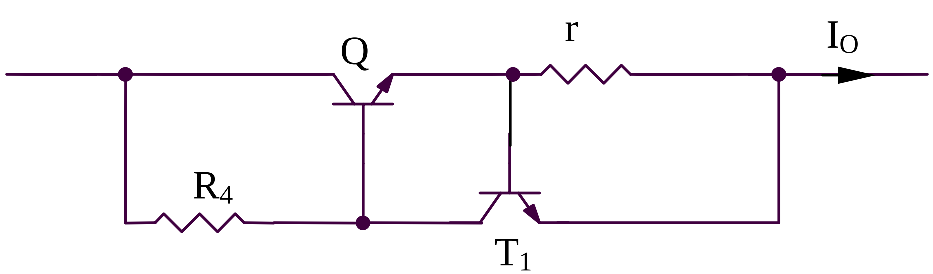

$$V_R = V_O \frac{R_2}{R_1 + R_2}$$

$$V_O = V_R\left(1 + \frac{R_1}{R_2}\right)$$

# Protectia la suprasarcina (1)

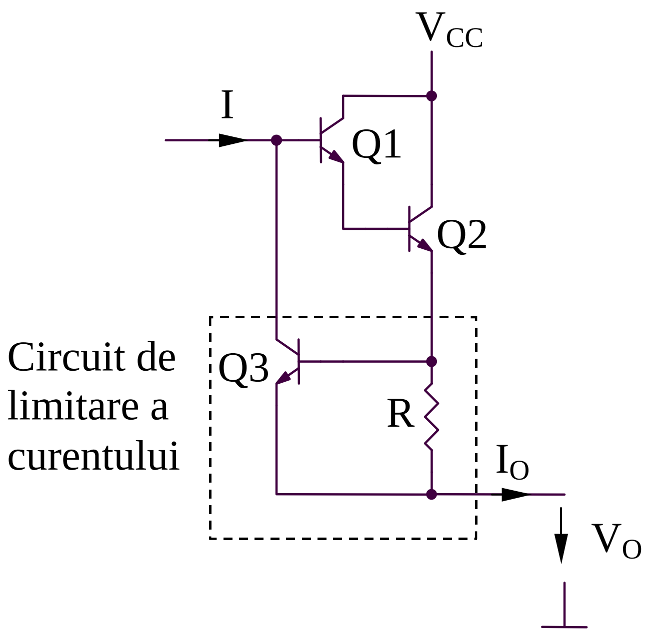



$$I_{OL} = \frac{V_{D1} + V_{D2} - V_{BE}}{r} \cong \frac{V_D}{r}$$



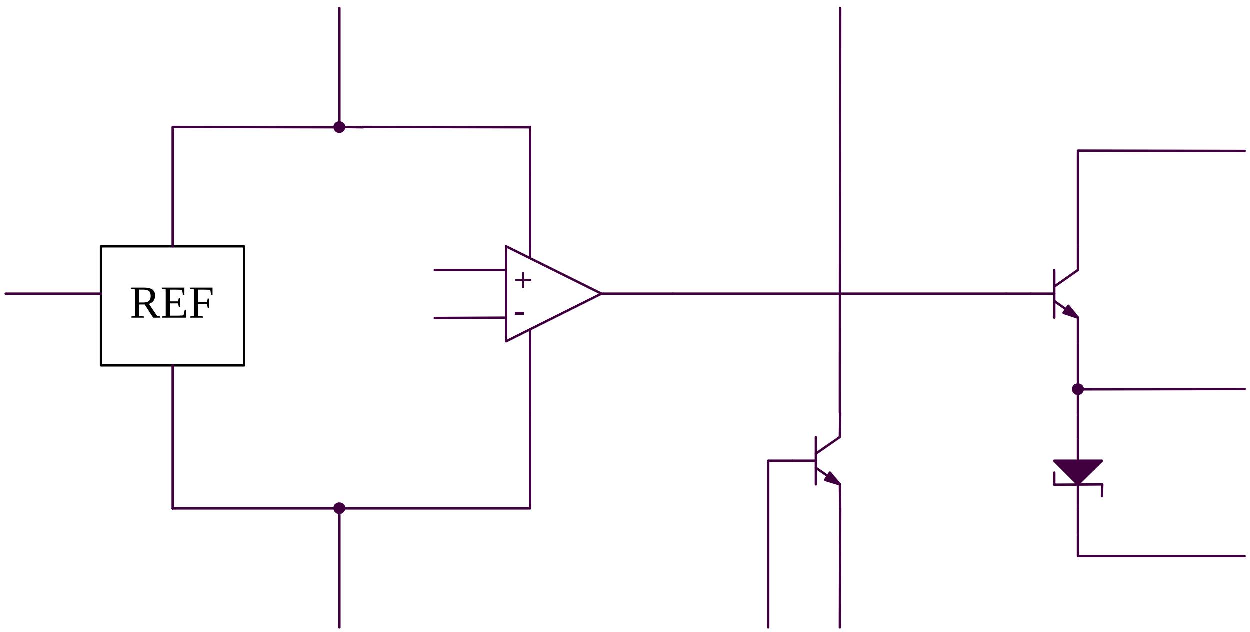

$$I_{OL} = \frac{V_{BE}}{r}$$

# Protectia la suprasarcina (2)

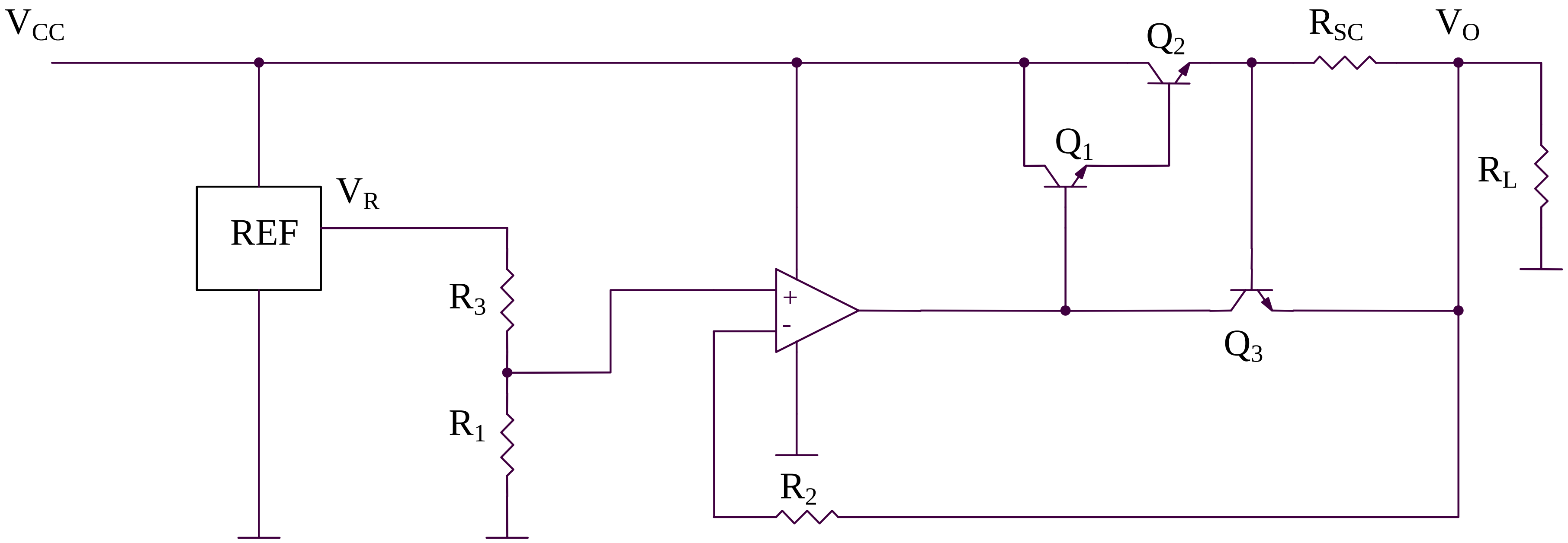



$$I_{OL} = \frac{V_{BE3}}{R}$$

# circuitul BA 723

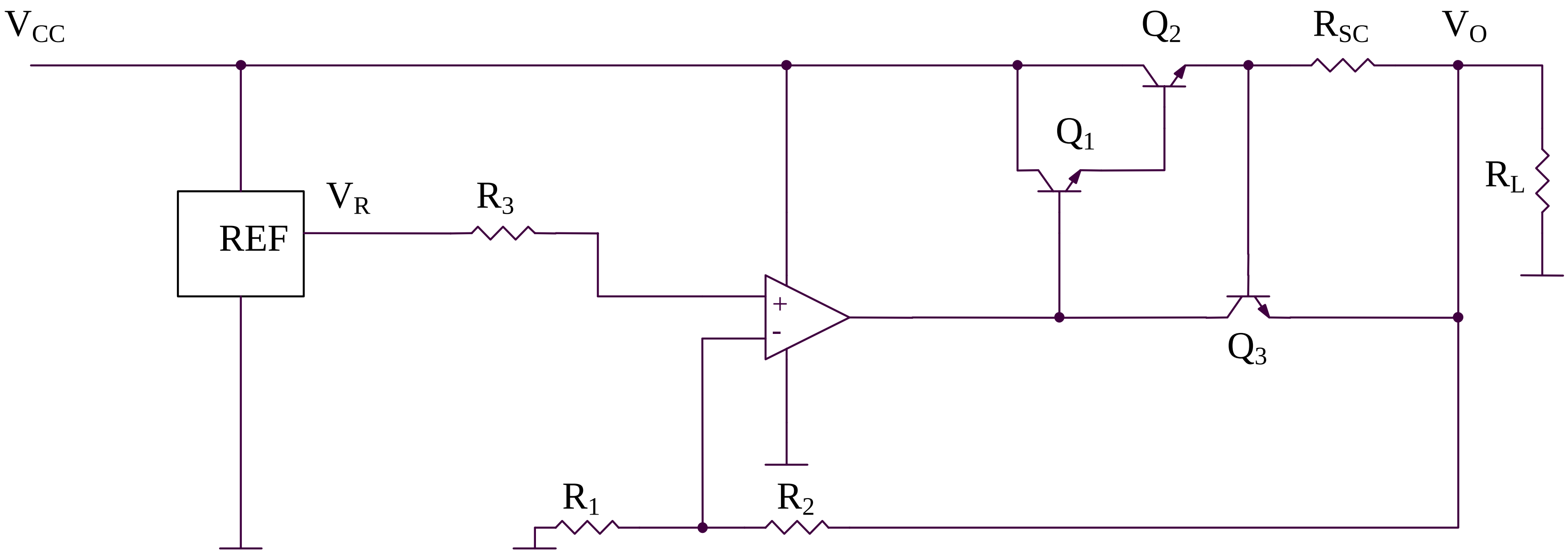


# Sursa de tensiune pentru $V_O < V_R$




$$V_O = V_R \frac{R_1}{R_1 + R_3} < V_R \qquad I_{Osc} = \frac{V_{BE}}{R_{sc}}$$

# Sursa de tensiune pentru $V_O > V_R$

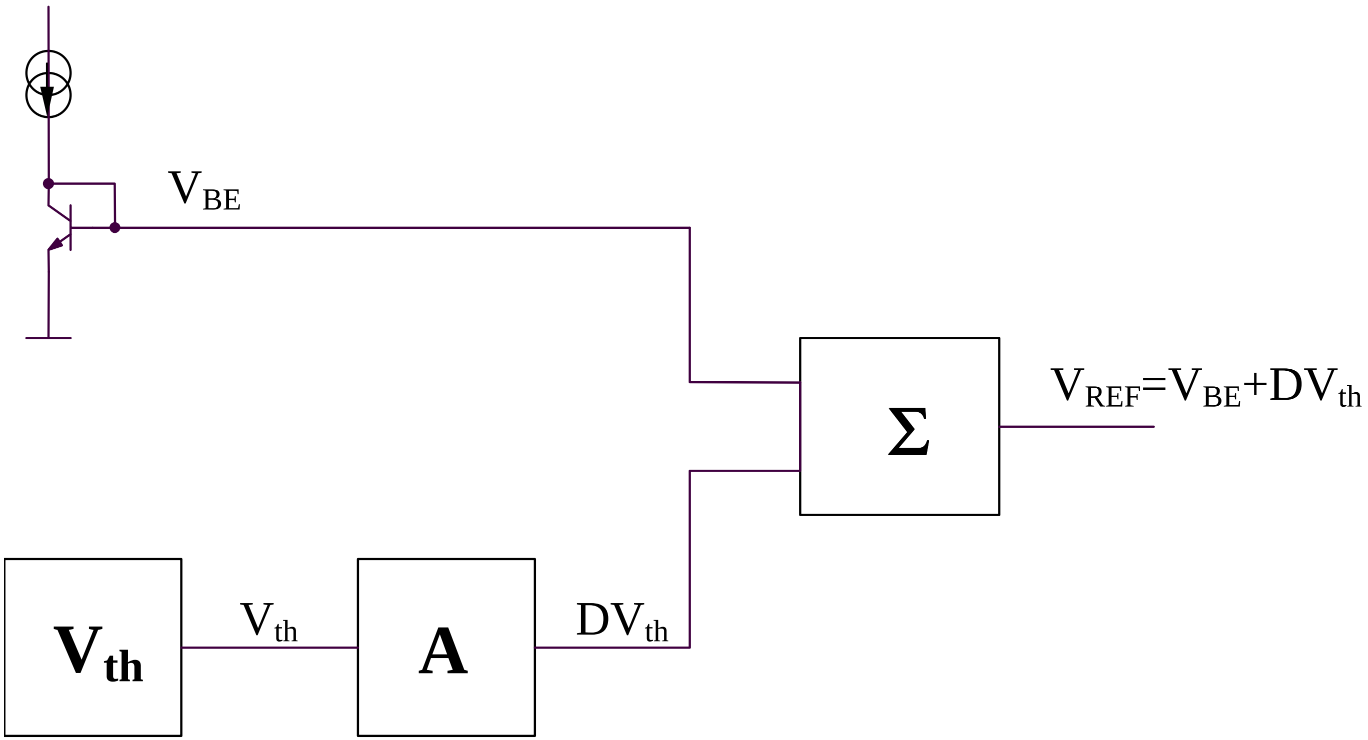



$$V_O \frac{R_1}{R_1 + R_2} = V_R \Rightarrow V_O = V_R\left(1 + \frac{R_2}{R_1}\right) > V_R$$

$$I_{Osc} = \frac{V_{BE}}{R_{sc}}$$

# 3.2.3. Surse de tensiune compensate cu temperatura

# Referinte de tensiune bandgap (banda interzisa)



# Dependenta de temperatura a tensiunii $V_{BE}$

$$\left.\begin{aligned} V_{BE}(T) &= V_{th}\ln\left[\frac{I_C(T)}{I_S(T)}\right] \\ I_S(T) &= CT^{\eta}\exp\left(-\frac{E_{GO}}{V_{th}}\right) \end{aligned}\right\} \Rightarrow \left.\begin{aligned} V_{BE}(T) &= E_{G0} + \frac{kT}{q}\ln\left[\frac{I_C(T)}{CT^{\eta}}\right] \\ V_{BE}(T_O) &= E_{GO} + \frac{kT_O}{q}\ln\left[\frac{I_C(T_O)}{CT_O^{\eta}}\right] \\ I_C(T) &= BT^{\alpha} \end{aligned}\right\} \Rightarrow$$

$$\Rightarrow V_{BE}(T) = E_{GO} + \frac{V_{BE}(T_O) - E_{GO}}{T_O}T + (\alpha - \eta)\frac{KT}{q}ln\left(\frac{T}{T_O}\right)$$

$$\frac{V_{BE}(T_O) - E_{GO}}{T_O} \cong -2{,}1mV / K < 0$$

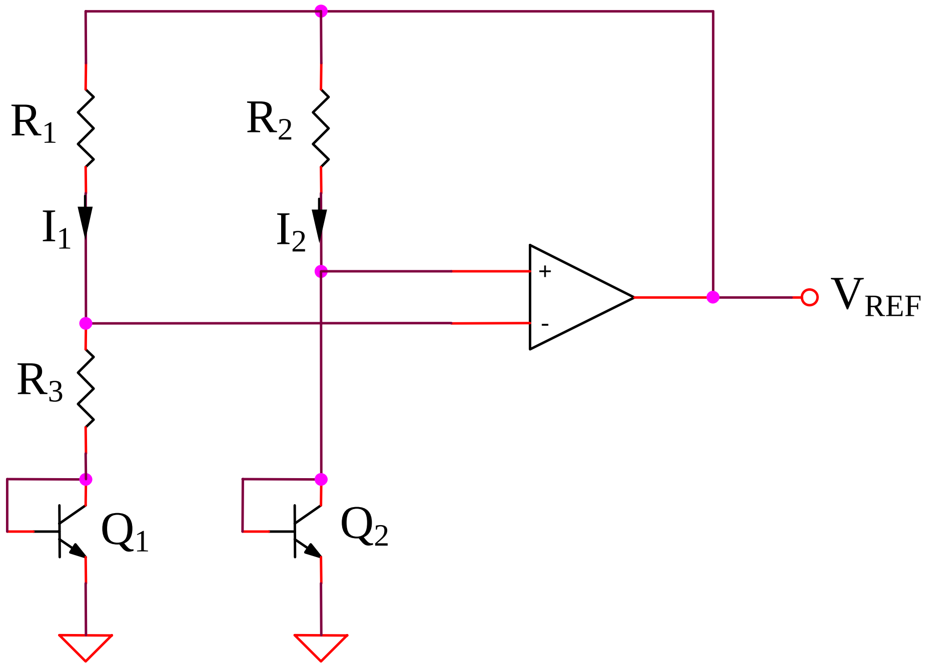
# Functionarea referintelor de tensiune

$$\left.\begin{aligned} V_{REF}(T) &= DV_{th} + V_{BE}(T) \\ V_{BE}(T) &= A + BT + CT\ln\left(\frac{T}{T_O}\right) \end{aligned}\right\} \Rightarrow$$

$$\Rightarrow V_{REF}(T) = A + \left(B + D\frac{k}{q}\right)T + CT\ln\left(\frac{T}{T_O}\right)$$

$$B + D\frac{k}{q} = 0 \Rightarrow V_{REF}(T) = A + CT\ln\left(\frac{T}{T_O}\right)$$

# Referinta de tensiune (1)



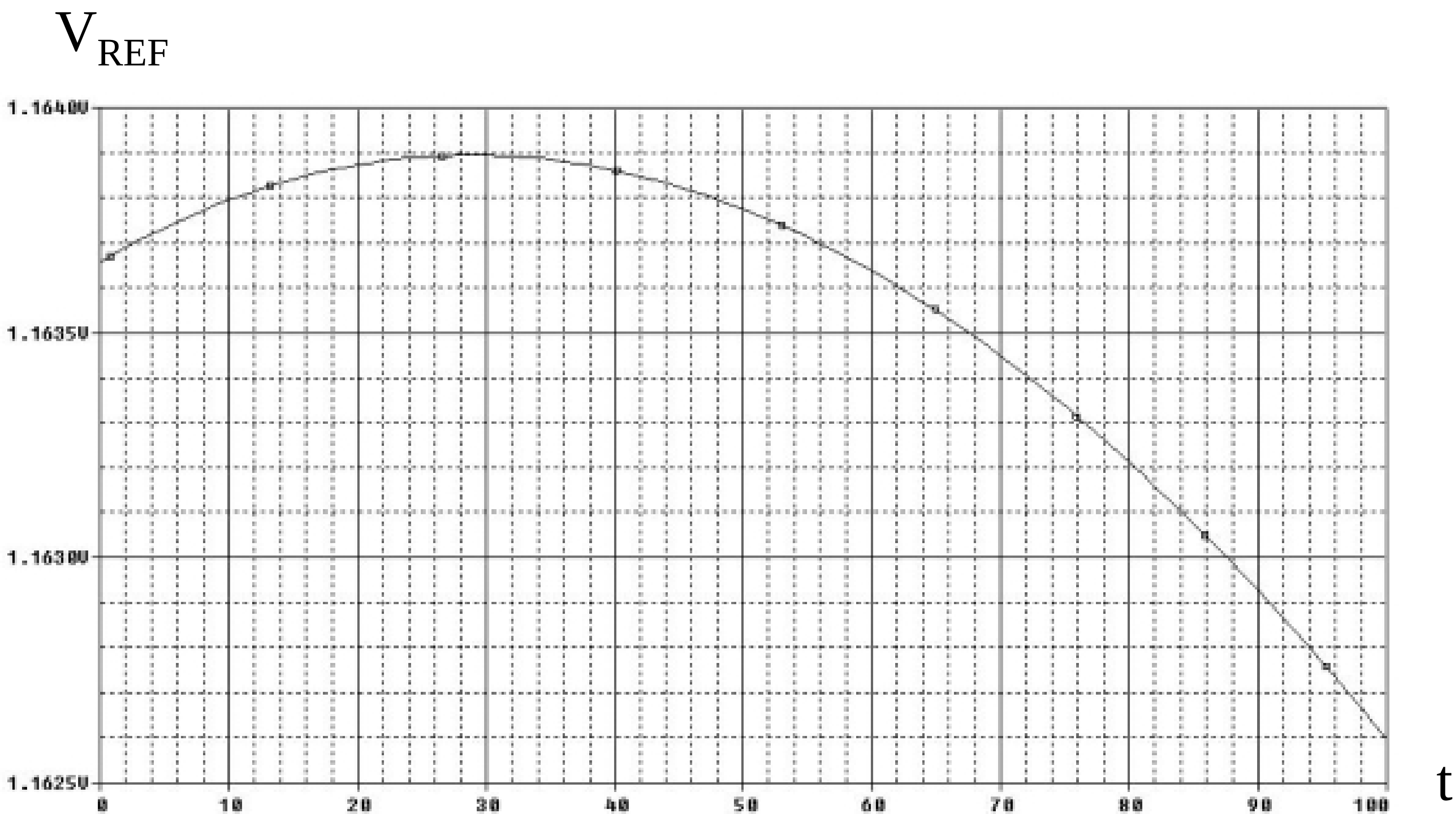

$$\left.\begin{aligned} I_1 &= \frac{V_{BE2} - V_{BE1}}{R_3} = \frac{kT}{qR_3}\ln\left(\frac{I_2}{I_1}\right) \\ I_1 R_1 &= I_2 R_2 \end{aligned}\right\} \Rightarrow$$

$$\Rightarrow \quad I_1 = \frac{kT}{qR_3}\ln\left(\frac{R_1}{R_2}\right)$$

$$\left.\begin{aligned} V_{REF}(T) &= I_1(T) R_1 + V_{BE2}(T) \\ V_{BE}(T) &= A + BT + CT\ln\left(\frac{T}{T_O}\right) \end{aligned}\right\} \Rightarrow$$

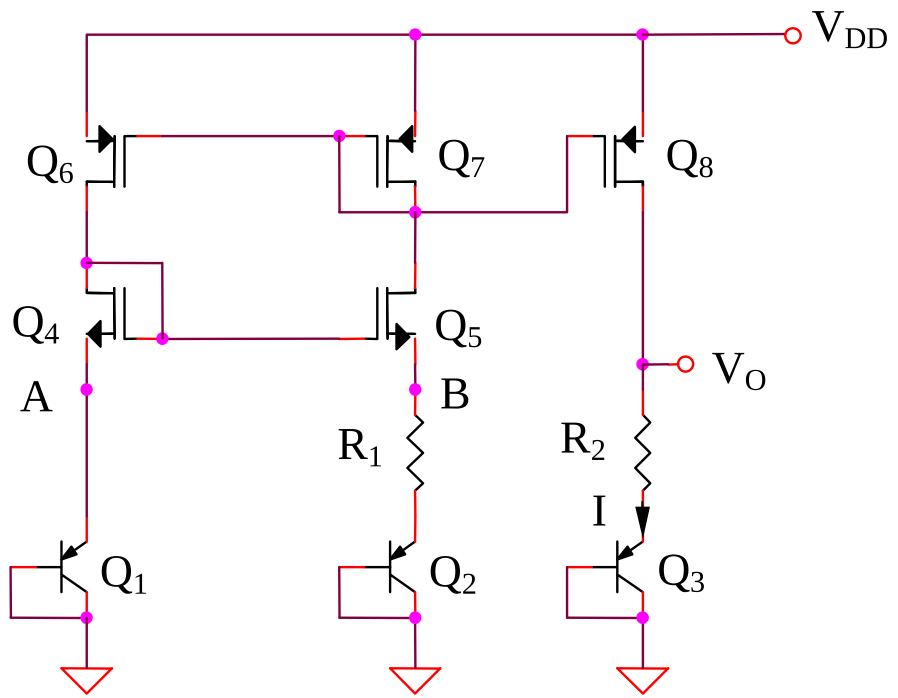
$$\Rightarrow V_{REF}(T) = A + \left[B + \frac{k}{q}\frac{R_1}{R_3}\ln\left(\frac{R_1}{R_2}\right)\right]T + CT\ln\left(\frac{T}{T_O}\right)$$

$$B + \frac{k}{q}\frac{R_1}{R_3}\ln\left(\frac{R_1}{R_2}\right) = 0 \Rightarrow V_{REF}(T) = A + CT\ln\left(\frac{T}{T_O}\right) \cong A \cong 1{,}2V$$



VREF
1.1640V
1.1635V
1.1630V
1.1625V
0
10
20
30
40
50
60
70
80
90
100
t

# Referinta de tensiune (2)




$$V_A - V_B = V_{GS5} - V_{GS4} = (V_{GS5} - V_T) - (V_{GS4} - V_T) = \sqrt{\frac{2I_{D5}}{K_5}} - \sqrt{\frac{2I_{D4}}{K_4}}$$

$$V_A - V_B = \sqrt{\frac{2I_{D5}}{K_5}}\left(1 - \sqrt{\frac{I_{D4}}{I_{D5}}\frac{K_5}{K_4}}\right) = \sqrt{\frac{2I_{D5}}{K_5}}\left(1 - \sqrt{\frac{I_{D6}}{I_{D7}}\frac{(W/L)_5}{(W/L)_4}}\right)$$

$$V_A - V_B = \sqrt{\frac{2I_{D5}}{K}}\left(1 - \sqrt{\frac{(W/L)_5}{(W/L)_4}\frac{(W/L)_6}{(W/L)_7}}\right)$$

Pentru: $$\frac{(W/L)_4}{(W/L)_5} = \frac{(W/L)_6}{(W/L)_7} \Rightarrow V_A = V_B$$

$$\Rightarrow V_O(T) = /V_{BE_3}(T)/ + I(T)R_2 = /V_{BE_3}(T)/ + \frac{/V_{BE_1}(T)/ - /V_{BE_2}(T)/}{R_1}R_2$$

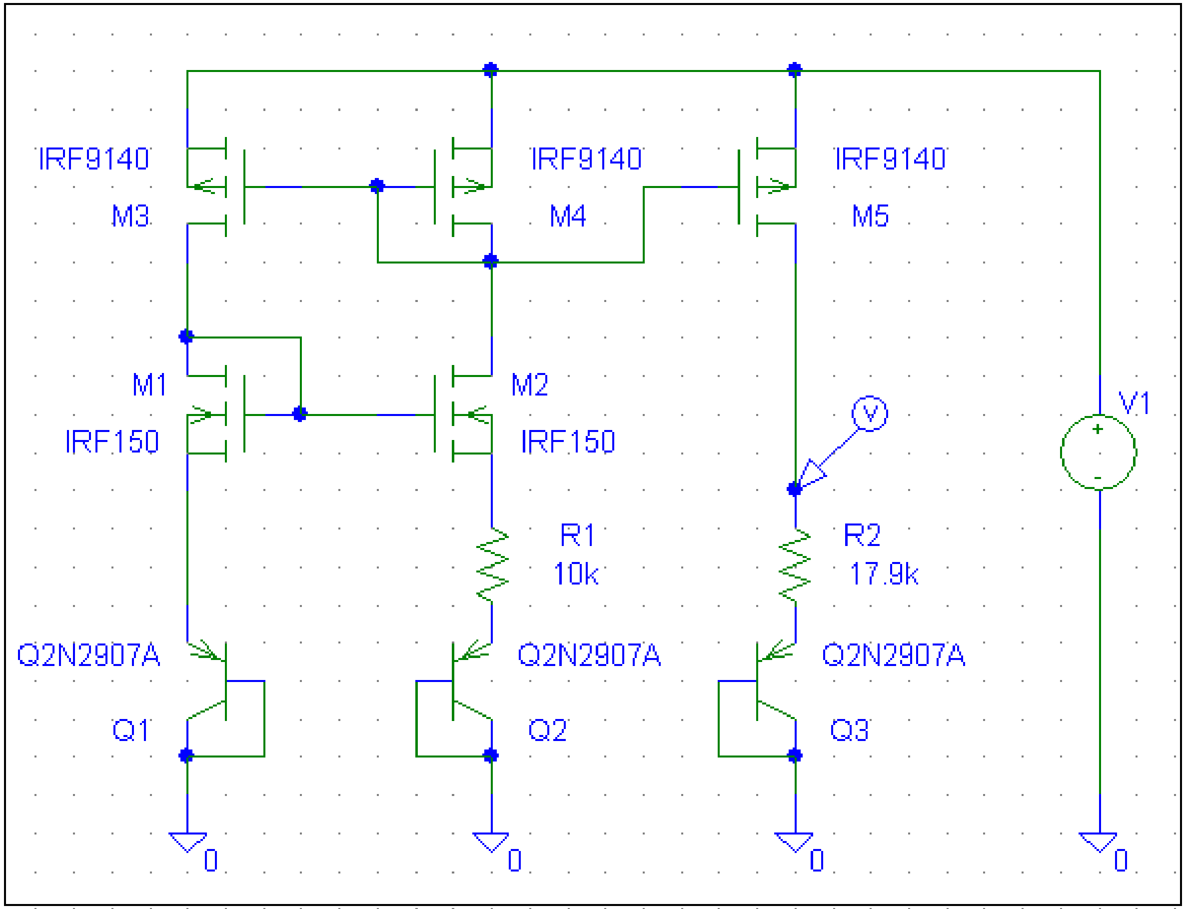
$$V_O(T) = /V_{BE_3}(T)/ + \frac{R_2}{R_1}\frac{kT}{q}\ln\frac{I_{D6}}{I_{D7}}$$

$$\left.\begin{aligned}
&V_O(T) = /V_{BE_3}(T)/ + \frac{R_2}{R_1}\frac{kT}{q}\ln\left[\frac{(W/L)_6}{(W/L)_7}\right] \\
&/V_{BE}(T)/ = A + BT + CT\ln\left(\frac{T}{T_0}\right) \\
&B + \frac{R_2}{R_1}\frac{k}{q}\ln\left[\frac{(W/L)_6}{(W/L)_7}\right] = 0
\end{aligned}\right\} \Rightarrow V_O(T) = A + CT\ln\left(\frac{T}{T_0}\right)$$

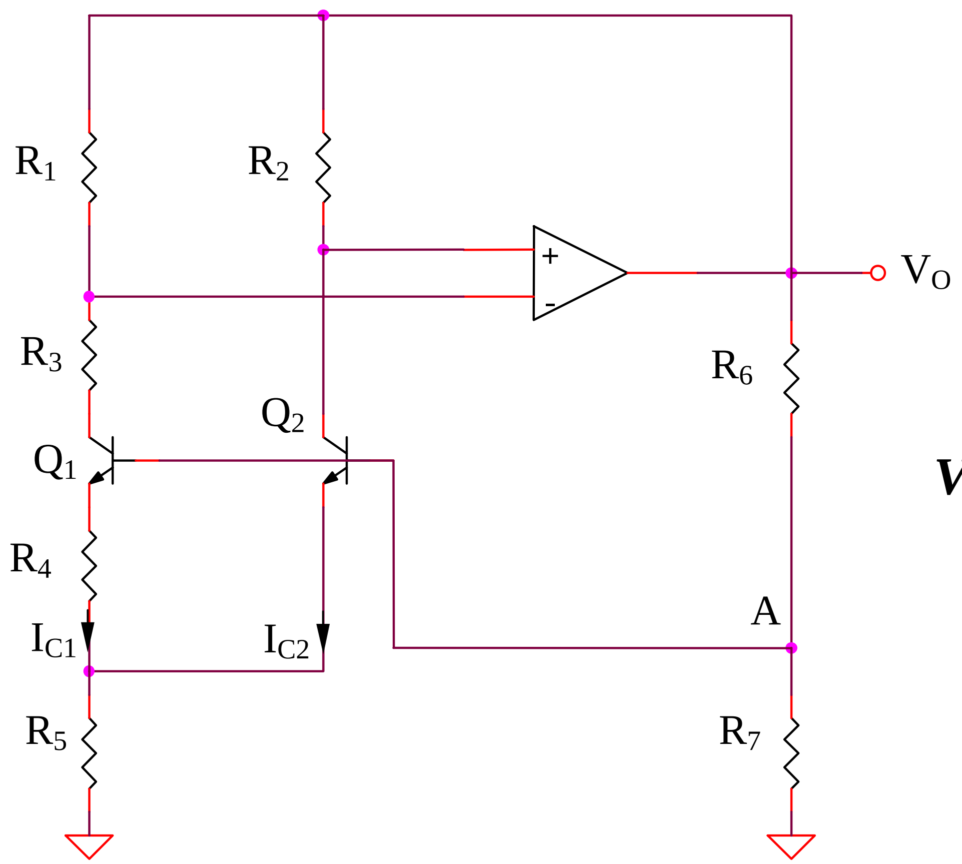
# SIMULARE pentru referinta de tensiune (2)
# Dependenta de temperatura a tensiunii de referinta

# SIMULARE pentru referinta de tensiune (2)
# Dependenta de temperatura a tensiunii de referinta

## SIM 3.13: $V_{D5}$ (t)



# Referinta de tensiune (3)




$$\left.\begin{aligned} I_{C1} &= \frac{V_{BE2} - V_{BE1}}{R_4} = \frac{V_{th}}{R_4}\ln\frac{I_{C2}}{I_{C1}} \\ I_{C1}R_1 &= I_{C2}R_2 \end{aligned}\right\} \Rightarrow$$

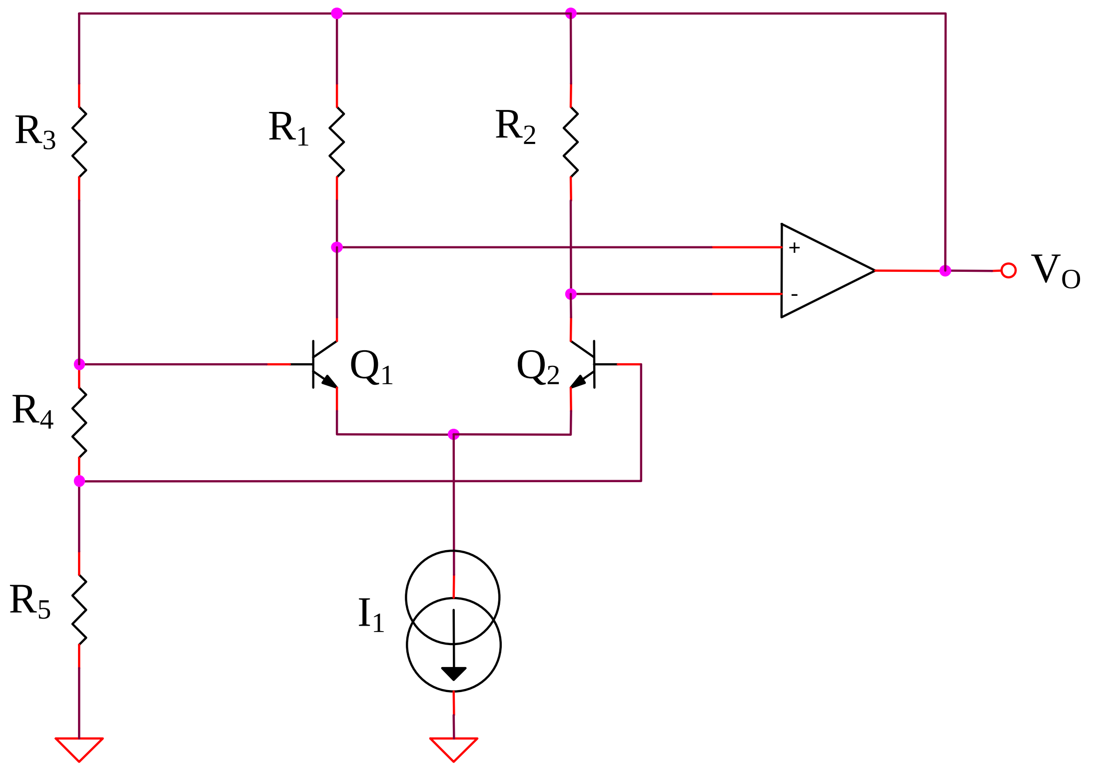
$$\Rightarrow I_{C1} = \frac{V_{th}}{R_4}\ln\frac{R_1}{R_2}$$

$$\left.\begin{aligned} V_A(T) &= (I_{C1} + I_{C2})R_5 + V_{BE2}(T) \\ V_A(T) &= V_O(T)\frac{R_7}{R_6 + R_7} \end{aligned}\right\} \Rightarrow$$

$$\left.\begin{aligned} &\Rightarrow V_O(T) = \left(1 + \frac{R_6}{R_7}\right)\left[V_{BE_2}(T) + \frac{R_5}{R_4}\left(1 + \frac{R_1}{R_2}\right)V_{th}\ln\left(\frac{R_1}{R_2}\right)\right] \\ &\frac{R_5}{R_4}\left(1 + \frac{R_1}{R_2}\right)\frac{k}{q}\ln\left(\frac{R_1}{R_2}\right) + B = 0 \end{aligned}\right\} \Rightarrow V_O(T) = \left(1 + \frac{R_6}{R_7}\right)\left[A + CT\ln\left(\frac{T}{T_0}\right)\right]$$

# Senzori de temperatura

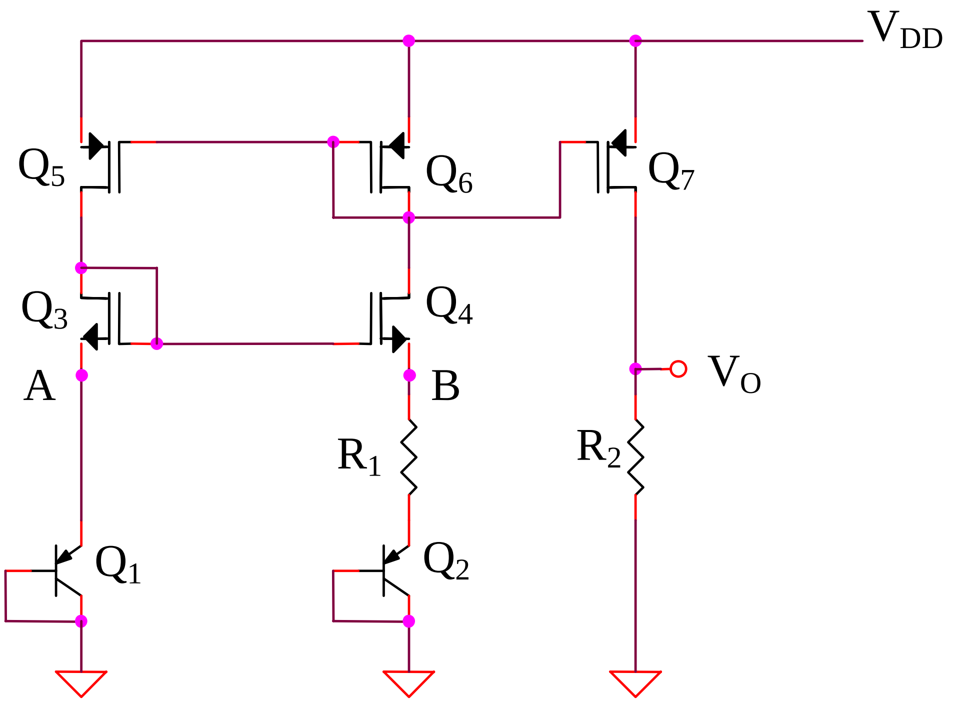
## Exemplu (1)




$$V_O(T)\frac{R_4}{R_3+R_4+R_5}=V_{BE1}-V_{BE2}=V_{th}\ln\frac{I_{C1}}{I_{C2}}=V_{th}\ln\frac{R_2}{R_1}\Rightarrow$$

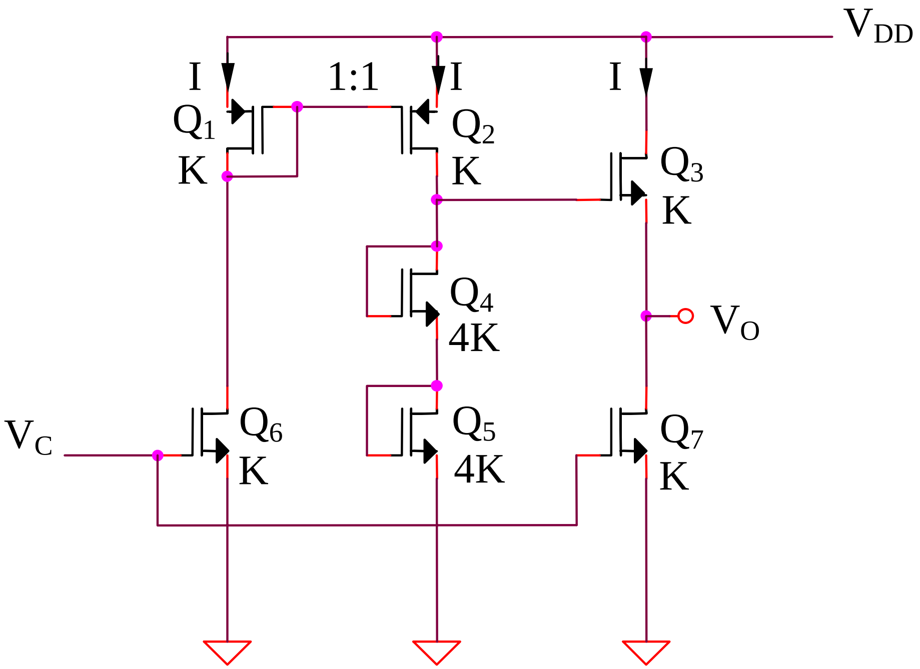
$$\Rightarrow V_O(T)=\left(1+\frac{R_3+R_5}{R_4}\right)V_{th}\ln\left(\frac{R_2}{R_1}\right)=ct.T$$

# Exemplu (2)




$$V_O = R_2 I_{D7}(T) = R_2 I_{D4}(T) = R_2 \frac{\left|V_{BE_1}\right| - \left|V_{BE_2}\right|}{R_1} = \frac{R_2}{R_1} V_{th} \ln\left[\frac{(W/L)_5}{(W/L)_6}\right] = ct.T$$

# Exemplu (3) – circuit de extragere a tensiunii de prag




$$V_O = 2V_{GS_4} - V_{GS_3} = 2\left(V_T + \sqrt{\frac{2I}{4K}}\right) - \left(V_T + \sqrt{\frac{2I}{K}}\right) = V_T = V_{T0} + a\left(T - T_0\right)$$