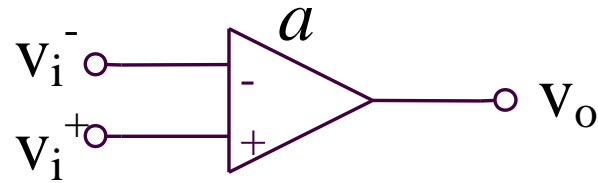# Capitolul 6
# Amplificatoare operationale.
# Structuri interne

# 6.1. Introducere

# 6.1. Introducere

$$v_O = a\left(v_i^+ - v_i^-\right)$$

**Un AO prezinta:**

- intrare diferentiala si iesire simpla

- capacitatea de a rejecta semnalele parazite

# 6.1. Introducere

## AO ideal

• impedanta de intrare infinita
• impedanta de iesire nula
• amplificare in tensiune infinita
• banda de frecventa infinita (raspuns instantaneu) – slew rate infinit
• tensiune de iesire nula pentru tensiune de intrare nula
• diferenta de potential nula intre cele doua intrari
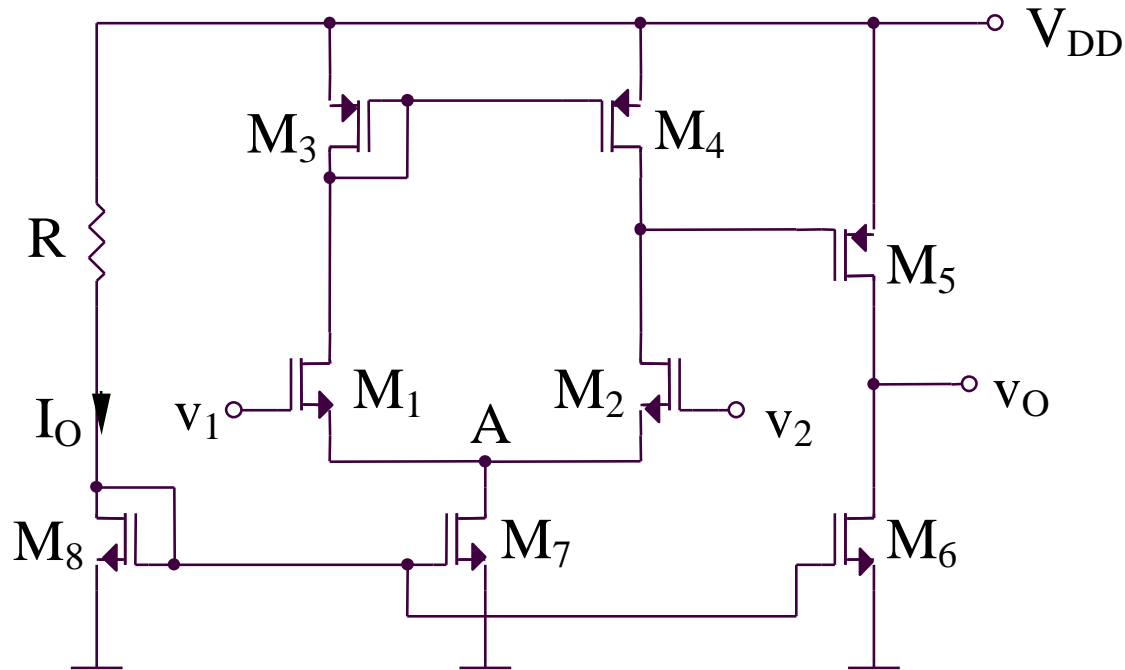• curenti nuli de intrare

## AO real:

• impedanta de intrare foarte mare
• impedanta de iesire mica
• amplificare in tensiune foarte mare

# 6.2. Structuri interne de amplificatoare operationale

# *Amplificatoare operationale clasice in tehnologie CMOS*

# 6.2.1. Amplificator operational cu un etaj de amplificare



**Regim static**

$$I_{D9} \overset{not}{=} I_O = \frac{K}{2}(V_{C1} - V_T)^2$$

$$I_{D1} = I_{D2} = ... = I_{D8} = I_O / 2$$

**Regim dinamic**

$$i_{D6} - i_{D5} = i_{D3} - i_{D8} = i_{D3} - i_{D4} = i_{D2} - i_{D1} = g_{m1}(v_2 - v_1)$$

$$v_O = (i_{D6} - i_{D5})R_O = g_{m1}(v_2 - v_1)R_O \qquad R_O = r_{ds6} \,//\, r_{ds5} = r_{ds5} / 2$$

$$v_O = g_{m1}(v_2 - v_1)R_O = \frac{1}{2}g_{m1}r_{ds5}(v_2 - v_1)$$

$$|a| = \frac{1}{2}g_{m1}r_{ds5} = \frac{1}{\lambda}\sqrt{\frac{K}{I_O}}$$

# 6.2.2. Amplificator operational cu 2 etaje de amplificare (1)



## Regim static

$$\left. \begin{array}{l} RI_O + V_{GS8} = V_{DD} \\[2em] I_O = \dfrac{K}{2}\left(V_{GS8} - V_T\right)^2 \end{array} \right\} \Rightarrow V_{DD} = V_{GS8} + \dfrac{RK}{2}\left(V_{GS8} - V_T\right)^2 \Rightarrow V_{GS8}\ \left(V_{GS8} > V_T\right)$$

$$\Rightarrow I_O = \dfrac{K}{2}\left(V_{GS8} - V_T\right)^2$$

$$I_{D5} = I_{D6} = I_{D7} = I_{D8} = I_O$$

$$I_{D1} = I_{D2} = I_{D3} = I_{D4} = I_{D7}/2 = I_O/2$$

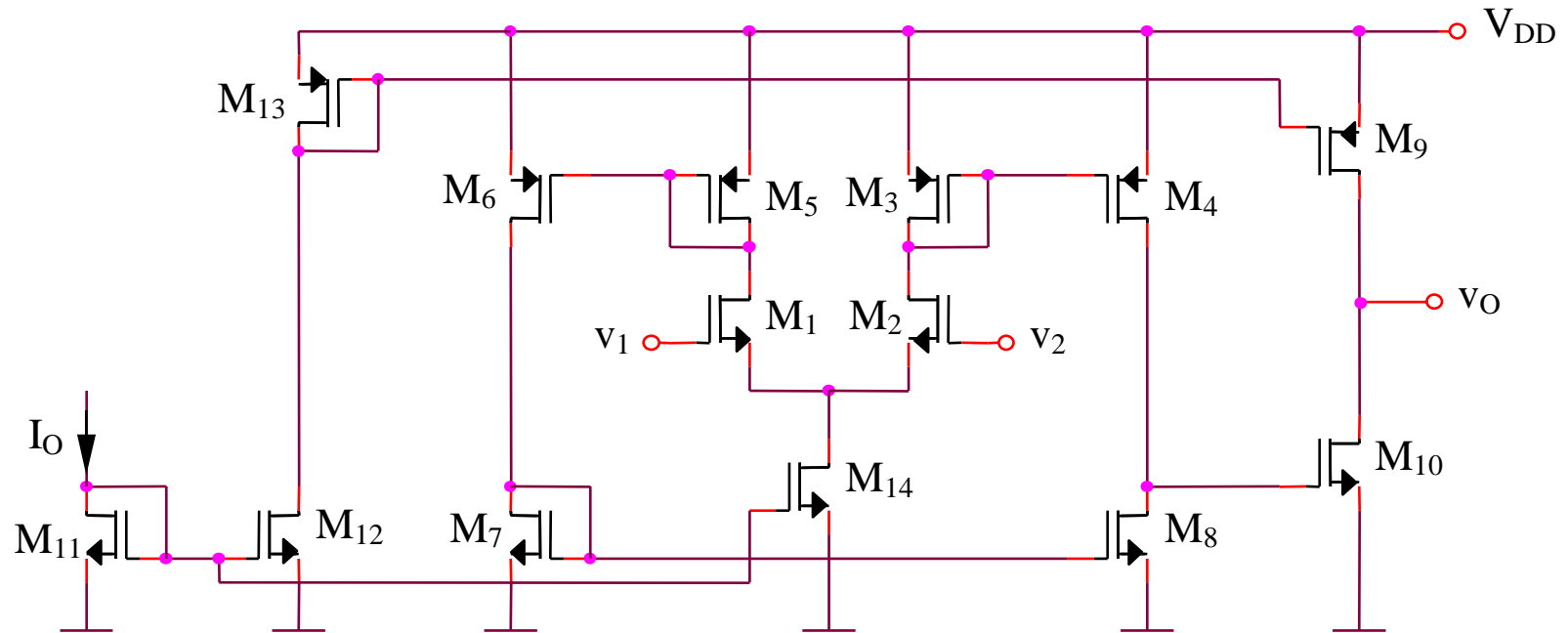## Regim dinamic

**Amplificarea circuitului**

$$|a| = g_{m1}(r_{ds2} // r_{ds4})g_{m5}(r_{ds5} // r_{ds6})$$

**Domeniul maxim al tensiunii de intrare de mod comun**

$$V_{IC}^{max} = V_{DD} - V_{SG5} - V_{DS2sat} + V_{GS2} = V_{DD} - V_{SG5} + V_T = V_{DD} - \sqrt{\frac{2I_O}{K}}$$

$$V_{IC}^{min} = V_{DS7sat} + V_{GS1} = V_{GS7} + V_{GS1} - V_T = V_T + (\sqrt{2} + 1)\sqrt{\frac{I_O}{K}}$$

# 6.2.3. Amplificator operational cu 2 etaje de amplificare (2)



**Regim static**

$$I_{D1} = \ldots = I_{D8} = \frac{I_O}{2}$$

$$I_{D9} = \ldots = I_{D14} = I_O$$

# Regim dinamic

**Amplificarea circuitului**

$$|a| = g_{m1}(r_{ds4} /\!/ r_{ds8})g_{m10}(r_{ds10} /\!/ r_{ds9}) = \frac{1}{4}g_{m1}g_{m10}r_{ds4}r_{ds10}$$

**Domeniul maxim al tensiunii de intrare de mod comun**

$$V_{IC}^{\mathbf{max}} = V_{DD} - V_{SG3} - V_{DS2sat} + V_{GS2} = V_{DD} - \sqrt{\frac{I_O}{K}}$$

$$V_{IC}^{\mathbf{min}} = V_{GS2} + V_{DS14sat} = (\sqrt{2} + 1)\sqrt{\frac{I_O}{K}} + V_T$$
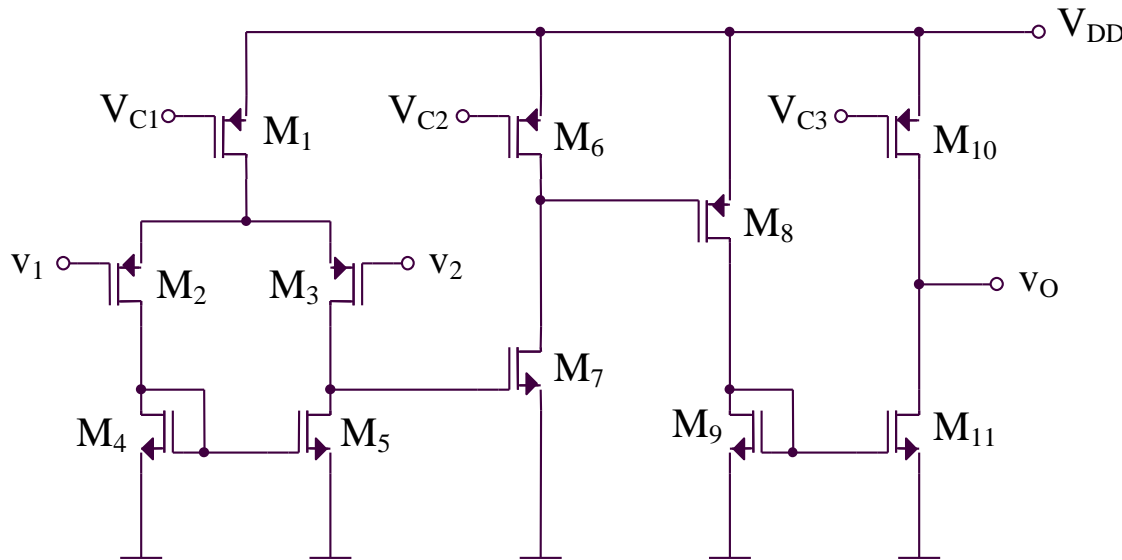
# 6.2.4. Amplificator operational cu 3 etaje de amplificare



**Regim static**

$$I_{D1} = \frac{K}{2}\left(V_{DD} - V_{C1} - V_T\right)^2$$

$$I_{D6} = I_{D7} = \frac{K}{2}\left(V_{DD} - V_{C2} - V_T\right)^2$$

$$I_{D10} = I_{D11} = I_{D8} = I_{D9} =$$

$$= \frac{K}{2}\left(V_{DD} - V_{C3} - V_T\right)^2$$

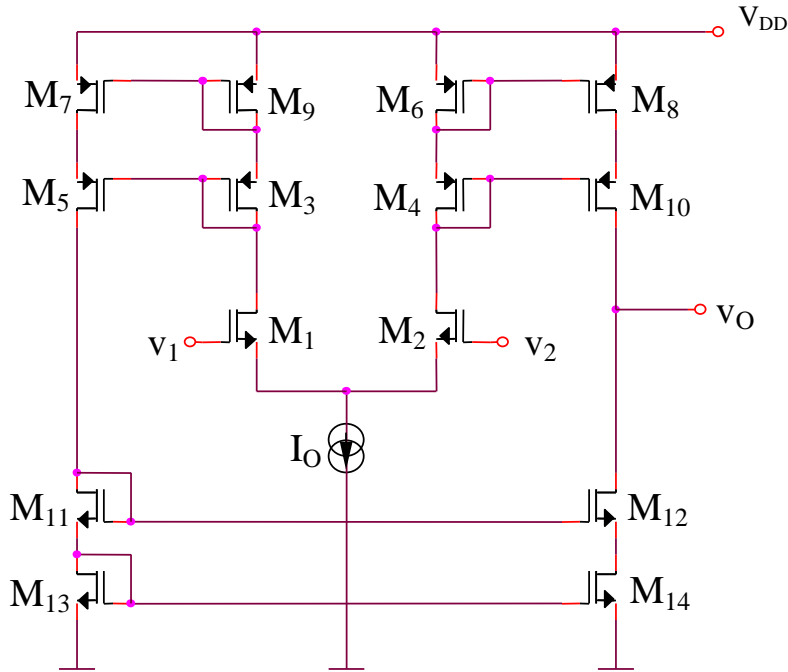$$I_{D2} = I_{D3} = I_{D4} = I_{D5} = \frac{I_{D1}}{2}$$

## Regim dinamic

$$A_{ddI} = g_{m2}\left(r_{ds3} \mathbin{/\!/} r_{ds5}\right)$$

$$A_{II} = -g_{m7}\left(r_{ds6} \mathbin{/\!/} r_{ds7}\right)$$

$$A_{III} = -g_{m8}\left(r_{ds10} \mathbin{/\!/} r_{ds11}\right)$$

# *Amplificatoare operationale cascod in tehnologie CMOS*

# 6.2.5. Amplificator operational cascod cu un etaj de amplificare (1)



**Regim static**

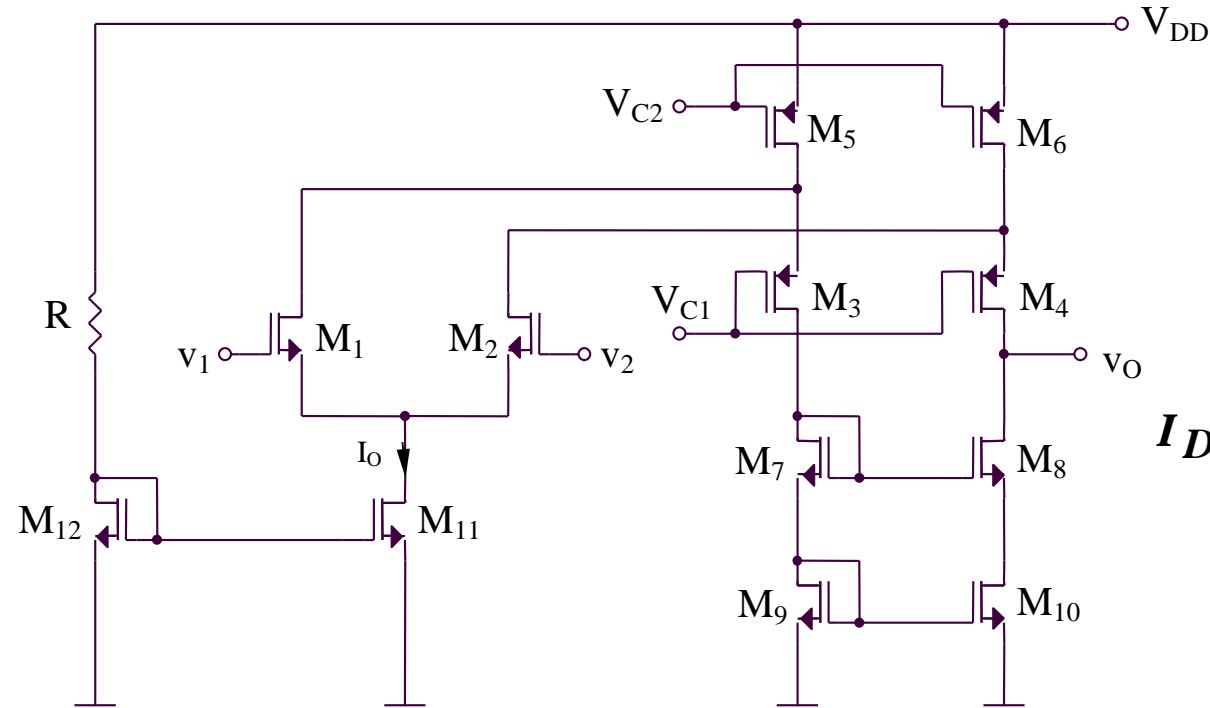$$I_{D1} = I_{D2} = ... = I_{D14} = I_O / 2$$

**Regim dinamic**

$$R_O = g_{m10}r_{ds10}^2 \;/\!/\; g_{m12}r_{ds12}^2 = \frac{1}{2}g_{m10}r_{ds10}^2$$

$$v_O = g_{m1}(v_2 - v_1)R_O = \frac{1}{2}g_{m1}g_{m10}r_{ds10}^2(v_2 - v_1)$$

$$|a| = \frac{1}{2}g_{m1}g_{m10}r_{ds10}^2$$

# 6.2.6. Amplificator operational cascod cu un etaj de amplificare (2)



**Regim static**

$$I_{D1} = I_{D2} = ... = I_{D10} = I_{D11}/2 = I_{D12}/2 = I_O/2$$

**Regim dinamic**

$$|a| = g_{m1}R_O$$

$$R_O = g_{m9}r_{ds9}r_{ds7} \; // \; g_{m8}r_{ds8}r_{ds6} = \frac{1}{2}g_{m9}r_{ds9}^2$$

# *Amplificatoare operationale cascoda intoarsa (folded cascod) in tehnologie CMOS*

# 6.2.7. Amplificator operational cascoda intoarsa (1)



**Regim static**

$$I_{D1} = I_{D2} = I_O / 2$$

$$I_{D11} = I_{D12} = I_O$$

$$I_{D5} = I_{D6} = \frac{K}{2}(V_{DD} - V_{C2} - V_T)^2$$

$$I_{D3} = I_{D4} = I_{D7} = ...$$
$$... = I_{D10} = I_{D6} - I_{D2}$$

**Regim dinamic**

$$i_{D4} - i_{D8} = i_{D4} - i_{D3} = (I_{D6} - i_{D2}) - (I_{D5} - i_{D1}) = i_{D1} - i_{D2}$$

$$|a| = g_{m1} R_O$$

$$R_O = r_{ds8} g_{m8} r_{ds10} // [r_{ds4} g_{m4} (r_{ds6} // r_{ds2})]$$

# 6.2.8. Amplificator operational cascoda intoarsa (2)



**Regim static**

$$I_{D3} = I_{D4} = I_{D5} = I_{D9} = I_O$$

(fixati de $V_{C1}, V_{C3}$)

$$I_{D1} = I_{D2} = \frac{I_{D3}}{2} = \frac{I_O}{2}$$

$$I_{D6} = I_{D7} = I_{D8} = I_{D10} =$$

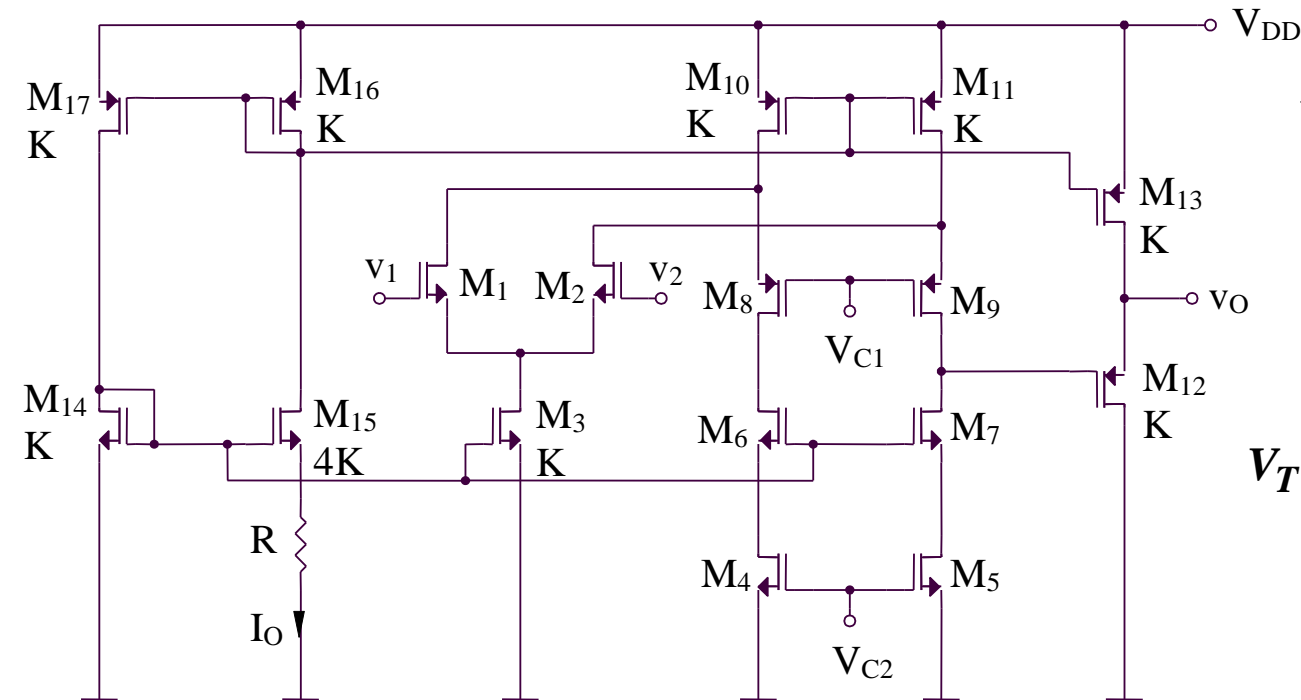$$= I_{D11} = I_{D12} = I_{D9} - I_{D2} = \frac{I_O}{2}$$

**Regim dinamic**

$$i_O = i_{D7} - i_{D6} = i_{D10} - i_{D6} = (i_{D9} - i_{D2}) - (i_{D5} - i_{D1}) = i_{D1} - i_{D2} = g_{m1}(v_1 - v_2)$$

$$v_O = i_O R_O = g_{m1} R_O (v_1 - v_2) = g_{m1}(v_1 - v_2)[r_{ds7} g_{m7} r_{ds8} \,//\, r_{ds6} g_{m6}(r_{ds5} \,//\, r_{ds1})]$$

**Amplificarea:** $\quad A = \dfrac{v_o}{v_1 - v_2} = g_{m1}\left[g_{m7} r_{ds8}^2 \,//\, g_{m6} r_{ds6}(r_{ds5} \,//\, r_{ds1})\right]$

# 6.2.9. Amplificator operational cascoda intoarsa (3)



**Regim static**

$V_{C2}$ fixeaza $I_{C4} = I_{C5} = I_O/2$

$$V_{GS14} = V_{GS15} + I_O R$$

$$V_T + \sqrt{\frac{2I_O}{K}} = V_T + \sqrt{\frac{2I_O}{4K}} + I_O R$$
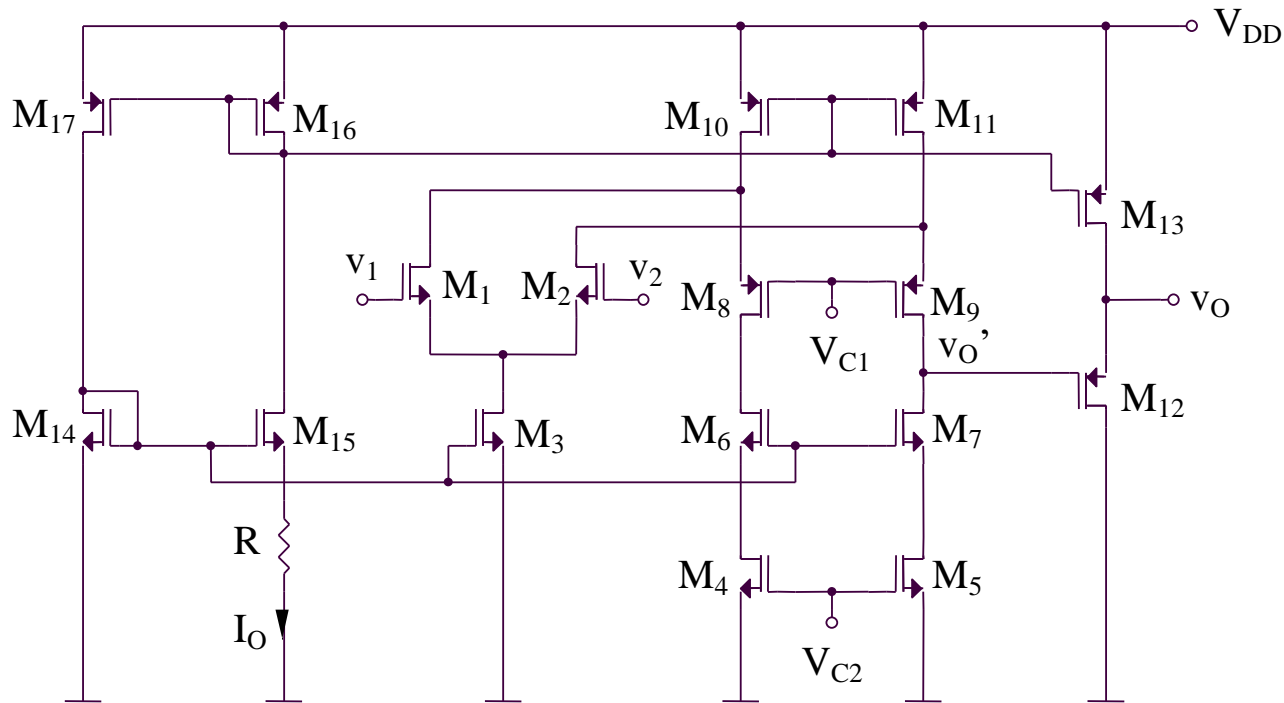
$$I_O = \frac{1}{2KR^2}$$

$$I_{D1} = I_{D2} = I_{D4} = \dots = I_{D9} = \frac{I_O}{2}$$

$$I_{D3} = I_O = I_{D10} = \dots = I_{D17}$$

$$I_{D4} = \frac{I_O}{2} = \frac{1}{4KR^2} = \frac{K}{2}\left(V_{C2} - V_T\right)^2$$

# 6.2.9. Amplificator operational cascoda intoarsa (3) - continuare
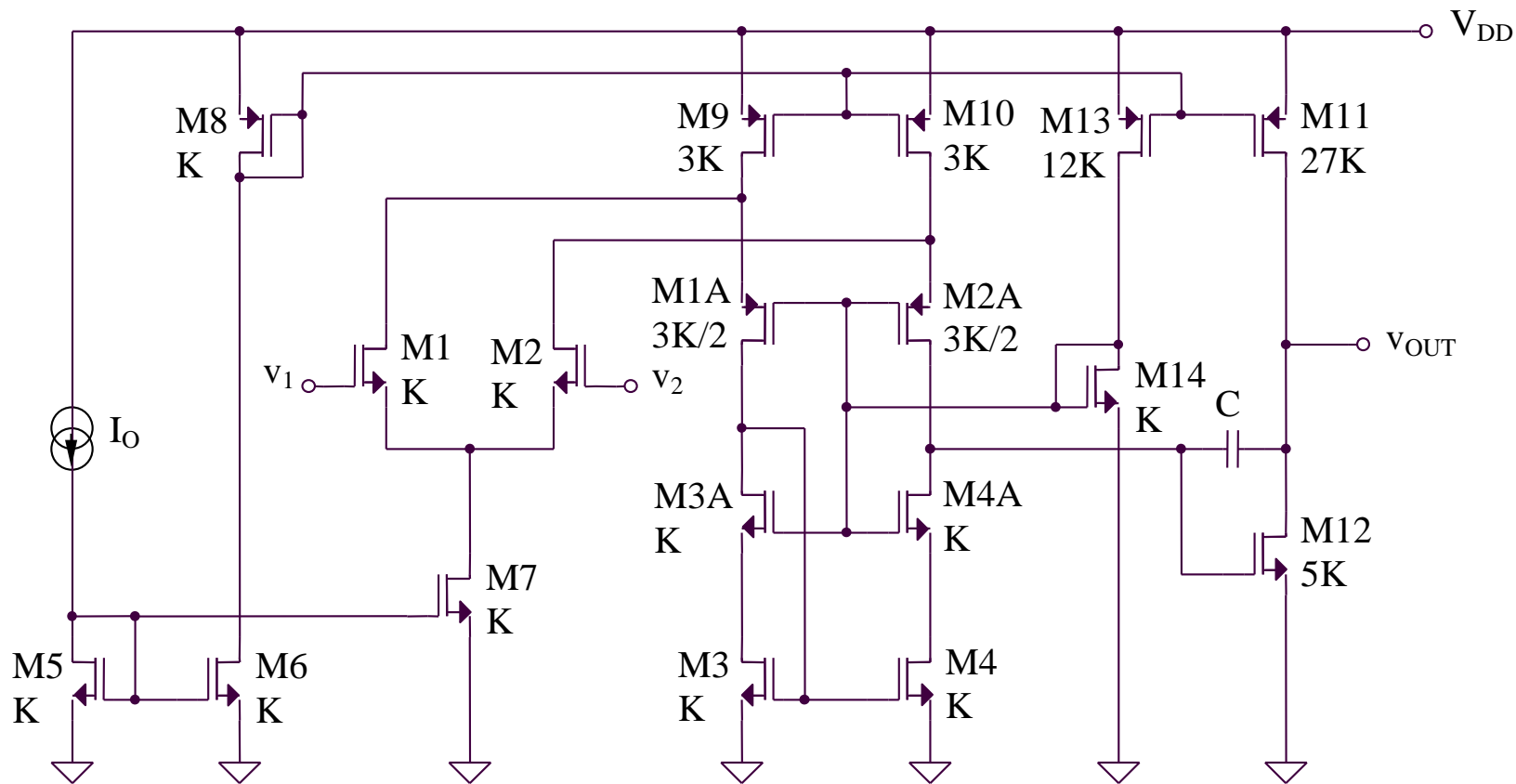


**Regim dinamic**

**Curentul de iesire pentru calculul $v_O$':**

$$i_O' = i_{D9} - i_{D7} = i_{D9} - i_{D8} = (i_{D11} - i_{D2}) - (i_{D10} - i_{D1}) = i_{D1} - i_{D2} = g_{m1}(v_1 - v_2)$$

$$v_O' = i_O' R_O' = g_{m1} R_O' (v_1 - v_2)$$

**Amplificarea:** $\quad A = g_{m1} R_O' = g_{m1}\{r_{ds7} g_{m7} r_{ds5} \mathbin{/\mkern-5mu/} [r_{ds9} g_{m9} (r_{ds11} \mathbin{/\mkern-5mu/} r_{ds2})]\}$
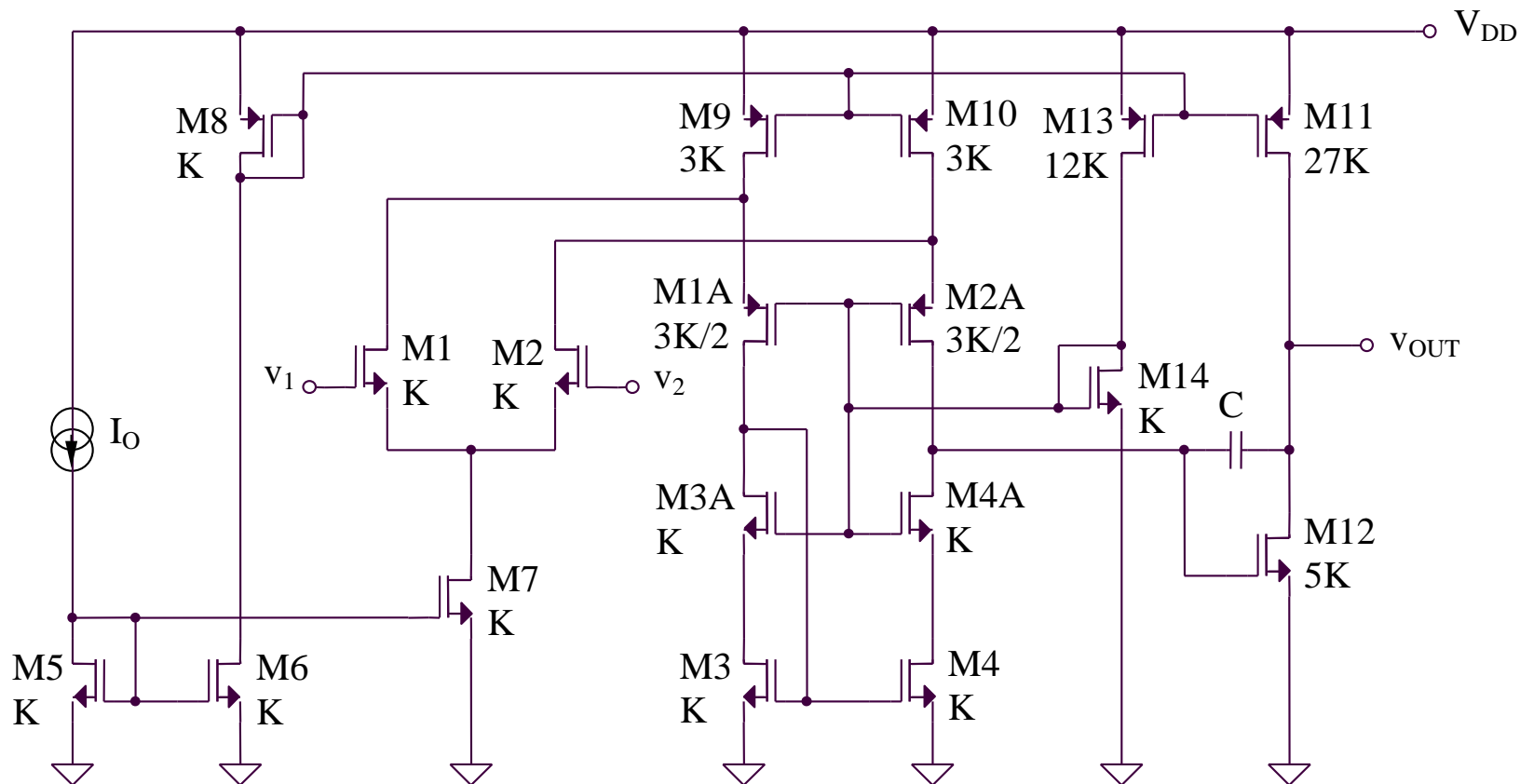
# 6.2.10. Amplificator operational cascoda intoarsa (4)



**Regim static**

$$I_{D5} = I_{D6} = I_{D7} = I_{D8} = I_O; \ I_{D9} = I_{D10} = 3I_O; \ I_{D13} = I_{D14} = 12I_O$$

$$I_{D11} = I_{D12} = 27I_O; \ I_{D3A} = I_{D4A} = I_{D1A} = I_{D2A} = I_{D3} = I_{D4} = 3I_O - \frac{I_O}{2} = \frac{5I_O}{2}$$

# 6.2.10. Amplificator operational cascoda intoarsa (4) - continuare



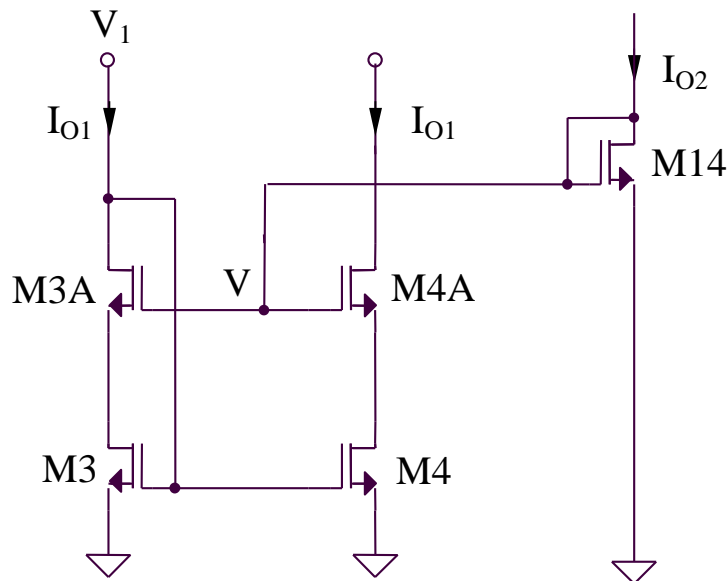**Regim dinamic**

$$|a_1| = g_{m1}R_{O1}$$

$$R_{O1} = g_{m4A}r_{ds4A}^2 /\!/ r_{ds2A}[1 + g_{m2A}(r_{ds10} /\!/ r_{ds2})]$$

$$a_2 = -g_{m12}R_{O2}$$

$$R_{O2} = r_{ds11} /\!/ r_{ds12}$$

# 6.2.10. Amplificator operational cascoda intoarsa (4) - continuare

## Analiza functionarii sursei de curent pentru tensiuni reduse



Tranzistoare identice

$$V_{GS3A} = V_{GS4A} =$$

$$= V_{GS3} = V_{GS4} \overset{not}{=} V_{GS} =$$

$$= V_T + \sqrt{\frac{2I_{O1}}{K}}$$

$$V = V_{GS14} = V_T + \sqrt{\frac{2I_{O2}}{K}}$$

$$V_{DS3} = V_{DS4} = V - V_{GS} > V_{GS} - V_T \Rightarrow V > 2V_{GS} - V_T$$

$$V_{DS3A} = V_{GS} - (V - V_{GS}) = 2V_{GS} - V > V_{GS} - V_T \Rightarrow V < V_{GS} + V_T$$
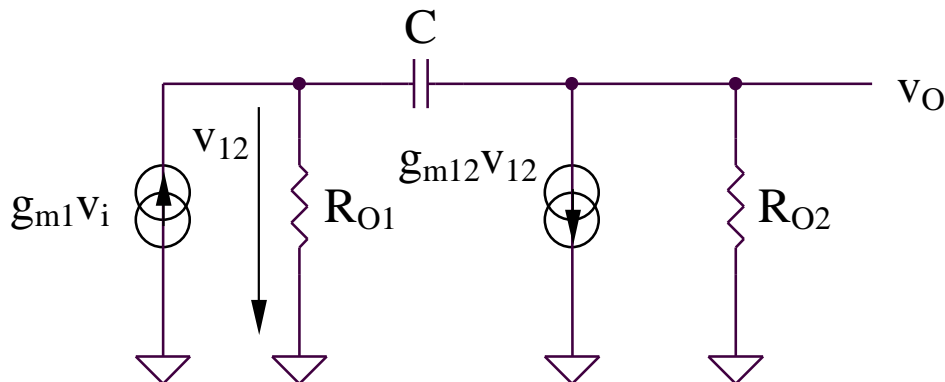
Se obtine:

Deci:

$$2\left(V_T + \sqrt{\frac{2I_{O1}}{K}}\right) - V_T < V_T + \sqrt{\frac{2I_{O2}}{K}} < \sqrt{\frac{2I_{O1}}{K}} + 2V_T$$

$$4I_{O1} < I_{O2} \quad si \quad \sqrt{\frac{2I_{O2}}{K}} - \sqrt{\frac{2I_{O1}}{K}} < V_T \quad \text{- conditii de proiectare}$$

**Avantaj:** $V_{1min} = V_{GS}$ (fata de oglinda clasica cascod avand $V_{1min} = 2V_{GS}$)

## Efectul capacitorului C de compensare Miller



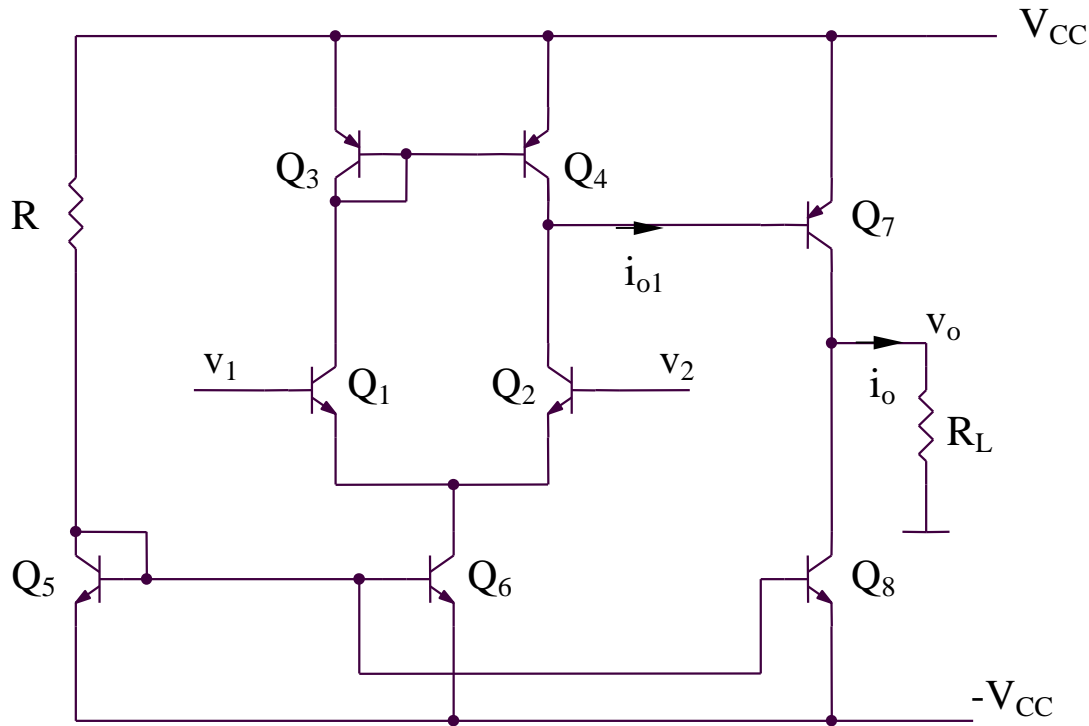$$v_{12}\left(\frac{1}{R_{O1}} + sC\right) = g_{m1}v_i + v_O sC$$

$$v_O\left(\frac{1}{R_{O2}} + sC\right) = v_{12}sC - g_{m12}v_{12}$$

Rezulta:

$$a = -g_{m1}g_{m12}R_{O1}R_{O2}\frac{1 - \dfrac{sC}{g_{m12}}}{1 + g_{m12}R_{O1}R_{O2}sC} = a_1 a_2 \frac{1 - \dfrac{sC}{g_{m12}}}{1 + g_{m12}R_{O1}R_{O2}sC}$$

# *Amplificatoare operationale in tehnologie bipolara*

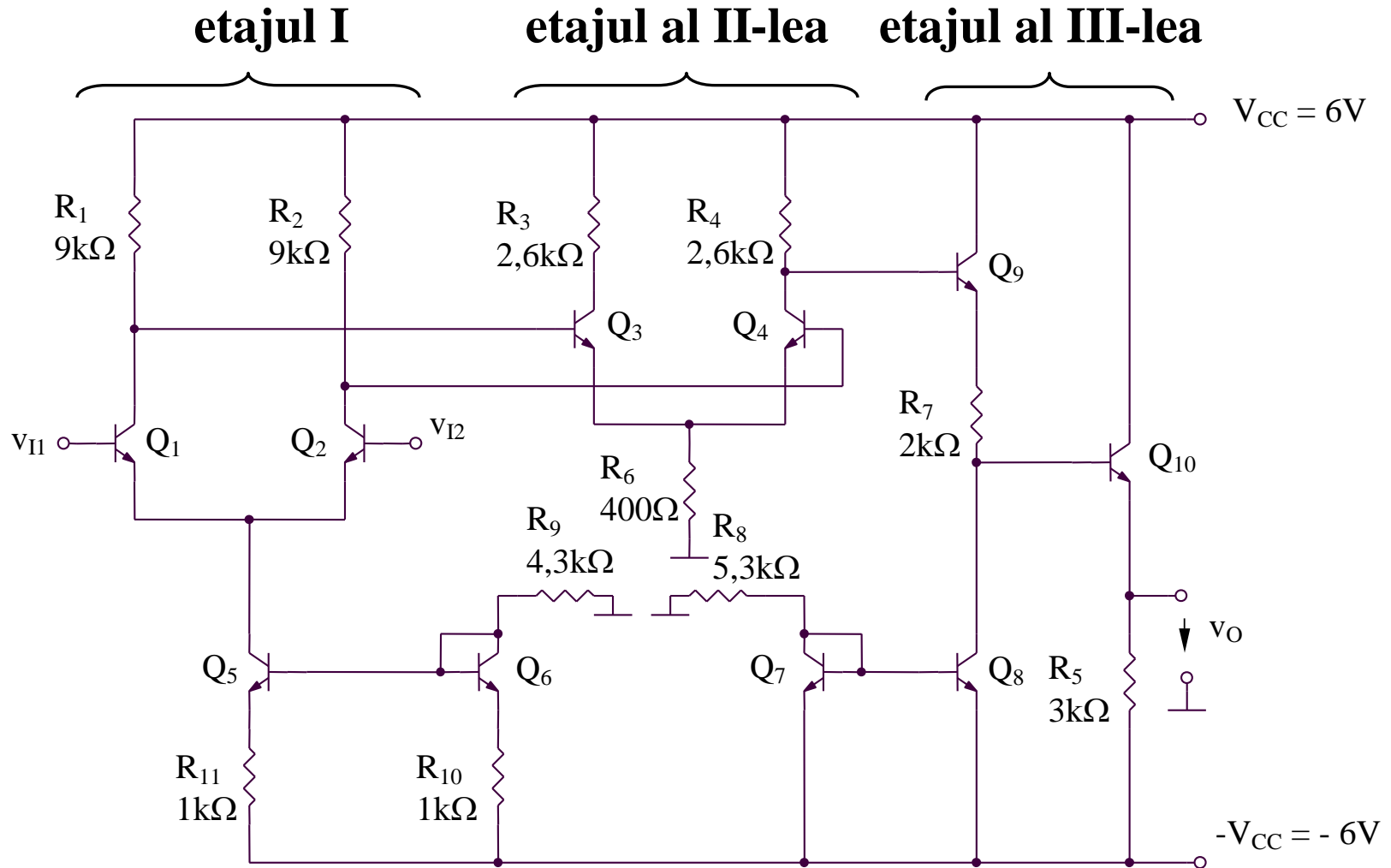# 6.2.11. Amplificator operational cu 2 etaje de amplificare



**Regim static**

$$I_{C5,6,7,8} = \frac{2V_{CC} - V_{BE}}{R}$$

$$I_{C1,2,3,4} = \frac{I_{C5}}{2}$$

**Regim dinamic**

$$\left. \begin{array}{l} i_{o1} = g_{m1}(v_1 - v_2) \\[2em] A_{dd} = \dfrac{v_o}{v_1 - v_2} = \dfrac{i_o R_L}{v_1 - v_2} = \dfrac{\beta_7 i_{o1} R_L}{v_1 - v_2} \end{array} \right\} \Rightarrow A_{dd} = g_{m1}\beta_7 R_L$$

# 6.2.12. Amplificator operational cu 3 etaje de amplificare

etajul I    etajul al II-lea    etajul al III-lea



$V_{CC} = 6V$

$R_1$ $9k\Omega$
$R_2$ $9k\Omega$
$R_3$ $2,6k\Omega$
$R_4$ $2,6k\Omega$
$Q_9$
$Q_3$
$Q_4$
$R_7$ $2k\Omega$
$Q_{10}$
$v_{I1}$ $Q_1$
$Q_2$ $v_{I2}$
$R_6$ $400\Omega$
$R_9$ $4,3k\Omega$
$R_8$ $5,3k\Omega$
$v_O$
$Q_5$
$Q_6$
$Q_7$
$Q_8$ $R_5$ $3k\Omega$
$R_{11}$ $1k\Omega$
$R_{10}$ $1k\Omega$
$-V_{CC} = -6V$

# Regim static

$$I_{C6} = \frac{V_{CC} - V_{BE6}}{R_9 + R_{10}} = 1mA$$

$$I_{C5} = I_{C6}\frac{R_{10}}{R_{11}} = 1mA$$

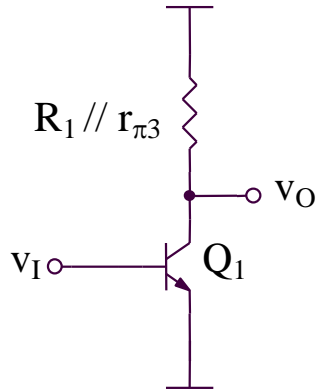$$I_{C1} = I_{C2} = \frac{I_{C5}}{2} = 0,5mA$$

$$I_{C3} = I_{C4} = \frac{V_{CC} - R_2 I_{C2} - V_{BE3}}{2R_6} = 2mA$$

$$I_{C7} = I_{C8} = I_{C9} = \frac{V_{CC} - V_{BE7}}{R_8} = 1mA$$

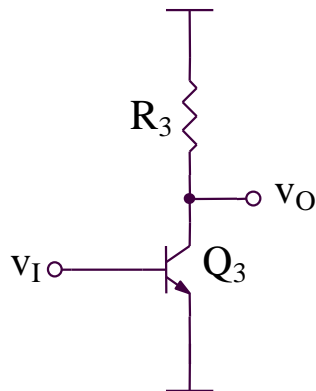$$I_{C10} = \frac{2V_{CC} - I_{C4}R_4 - I_{C9}R_7 - V_{BE9} - V_{BE10}}{R_5} \cong 1mA$$

# Regim dinamic (analiza de mod diferential)

**Semicircuitul de mod diferential (etajul I)**



$$A_{dd\,I} = -g_{m1}\left(R_1 \,//\, r_{\pi 3} \,//\, r_{o1}\right)$$

**Semicircuitul de mod diferential (etajul al II-lea)**



$$A_{dd\,II} \cong -g_{m3}\left(R_3 \,//\, r_{o3}\right)\frac{1}{2}$$

**Etajul al III-lea**

$$A_{III} \cong 1$$

# Regim dinamic (analiza de mod comun)
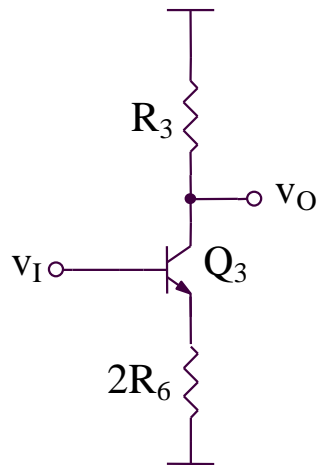
**Semicircuitul de mod comun (etajul I)**

$$A_{cc\,I} = -\frac{\beta(R_1 \mathbin{/\mkern-5mu/} R_{I2})}{r_{\pi 1} + (\beta + 1)2R_{O1}}$$
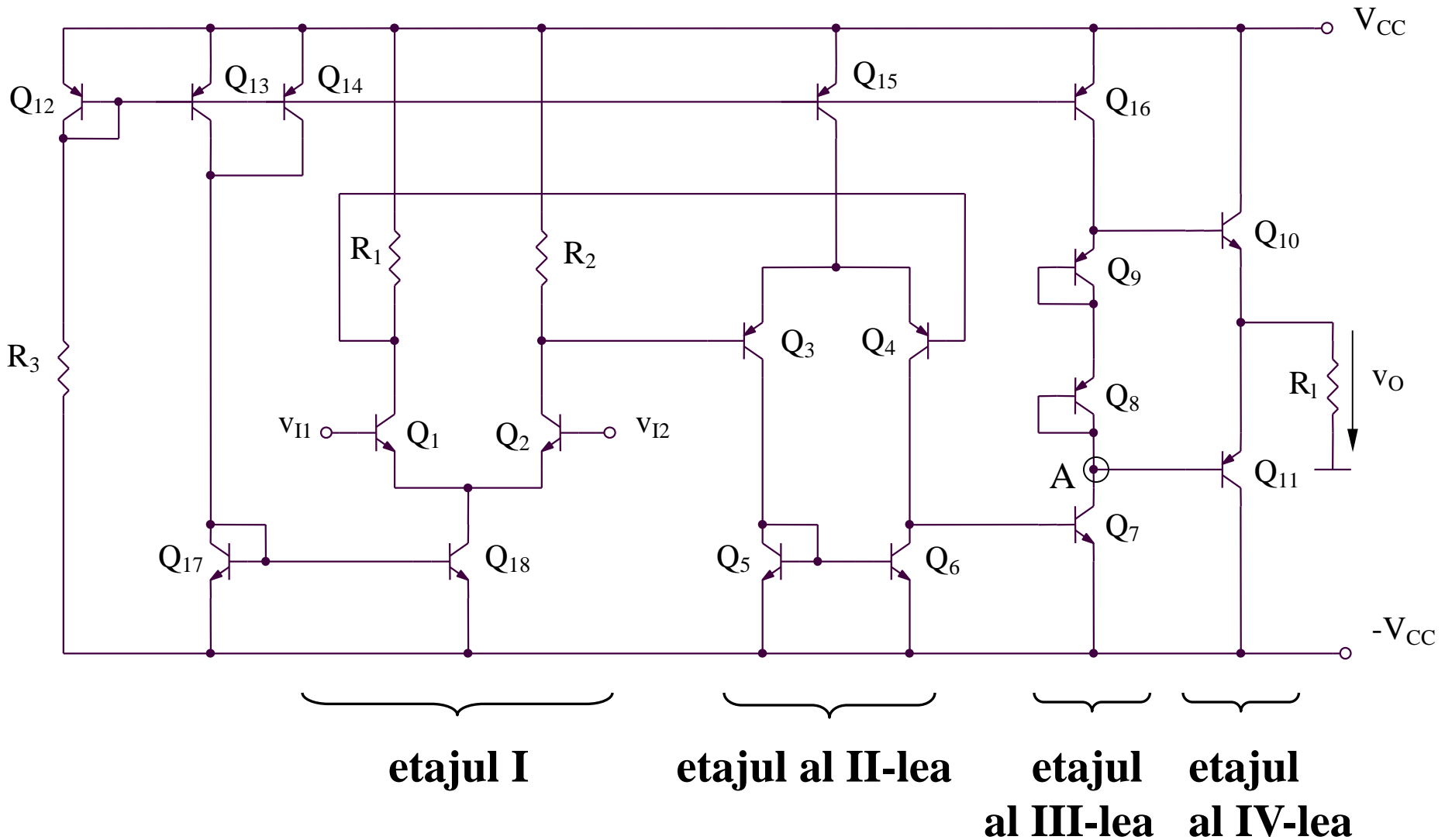
$$R_{I2} = r_{\pi 3} + (\beta + 1)2R_6$$

$$R_{O1} = r_{o5}\left(1 + \frac{\beta R_{11}}{r_{\pi 5} + R_{11} + (1/g_{m6} + R_{10}) \mathbin{/\mkern-5mu/} R_9}\right)$$

**Semicircuitul de mod comun (etajul al II-lea)**

$$A_{cc\,II} = -\frac{\beta R_3}{r_{\pi 3} + (\beta + 1)2R_6}$$

# 6.2.13. Amplificator operational cu 4 etaje de amplificare



etajul I    etajul al II-lea    etajul al III-lea    etajul al IV-lea

# Regim static

$$I_{C12} = \frac{2V_{CC} - V_{BE}}{R_3} = I_{C13} = I_{C14} = I_{C15} = I_{C16} = I_{C9} = I_{C8} = I_{C7} = I$$
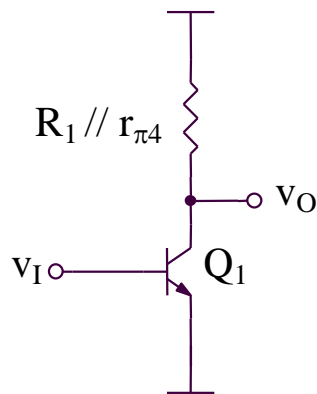
$$I_{C17} = I_{C18} = 2I \qquad I_{C3} = I_{C4} = I_{C5} = I_{C6} = I/2 \qquad I_{C1} = I_{C2} = I$$

$$/V_{BE8}/ + /V_{BE9}/ = V_{BE10} + V_{EB11} \Rightarrow 2V_{th}\,ln\frac{I}{I_{S8}} = 2V_{th}\,ln\frac{I_{C10}}{I_{S10}} \Rightarrow$$

$$\Rightarrow I_{C10} = I_{C11} = I\frac{I_{S10}}{I_{S8}} = I\frac{A_{10}}{A_8}$$
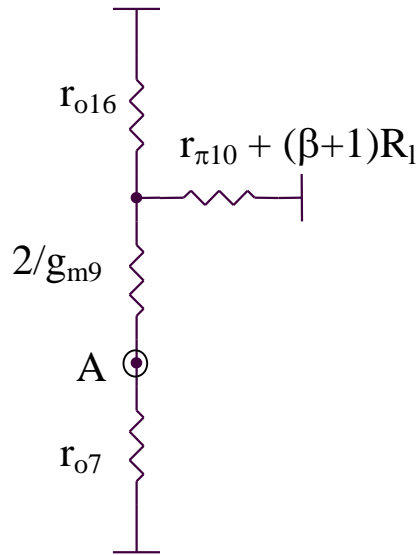
# Regim dinamic
## Amplificarea primului etaj



$$A_{dd\,I} = -g_{m1}\left(R_1\,//\,r_{\pi4}\,//\,r_{o1}\right)$$

**Amplificarea etajului al II-lea**

$$A_{dd\,II} = g_{m3}\left(r_{o6} \,//\, r_{o4} \,//\, r_{\pi7}\right)$$

**Amplificarea etajului al III-lea**



$r_{o16}$

$r_{\pi10} + (\beta+1)R_l$

$2/g_{m9}$

A

$r_{o7}$

$$A_{III} = -g_{m7}\left(r_{o7} \,//\, r_{o16} \,//\, \beta R_l\right)$$

**Amplificarea etajului al IV-lea**

$$A_{IV} = \frac{\beta R_l}{r_{\pi10} + \beta R_l} \cong 1$$

**Rezistenta de intrare de mod diferential**

$$R_{id} = 2r_{\pi 1}$$

**Domeniul maxim al tensiunii de intrare de mod comun**

$$V_{IC}^{min} = -V_{CC} + V_{BE1} + V_{CE18sat}$$

$$V_{IC}^{max} = V_{CC} - R_1 I_{C1} - V_{CE1sat} + V_{BE1}$$

**Excursia maxima a tensiunii de iesire**

$$V_{Omax}^{+} = min\left(V_{CC} - /V_{CE16sat}/ - V_{BE10}\, ;\, I_{C16}\beta R_l\right)$$

$$V_{Omax}^{-} = -V_{CC} + V_{CE7sat} + /V_{BE11}/$$

***Amplificatoare operationale transconductanta (operational transconductance amplifiers – OTA) in tehnologie CMOS***

**Diferente fata de amplificatorul operational clasic:**

- iesire in curent
- este utilizat in mod uzual in bucla deschisa, fara reactie negativa; amplitudinea tensiunii de iesire este controlata prin intermediul rezistentei de iesire

$$i_{OUT} = G_m(v_1 - v_2)$$

$$v_{OUT} = i_{OUT} R_O = G_m R_O (v_1 - v_2)$$

$$a = \frac{v_{OUT}}{v_1 - v_2} = G_m R_O$$

**Dezavantaje:**

- neliniaritatea amplificatorului transconductanta
- dependenta de temperatura a transconductantei echivalente