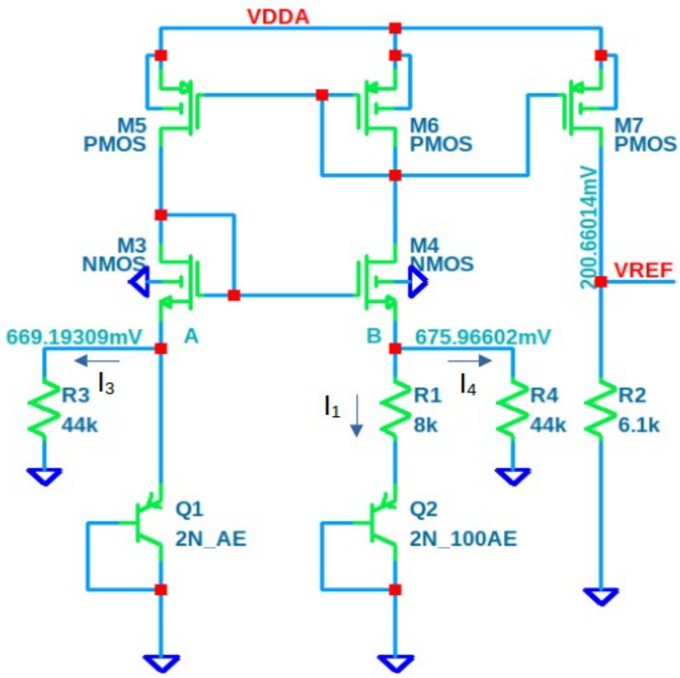


Analysis

V_A - V_B potential difference is given by:

$$-V_A - V_{GS3} + V_{GS4} + V_B = 0$$

$$then\, V_A - V_B = V_{GS4} - V_{GS3} = \left(V_T + \sqrt{\frac{2I_{D4}}{K_4}}\right) - \left(V_T + \sqrt{\frac{2I_{D3}}{K_3}}\right) = \sqrt{\frac{2I_{D4}}{K_4}}\left(1 - \sqrt{\frac{I_{D3}}{I_{D4}}\frac{K_4}{K_3}}\right)$$

$$where\, K = \mu C_{ox}\frac{W}{L}$$

Because of the current mirror M5 – M6 we can write:

$$\frac{I_{D3}}{I_{D4}} = \frac{I_{D5}}{I_{D6}} = \frac{K_5}{K_6}$$

$$so\, V_A - V_B = \sqrt{\frac{2I_{D4}}{K_4}}\left(1 - \sqrt{\frac{K_5}{K_6}\frac{K_4}{K_3}}\right)$$

The condition to make the V_A – V_B difference equal to zero is:

$$K_4 K_5 = K_3 K_6$$

equivalent with:

$$\left(\frac{W}{L}\right)_4 \left(\frac{W}{L}\right)_5 = \left(\frac{W}{L}\right)_3 \left(\frac{W}{L}\right)_6$$

Because $K_4 K_5 = K_3 K_6, V_A = V_B$ we get:

$$-V_{EB1} + I_3 R_3 = 0 \rightarrow I_3 = I_4 = \frac{V_{EB1}}{R_{3,4}}$$

I_1 current expression is given by:

$$-V_{EB2}-I_1R_1+V_{EB1}=0 \rightarrow I_1=\frac{V_{EB1}-V_{EB2}}{R_1}=\frac{kT}{qR_1}\ln\left(\frac{I_{S2}}{I_{S1}}\frac{I_{C1}}{I_{C2}}\right)$$

Knowing:

$$I_{D5}-I_3-I_{C1}=0 \rightarrow I_{C1}=I_{D5}-I_3$$

and:

$$I_{D6}-I_4-I_{C2}=0 \rightarrow I_{C2}=I_{D6}-I_4$$

with T_5 and T_6 being identical, $I_{D5} = I_{D6}$ so $I_{C1} = I_{C2}$, resulting:

$$I_1=\frac{kT}{qR_1}\ln\left(\frac{I_{S2}}{I_{S1}}\right)$$

The reference voltage Vref is:

$$V_{Ref}(T)=(I_1+I_4)R_2=\frac{R_2}{R_1}\frac{kT}{q}\ln\left(\frac{I_{S2}}{I_{S1}}\right)+\frac{R_2}{R_4}V_{EB1}(T)$$

$$V_{Ref}(T)=\frac{R_2}{R_1}\frac{kT}{q}\ln\left(\frac{I_{S2}}{I_{S1}}\right)+\frac{R_2}{R_4}\left[E_{G0}+\frac{V_{BE}(T_0)-E_{G0}}{T_0}T+(1-\eta)\frac{kT}{q}\ln\left(\frac{T}{T_0}\right)\right]$$

To produce a correction of first order on the temperature characteristic voltage reference, implies to cancel the linear temperature dependent parameters:

$$\frac{k}{qR_1}\ln\left(\frac{I_{S2}}{I_{S1}}\right)+\frac{V_{BE}(T_0)-E_{G0}}{R_4T_0}=0$$

Giving us:

$$V_{Ref}(T)=\frac{R_2}{R_4}\left[E_{G0}+(1-\eta)\frac{kT}{q}\ln\left(\frac{T}{T_0}\right)\right]$$

Design

All MOS transistors have identical aspect ratios, the bipolar saturation currents ratio I_{S2}/I_{S1} = 100, $V_{EB1}(T_0)$ = 0.6 V, $R_3 = R_4$.

The linear temperature correction characteristic of Vref implies respecting the following relation:

$$\frac{k}{qR_1}\ln\left(\frac{I_{S2}}{I_{S1}}\right)+\frac{V_{BE}(T_0)-E_{G0}}{R_4T_0}=0$$

$$\text{from } which\, we\, get\, \frac{R_4}{R_1}=\frac{E_{G0}-V_{\mathrm{BE}}(T_0)}{\frac{kT_0}{q}\ln\left(\frac{I_{S2}}{I_{S1}}\right)}=\frac{1.2-0.6}{\frac{1.38\text{e-}23\cdot 273}{1.6\text{e-}19}\ln(100)}=5.54$$

Selecting R_1 = 8k we get

$$R_4 = 5.54 \cdot 8e3 = 44e3\,\Omega$$

From the voltage – current relationship of MOS transistors in saturation we get:

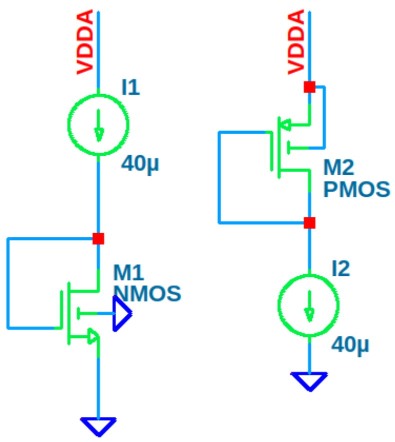
$$I_{D3,4} = \frac{Kn'}{2}\frac{W}{L}(V_{GS} - V_T)^2$$

$$I_{D5,6} = \frac{Kp'}{2}\frac{W}{L}(V_{SG} - |V_T|)^2$$

$$\frac{W}{L} = \frac{2 I_D}{K'(V_{GS} - V_T)^2}$$

→ an easier way to design is by using NMOS and PMOS references

We will start by using the following reference set (MOSFET model file 180 nm TSMC process):



The references have been selected to have the following characteristics:

	NREF	PREF
L [m]	180e-9	180e-9
W [m]	2e-6	6e-6
ID [A]	40e-6	40e-6
Vov [V]	127e-3	153e-3
Vth [V]	486e-3	520e-3
Gm [A/V]	496e-6	447e-6
Rds [Ohm]	80.6e3	108e3

We want to design for:

	NMOS	PMOS
L [m]	2e-6	2e-6
ID	32e-6	32e-6
Vov	140e-3	140e-3

Using our references we get the following parameters:

	NMOS	PMOS
L [m]	2e-6	2e-6
W [m]	14.6e-6	63.7e-6
ID [A]	32e-6	32e-6
Vov [V]	140e-3	140e-3
Gm [A/V]	360e-6	390e-6

SPICE simulation gives us:

	NMOS	PMOS
L [m]	2e-6	2e-6
W [m]	14.6e-6	63.7e-6
ID [A]	34e-6	34.7e-6
Vov [V]	161e-3	156e-3
Gm [A/V]	365e-6	358e-6

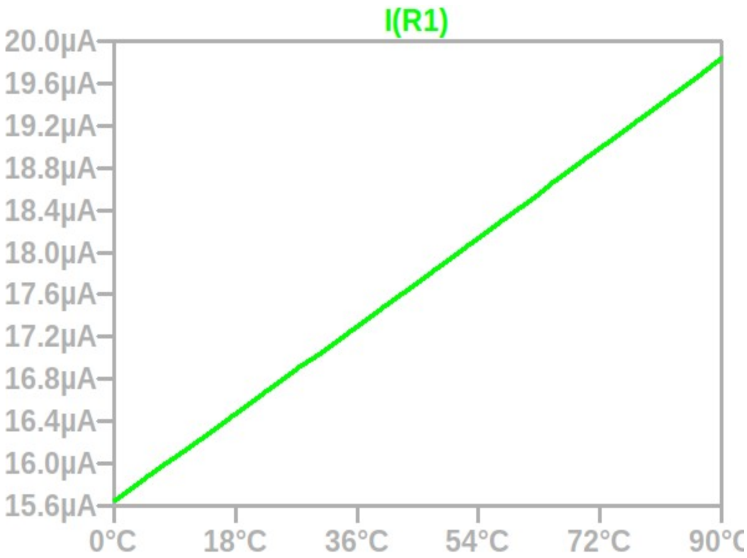
Note that here we will use for all transistors the same aspect ratio. (PMOS or NMOS transistor width can be further refined to have identical dc currents)

From I_1 equation we can see that the temperature dependence of it is linear:

$$I_1(T)=AT$$

'A' being a constant of value:

$$\text{from } I_1=\frac{kT}{qR_1}\ln\left(\frac{I_{S2}}{I_{S1}}\right) \textit{we have } A=\frac{k}{qR_1}\ln\left(\frac{I_{S2}}{I_{S1}}\right)=\frac{1.38\text{e-}23}{1.6\text{e-}19\cdot 8\text{e}3}\ln(100)=49.6\,nA/K$$



From the simulation we get A = 47.97 nA/K. (I_1 is PTAT, whereas I_4 is CTAT and both cancel each other)

Selecting the R_4/R_1 ratio derived earlier, from simulation we can also see that the temperature dependence of the voltage reference will depend only on the logarithmic equation: