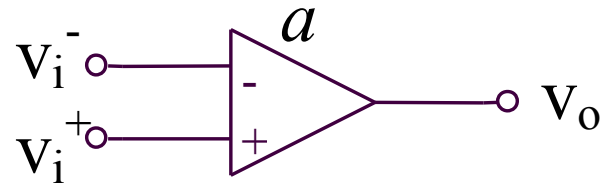


**Capitolul 6**  
**Amplificatoare operationale.**  
**Structuri interne**

## **6.1. Introdúcere**

## 6.1. Introducere



$$v_o = a(v_i^+ - v_i^-)$$

**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

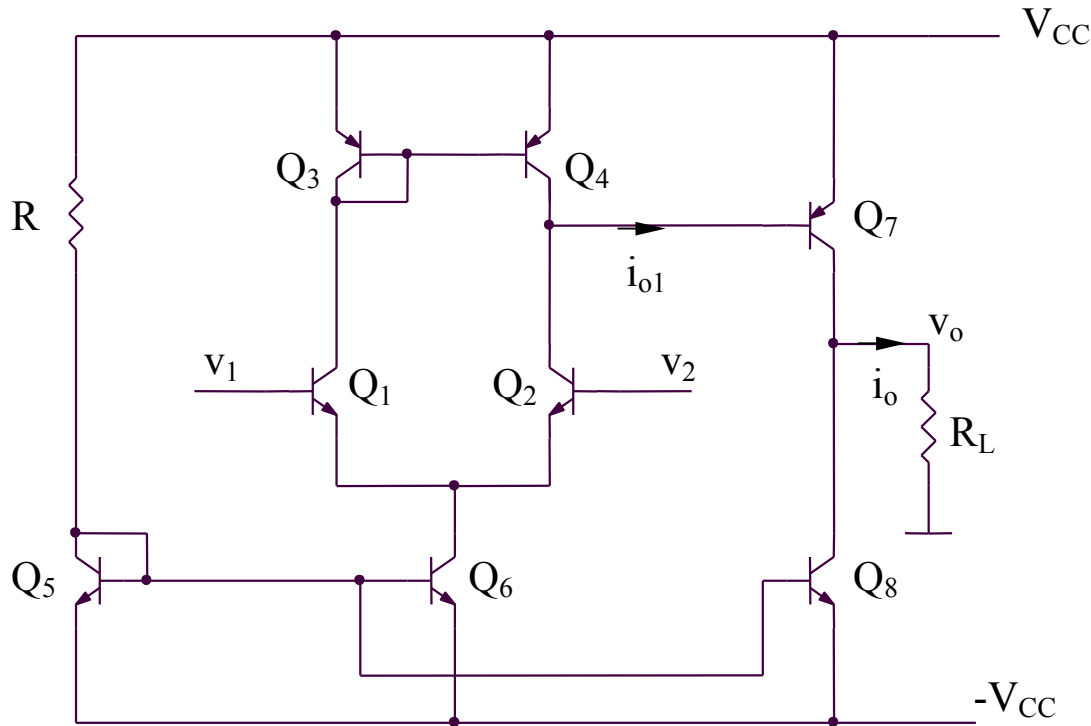
### **AO real:**

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

## **6.2. Structuri interne de amplificatoare operationale**

*Amplificatoare operationale in tehnologie bipolara*

## 6.2.1. Amplificator operational cu 2 etaje de amplificare



**Regim static**

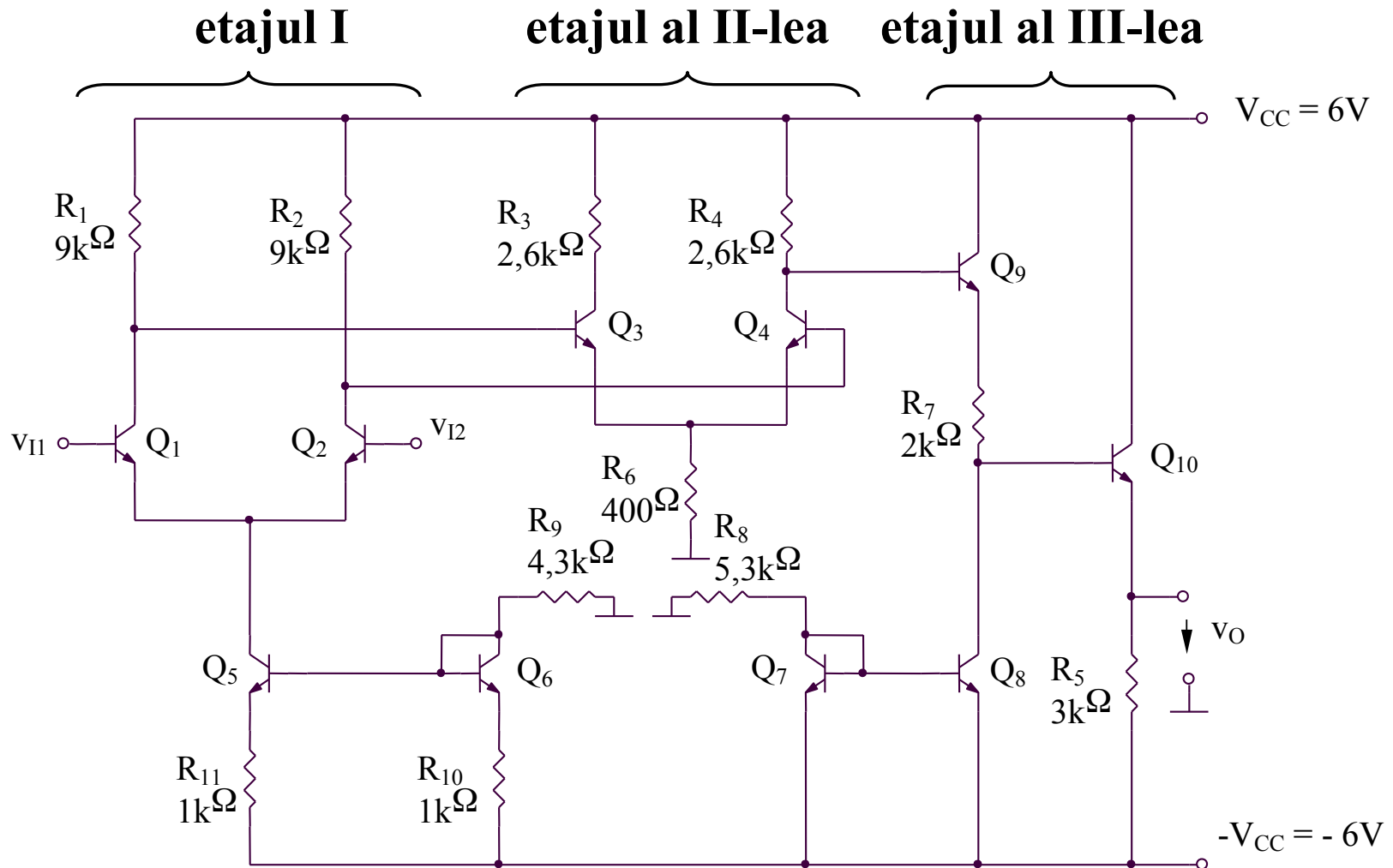
$$I_{C5,6,7,8} = \frac{2V_{CC} - V_{BE}}{R}$$

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

**Regim dinamic**

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

## 6.2.2. Amplificator operational cu 3 etaje de amplificare





## Regim static

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

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

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

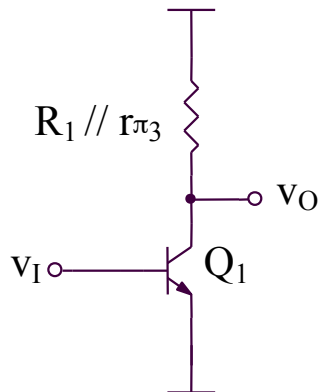
$$I_{C3} = I_{C4} = \frac{V_{CC} - R_2 I_{C2} - V_{BE3}}{2R_6} = 2mA$$

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

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

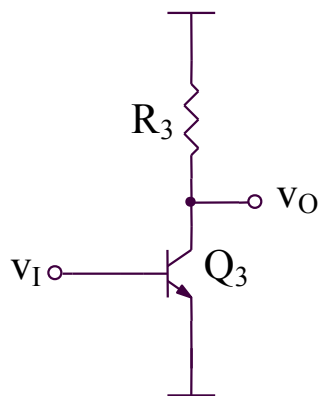
# Regim dinamic (analiza de mod diferential)

## Semicircuitul de mod diferential (etajul I)



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

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



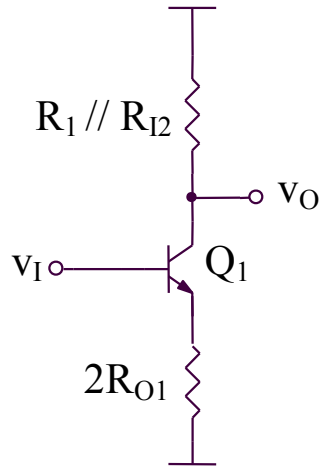
$$A_{dd II} \cong -g_{m3}(R_3 // r_{o3}) \frac{1}{2}$$

## Etajul al III-lea

$$A_{dd III} \cong 1$$

# Regim dinamic (analiza de mod comun)

## Semicircuitul de mod comun (etajul I)

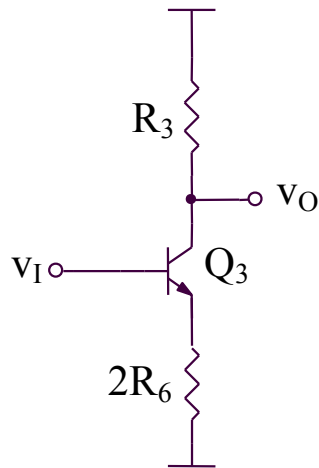


$$A_{cc I} = - \frac{\beta(R_1 // R_{I2})}{r_{\pi 1} + (\beta + 1)2R_{O1}}$$

$$R_{I2} = r_{\pi 3} + (\beta + 1)2R_6$$

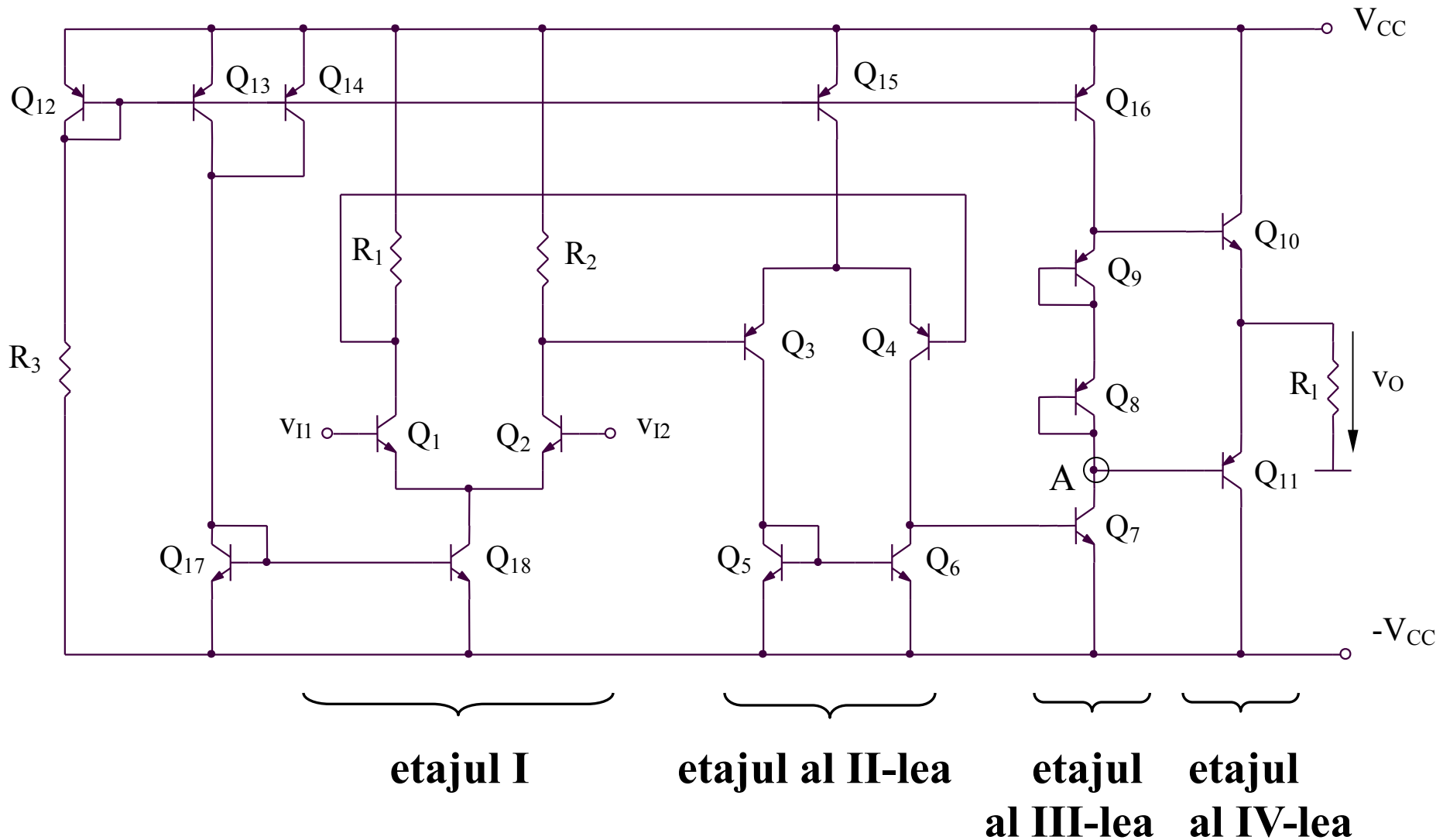
$$R_{O1} = r_{o5} \left( 1 + \frac{\beta R_{11}}{r_{\pi 5} + R_{11} + (1/g_{m6} + R_{10}) // R_9} \right)$$

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



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

## 6.2.3. Amplificator operational cu 4 etaje de amplificare



## Regim static

$$I_{C12} = \frac{2V_{CC} - V_{BE}}{R_3} = I_{C13} = I_{C14} = I_{C15} = I_{C16} = I_{C9} = I_{C8} = I_{C7} = I$$

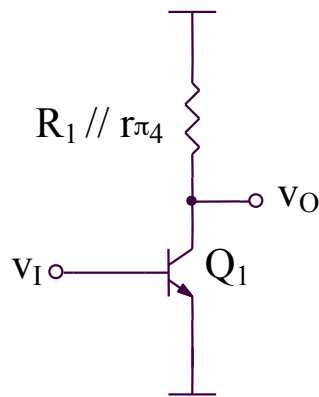
$$I_{C17} = I_{C18} = 2I \quad I_{C3} = I_{C4} = I_{C5} = I_{C6} = I/2 \quad I_{C1} = I_{C2} = I$$

$$/V_{BE8}/ + /V_{BE9}/ = V_{BE10} + V_{BE11} \Rightarrow 2V_{th} \ln \frac{I}{I_{S8}} = 2V_{th} \ln \frac{I_{C10}}{I_{S10}} \Rightarrow$$

$$\Rightarrow I_{C10} = I_{C11} = I \frac{I_{S10}}{I_{S8}} = I \frac{A_{10}}{A_8}$$

## Regim dinamic

### Amplificarea primului etaj

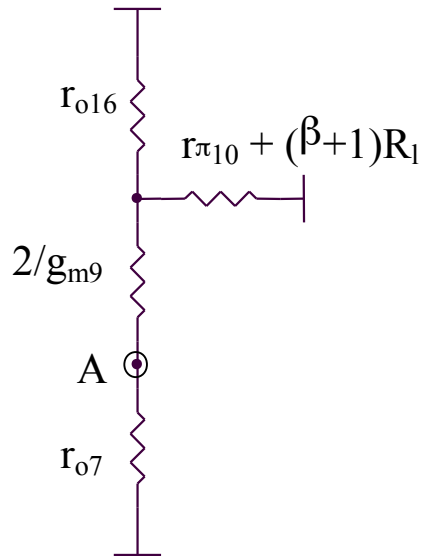


$$A_{dd I} = -g_{m1} (R_1 // r_{\pi 4} // r_{o1})$$

## Amplificarea etajului al II-lea

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

## Amplificarea etajului al III-lea



$$A_{dd III} = -g_{m7} (r_{o7} // r_{o16} // \beta R_1)$$

## Amplificarea etajului al IV-lea

$$A_{IV} = \frac{\beta R_1}{r_{\pi10} + \beta R_1} \cong 1$$

## Rezistența 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

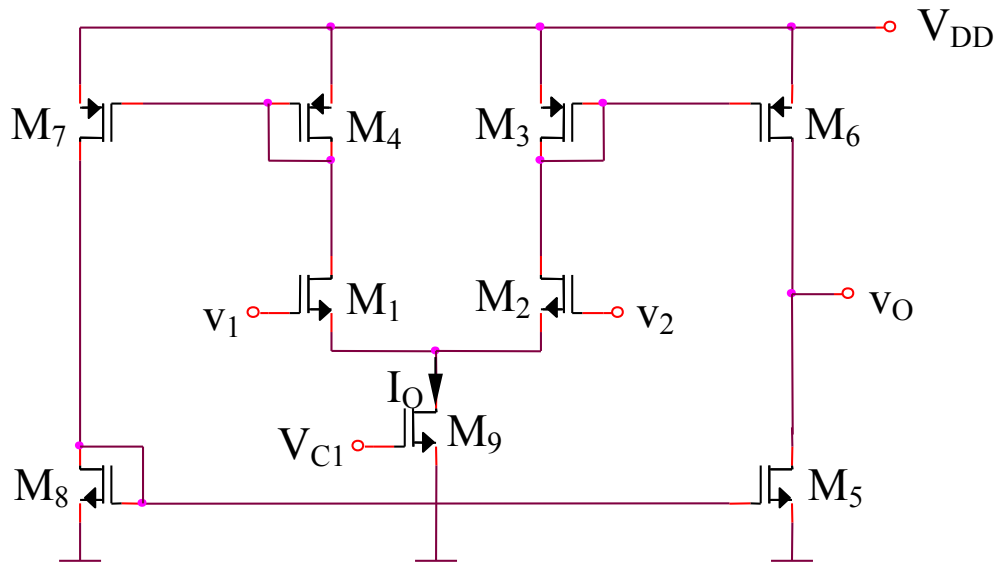
$$V_O^{max} = \min(V_{CC} - |V_{CE16sat}| - V_{BE10}; I_{C16} \beta R_l)$$

$$V_O^{min} = -V_{CC} + V_{CE7sat} + |V_{BE11}|$$

*Amplificatoare operationale clasice in tehnologie CMOS*



## 6.2.4. Amplificator operational cu un etaj de amplificare



**Regim static**

$$I_{D9} = I_O = \frac{K}{2} (V_{C1} - V_T)^2$$

$$I_{D1} = I_{D2} = \dots = I_{D8} = I_O / 2$$

**Regim dinamic**

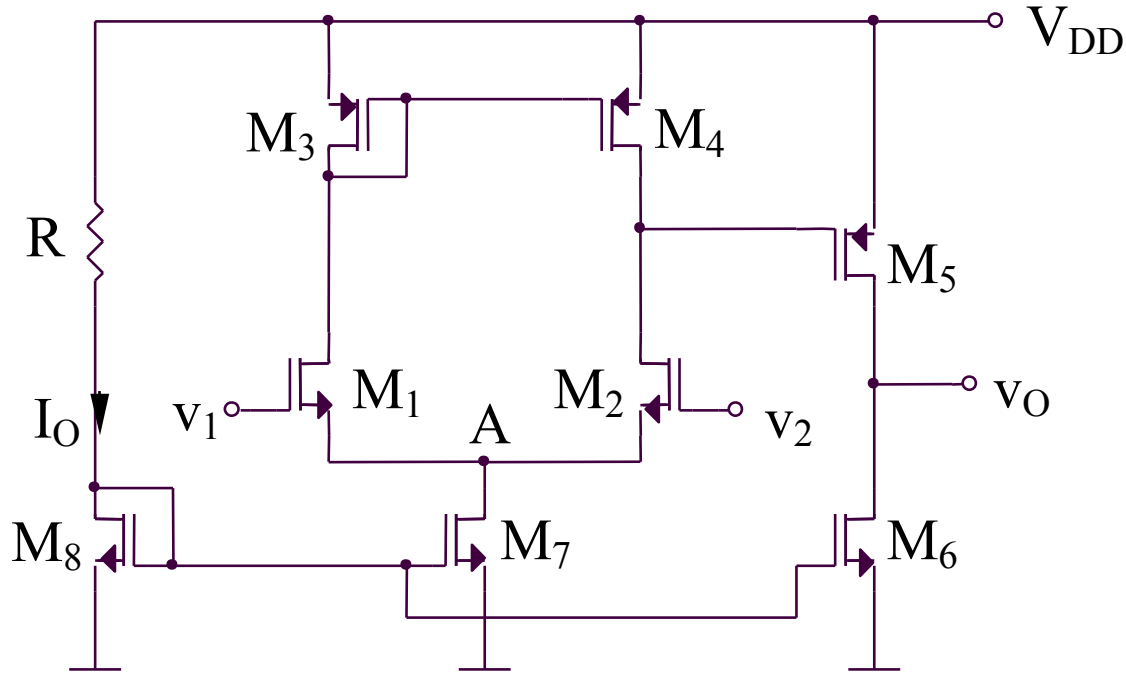
$$i_{D6} - i_{D5} = i_{D3} - i_{D8} = i_{D3} - i_{D4} = i_{D2} - i_{D1} = g_{m1}(v_2 - v_1)$$

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

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

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

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



**Regim static**

$$\left. \begin{aligned} RI_O + V_{GS8} &= V_{DD} \\ I_O &= \frac{K}{2} (V_{GS8} - V_T)^2 \end{aligned} \right\} \Rightarrow V_{DD} = V_{GS8} + \frac{RK}{2} (V_{GS8} - V_T)^2 \Rightarrow V_{GS8} \quad (V_{GS8} > V_T)$$

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

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

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

## Regim dinamic

### Amplificarea circuitului

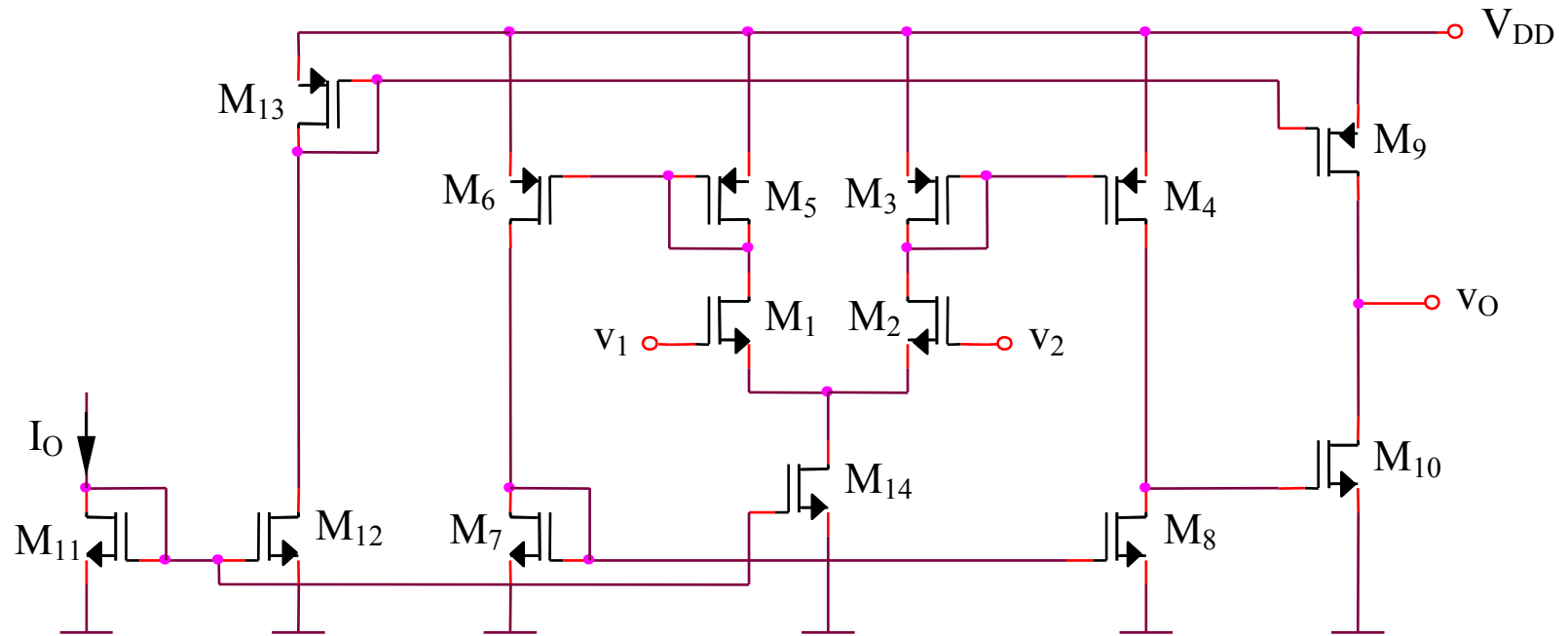
$$a = g_{m1}(r_{ds2} // r_{ds4})g_{m5}(r_{ds5} // r_{ds6})$$

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

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

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

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



**Regim static**

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

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

# 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

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

$$V_{IC}^{\min} = V_{GS2} + V_{DS14sat} = (\sqrt{2} + 1)\sqrt{\frac{I_O}{K}} + V_T$$

## 6.2.7. Amplificator operational cu 3 etaje de amplificare

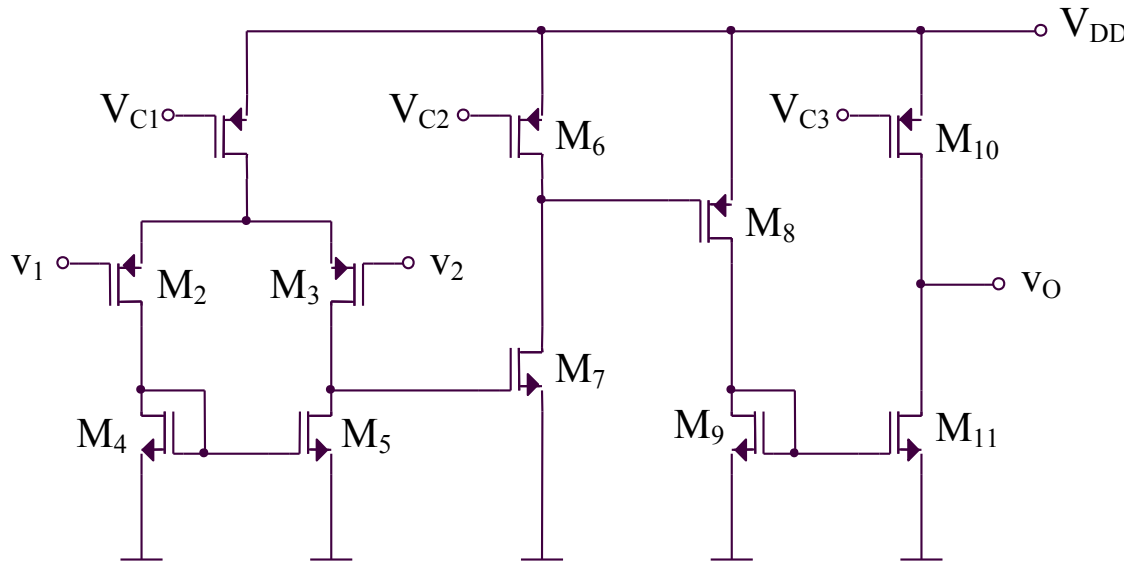
### Regim static

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

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

$$I_{D10} = I_{D11} = I_{D8} = I_{D9} = \\ = \frac{K}{2}(V_{DD} - V_{C3} - V_T)^2$$

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



### Regim dinamic

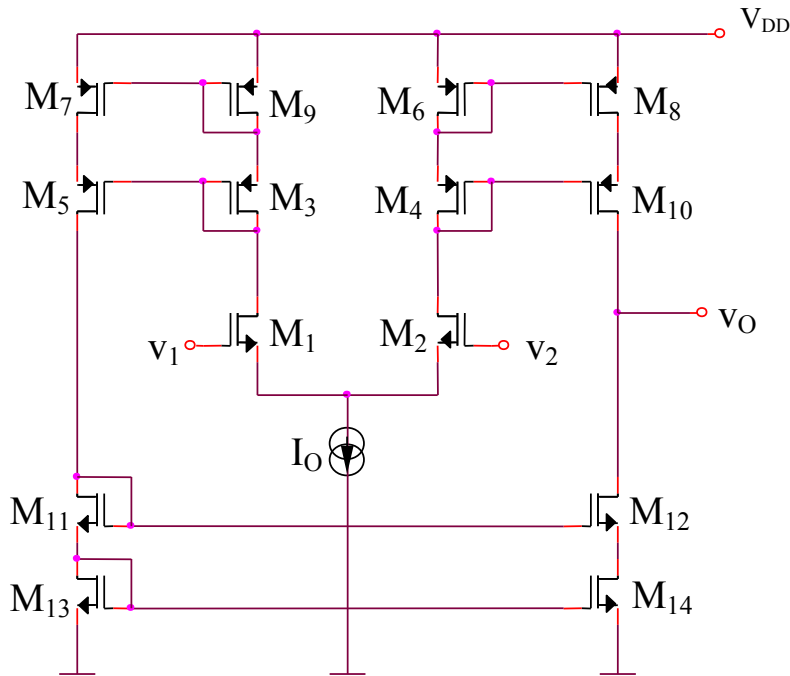
$$A_{dd1} = g_{m2}(r_{ds3} // r_{ds5})$$

$$A_{dd2} = -g_{m7}(r_{ds6} // r_{ds7})$$

$$A_{dd3} = -g_{m8}(r_{ds10} // r_{ds11})$$

# *Amplificatoare operationale cascod in tehnologie CMOS*

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



**Regim static**

$$I_{D1} = I_{D2} = \dots = I_{D14} = I_O / 2$$

**Regim dinamic**

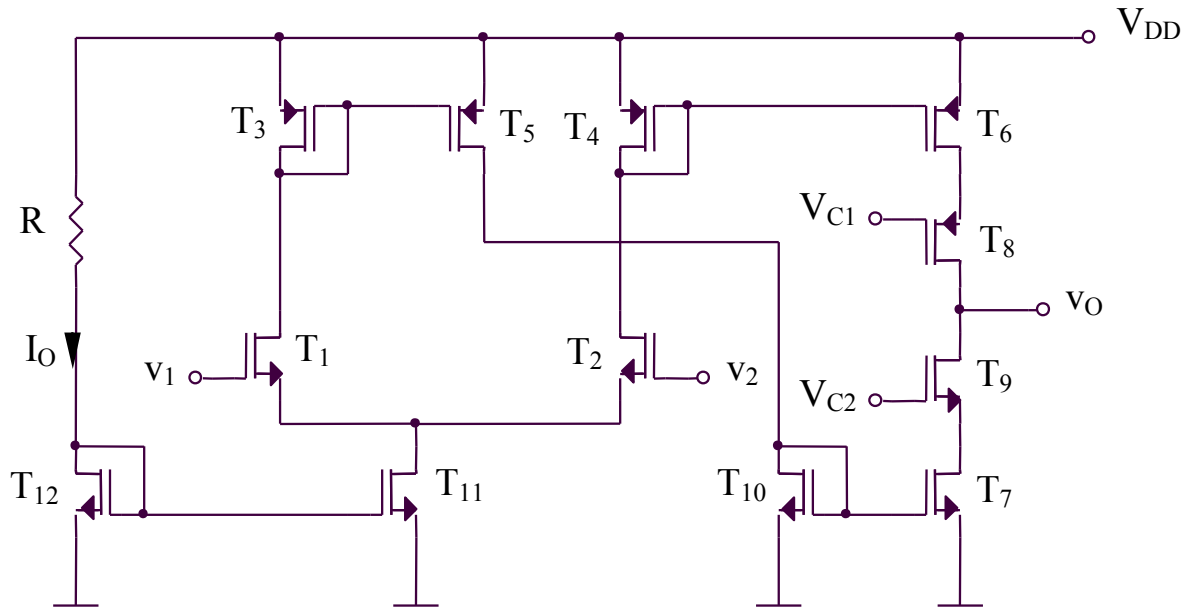
$$R_O = g_{m10} r_{ds10}^2 // g_{m12} r_{ds12}^2 = \frac{1}{2} g_{m10} r_{ds10}^2$$

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

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



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



**Regim static**

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

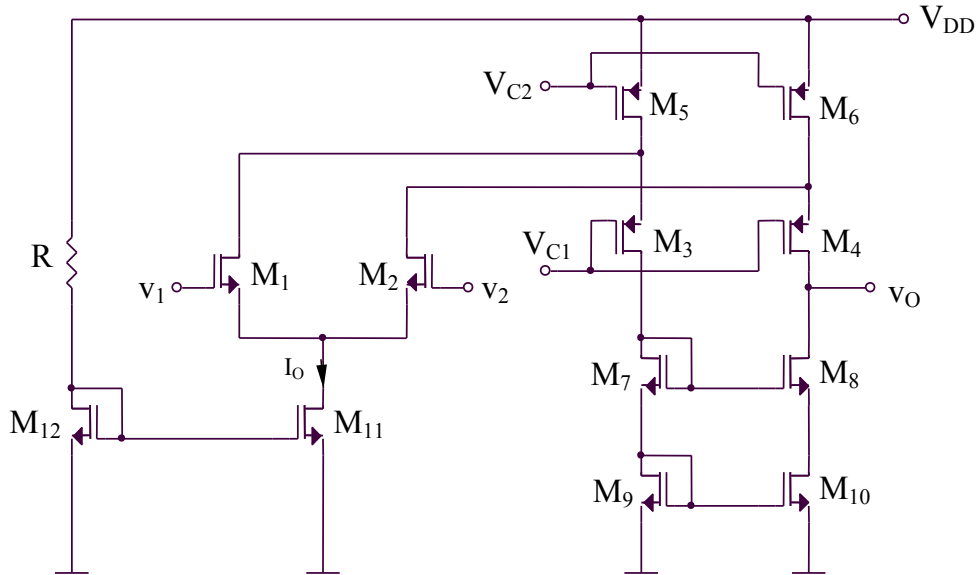
**Regim dinamic**

$$a = g_{m1} R_O$$

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

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

## 6.2.10. Amplificator operational cascada intoarsa (1)



**Regim static**

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

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

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

$$I_{D3} = I_{D4} = I_{D7} = \dots$$

$$\dots = I_{D10} = I_{D6} - I_{D2}$$

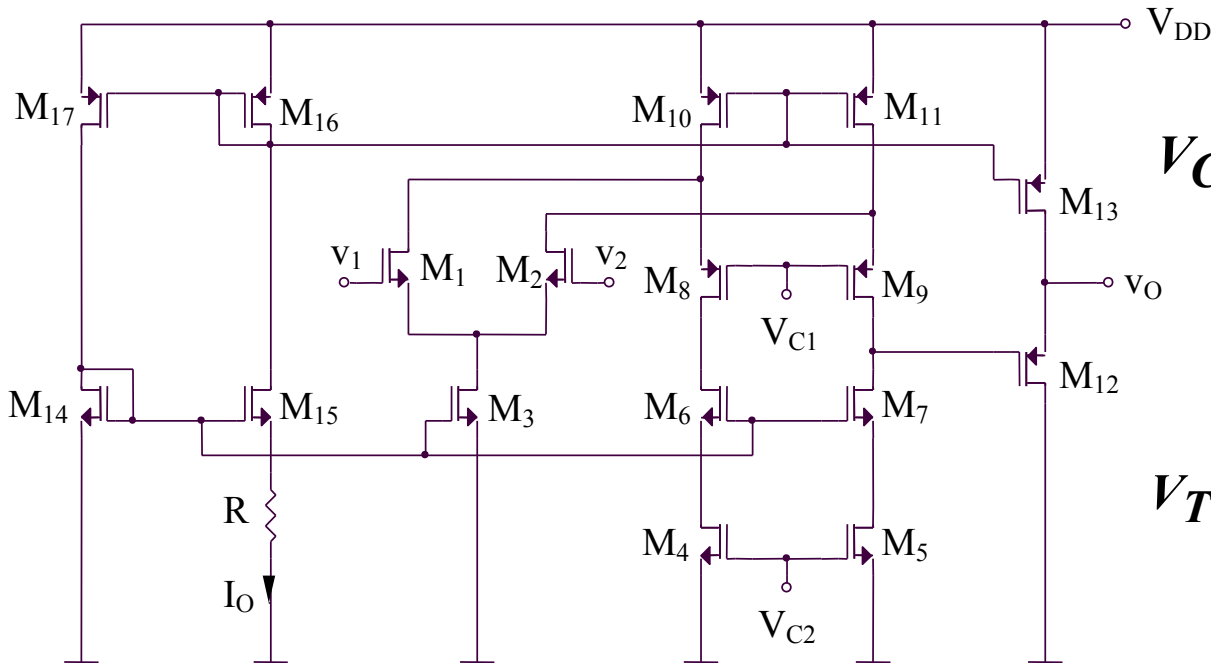
**Regim dinamic**

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

$$a = g_{m1} R_O$$

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

## 6.2.11. Amplificator operational cascada intoarsa (2)



**Regim static**

$$V_{C2} \text{ asigura } I_{D4} = I_{D5} = I_O / 2$$

$$K_{15} = 4K_{14} = 4K$$

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

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

$$I_O = \frac{1}{2KR^2}$$

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

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

**Regim dinamic**

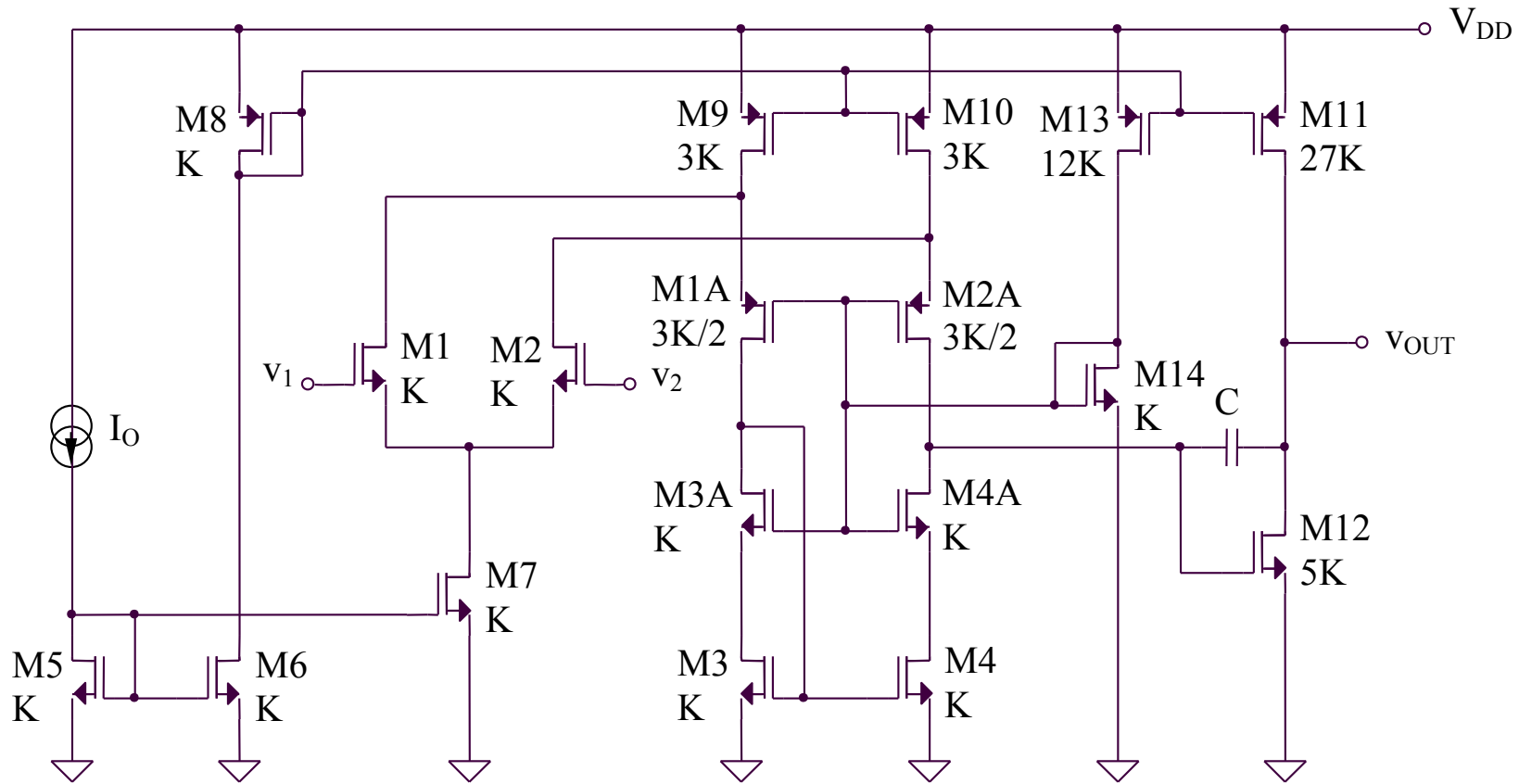
$$i_{D9} - i_{D7} = i_{D9} - i_{D8} = (I_{D11} - i_{D2}) - (I_{D10} - i_{D1}) = i_{D1} - i_{D2}$$

$$a_1 = g_{m1} R_O$$

$$a_1 = g_{m1} \left\{ r_{ds7} g_{m7} r_{ds5} // \left[ r_{ds9} g_{m9} (r_{ds11} // r_{ds2}) \right] \right\}$$

$$a_2 \cong 1$$

## 6.2.12. Amplificator operational cascada intoarsa (3)

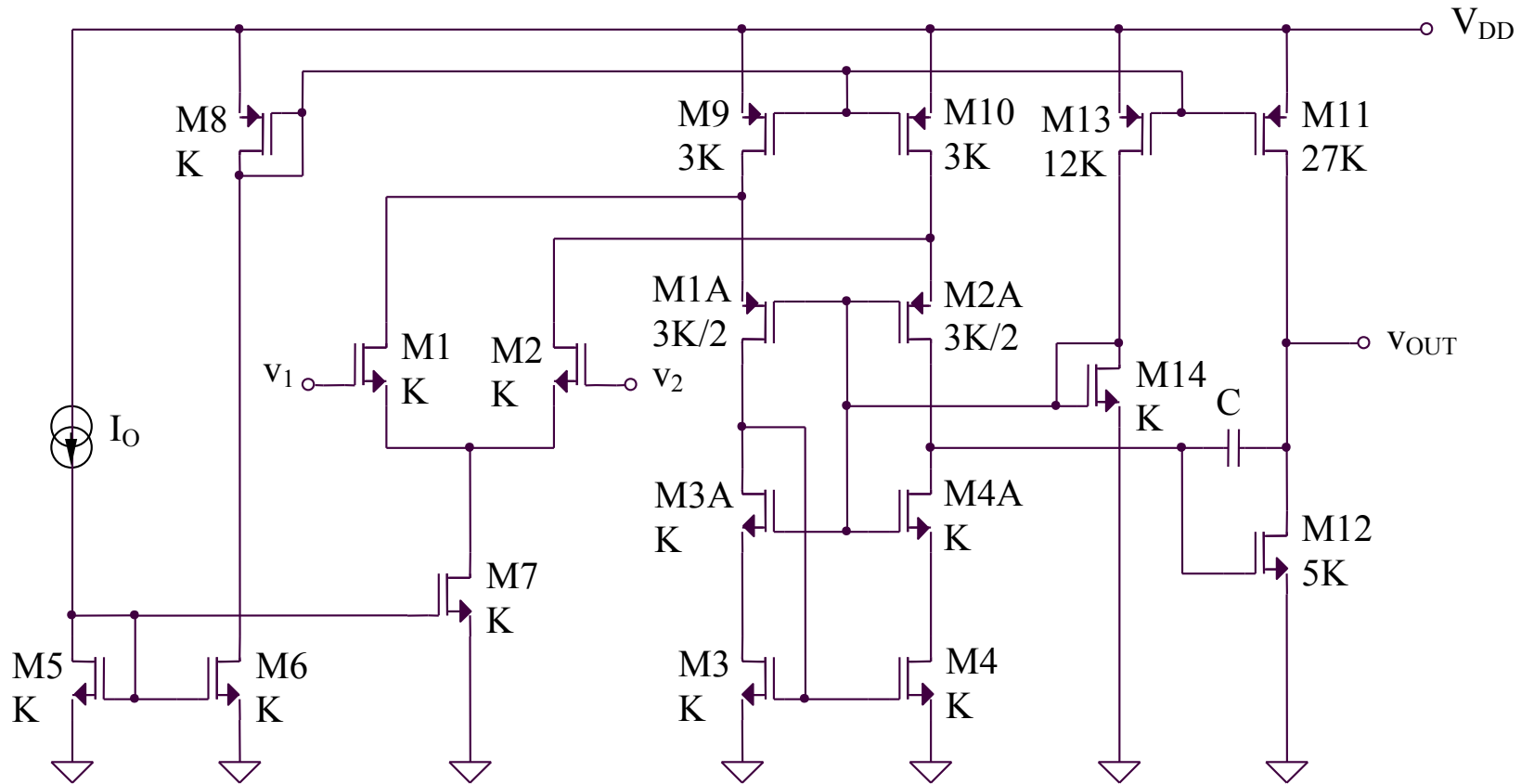


**Regim static**

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

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

## 6.2.12. Amplificator operational cascada intoarsa (3)



**Regim dinamic**

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

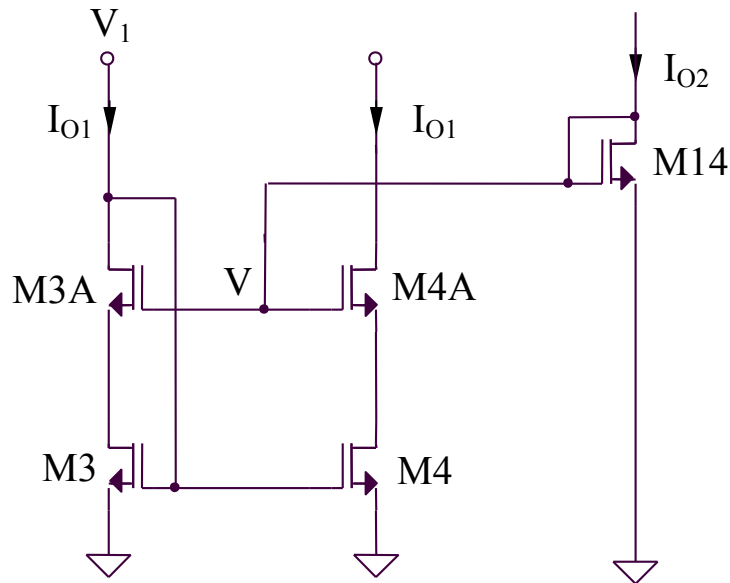
$$R_{O1} = g_{m4A}r_{ds4A}^2 // r_{ds2A} [1 + g_{m2A}(r_{ds10} // r_{ds2})]$$

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

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

## 6.2.12. Amplificator operational cascada intoarsa (3)

### Analiza functionarii sursei de curent pentru tensiuni reduse



Tranzistoare identice

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

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

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

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

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

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

Se obtine:

Deci:

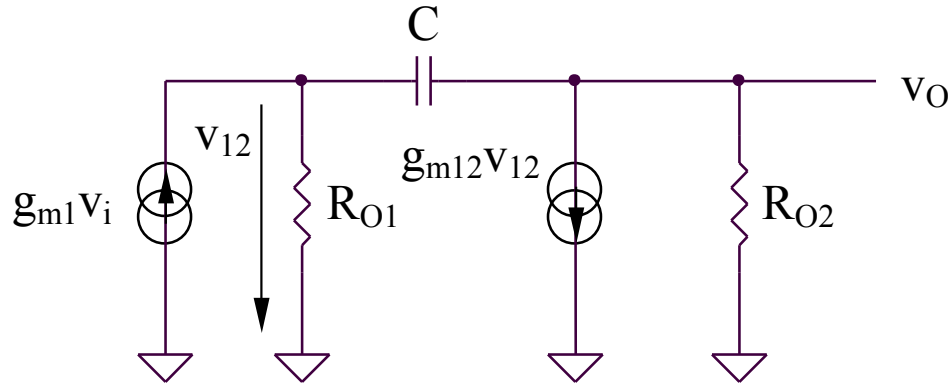
$$2\left(V_T + \sqrt{\frac{2I_{O1}}{K}}\right) - V_T < V_T + \sqrt{\frac{2I_{O2}}{K}} < \sqrt{\frac{2I_{O1}}{K}} + 2V_T$$

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

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

## 6.2.12. Amplificator operational cascada intoarsa (3)

### 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:

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



*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

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

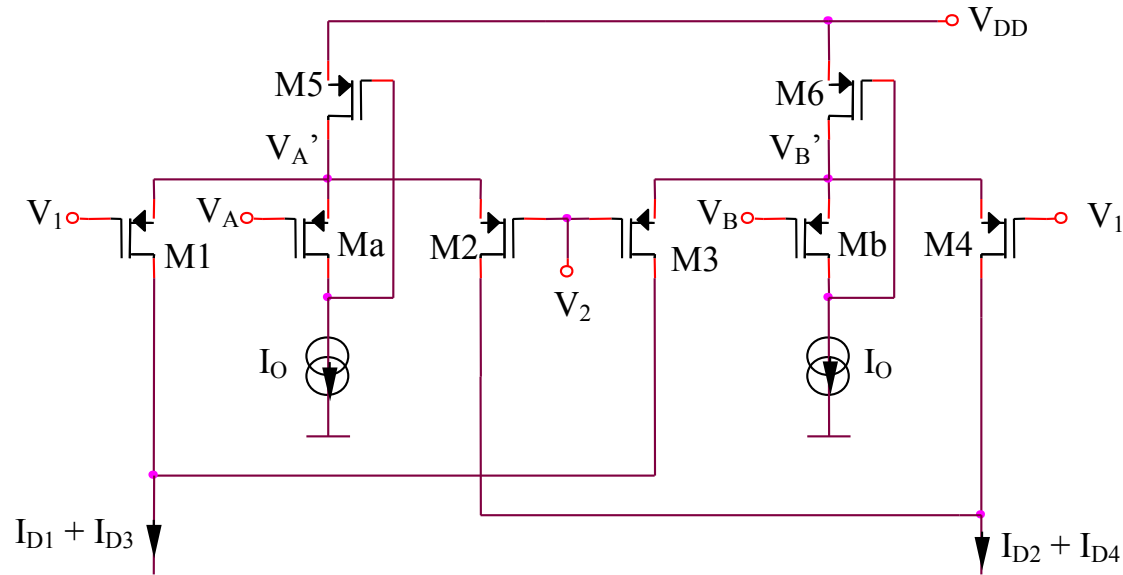
$$v_{OUT} = i_{OUT} R_O = G_m R_O (v_1 - v_2)$$

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

## Dezavantaje:

- neliniaritatea amplificatorului transconductanta
- dependenta de temperatura a transconductantei echivalente

## 6.2.13. Amplificator operational transconductanta (1)



$$i_{OUT} = \frac{K}{2}(V_{A'} - V_1 - V_T)^2 + \frac{K}{2}(V_{B'} - V_2 - V_T)^2 - \frac{K}{2}(V_{A'} - V_2 - V_T)^2 - \frac{K}{2}(V_{B'} - V_1 - V_T)^2$$

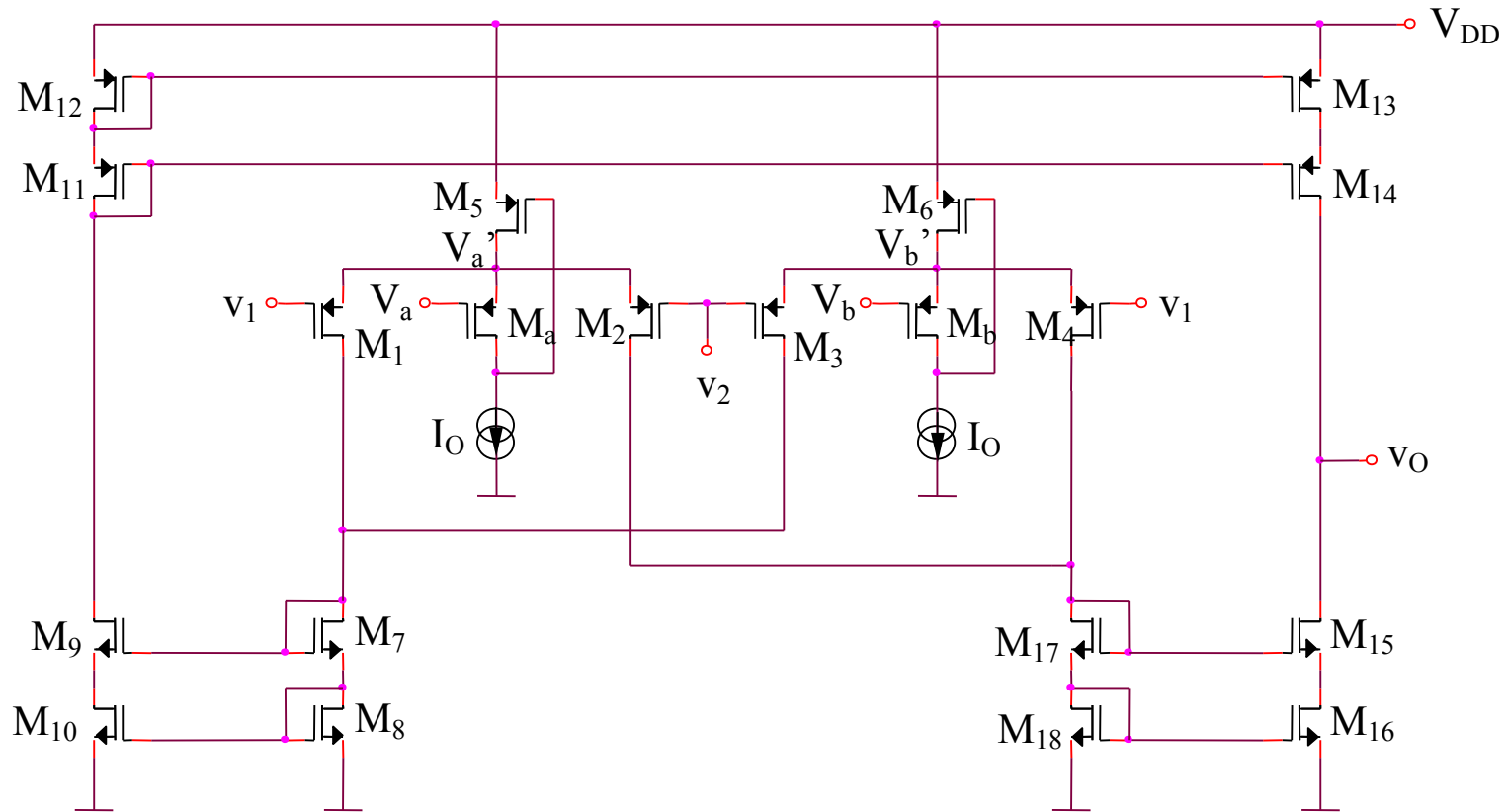
$$i_{OUT} = \frac{K}{2}(V_2 - V_1)(2V_{A'} - V_1 - V_2 - 2V_T) + \frac{K}{2}(V_1 - V_2)(2V_{B'} - V_1 - V_2 - 2V_T)$$

$$i_{OUT} = K(V_{B'} - V_{A'})(V_1 - V_2)$$

$$V_{A'} = V_A + V_{SGa} = V_A + V_T + \sqrt{\frac{2I_O}{K}} \quad V_{B'} = V_B + V_{SGb} = V_B + V_T + \sqrt{\frac{2I_O}{K}}$$

$$i_{OUT} = K(V_B - V_A)(V_1 - V_2)$$

## 6.2.13. Amplificator operational transconductanta (1) - aplicatie AO

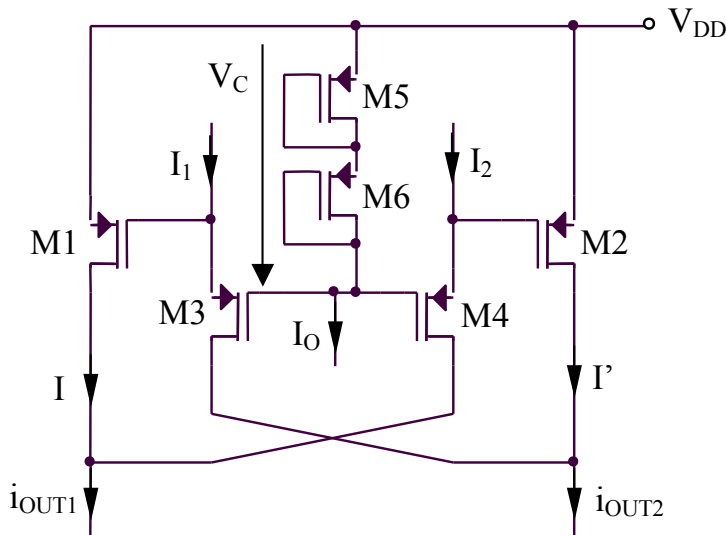


$$R_O = r_{ds14}g_{m14}r_{ds13} // r_{ds15}g_{m15}r_{ds16} = \frac{1}{2}g_{m15}r_{ds15}^2$$

$$a = G_m R_O = \frac{1}{2}K(V_B - V_A)g_{m15}r_{ds15}^2$$

## 6.2.14. Amplificator operational transconductanta (2)

### Circuit de extragere a radacinii patrate (I)



$$V_{SG1} + V_{SG3} = V_{SG5} + V_{SG6}$$

$$\sqrt{I} = \sqrt{\frac{K}{2}}(V_C - 2V_T) - \sqrt{I_1}$$

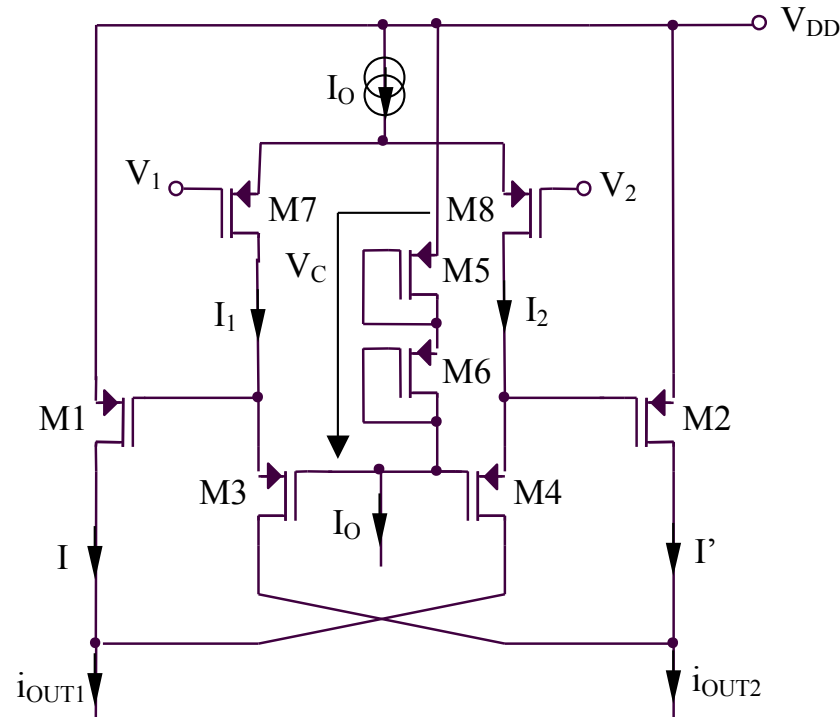
$$I = I_1 + \frac{K}{2}(V_C - 2V_T)^2 - \sqrt{2KI_1}(V_C - 2V_T)$$

$$i_{OUT1} = I + I_2 = I_1 + I_2 + \frac{K}{2}(V_C - 2V_T)^2 - \sqrt{2KI_1}(V_C - 2V_T)$$

$$i_{OUT2} = I_1 + I_2 + \frac{K}{2}(V_C - 2V_T)^2 - \sqrt{2KI_2}(V_C - 2V_T)$$

$$i_{OUT} = i_{OUT1} - i_{OUT2} = \sqrt{2K}(V_C - 2V_T)(\sqrt{I_2} - \sqrt{I_1})$$

## 6.2.14. Amplificator operational transconductanta (2)



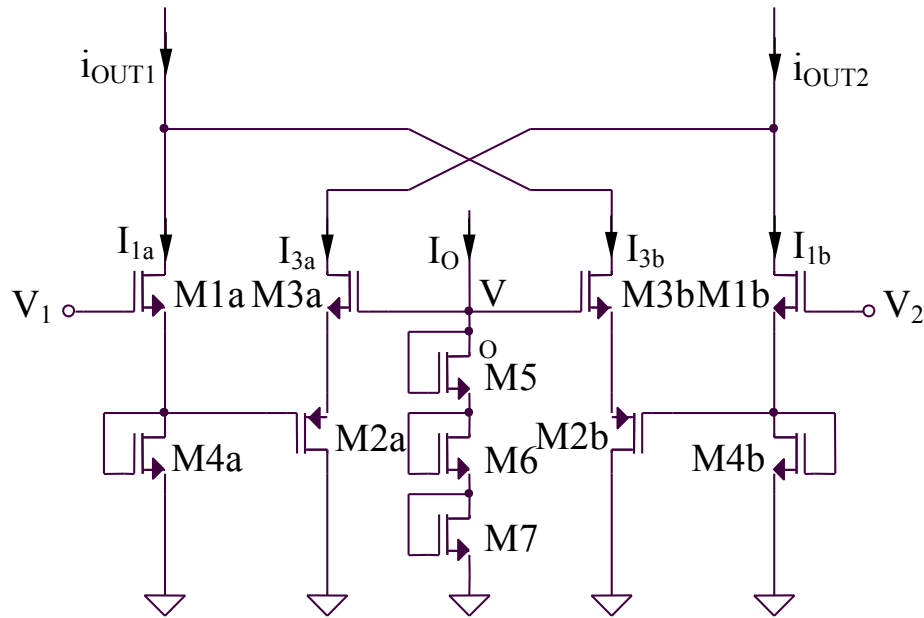
$$V_C = V_{SG5} + V_{SG6} = 2V_T + 2\sqrt{\frac{2I_O}{K}}$$

$$i_{OUT1} - i_{OUT2} = 4\sqrt{I_O}(\sqrt{I_2} - \sqrt{I_1})$$

$$i_{OUT1} - i_{OUT2} = 4\sqrt{I_O}\sqrt{\frac{K}{2}}(V_{SG8} - V_{SG7}) = \sqrt{8KI_O}(V_1 - V_2)$$

$$G_m = \sqrt{8KI_O}$$

## 6.2.15. Amplificator operational transconductanta (3)



$$V_O - \frac{V_1}{2} = 2V_{GS3a} = 2 \left( V_T + \sqrt{\frac{2I_{3a}}{4K}} \right)$$

$$I_{3a} = \frac{K}{2} \left( V_O - \frac{V_1}{2} - 2V_T \right)^2$$

$$I_{1a} = \frac{K}{2} \left( \frac{V_1}{2} - V_T \right)^2$$

$$I_{1a} - I_{3a} = \frac{K}{2} (V_O - 3V_T)(V_1 - V_O + V_T)$$

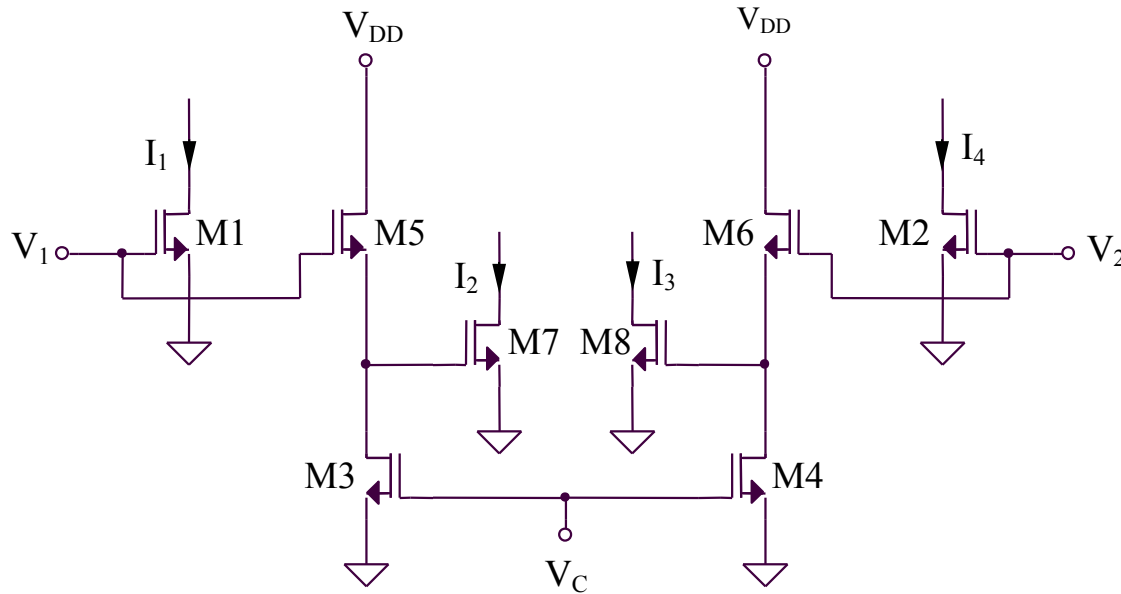
$$I_{1b} - I_{3b} = \frac{K}{2} (V_O - 3V_T)(V_2 - V_O + V_T)$$

$$\begin{aligned} i_{OUT1} - i_{OUT2} &= (I_{1a} + I_{3b}) - (I_{1b} + I_{3a}) = (I_{1a} - I_{3a}) - (I_{1b} - I_{3b}) = \\ &= \frac{K}{2} (V_O - 3V_T)(V_1 - V_2) \end{aligned}$$

$$i_{OUT1} - i_{OUT2} = 3 \sqrt{\frac{KI_O}{2}} (V_1 - V_2)$$

$$G_m = \frac{i_{OUT1} - i_{OUT2}}{V_1 - V_2} = 3 \sqrt{\frac{KI_O}{2}}$$

## 6.2.16. Amplificator operational transconductanta (4)



$$I_1 - I_2 = \frac{K}{2} (V_1 - V_T)^2 - \frac{K}{2} (V_1 - V_C - V_T)^2 = \frac{K}{2} V_C (2V_1 - V_C - 2V_T)$$

$$I_4 - I_3 = \frac{K}{2} V_C (2V_2 - V_C - 2V_T)$$

$$i_{OUT} = (I_1 - I_2) - (I_4 - I_3) = KV_C (V_1 - V_2)$$