Capitolul 2. Surse de curent

1. Clasificare

1. Clasificare

1. Surse de curent elementare

2. Surse de curent cascod

3. Surse de curent cu autopolarizare

4. Surse de curent cu dependenta redusa cu temperatura

2. Parametrii surselor de curent

2. Parametrii surselor de curent

1. Curentul de iesire, I_O
2. Rezistenta de iesire, R_O
3. Tensiunea minima de iesire, V_{omin}
4. Coeficientul relativ de variatie cu temperatura, TCR

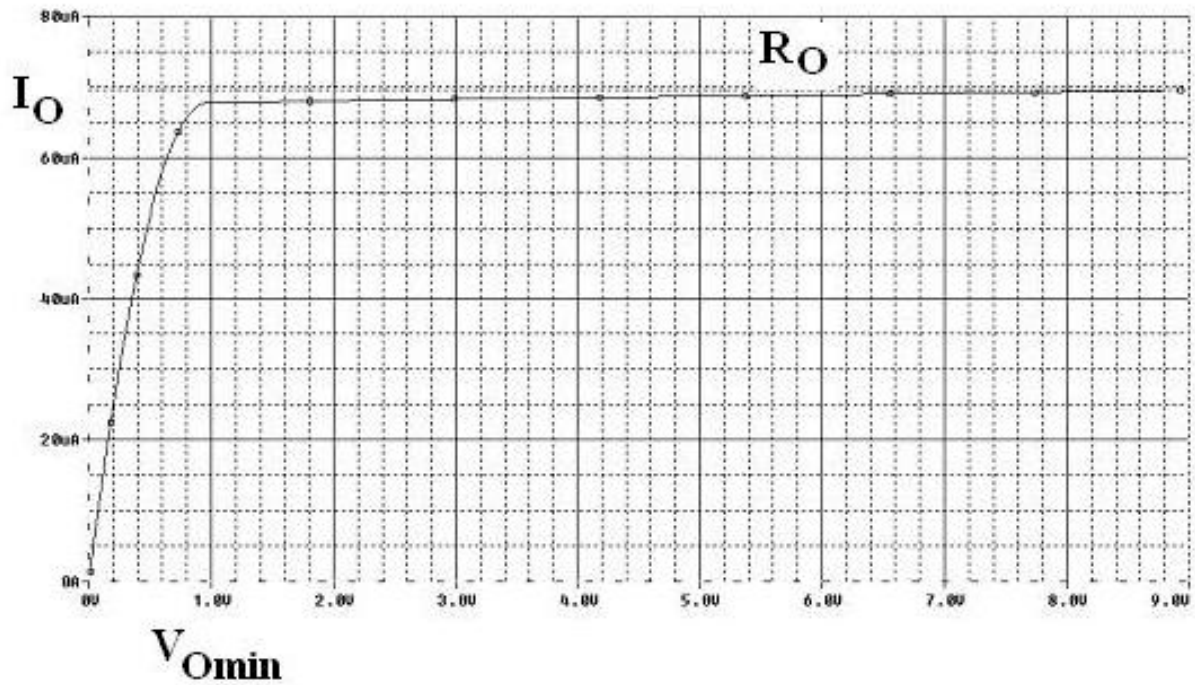
$$TCR = \frac{1}{T}\frac{dI_O}{dT}$$

5. Sensibilitatea curentului de iesire fata de variatiile V_{DD}

$$S_{I_O}^{V_{DD}} = \frac{dI_O / I_O}{dV_{DD} / V_{DD}} = \frac{V_{DD}}{I_O}\frac{dI_O}{dV_{DD}}$$

6. Precizia de realizare a sursei de curent

Caracteristica de iesire

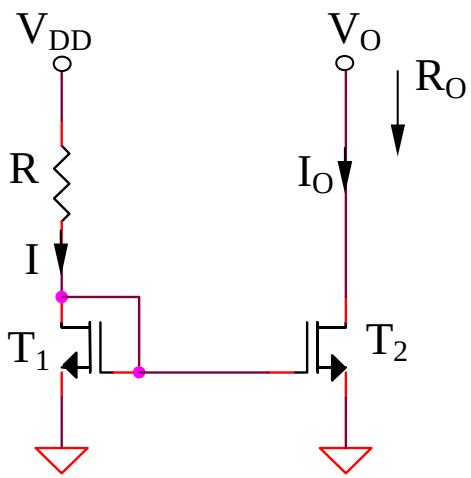


3. Surse de curent elementare

3. Surse de curent elementare

Oglinda de curent

Calculul curentului de iesire I_O ($T_1 = T_2$)



$$I = \frac{K}{2}(V_{GS1} - V_T)^2 = \frac{K}{2}(V_{GS2} - V_T)^2 = I_O$$

$$V_{DD} = I_O R + V_{GS1}$$

$$I_O = \frac{K}{2}(V_{GS1} - V_T)^2$$

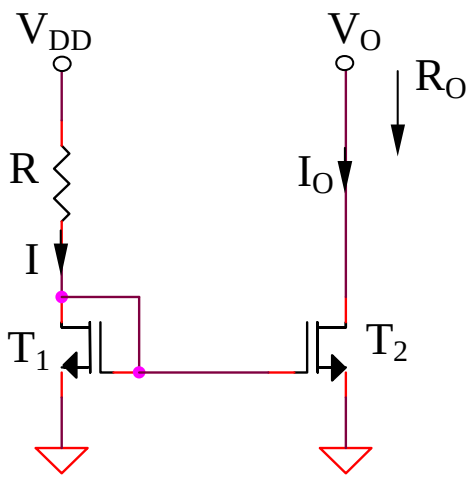
$$V_{DD} = \frac{KR}{2}(V_{GS1} - V_T)^2 + V_{GS1}$$

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

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

3. Surse de curent elementare

Oglinda de curent



Calculul rezistentei de iesire R_O

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

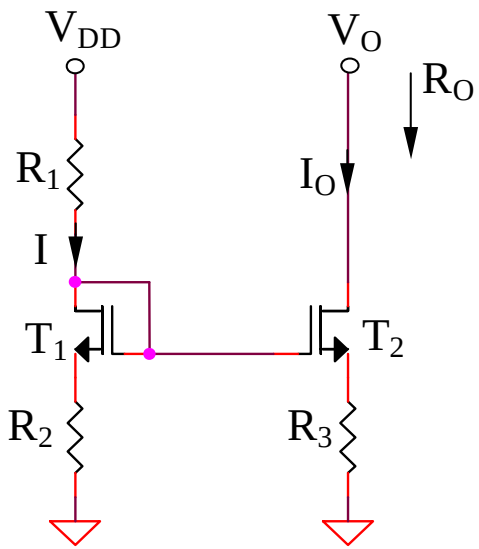
Calculul tensiunii minime de iesire V_{Omin}

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

Erorile introduse de efectul de modulare a lungimii canalului

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

Sursa de curent cu rezistente in sursa



Calculul curentului de iesire I_O

$$V_{DD} = I(R_1 + R_2) + V_{GS1}$$

$$I = \frac{K}{2}(V_{GS1} - V_T)^2$$

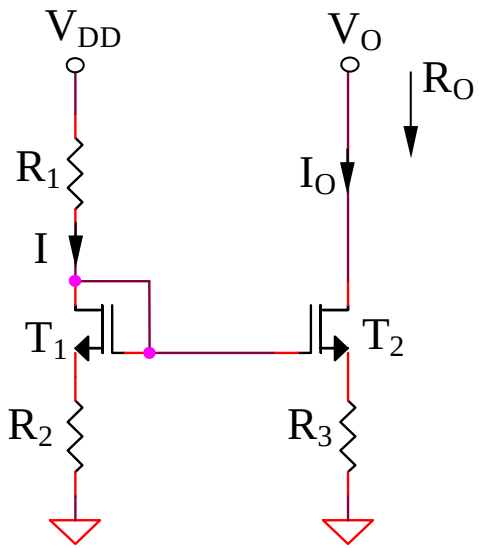
$$V_{GS1} > V_T$$

$$V_{GS1} = V_T - \frac{1}{K(R_1 + R_2)} + \frac{1}{K(R_1 + R_2)}\sqrt{1 + 2K(R_1 + R_2)(V_{DD} - V_T)}$$

$$V_{GS1} + \frac{KR_2}{2}(V_{GS1} - V_T)^2 = V_{GS2} + \frac{KR_3}{2}(V_{GS2} - V_T)^2$$

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

Sursa de curent cu rezistente in sursa



Calculul rezistentei de iesire R_O

$$R_O = r_{ds2}\left(1 + g_{m2} R_3\right)$$

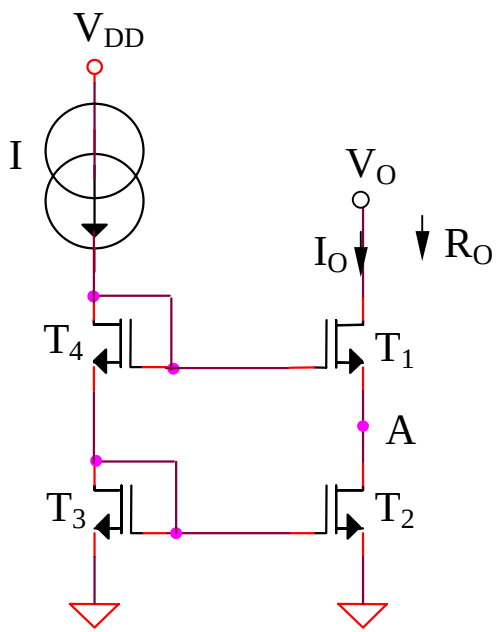
Calculul tensiunii minime de iesire V_{Omin}

$$V_{O\,min} = V_{DS2\,sat} + I_O R_3 = V_{GS2} - V_T + I_O R_3 = \sqrt{\frac{2I_O}{K}} + I_O R_3$$

4. Surse de curent cascod

4. Surse de curent cascod

Sursa de curent cascod (I)



Calculul curentului de iesire I_O ($T_2 = T_3$)

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

Calculul rezistentei de iesire R_O

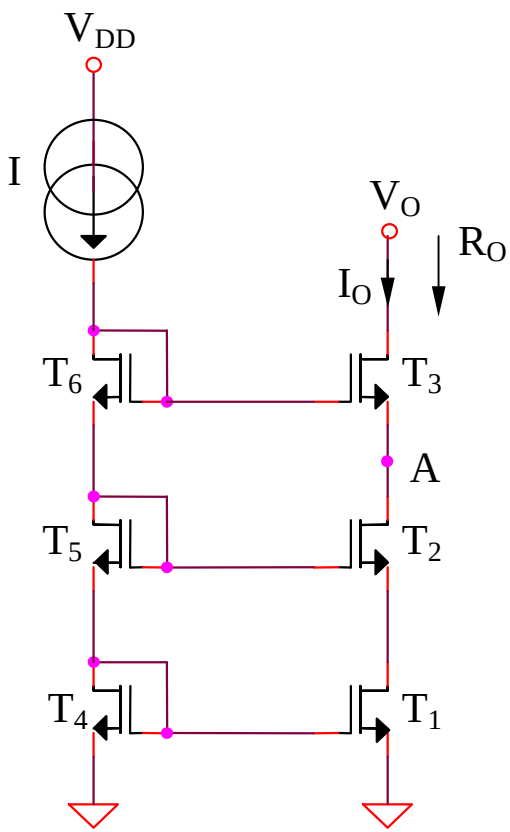
$$R_0 = r_{ds1}\left(1 + g_{m1} r_{ds2}\right) \cong g_m r_{ds}^2$$

Calculul tensiunii minime de iesire V_{Omin}

$$V_{O\,min} = V_A + V_{DS1sat} = V_{GS} + \left(V_{GS} - V_T\right) = 2V_{GS} - V_T \cong V_T + 2\sqrt{\frac{2I}{K}}$$

4. Surse de curent cascod

Sursa de curent cascod (II)



Calculul curentului de iesire I_O ($T_1 = T_4$)

$$I_O \cong I$$

Calculul rezistentei de iesire R_O

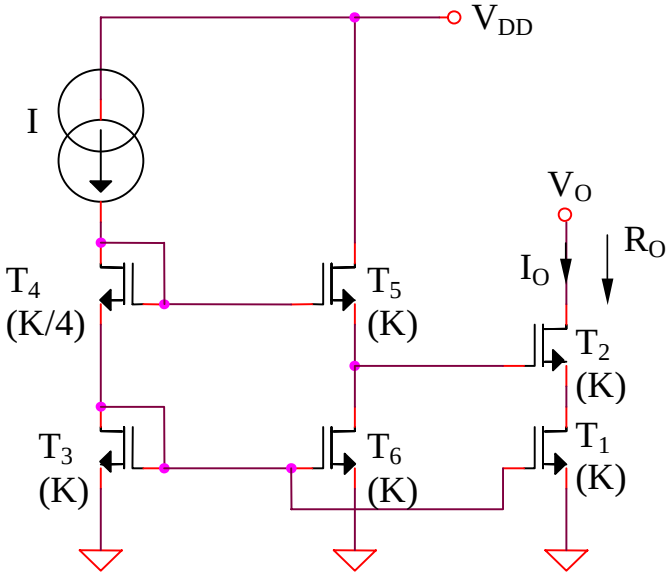
$$R_O = r_{ds3}\left[1 + g_{m3} r_{ds2}\left(1 + g_{m2} r_{ds1}\right)\right] \cong g_m^2 r_{ds}^3$$

Calculul tensiunii minime de iesire V_{Omin}

$$V_{O\,min} = V_A + V_{DS\,3sat} = 3V_{GS} - V_T$$

4. Surse de curent cascod

Sursa de curent cascod (III)



Calculul curentului de iesire I_O

$$I_O \cong I$$

Calculul rezistentei de iesire R_O

$$R_O = r_{ds2}\left(1 + g_{m2} r_{ds1}\right) \cong g_m r_{ds}^2$$

Calculul tensiunii minime de iesire V_{Omin}

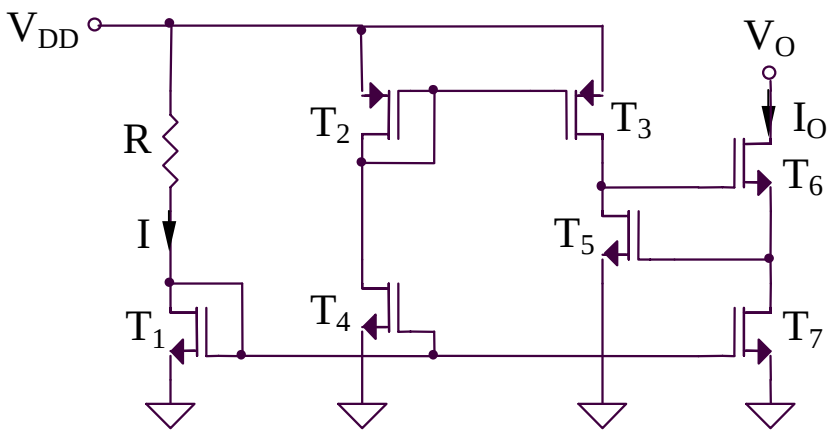
$$V_{DS1} = V_{GS3} + V_{GS4} - V_{GS5} - V_{GS2}$$

$$V_{DS1} = \left(V_T + \sqrt{\frac{2I}{K}}\right) + \left(V_T + \sqrt{\frac{8I}{K}}\right) - \left(V_T + \sqrt{\frac{2I}{K}}\right) - \left(V_T + \sqrt{\frac{2I}{K}}\right) = \sqrt{\frac{2I}{K}} = V_{GS1} - V_T$$

$$V_{O\,min} = V_{DS2\,sat} + V_{DS1} = 2\sqrt{\frac{2I}{K}}$$

4. Surse de curent cascod

Sursa de curent cascod (IV)



Calculul curentului de iesire I_O

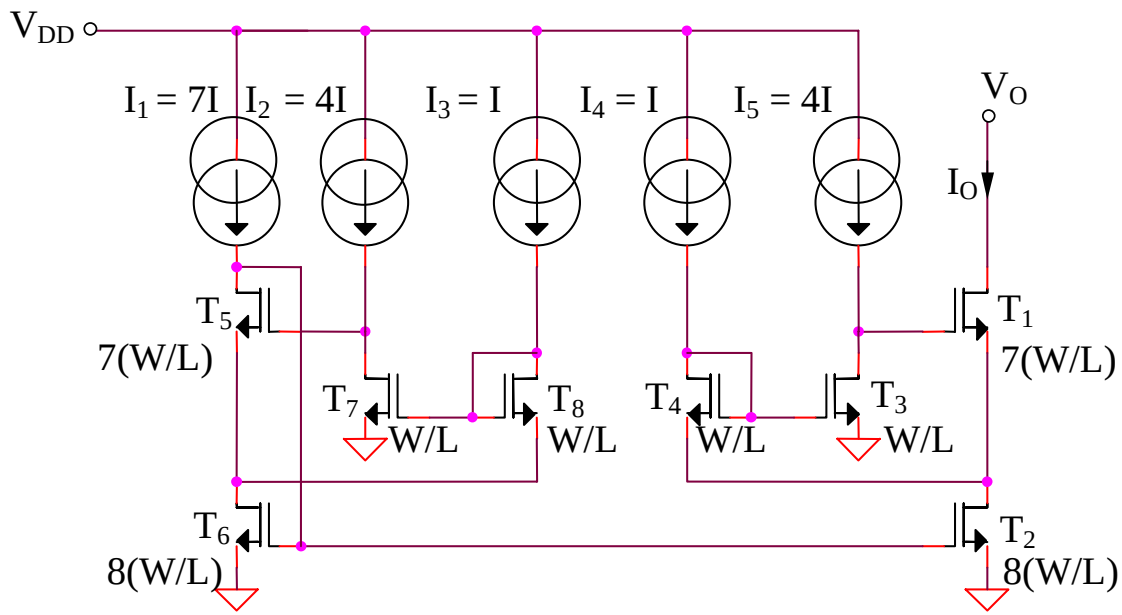
$$I_O = I$$

Calculul tensiunii minime de iesire V_{Omin}

$$V_{O\,min} = V_{DS6\,sat} + V_{DS7} = 2V_{GS} - V_T = V_T + 2\sqrt{\frac{2I}{K}}$$

4. Surse de curent cascod

Sursa de curent cascod (V)

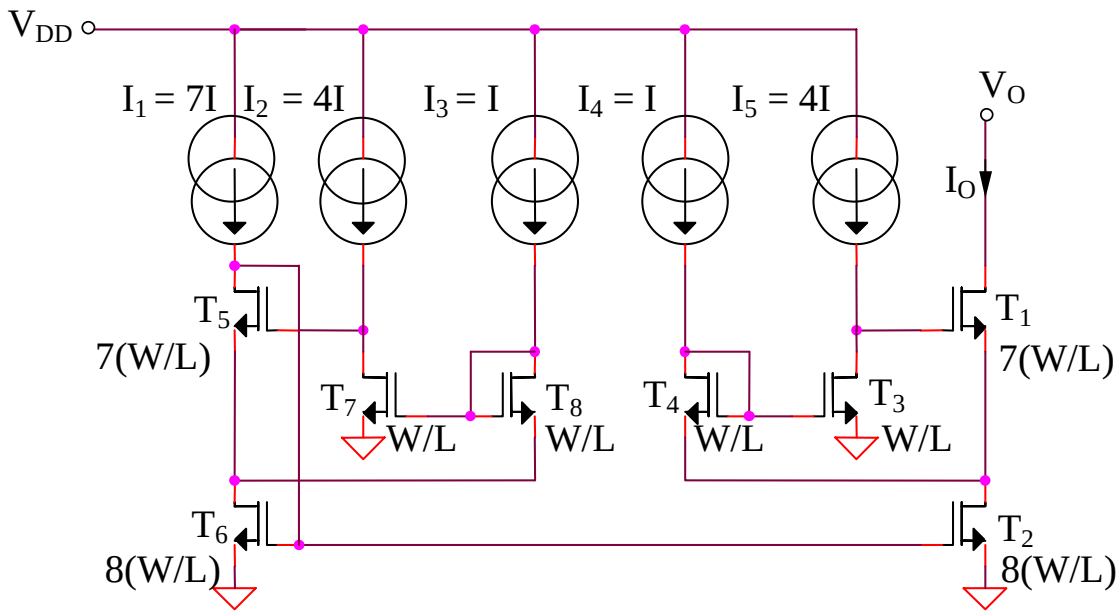


Calculul curentului de iesire I_O

$$I_O = 8I - I = 7I$$

4. Surse de curent cascod

Sursa de curent cascod (V)



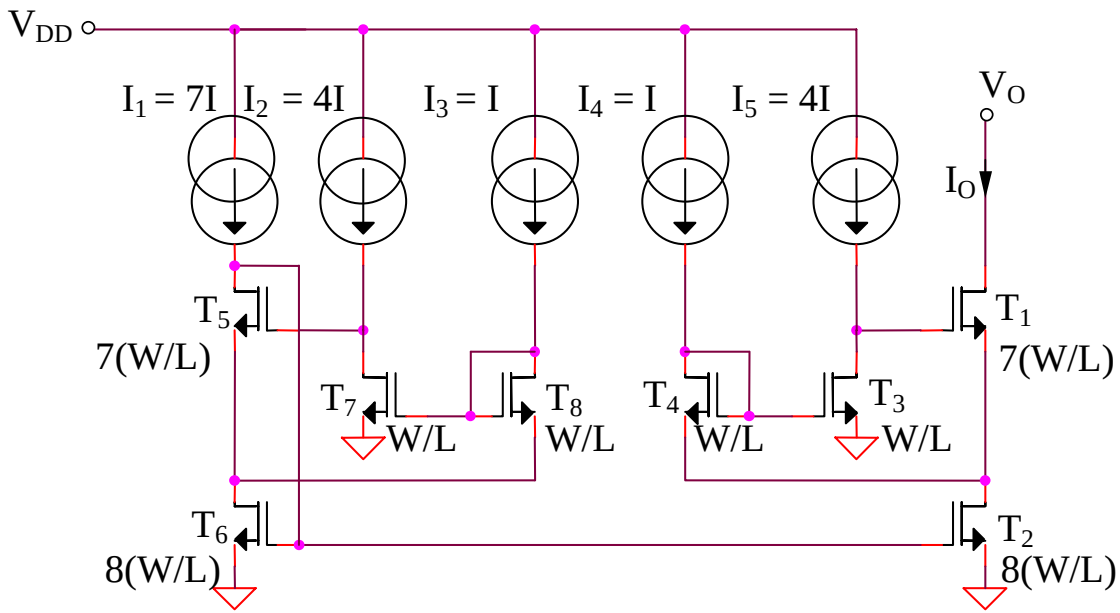
Calculul tensiunii minime de iesire V_{Omin}

$$4I = \frac{K'}{2}(W/L)(V_{GS3} - V_T)^2 \qquad 8I = \frac{K'}{2}8(W/L)(V_{GS2} - V_T)^2$$

$$I = \frac{K'}{2}(W/L)(V_{GS4} - V_T)^2 \qquad 7I = \frac{K'}{2}7(W/L)(V_{GS1} - V_T)^2$$

4. Surse de curent cascod

Sursa de curent cascod (V)



Calculul tensiunii minime de iesire V_{Omin}

$$V_{GS4} - V_T = V_{GS2} - V_T \qquad V_{GS1} - V_T = V_{GS2} - V_T$$

$$V_{GS3} - V_T = 2(V_{GS2} - V_T)$$

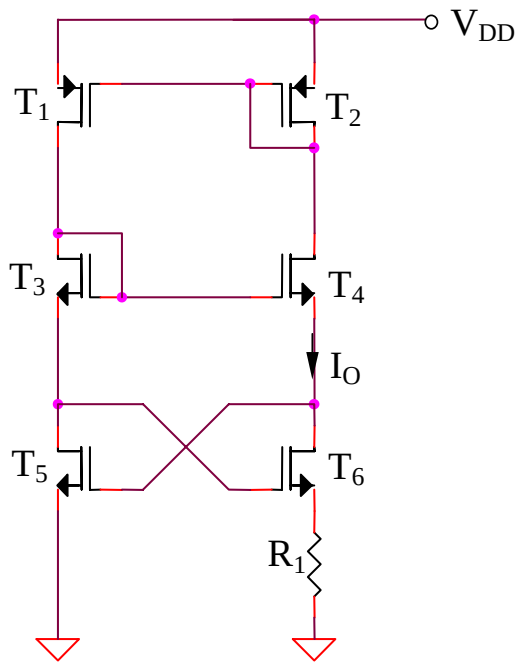
$$V_{DS2} = V_{GS3} - V_{GS4} = (V_{GS3} - V_T) - (V_{GS4} - V_T) = V_{GS2} - V_T = V_{DS2sat}$$

$$V_{Omin} = V_{DS1sat} + V_{DS2} = 2(V_{GS2} - V_T) = 2\sqrt{\frac{2I}{K'(W/L)}}$$

5. Surse de curent cu autopolarizare

5. Surse de curent cu autopolarizare

Sursa de curent cu autopolarizare (I)

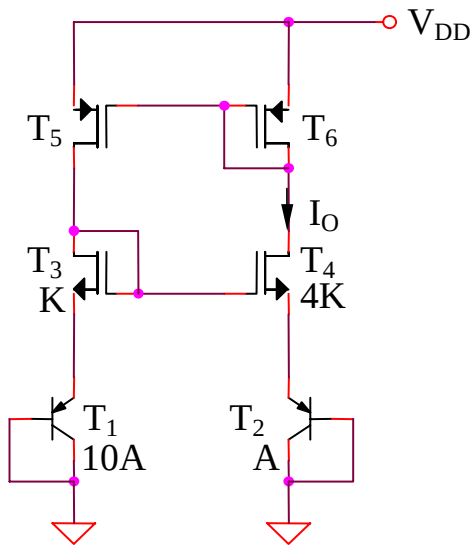


$$I_D = I_{D0}\frac{W}{L}exp\left(\frac{V_{GS}-V_T}{nV_{th}}\right)$$

$$I_O = \frac{V_{GS4}+V_{GS5}-V_{GS3}-V_{GS6}}{R_1} = \frac{nV_{th}}{R_1}ln\left[\frac{(W/L)_3(W/L)_6}{(W/L)_4(W/L)_5}\right]$$

5. Surse de curent cu autopolarizare

Sursa de curent cu autopolarizare (II)

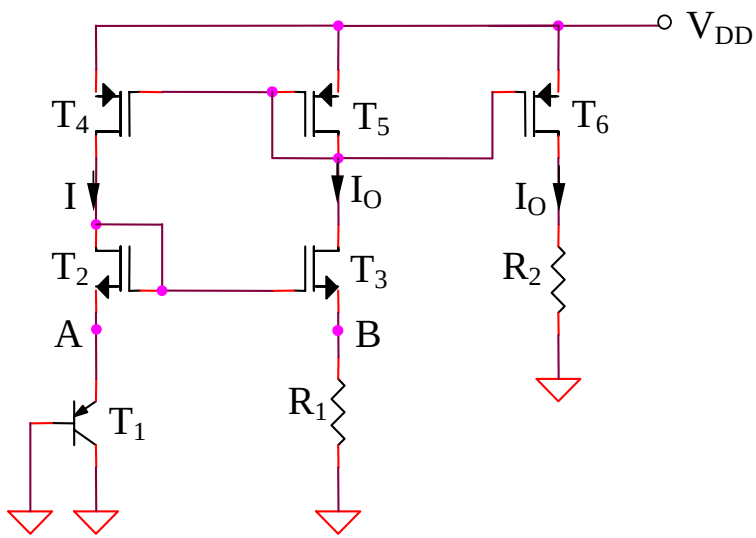


$$V_T + \sqrt{\frac{2I_O}{4K'(W/L)}} + V_{th}\, ln\left(\frac{I_O}{I_S}\right) = V_T + \sqrt{\frac{2I_O}{K'(W/L)}} + V_{th}\, ln\left(\frac{I_O}{10I_S}\right)$$

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

5. Surse de curent cu autopolarizare

Sursa de curent cu autopolarizare (III)



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

$$S_{I_O}^{V_{DD}} = \frac{V_{DD}}{I_O}\frac{dI_O}{dV_{DD}}$$

$$V_{SD4} = V_{DD} - V_{GS2} - V_{EB1}$$

$$V_{SD5} = V_{SG5}$$

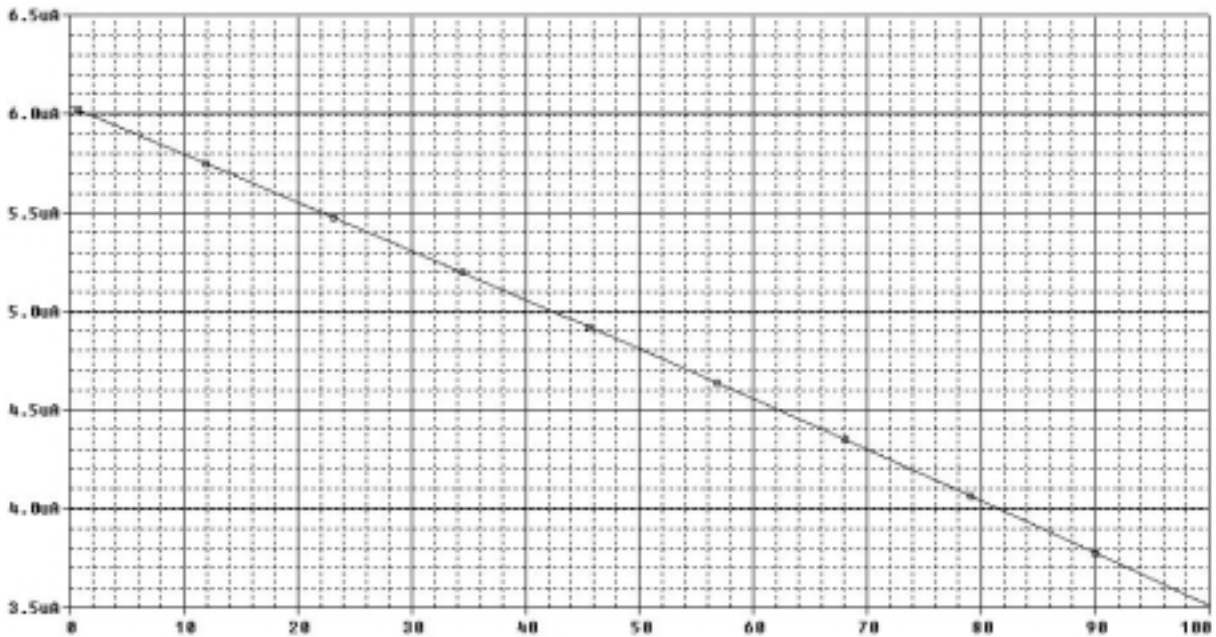
$$I_O = \frac{V_{EB1}}{R_1} = \frac{V_{th}}{R_1} ln\left(\frac{I}{I_S}\right) = \frac{V_{th}}{R_1} ln\left(\frac{I_O}{I_S}\frac{1+\lambda V_{SD4}}{1+\lambda V_{SD5}}\right) = \frac{V_{th}}{R_1} ln\left(\frac{I_O}{I_S}\right) + \frac{V_{th}}{R_1} ln\left(\frac{1+\lambda V_{SD4}}{1+\lambda V_{SD5}}\right)$$

$$\frac{dI_O}{dV_{DD}} = \frac{V_{th}}{R_1 I_O}\frac{dI_0}{dV_{DD}} + \frac{\lambda V_{th}}{R_1}$$

$$S_{I_O}^{V_{DD}} \cong \frac{\lambda V_{DD}}{\frac{V_{BE}}{V_{th}} - 1} \cong \frac{V_{th}}{V_{BE}} \lambda V_{DD}$$

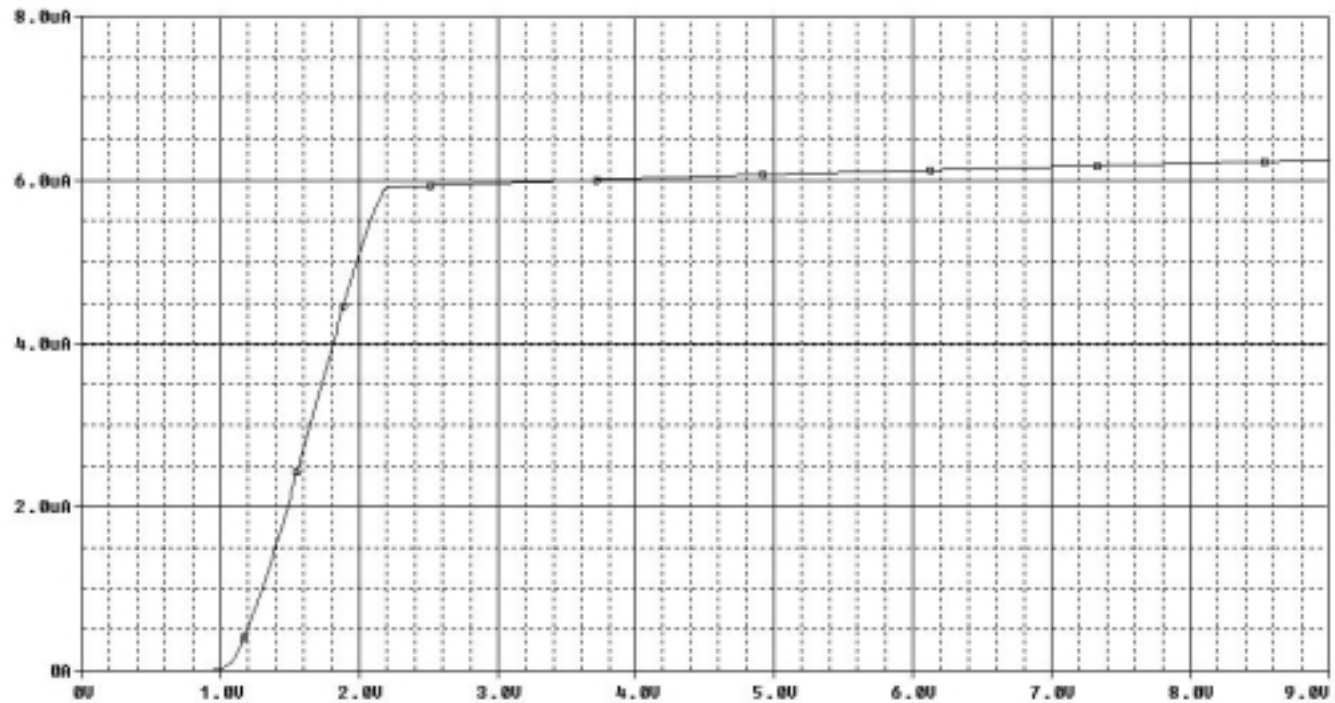
5. Surse de curent cu autopolarizare

Dependenta I_O (T)



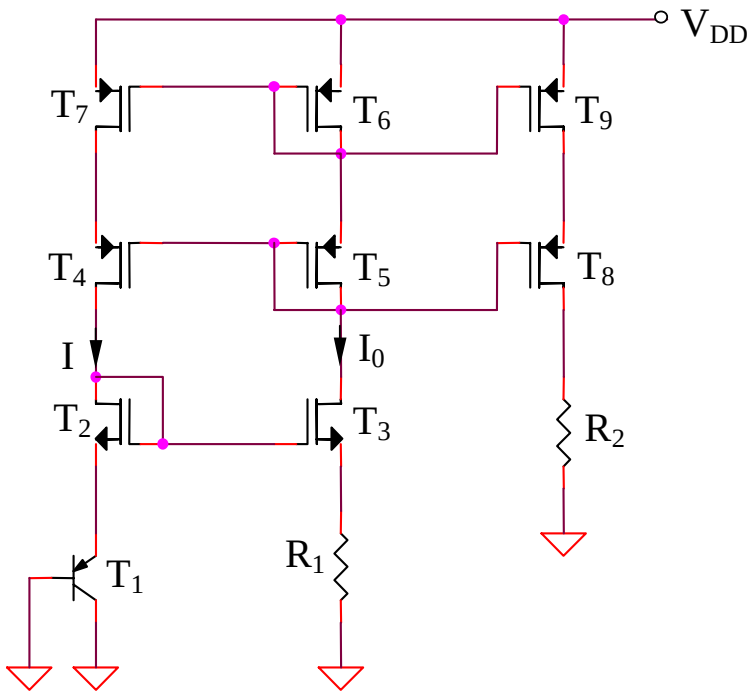
5. Surse de curent cu autopolarizare

Dependenta I_O (V_{DD})



5. Surse de curent cu autopolarizare

Sursa de curent cu autopolarizare (IV)



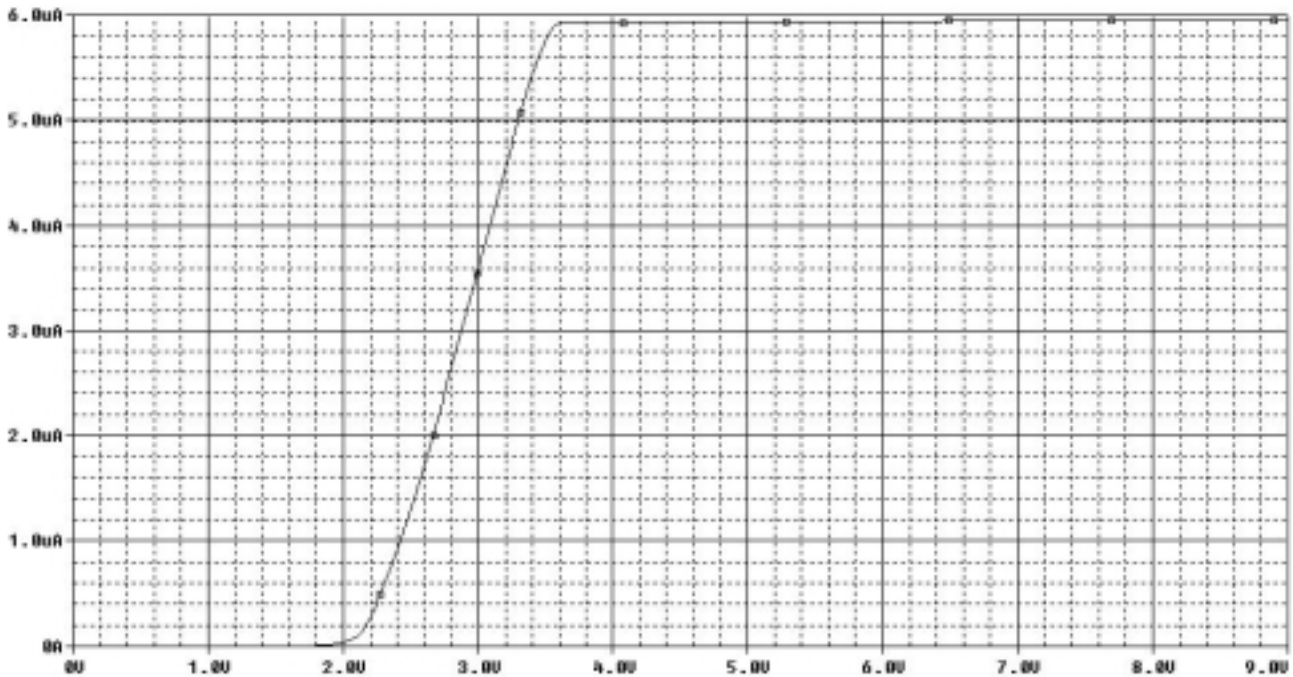
$$I_O = \frac{V_{EB1}}{R_1}$$

$$I_O = \frac{V_{th}}{R_1} ln\left(\frac{I_O}{I_S} \frac{1+\lambda_7 V_{SG6}}{1+\lambda_6 V_{SG6}} \right)$$

$$S_{I_O}^{V_{DD}} = \frac{V_{th} V_{DD}}{V_{BE}} (\lambda_7 - \lambda_6) \frac{dV_{SG6}}{dV_{DD}}$$

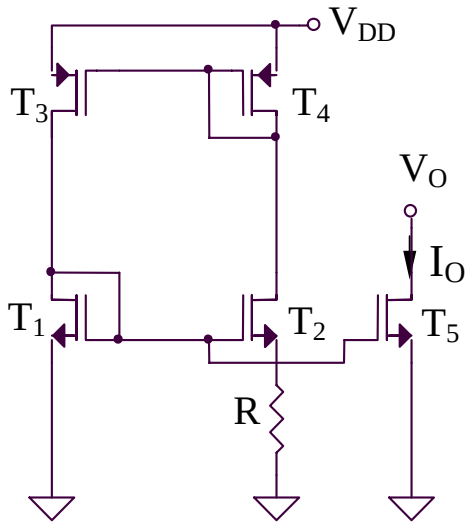
5. Surse de curent cu autopolarizare

Dependenta I_O (V_{DD})



5. Surse de curent cu autopolarizare

Sursa de curent cu autopolarizare (V)



$$I_O \cong \frac{nV_{th}}{R} ln\left[\frac{(W/L)_2}{(W/L)_1}\right] + \frac{nV_{th}}{R} ln\left[1+\lambda(V_{DD}-2V_{GS})\right]$$

$$\lambda(V_{DD}-2V_{GS}) << 1$$

$$I_O \cong \frac{nV_{th}}{R} ln\left[\frac{(W/L)_2}{(W/L)_1}\right] + \lambda\frac{nV_{th}}{R}(V_{DD}-2V_{GS})$$

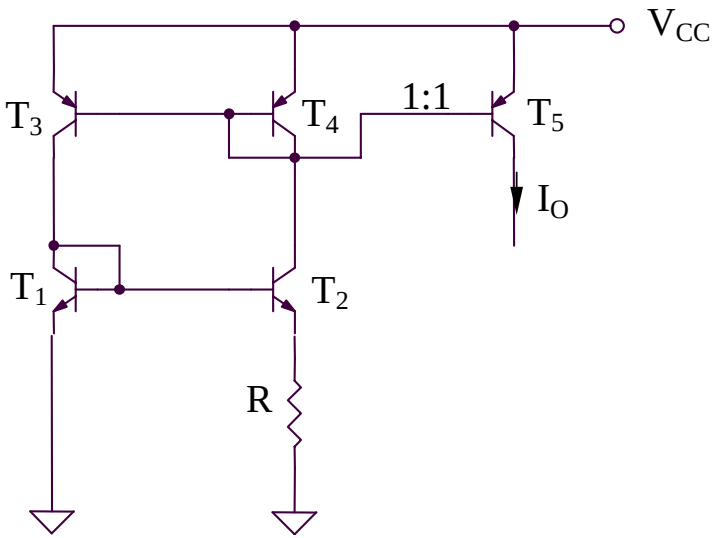
$$S_{I_O}^{V_{DD}} \cong \frac{\lambda V_{DD}}{ln\left[\frac{(W/L)_2}{(W/L)_1}\right]}$$

6. Surse de curent cu dependenta redusa cu temperatura

6. Surse de curent cu dependenta redusa cu temperatura

6.1. Surse de curent PTAT (I) (Proportional To Absolute Temperature)

$$I_O = \frac{V_{BE1} - V_{BE2}}{R} = \frac{V_{th}}{R} \ln\left(\frac{I_{C1}}{I_{C2}} \frac{I_{S2}}{I_{S1}}\right) = \frac{V_{th}}{R} \ln\left(n \frac{I_{C3}}{I_{C4}}\right)$$



$$\frac{I_{C3}}{I_{C4}} = \frac{I_{S3}}{I_{S4}} \frac{1 + \frac{V_{CC} - V_{BE1}}{V_A}}{1 + \frac{V_{EB4}}{V_A}} \cong 1 + \frac{V_{CC}}{V_A}$$

$$I_O = \frac{V_{th}}{R} \ln n + \frac{V_{th}}{R} \ln\left(1 + \frac{V_{CC}}{V_A}\right)$$

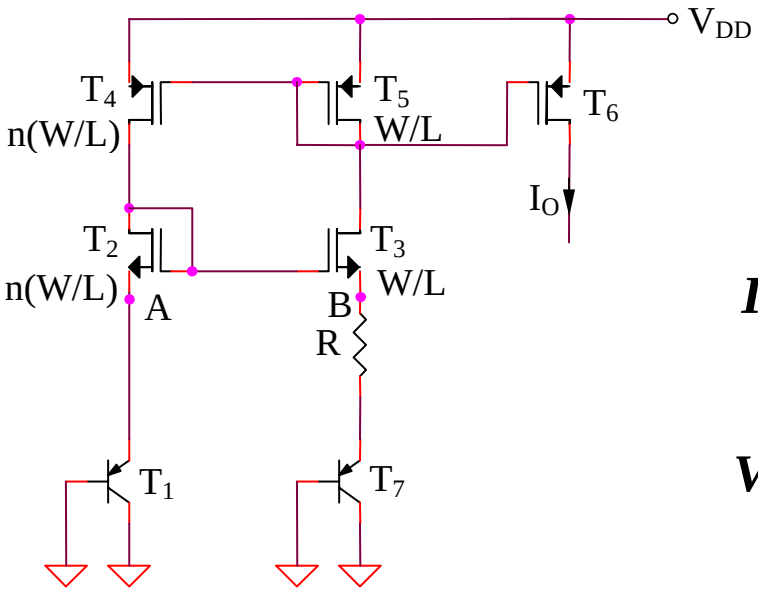
$$I_{S2} / I_{S1} = n$$

$$I_{S3} = I_{S4}$$

$$S_{I_O}^{V_{CC}} = \frac{V_{CC}}{I_O} \frac{dI_O}{dV_{CC}} \cong \frac{V_{CC}}{V_A} \frac{1}{\ln(n)}$$

6. Surse de curent cu dependenta redusa cu temperatura

6.1. Surse de curent PTAT (II)



$$V_A - V_B = V_{GS3} - V_{GS2} = \left(V_T + \sqrt{\frac{2I_{D3}}{K_3}}\right) - \left(V_T + \sqrt{\frac{2I_{D2}}{K_2}}\right)$$

$$V_A - V_B = \sqrt{\frac{2I_{D3}}{K_3}}\left[1 - \sqrt{\frac{I_{D2}}{I_{D3}}\frac{(W/L)_3}{(W/L)_2}}\right]$$

$$I_{D2}/I_{D3} = I_{D4}/I_{D5} = (W/L)_4/(W/L)_5$$

$$V_A - V_B = \sqrt{\frac{2I_{D3}}{K_3}}\left[1 - \sqrt{\frac{(W/L)_4}{(W/L)_5}\frac{(W/L)_3}{(W/L)_2}}\right]$$

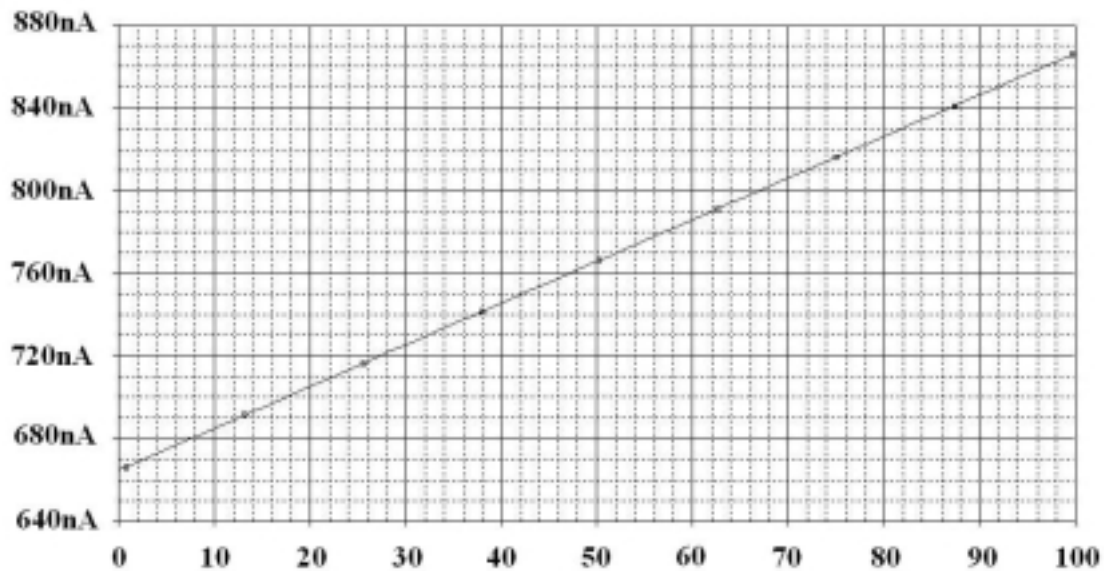
$$V_A = V_B \Rightarrow (W/L)_2(W/L)_5 = (W/L)_3(W/L)_4$$

$$I_O = \frac{|V_{BE1}| - |V_{BE7}|}{R} = \frac{V_{th}}{R} ln\left(\frac{I_{C1}}{I_{C7}}\frac{I_{S7}}{I_{S1}}\right) = \frac{V_{th}}{R} ln\left(n\frac{I_{S7}}{I_{S1}}\right)$$

6. Surse de curent cu dependenta redusa cu temperatura

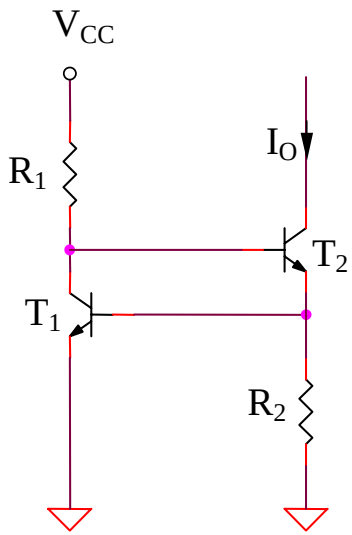
6.1. Surse de curent PTAT (II)

Dependenta I_O (T)



6. Surse de curent cu dependenta redusa cu temperatura

6.2. Surse de curent CTAT (I) (Complementary To Absolute Temperature)

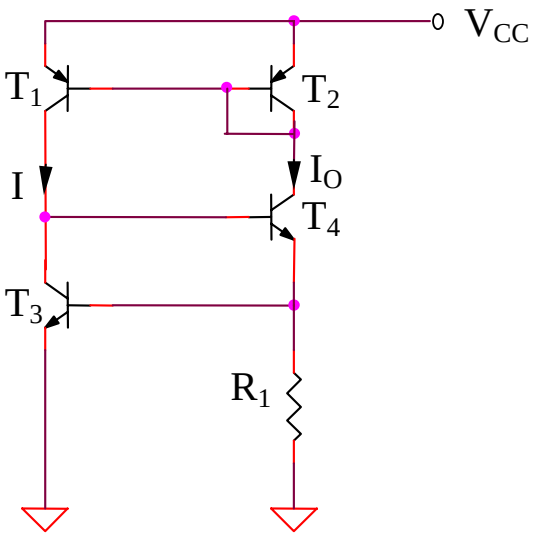


$$I_O = \frac{V_{BE1}}{R_2} \cong \frac{V_{th}}{R_2} ln \frac{V_{CC} - V_{BE1} - V_{BE2}}{R_1 I_S}$$

$$S_{I_O}^{V_{CC}} = \frac{V_{CC}}{I_O} \frac{dI_O}{dV_{CC}} \cong \frac{V_{th}}{V_{BE}} \cong 0.04$$

6. Surse de curent cu dependenta redusa cu temperatura

6.2. Surse de curent CTAT (II) (Complementary To Absolute Temperature)



$$I_O = \frac{V_{BE_3}}{R_1}$$

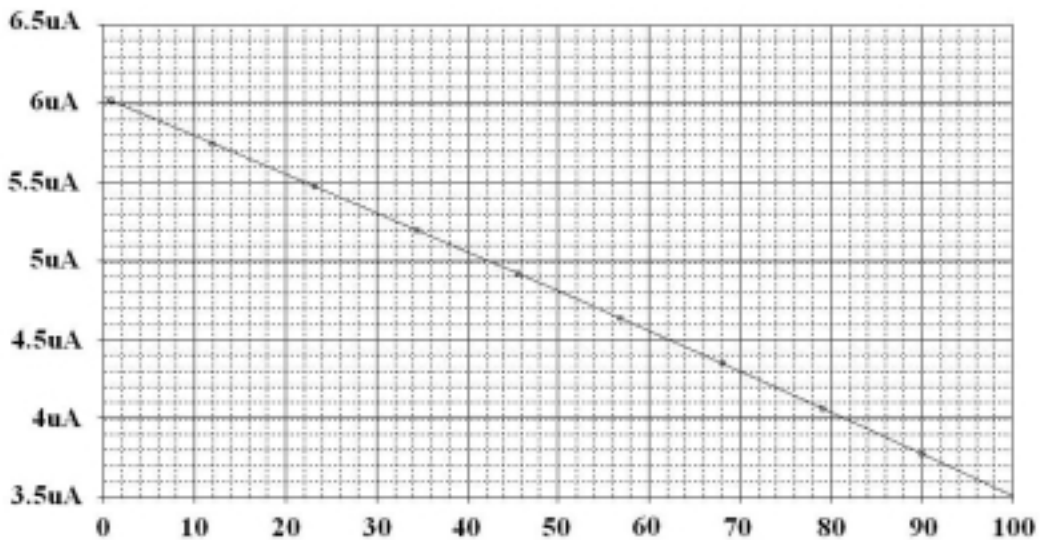
$$I_O = \frac{V_{th}}{R_1} ln\left(\frac{I_{C1}}{I_S}\right) = \frac{V_{th}}{R_1} ln\left[\frac{I_O}{I_S}\left(1 + \frac{V_{CC}}{V_A}\right)\right]$$

$$S_{I_O}^{V_{CC}} = \frac{V_{CC}}{I_O}\frac{dI_O}{dV_{CC}} = \frac{V_{th}}{V_{BE}}\frac{1}{1 + \frac{V_A}{V_{CC}}}$$

6. Surse de curent cu dependenta redusa cu temperatura

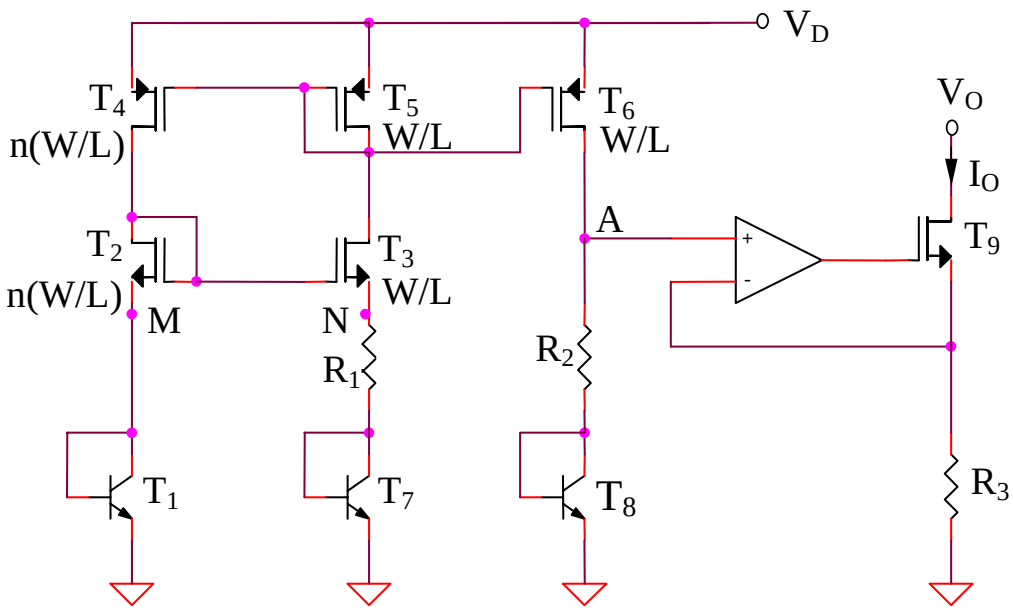
6.2. Surse de curent CTAT (II) (Complementary To Absolute Temperature)

Dependenta I_O (T)



6. Surse de curent cu dependenta redusa cu temperatura

6.3. Sursa de curent cu corectie liniara a caracteristicii



$$I_{S1} / I_{S7} = n$$

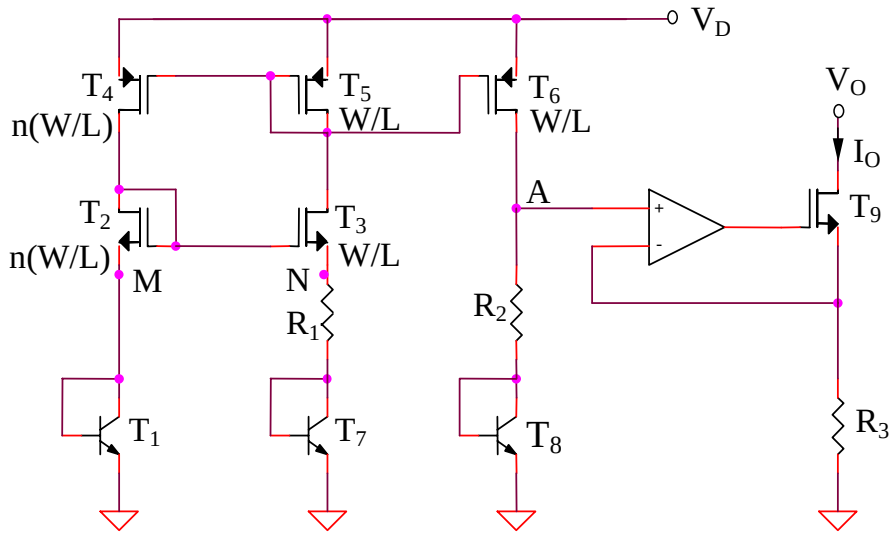
$$V_{GS2} = V_T + \sqrt{\frac{2I_{D2}}{K' n(W/L)}} = V_T + \sqrt{\frac{2I_{D3}}{K'(W/L)}} = V_{GS3}$$

$$\Rightarrow V_{R_2} = R_2 \frac{V_{BE1} - V_{BE7}}{R_1} = V_{PTAT} = \frac{R_2}{R_1} V_{th} \ln(n)$$

$$I_O(T) = \frac{1}{R_3}\left[\frac{R_2}{R_1} V_{th} \ln(n) + V_{BE8}(T)\right]$$

6. Surse de curent cu dependenta redusa cu temperatura

6.3. Sursa de curent cu corectie liniara a caracteristicii



$$I_O(T) = \frac{I}{R_3}\left[\frac{R_2}{R_1} V_{th}\, ln(n) + V_{BE8}(T)\right]$$

$$V_{BE}(T) = E_{G0} + \frac{V_{BE}(T_0) - E_{G0}}{T_0} T + (1-\eta)\frac{kT}{q} ln\left(\frac{T}{T_0}\right)$$

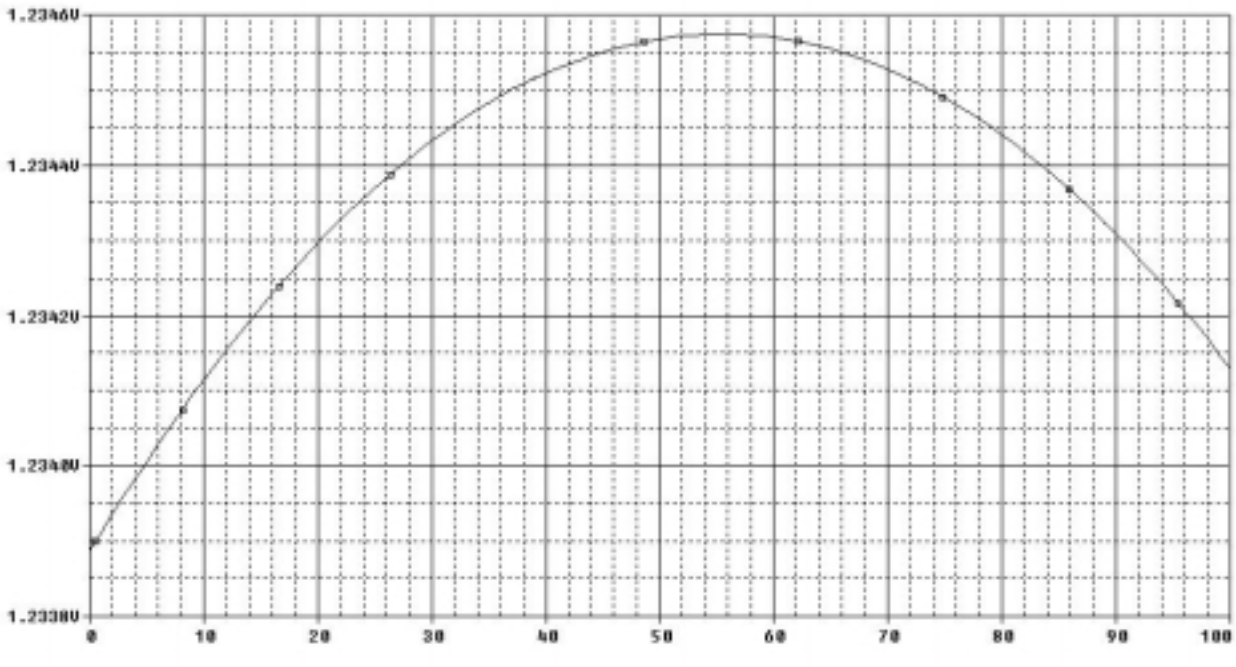
$$\textit{anulare termen liniar in } T \Rightarrow \frac{V_{BE}(T_0) - E_{G0}}{T_0} + \frac{R_2}{R_1}\frac{k}{q} ln(n) = 0$$

$$\Rightarrow I_O(T) = \frac{1}{R_3}\left[E_{G0} + (1-\eta)\frac{kT}{q} ln\left(\frac{T}{T_0}\right)\right]$$

6. Surse de curent cu dependenta redusa cu temperatura

6.3. Sursa de curent cu corectie liniara a caracteristicii

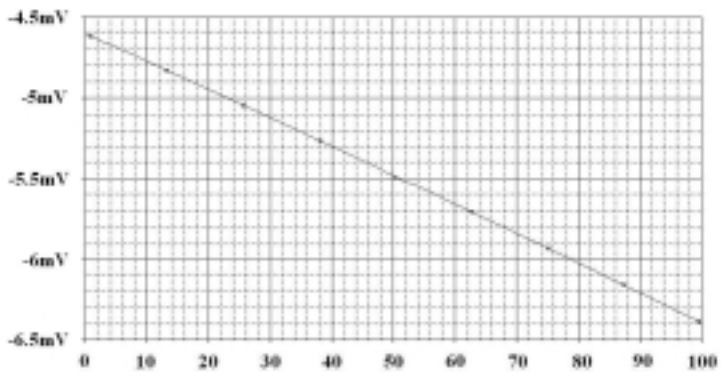
Dependenta I_O (T)

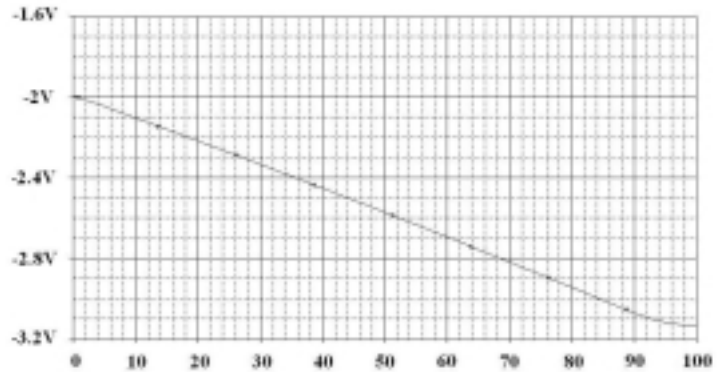


6. Surse de curent cu dependenta redusa cu temperatura

6.3. Sursa de curent cu corectie liniara a caracteristicii

Dependente $V_M - V_N$ (T)





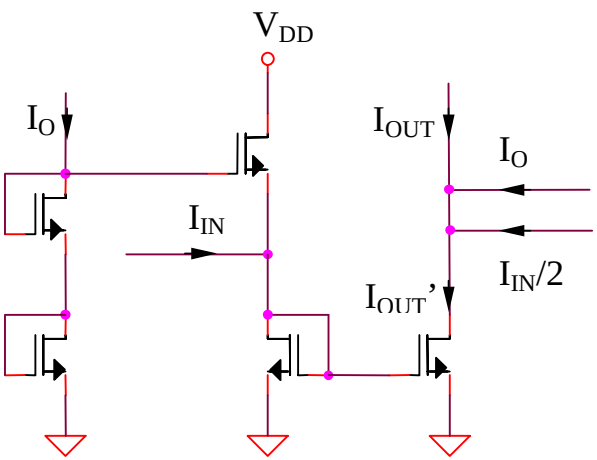
$(W/L)_2(W/L)_5 = (W/L)_3(W/L)_4$

$(W/L)_2(W/L)_5 \neq (W/L)_3(W/L)_4$

6. Surse de curent cu dependenta redusa cu temperatura

6.4. Surse de curent PTAT^2 (I)

$$2V_{GS}(I_O) = V_{GS}(I_{OUT}') + V_{GS}(I_{OUT}' - I_{IN})$$



$$2\sqrt{I_O} = \sqrt{I_{OUT}'} + \sqrt{I_{OUT}' - I_{IN}}$$

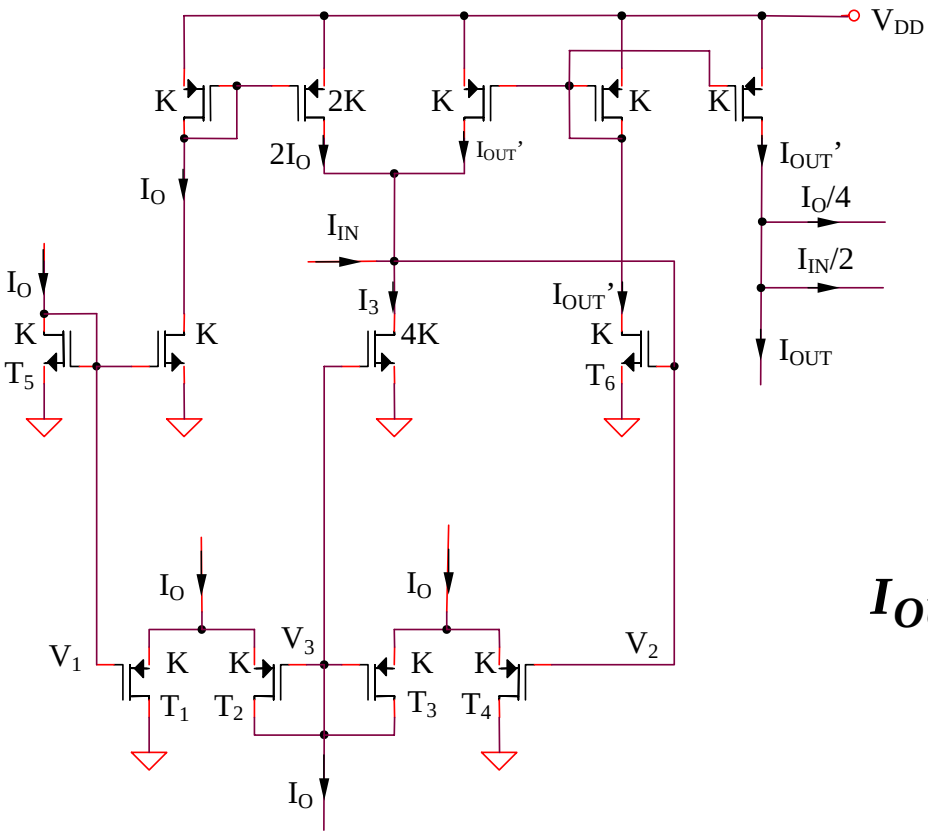
$$I_{OUT}' = I_O + \frac{I_{IN}}{2} + \frac{I_{IN}^2}{16 I_O}$$

$$I_{OUT} = I_{OUT}' - I_O - \frac{I_{IN}}{2} = \frac{I_{IN}^2}{16 I_O}$$

$$I_{IN} = ct.T \Rightarrow I_{OUT} = ct.T^2$$

6. Surse de curent cu dependenta redusa cu temperatura

6.4. Surse de curent PTAT^2 (II)



$$V_3 = V_T + \frac{1}{2}\left(\sqrt{\frac{2I_O}{K}} + \sqrt{\frac{2I_{OUT}'}{K}}\right)$$

$$I_3 = 2K(V_3 - V_T)^2 = I_O + I_{OUT}' + 2\sqrt{I_O I_{OUT}'}$$

$$I_3 = 2I_O + I_{OUT}' + I_{IN}$$

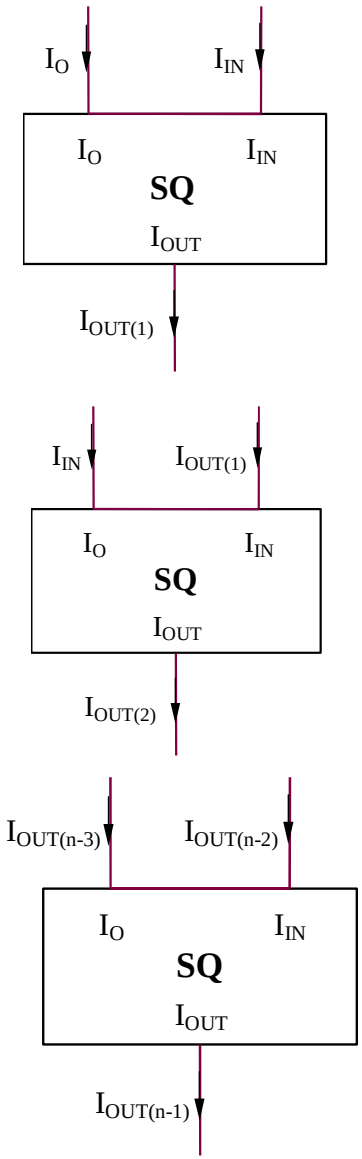
$$I_{OUT}' = \frac{I_O}{4}\left(1 + \frac{I_{IN}}{I_O}\right)^2 = \frac{I_O}{4} + \frac{I_{IN}}{2} + \frac{I_{IN}^2}{4I_O}$$

$$I_{OUT} = I_{OUT}' - \frac{I_O}{4} - \frac{I_{IN}}{2} = \frac{I_{IN}^2}{4I_O}$$

$$I_{IN} = ct.T \Rightarrow I_{OUT} = ct.T^2$$

6. Surse de curent cu dependenta redusa cu temperatura

6.5. Surse de curent PTAT^n



$$I_{OUT(1)} = \frac{I_{IN}^2}{I_O}$$

$$I_{OUT(2)} = \frac{I_{OUT(1)}^2}{I_{IN}} = \frac{I_{IN}^3}{I_O^2}$$

$$I_{OUT(n-1)} = \frac{I_{OUT(n-2)}^2}{I_{OUT(n-3)}} = \frac{I_{IN}^n}{I_O^{n-1}}$$