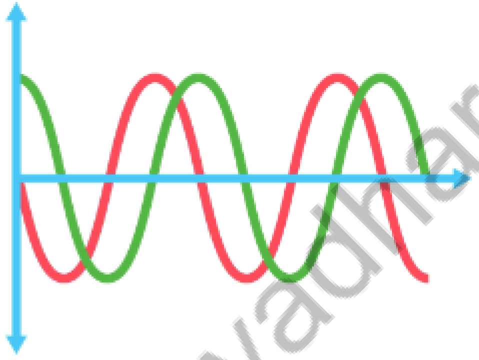
Course: Advanced Analog IC Design



Lecture 1: Bandgap Reference Circuits

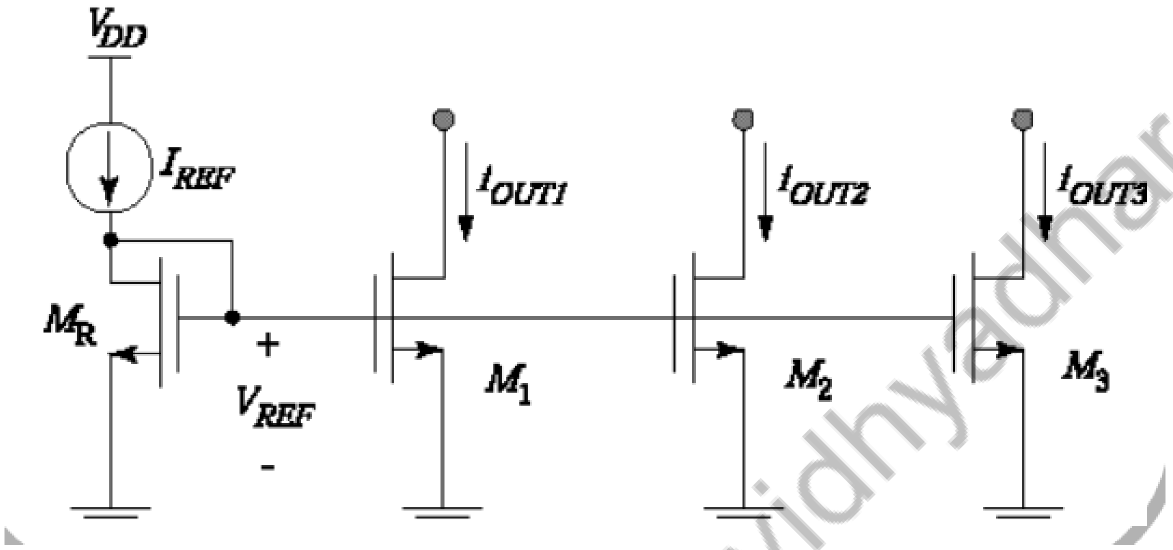
Reference: Design of Analog CMOS Integrated Circuits by Behzad Razavi

Prof. Sanjay Vidhyadharan

website: sanjayvidhyadharan.in

1. General Considerations

Current Mirrors



$$I_{REF} = \frac{1}{2}\mu_n C_{ox}(V_{GS}\text{-} V_{TN})^2 . (\frac{W}{L})_R$$

$$I_{OUT1} = \frac{1}{2}\mu_n C_{ox}(V_{GS}\text{-} V_{TN})^2 . (\frac{W}{L})_{OUT1}$$

$$I_{OUTN} = I_{REF}\frac{(\frac{W}{L})_{OUTN}}{(\frac{W}{L})_R}$$

Desirable Specs for I_{REF}

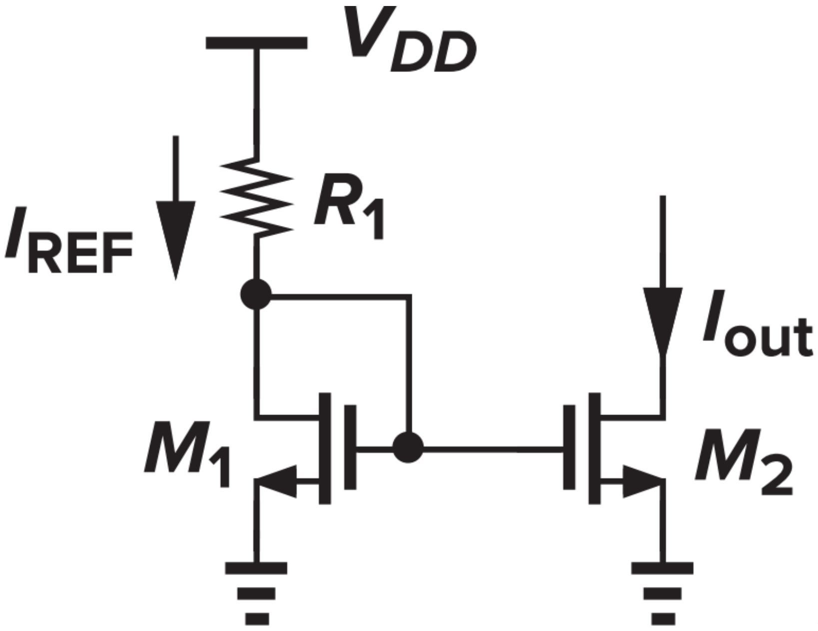
1. Independent of Temp
2. Independent of Process variation
3. Independent of VDD

Circuit requirement could be

1. Constant GM
2. Proportional to Absolute Temperature

2. Constant Current Sources

Current mirror biasing using a resistor



$$I_{REF} = \frac{1}{2}\mu_n C_{ox}(V_{GS} \text{-} V_{TN})^2.(\frac{W}{L})_R$$

$$I_{REF} = \frac{1}{2}\mu_n C_{ox}(V_{DD} \text{-} I_{REF}R - V_{TN})^2.(\frac{W}{L})_R$$

$$\frac{\delta I_{REF}}{\delta V_{DD}} = \frac{1}{2}\mu_n C_{ox}2(V_{DD} \text{-} I_{REF}R - V_{TN}).(\frac{W}{L})\ (1\text{-R}\,\frac{\delta I_{REF}}{\delta V_{DD}})$$

$$g_m = \mu_n C_{ox}\left(\frac{W}{L}\right)(V_{GS} - V_{Tn})$$

$$\frac{\delta I_{REF}}{\delta V_{DD}} = g_{m1}(1\text{-R}\,\frac{\delta I_{REF}}{\delta V_{DD}})$$

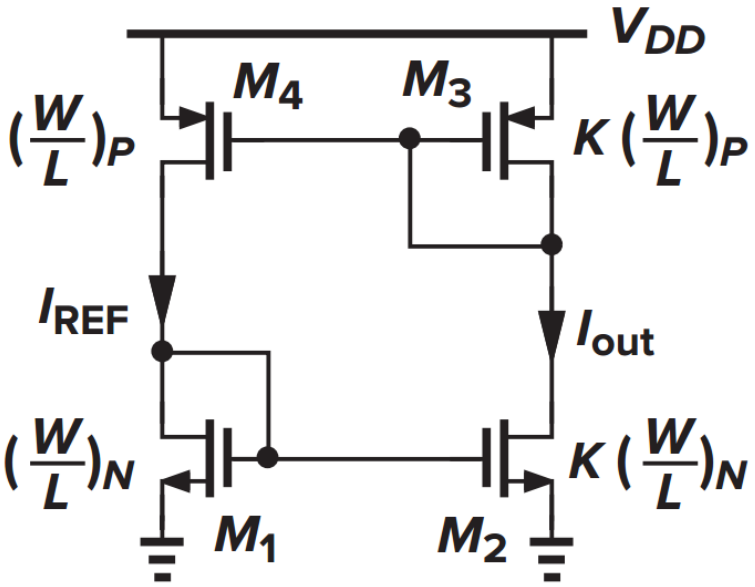
$$\frac{\delta I_{REF}}{\delta V_{DD}}(g_{m1} + R) = g_{m1}$$

$$\Delta I_{REF} = \frac{g_{m1}\Delta V_{DD}}{g_{m1} + R}$$

$$\Delta I_{OUT} = \frac{\Delta V_{DD}}{1+{}^{R}/_{g_{m1}}}\,\frac{({}^{W}/_{L})_2}{({}^{W}/_{L})_1}$$

2. Constant Current Sources

Supply-Independent Biasing



$$I_{REF} = \frac{1}{2}\mu_n C_{ox}(V_{GS1} - V_{TN})^2 . (\frac{W}{L})_1$$

$$I_{OUT} = \frac{1}{2}\mu_n C_{ox}(V_{GS1} - V_{TN})^2 . (\frac{W}{L})_2$$

$$I_{OUT} = K\ I_{REF}$$

Parameter	NMOSFETS	PMOSFETS	Units
V_{TH0}	0.5	-0.5	V
μC_{ox}	200	100	$\mu A/V^2$

$(W/L)_1 = 1$ $(W/L)_2 = 10$

$(W/L)_4 = 2$ $(W/L)_3 = 20$

Case 1 $V_{DD} = 1.8$ V,

$From\ M_1\ I_D\ Eqn:\ \ I_{REF} = 10\ \mu A = \frac{1}{2} 200\mu\ (V_{GS1} - 0.5)^2 1$

$V_{GS1} = 0.82\ V$

$I_{OUT} = K\ I_{REF} = 100\ \mu A$

$From\ M_3\ I_D\ Eqn:\ \ I_3 = 100\ \mu A = \frac{1}{2} 100\mu\ (1.8 - V_{G3} - 0.5)^2 20$

$V_{G3} = 0.98\ V = V_{DS2}$

$V_{ov2} = 0.82 - 0.5 = 0.32\ V\ i.e\ M_2\ in\ saturation$

$V_{SD} = 1.8 - 0.82 = 0.98\ V$

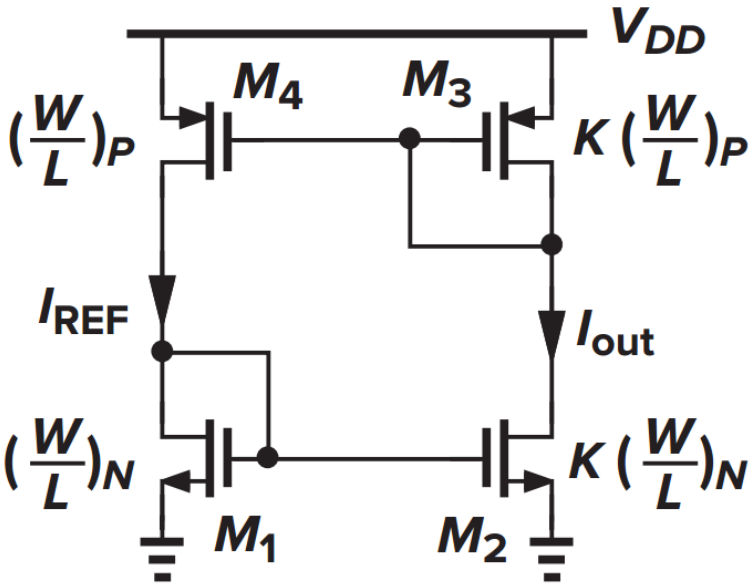
$V_{ov4} = 0.32\ \ M_4\ in\ saturation$

Case 2 $V_{DD} = 1.6$ V,

$V_{G3} = 0.78\ V\ \ M_2\ in\ saturation$

2. Constant Current Sources

Supply-Independent Biasing



$$I_{REF} = \frac{1}{2}\mu_n C_{ox}(V_{GS1}\text{-}\ V_{TN})^2.(\frac{W}{L})_1$$

$$I_{OUT} = \frac{1}{2}\mu_n C_{ox}(V_{GS1}\text{-}\ V_{TN})^2.(\frac{W}{L})_2$$

$$I_{OUT} = K\ I_{REF}$$

Parameter	NMOSFETS	PMOSFETS	Units
V_{TH0}	0.5	-0.5	V
μC_{ox}	200	100	$\mu A/V^2$

$(W/L)_1$= 1 $(W/L)_2$= 10

$(W/L)_4$= 2 $(W/L)_3$= 20

Case 3 V_{DD}= 1.8 V,

$From\ M_1\ I_D\ Eqn: \quad I_{REF} = 20\ \mu A = \frac{1}{2}200\mu\ (V_{GS1}\text{-}\ 0.5)^2 1$

V_{GS1}= 0.95 V

$I_{OUT} = K\ I_{REF} = 200\ \mu A$

$From\ M_1\ I_D\ Eqn: \quad I_3 = 200\ \mu A = \frac{1}{2}100\mu\ (1.8 - V_{G3}\text{-}\ 0.5)^2 20$

V_{G3}= 0.85 V $= V_{DS2}$

V_{ov2}= 0.95 − 0.5 = 0.45 V i.e M_2 in saturation

V_{SD}= 1.8 − 0.82 = 0.98 V

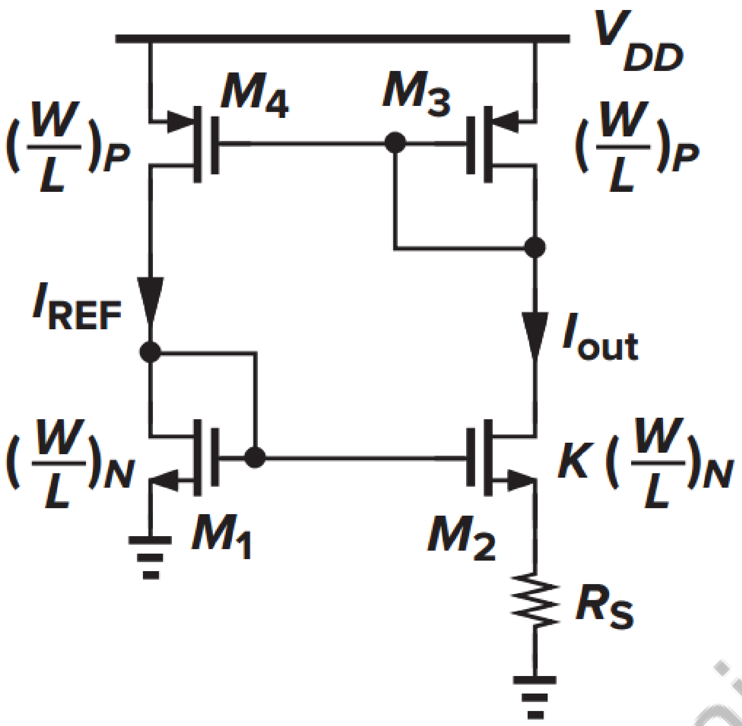
V_{ov4}= 0.32 M_4 in saturation

Case 4 V_{DD}= 1.6 V,

V_{G3}= 0.75 V M_2 in saturation

2. Constant Current Sources

Addition of R_S to define the currents



Since M3 and M4 are identical $I_{out} = I_{REF}$

$$\sqrt{\frac{2I_{out}}{\mu_n C_{ox}(W/L)_N}} + V_{TH1} = \sqrt{\frac{2I_{out}}{\mu_n C_{ox} K(W/L)_N}} + V_{TH2} + I_{out} R_S$$

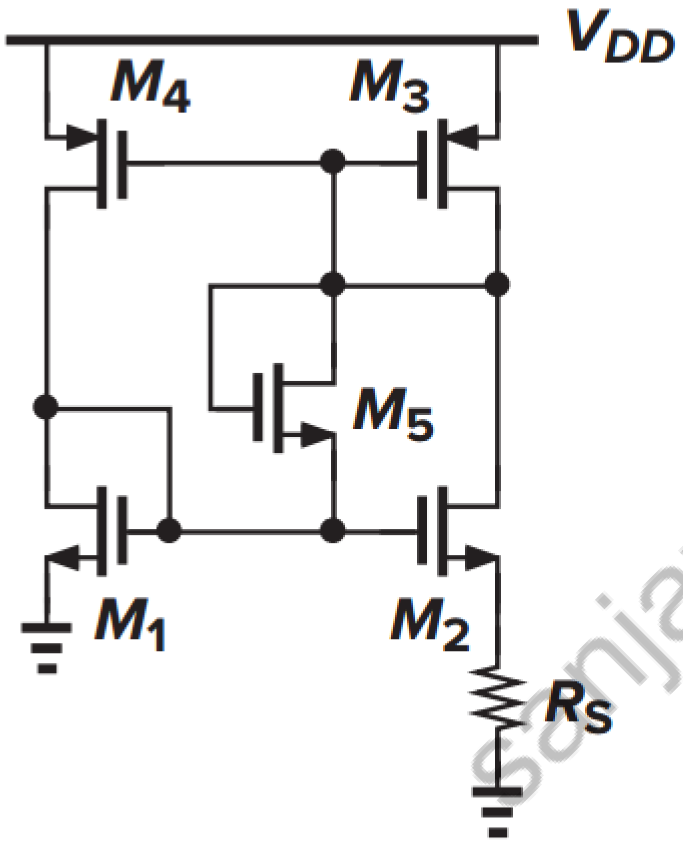
$$\sqrt{\frac{2I_{out}}{\mu_n C_{ox}(W/L)_N}}\left(1 - \frac{1}{\sqrt{K}}\right) = I_{out} R_S$$

$$I_{out} = \frac{2}{\mu_n C_{ox}(W/L)_N} \cdot \frac{1}{R_S^2}\left(1 - \frac{1}{\sqrt{K}}\right)^2$$

The current is independent of the supply voltage but still a function of process and temperature.

2. Constant Current Sources

Addition of start-up device to the circuit



M_5 provides a current path from V_{DD} through M_3 and M_1 to ground upon start-up.

$$V_{TH1} + V_{TH5} + |V_{TH3}| < V_{DD}$$

Latter to ensure that M_5 remains off after start-up.

$$V_{GS1} + V_{TH5} + |V_{GS3}| > V_{DD}$$

3. Temperature-Independent References

Negative-TC Voltage

For a bipolar device

$$I_C = I_S \exp(V_{BE}/V_T)$$

$$I_S = bT^{4+m} \exp \frac{-E_g}{kT}$$ saturation current

$E_g \approx 1.12$ eV is the bandgap energy of silicon.

$V_T = kT/q$

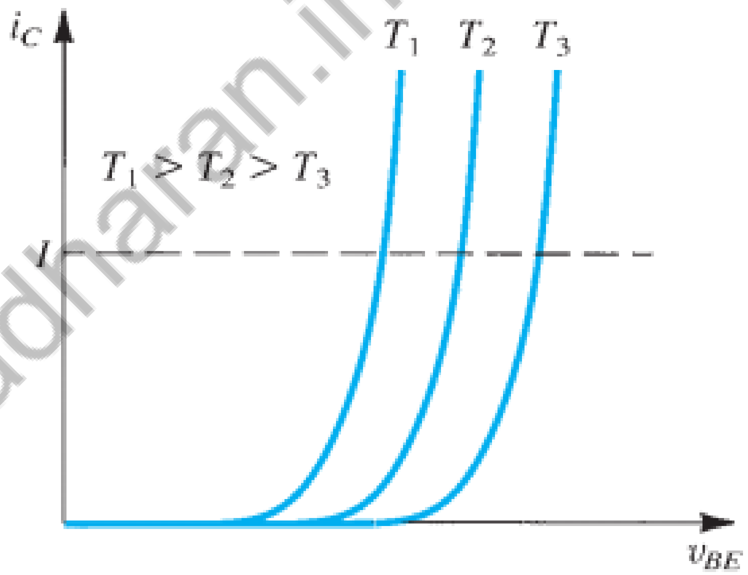
Ic approximately doubles for every 10ºC rise in temperature

$$V_{BE} = V_T \ln(I_C/I_S)$$

$$\frac{\partial V_{BE}}{\partial T} = \frac{\partial V_T}{\partial T} \ln \frac{I_C}{I_S} - \frac{V_T}{I_S} \frac{\partial I_S}{\partial T}$$

With $V_{BE} \approx 750$ mV and $T = 300$ K

$$\partial V_{BE}/\partial T \approx -1.5 \text{ mV/K}$$

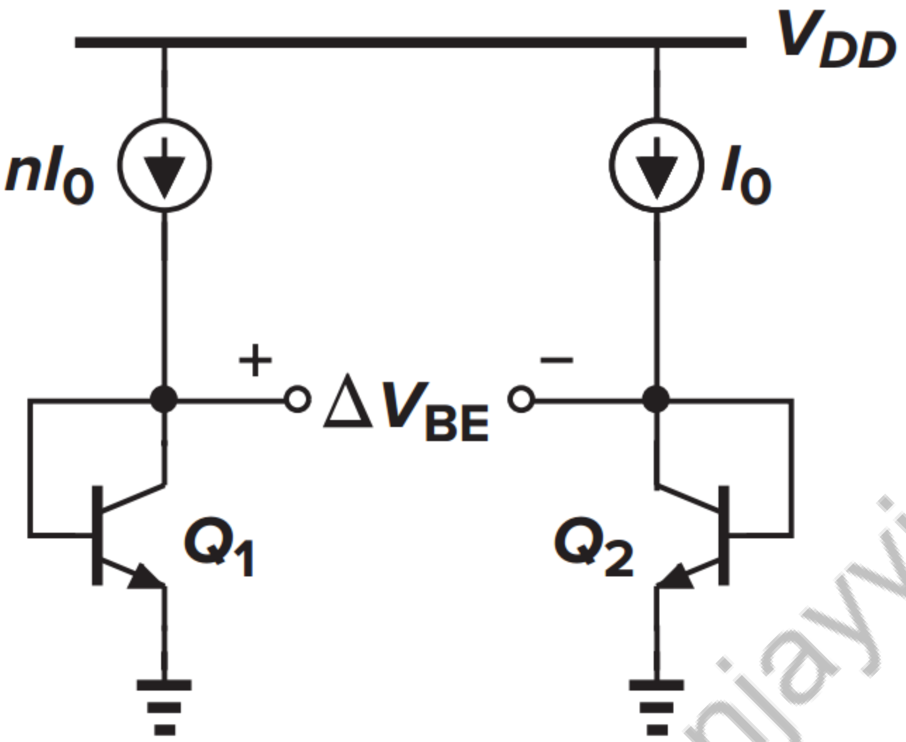


Effect of temperature on the i_C–v_{BE} characteristic. At a constant emitter current (broken line), V_{BE} changes by –2 mV/°C.

Ref: Sedra Smith

3. Temperature-Independent References

Positive-TC Voltage



PTAT : **P**roportional **T**o **A**bsolute **T**emperature

Generation of PTAT voltage.

$$\Delta V_{BE} = V_{BE1} - V_{BE2}$$
$$= V_T \ln \frac{nI_0}{I_{S1}} - V_T \ln \frac{I_0}{I_{S2}}$$
$$= V_T \ln n$$

Positive-TC Voltage

$$V_T = kT/q$$

K =1.380649 × 10^{-23} m^2 kg s^{-2} K^{-1}

Q =1.60217663 × 10^{-19} coulombs

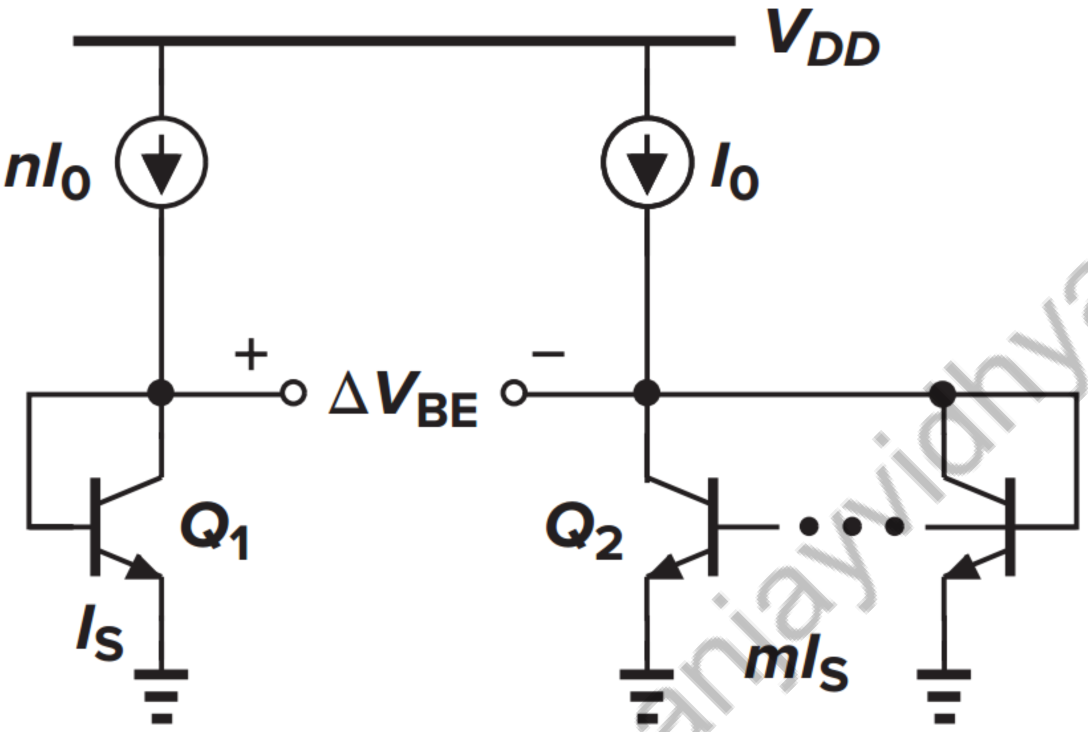
$$\partial V_T/\partial T \approx +0.087\,\text{mV/K},$$

$$\frac{\partial \Delta V_{BE}}{\partial T} = \frac{k}{q} \ln n$$

we have ln n ≈ 17.2 and hence $n = 2.95 \times 10^7$!! We can have TC of +1.5 mV/K so as to cancel the TC of the base-emitter voltage at T = 300 K

3. Temperature-Independent References

Positive-TC Voltage



$$\Delta V_{BE} = V_T \ln \frac{nI_0}{I_S} - V_T \ln \frac{I_0}{mI_S}$$

$$= V_T \ln(nm)$$

Temperature coefficient = $(k/q)\ln(nm)$

Band gap Reference

Assuming $V_{O1} = V_{O2}$

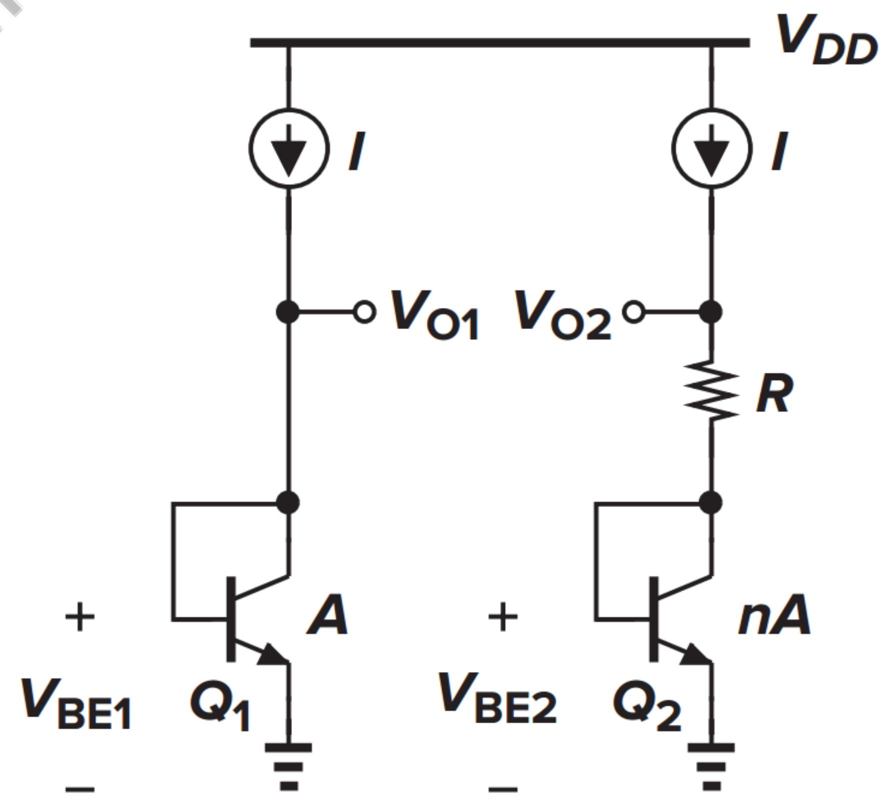
$$V_{BE1} = RI + V_{BE2}$$

$$RI = V_{BE1} - V_{BE2} = V_T \ln n$$

$$V_{O2} = V_{BE2} + V_T \ln n$$

V_{02} is a temperature-independent reference if ln n ≈ 17.2

$$V_{REF} \approx V_{BE} + 17.2V_T \approx 1.25\text{ V}$$



3. Temperature-Independent References

Band gap Reference

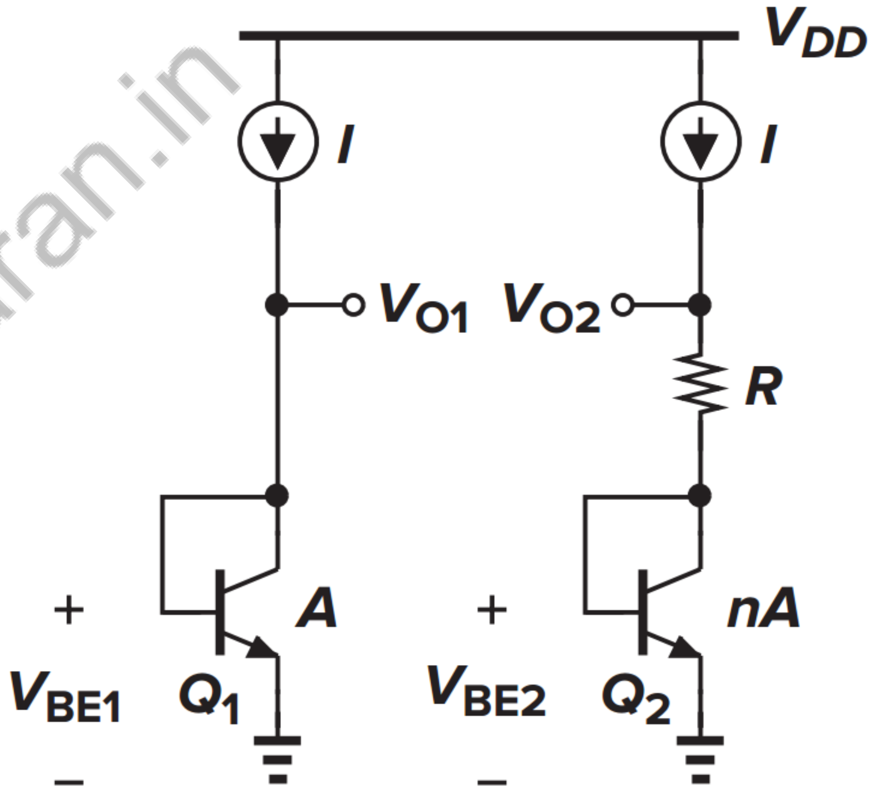
Assuming $V_{O1} = V_{O2}$

$$V_{BE1} = RI + V_{BE2}$$

$$RI = V_{BE1} - V_{BE2} = V_T \ln n$$

$$V_{O2} = V_{BE2} + V_T \ln n$$

V_{O2} is a temperature-independent reference if ln n ≈ 17.2



Three Issues

1. Guarantee that $V_{O1} = V_{O2}$
2. ln n = 17.2 translates to a prohibitively large n
3. $V_{O2} \approx V_{BE}1 \approx 800$ mV whereas,
   For temperature independence, we must have $V_{O2} = V_{BE2} + 17.2V_T \approx 1.25$ V

Band gap Reference

$V_{O1} = V_{O2}$

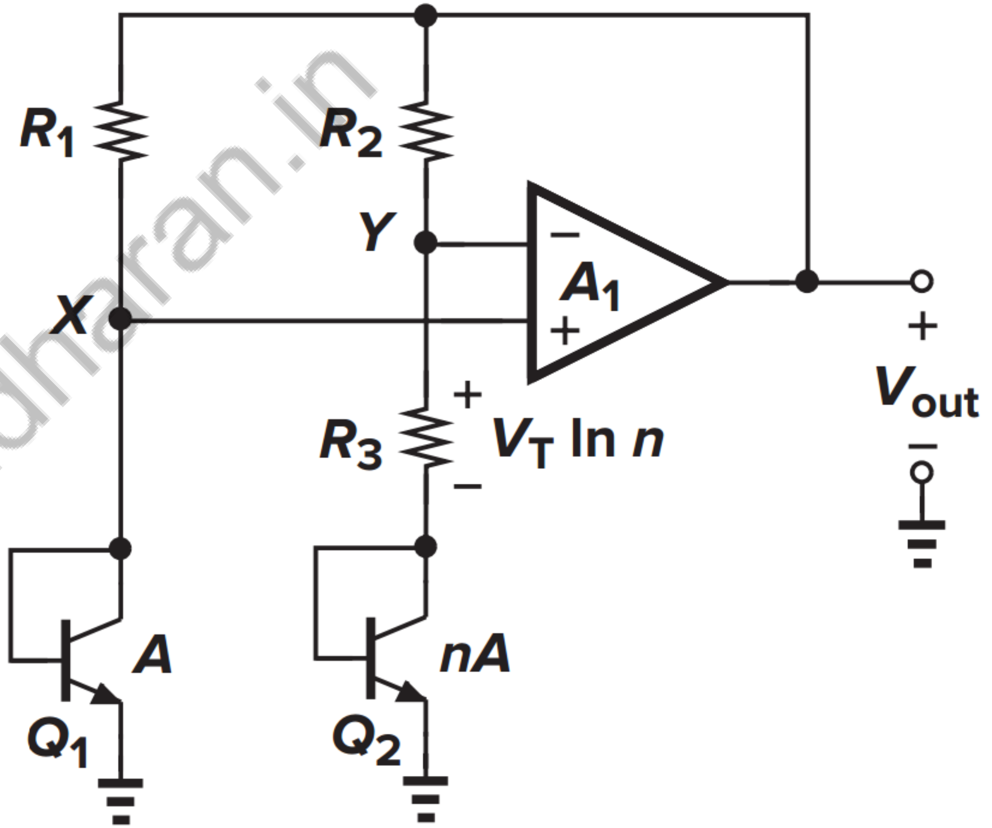
$$I = \frac{V_T \ln(n)}{R_3}$$

$$V_{out} = \frac{V_T \ln(n) R_2}{R_3} + V_T \ln(n) + V_{BE2}$$

$$V_{out} = V_T \ln(n) \left(1 + \frac{R_2}{R_3}\right) + V_{BE2}$$

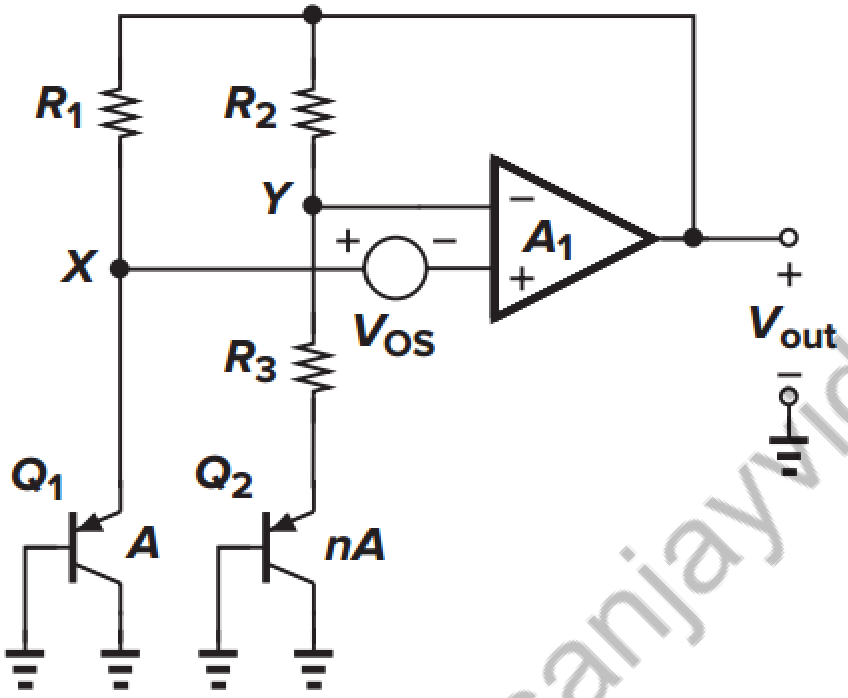
$$(1 + R_2/R_3) \ln n \approx 17.2.$$

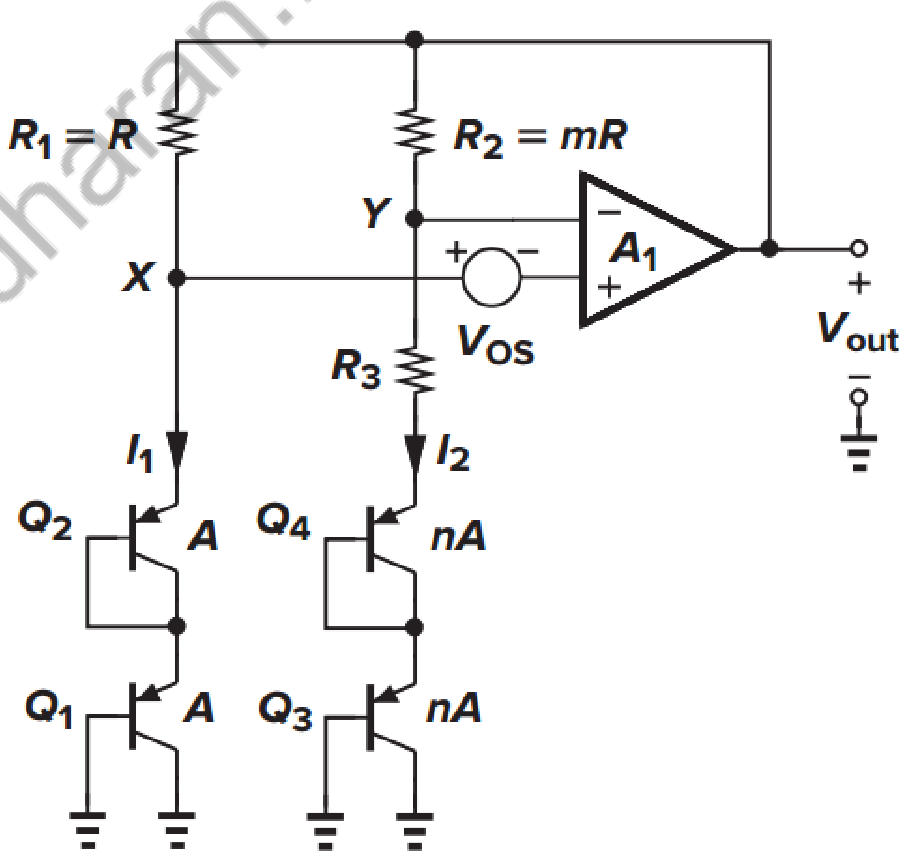
we may choose $n = 31$ and $R2/R3 = 4$.



3. Temperature-Independent References

Band gap Reference

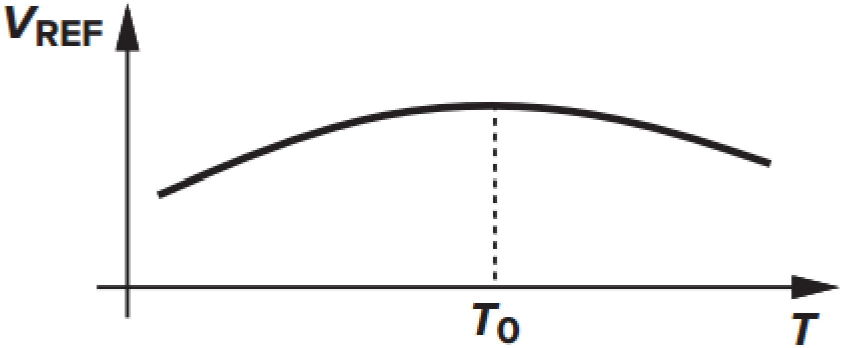




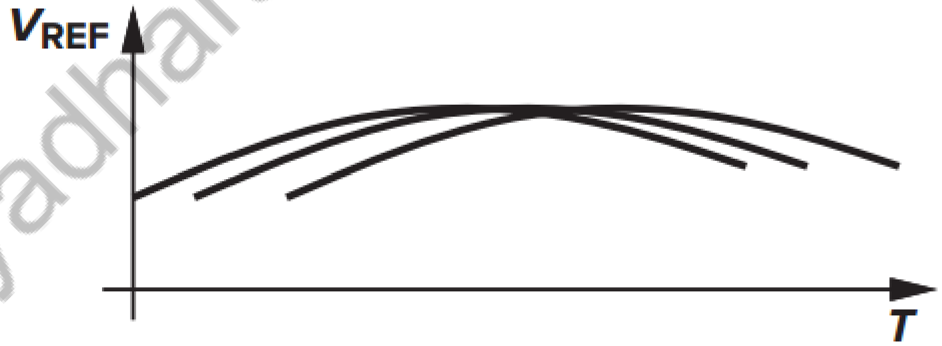
$$V_{out} \approx 2 \times 1.25\ \mathrm{V} = 2.5\ \mathrm{V},$$

3. Temperature-Independent References

Band gap Reference



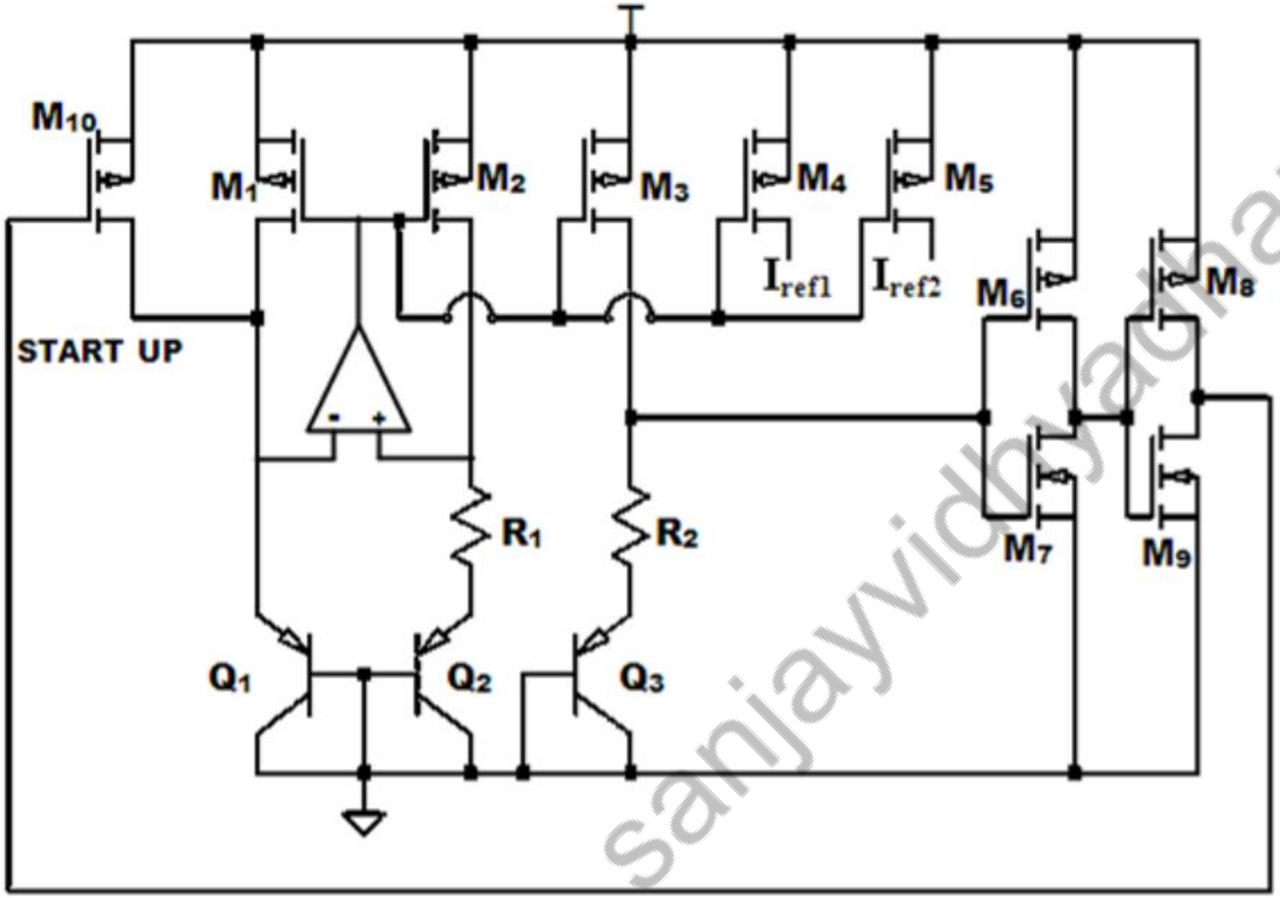
Curvature in temperature dependence of a bandgap voltage



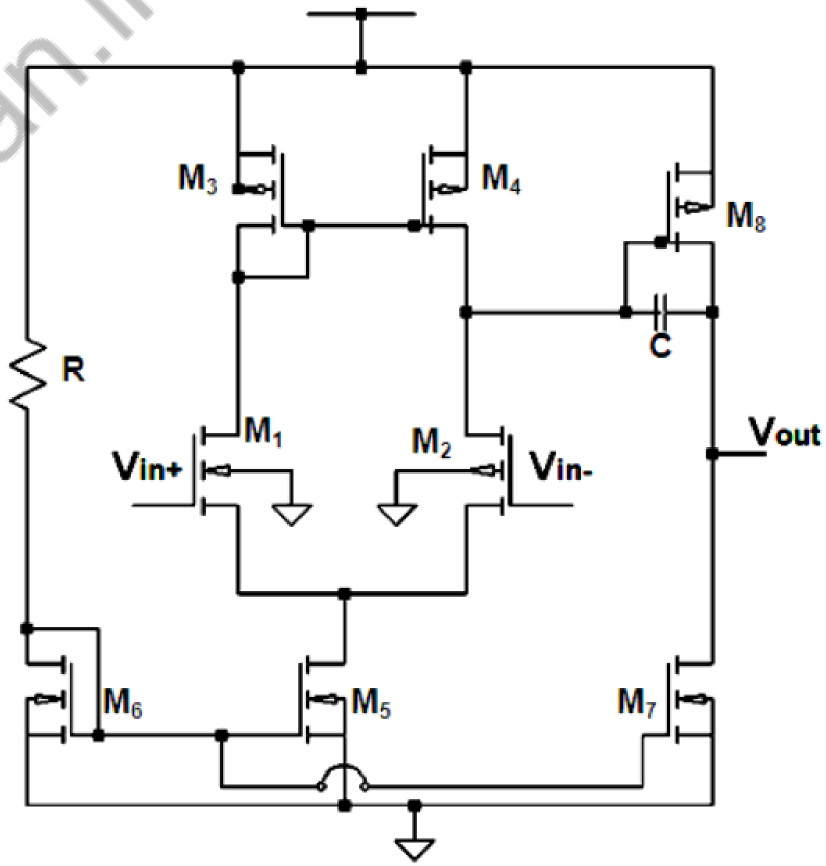
Variation of the zero-TC temperature for different samples.

3. Temperature-Independent References

Band gap Reference



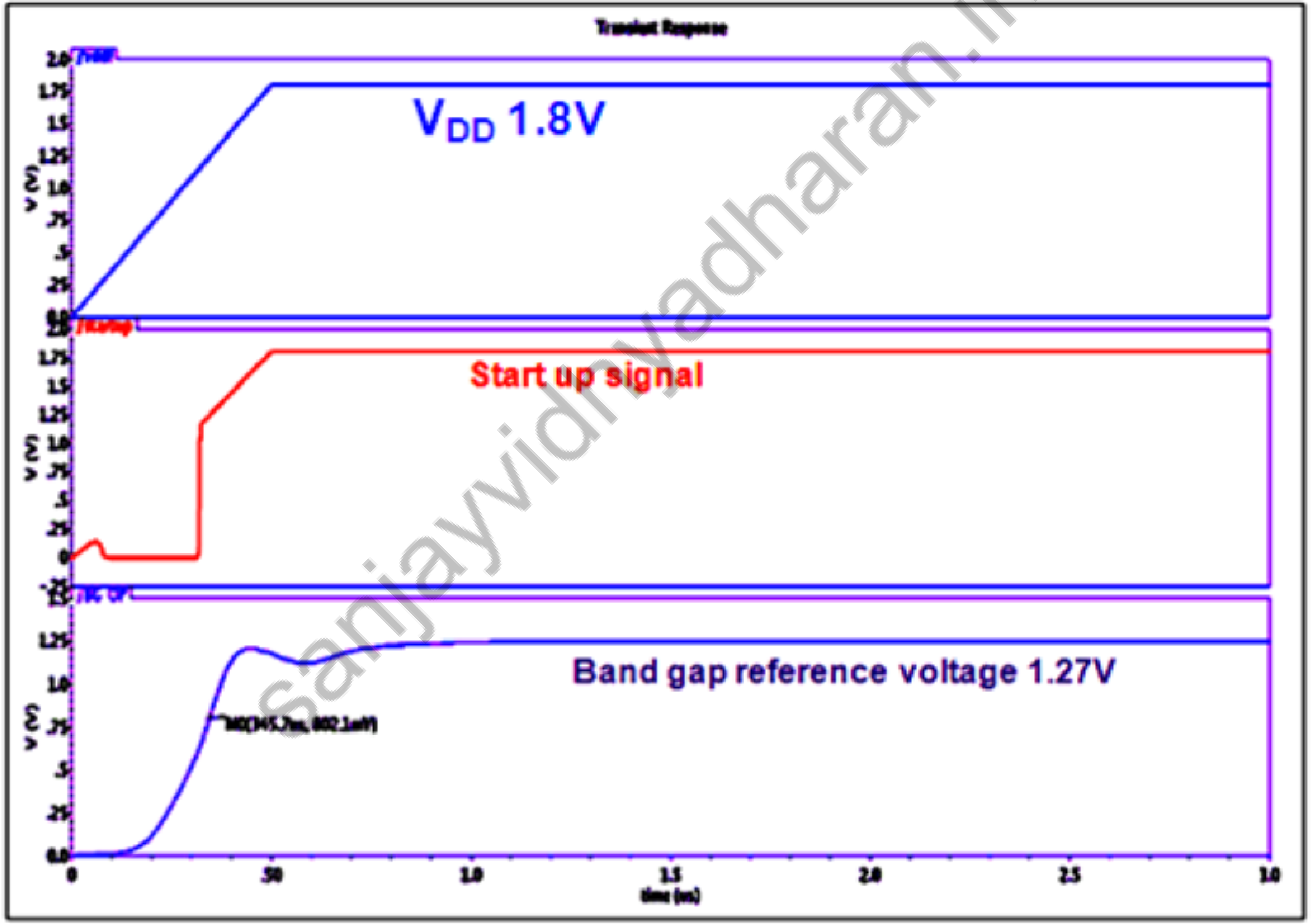
Bandgap reference circuit



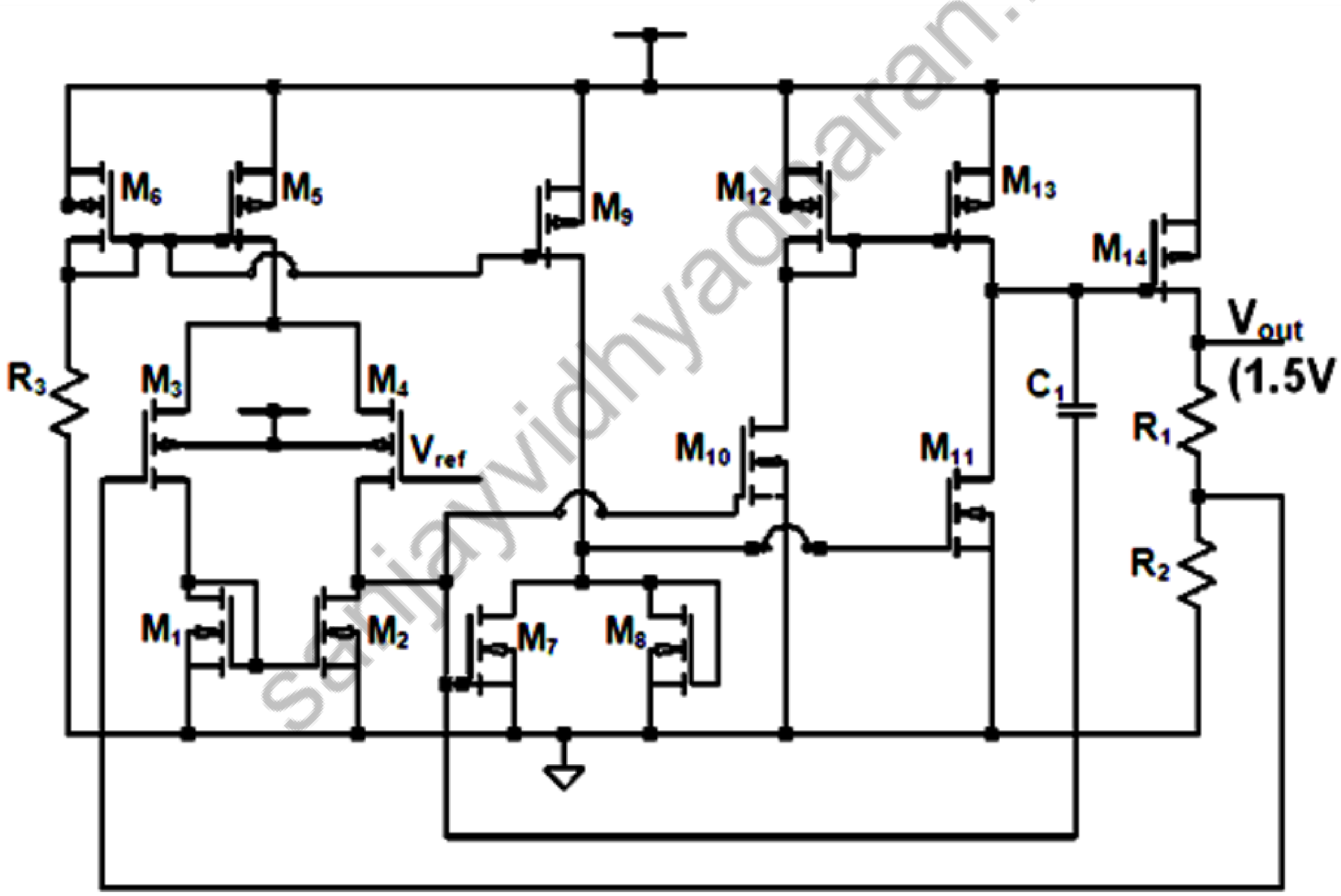
Op-amp used in bandgap reference circuit

3. Temperature-Independent References

Band gap Reference

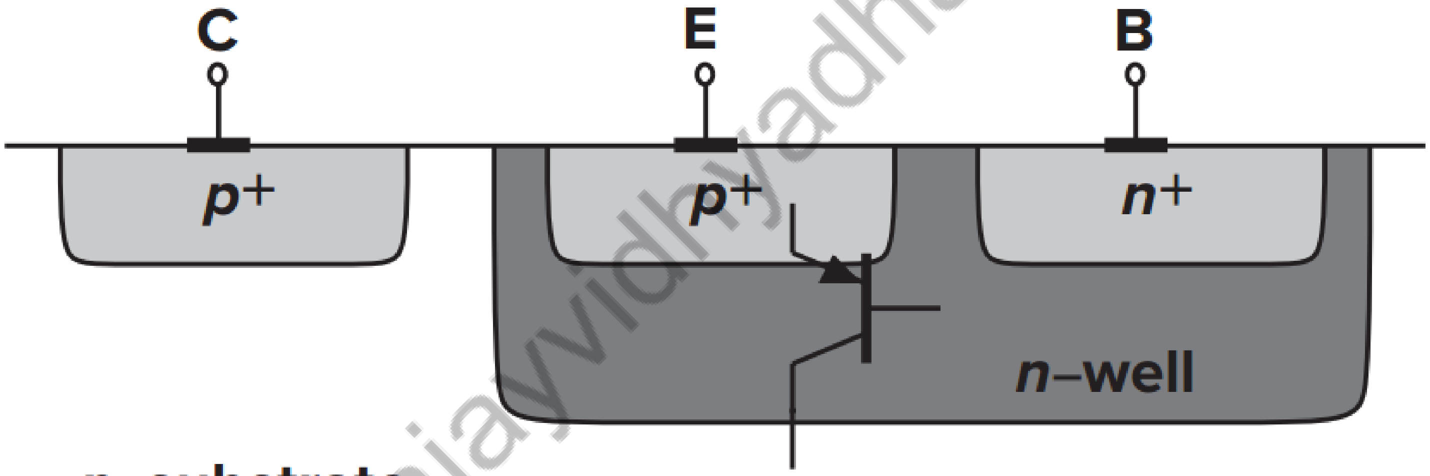


Linear regulator circuit

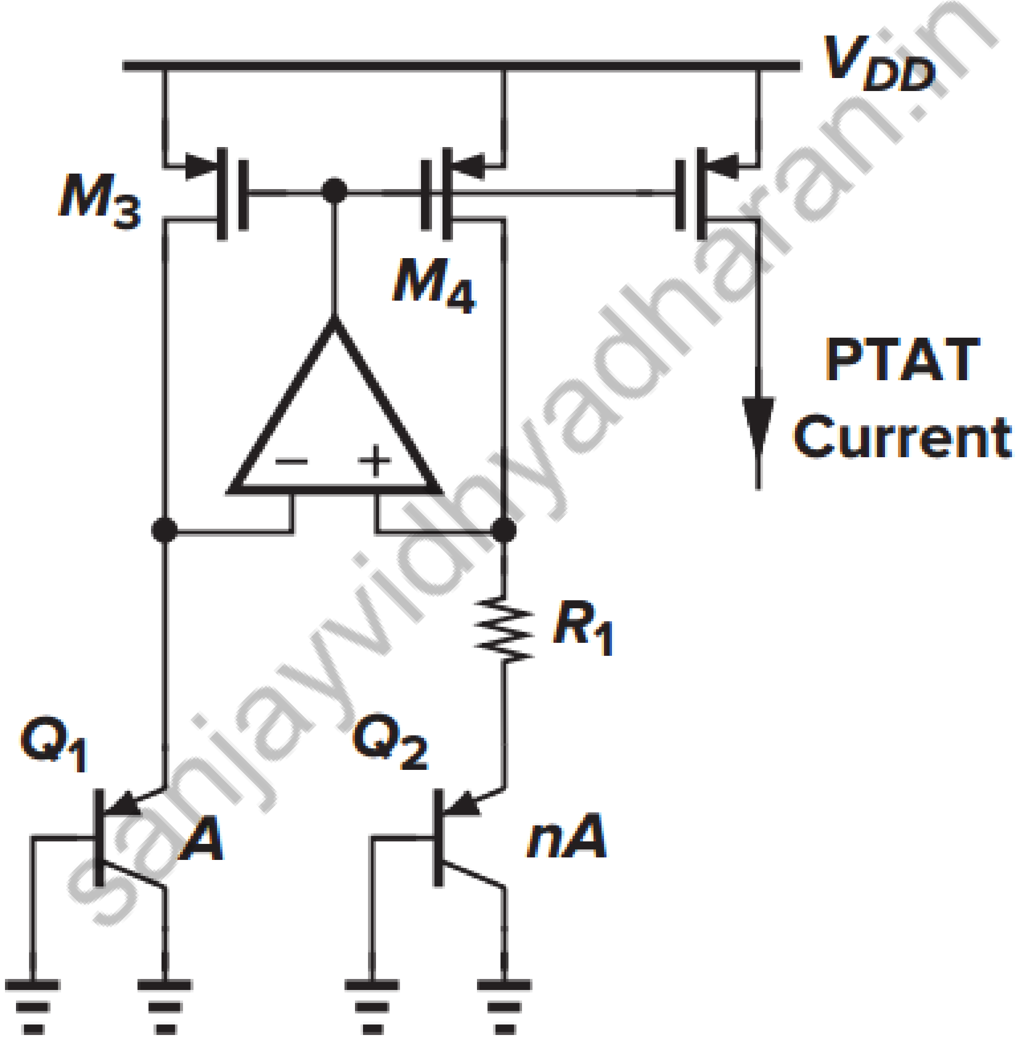


3. Temperature-Independent References

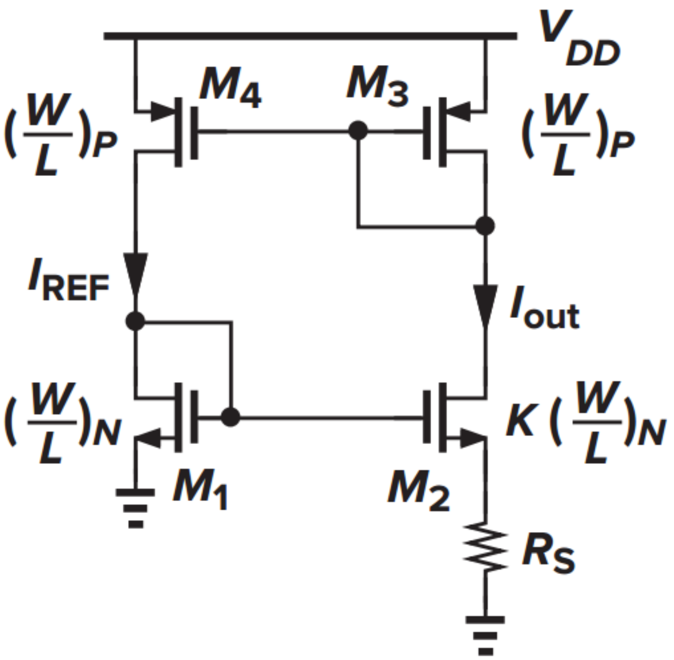
Realization of a *pnp* bipolar transistor in CMOS technology



4. PTAT Current Generation



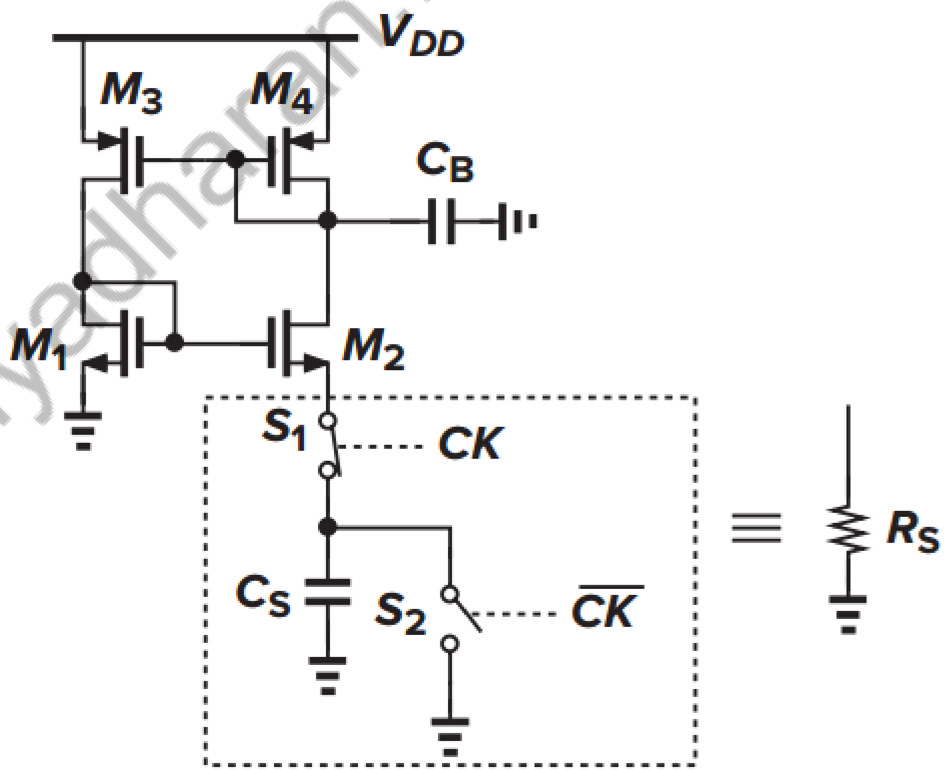
5. Constant-Gm Biasing



$$I_{out} = \frac{2}{\mu_n C_{ox}(W/L)_N} \cdot \frac{1}{R_S^2}\left(1 - \frac{1}{\sqrt{K}}\right)^2$$

$$g_{m1} = \sqrt{2\mu_n C_{ox}\left(\frac{W}{L}\right)_N I_{D1}}$$

$$= \frac{2}{R_S}\left(1 - \frac{1}{\sqrt{K}}\right)$$



Thankyou