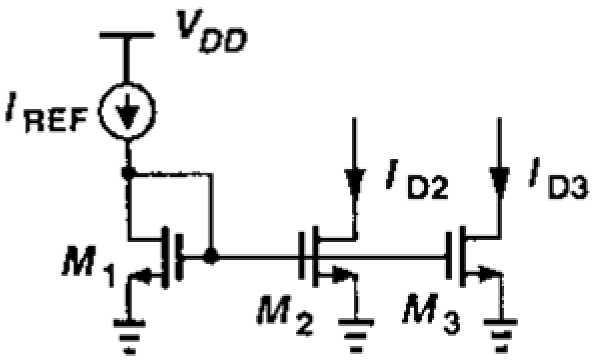
Voltage and Current References
Bandgap References

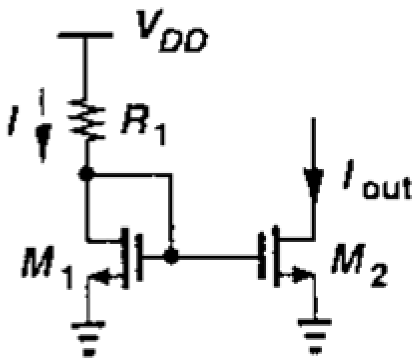
The objective of reference generation is to establish a dc voltage or current with following characteristics:

- Independent of the supply and process.
- Having a well-defined behavior with temperature.
  - Temperature independent.

Supply-Independent Biasing



(a)

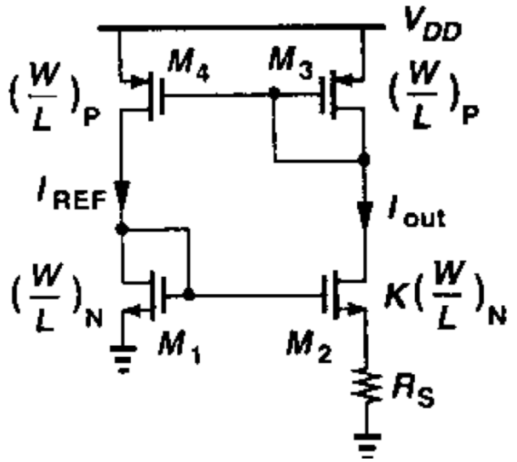


(b)

- In the design of current sources, we need to a golden current source, IREF. (Figure (a))
- If instead of IREF we use a resistor, the generated current sources will be supply-dependent. (Figure (b))

A Simple Circuit to Establish Supply-Independent Current Supply-Independent Biasing

$\lambda=0, \gamma=0$



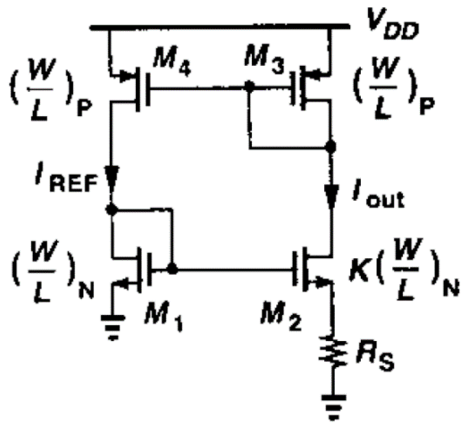
$$\sqrt{\frac{2I_{out}}{\mu_n C_{ox}(W/L)_N}} + V_{TH1} = \sqrt{\frac{2I_{out}}{\mu_n C_{ox} K(W/L)_N}} + V_{TH2} + I_{out}R_S$$

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

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

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

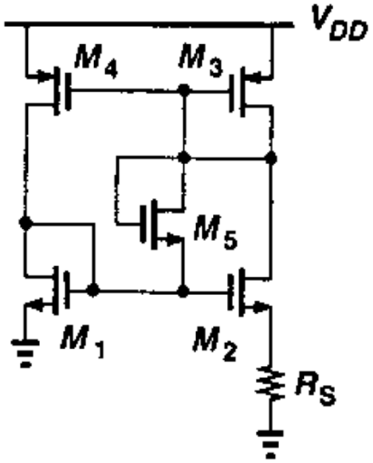
Start-up Problem



$I_{out}=0$ is another operating point of the above circuit because it satisfies the following equation. We call this problem as the start-up problem.

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

Addition of the Start-up devices



this technique is practical only if $V_{TH1} + V_{TH5} + |V_{TH3}| < V_{DD}$ and $V_{GS1} + V_{TH5} + |V_{GS3}| > V_{DD}$

Temperature-Independent References

if two quantities having opposite temperature coefficients (TCs) are added with proper weighting, the result displays a zero TC. For example,

$$V_{REF} = \alpha_1 V_1 + \alpha_2 V_2,$$

$$\alpha_1 \partial V_1/\partial T + \alpha_2 \partial V_2/\partial T = 0$$

Negative-TC Voltage

The base-emitter voltage of bipolar transistors or, more generally, the forward voltage of a *pn*-junction diode exhibits a negative TC.

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

$$V_T = kT/q$$

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

$$m \approx -3/2$$

b is a proportionality factor.

We assume that Ic is held constant.

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

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

$$\frac{\partial I_S}{\partial T} = b(4+m)T^{3+m} \exp \frac{-E_g}{kT} + bT^{4+m} \left(\exp \frac{-E_g}{kT} \right) \left(\frac{E_g}{kT^2} \right)$$

$$\frac{V_T}{I_S} \frac{\partial I_S}{\partial T} = (4+m)\frac{V_T}{T} + \frac{E_g}{kT^2} V_T$$

Continued

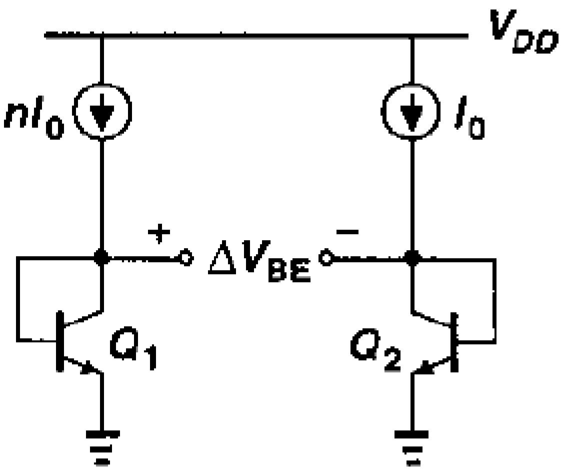
$$\frac{\partial V_{BE}}{\partial T} = \frac{V_T}{T} \ln \frac{I_C}{I_S} - (4+m)\frac{V_T}{T} - \frac{E_g}{kT^2} V_T$$

$$= \frac{V_{BE} - (4+m)V_T - E_g/q}{T}.$$

With $V_{BE} \approx 750$ mV and $T = 300$°K, $\partial V_{BE}/\partial T \approx -1.5$ mV/°K.

Positive-TC Voltage

if two bipolar transistors operate at unequal current densities, then the *difference* between their base-emitter voltages is directly proportional to the absolute temperature.



$$I_{S1} = I_{S2}$$

Generation of PTAT voltage.

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

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

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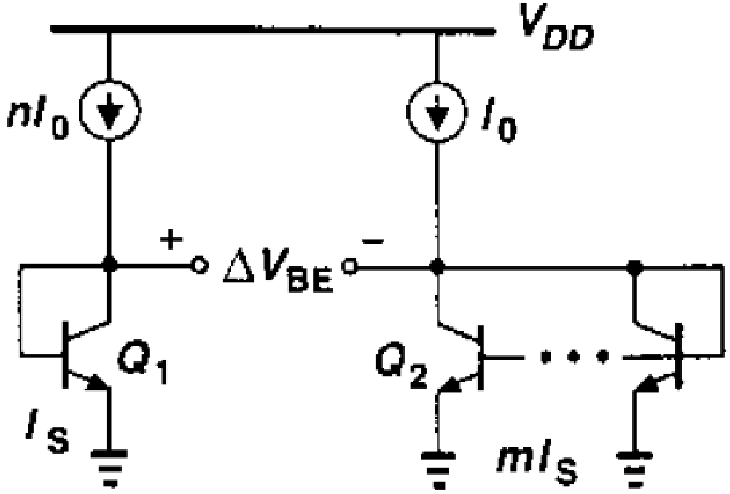
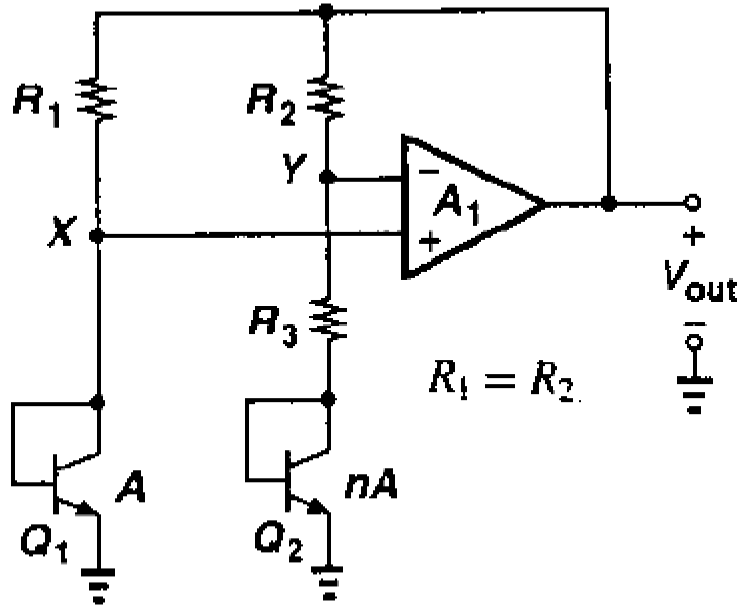


$$\begin{aligned}\Delta V_{BE} &= V_{BE1} - V_{BE2} \\ &= V_T \ln \frac{nI_0}{I_S} - V_T \ln \frac{I_0}{mI_S} \\ &= V_T \ln(nm).\end{aligned}$$

$$\frac{\partial \Delta V_{BE}}{\partial T} = (k/q)\ln(nm)$$

Bandgap References



$$V_X \cong V_Y \Rightarrow \frac{V_{out} - V_X}{R_1} \cong \frac{V_{out} - V_Y}{R_2} \Rightarrow I_{C1} = I_{C2}$$

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

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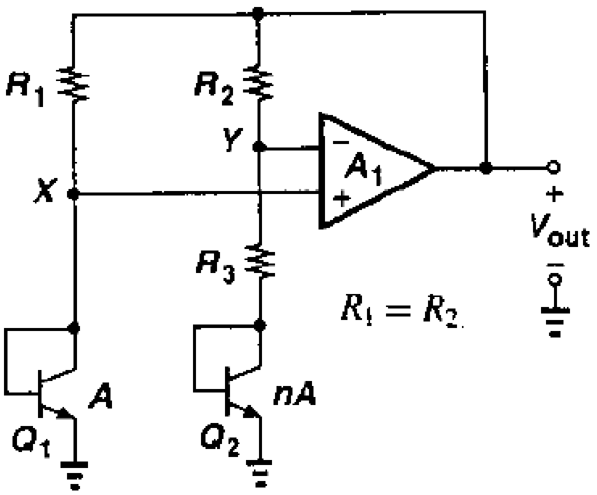

$$\left.\begin{aligned} V_{out} &= V_{BE1} + R_1 I_{C1} \\ V_{out} &= V_{BE2} + (R_2 + R_3) I_{C2} \\ I_{C1} &= I_{C2} \end{aligned}\right\} \Rightarrow \Delta V_{BE} = V_{BE1} - V_{BE2} = R_3 I_{C2} \Rightarrow I_{C2} = \frac{\Delta V_{BE}}{R_3}$$

$$V_{out} = (R_2 + R_3) I_{C2} + V_{BE2} = \boxed{\left(1 + \frac{R_2}{R_3}\right) \Delta V_{BE} + V_{BE2}}$$

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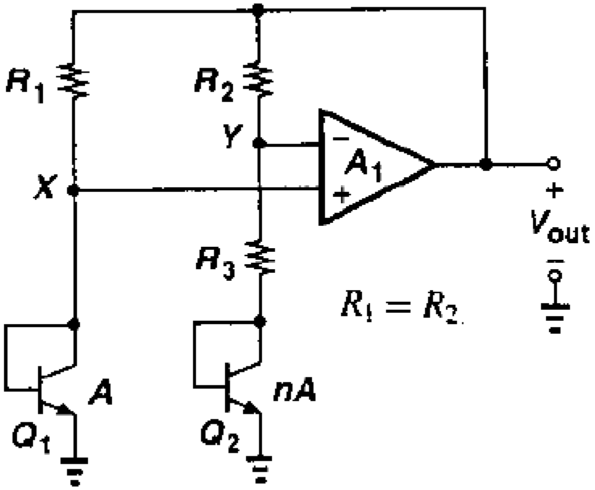

$$V_{out}=\left(1+\frac{R_2}{R_3}\right)\Delta V_{BE}+V_{BE2}=\left(1+\frac{R_2}{R_3}\right)V_T\ln(n)+V_{BE2}$$

$$\frac{\partial V_{out}}{\partial T}=0\Rightarrow\quad\left(1+\frac{R_2}{R_3}\right)\frac{k}{q}\ln(n)=-\frac{\partial V_{BE2}}{\partial T}$$

$$\boxed{\left(1+\frac{R_2}{R_3}\right)\frac{k}{q}\ln(n)=1.5\frac{mV}{{}^\circ K}}$$

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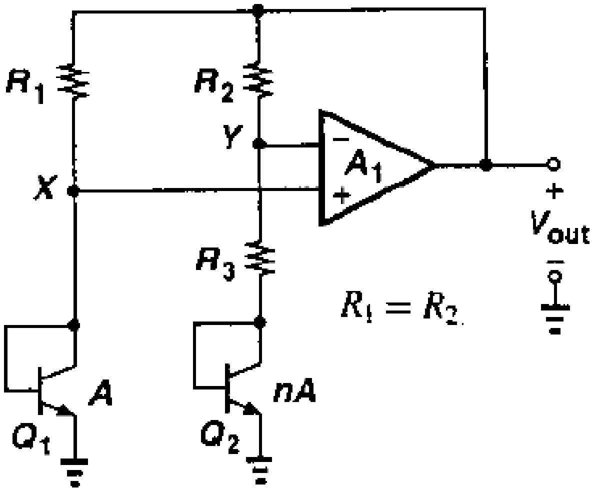
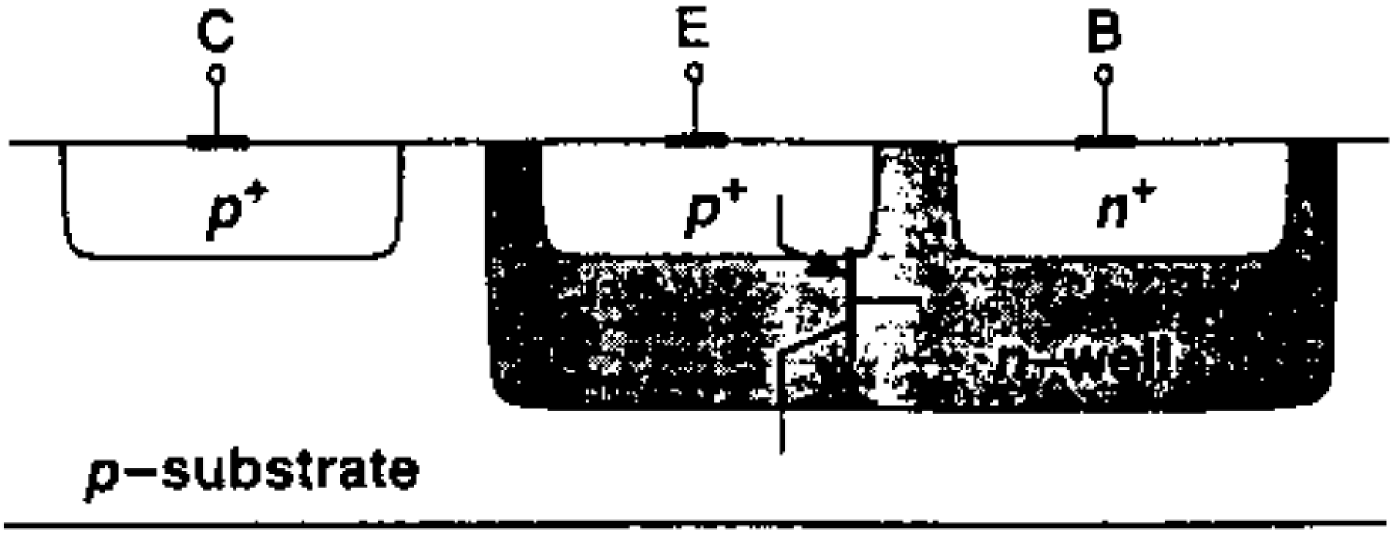


$R_1 = R_2$

Assuming V_{BE2}=750mV, we have:

$$V_{out} = \left(1 + \frac{R_2}{R_3}\right) V_T \ln(n) + V_{BE2} = 1.5 \frac{mV}{^\circ K} \times 300 + 750mV = 1.2V$$

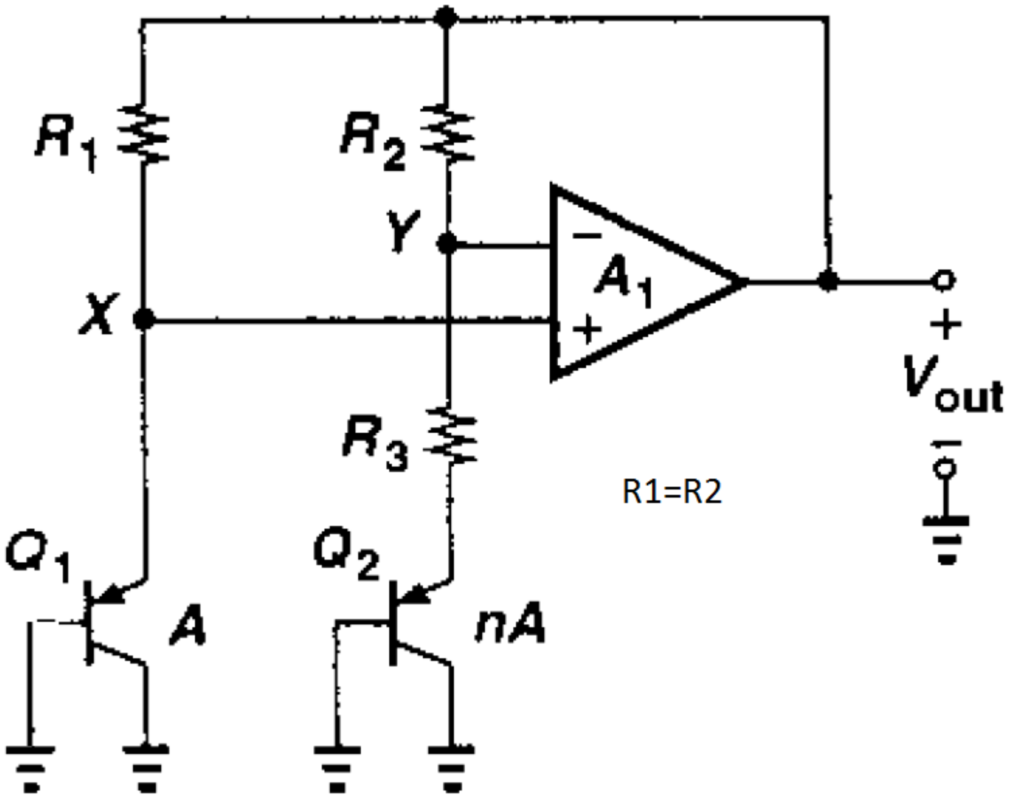
Compatibility with CMOS Technology



Realization of a *pnp* bipolar transistor in CMOS technology.

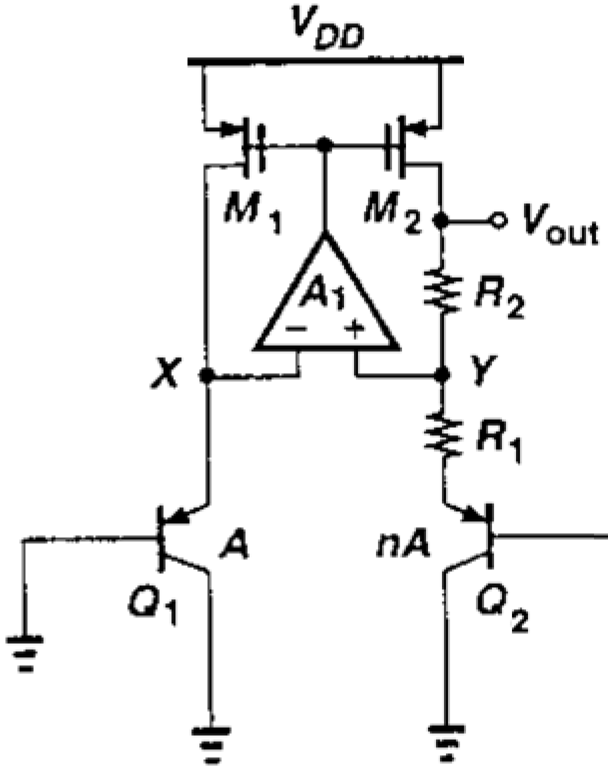
The *p*-type substrate acts as the collector and it is inevitably connected to the most negative supply (usually ground).

Modified Bandgap Circuit



R1=R2

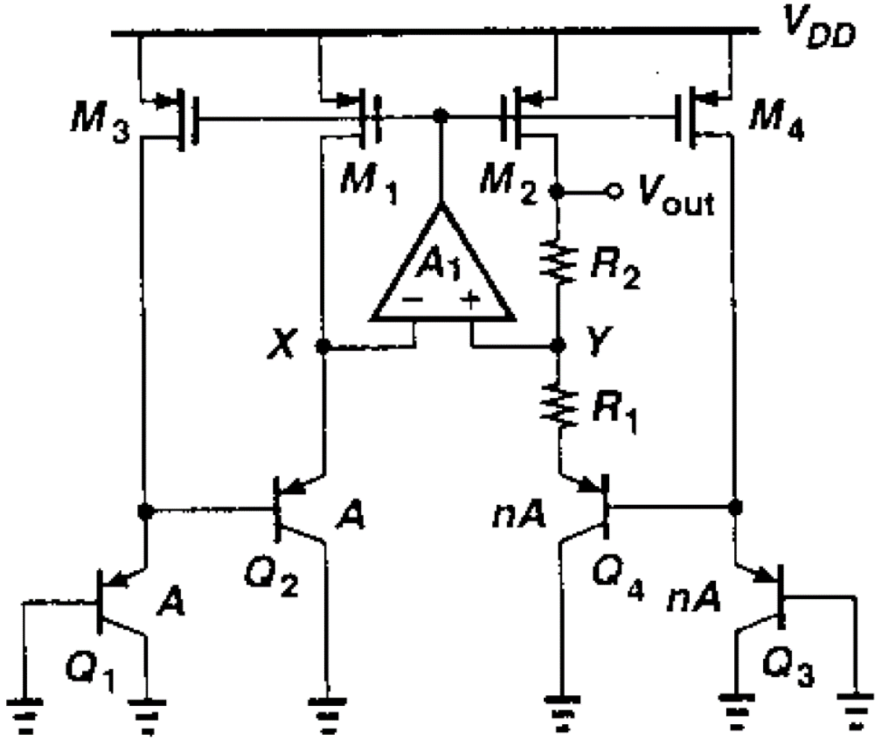
Bandgap Circuit



$$V_{out} = V_{EB2} + \left(1 + \frac{R_2}{R_1}\right) V_T \ln(n)$$

The drawback of the above circuit is that V_{DS1}#V_{DS2}. Therefore I_{D1} is not accurately identical to I_{D2}.

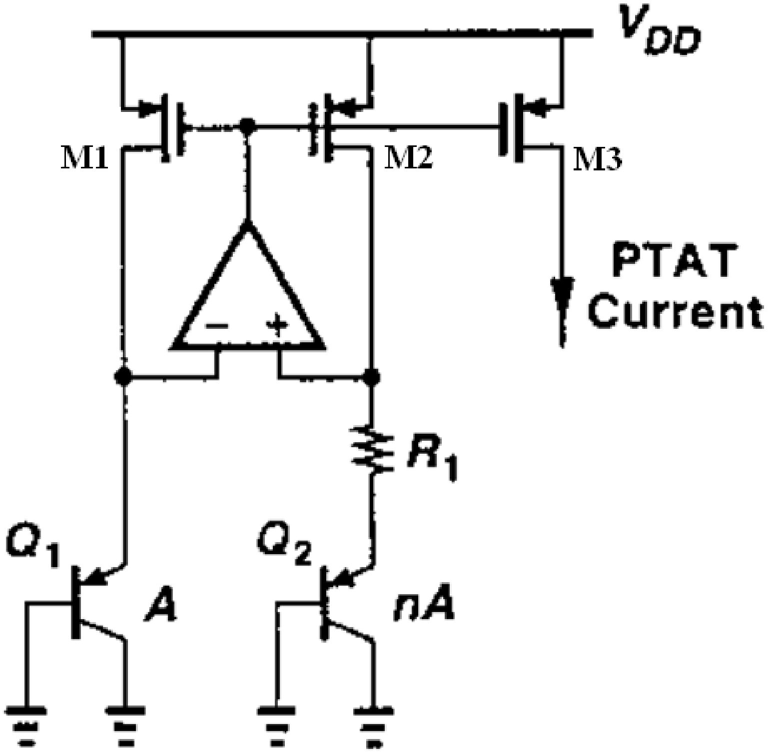
Bandgap Circuit (Vout=2.5V)



$$V_{out} = V_{EB3} + V_{EB4} + 2\left(1 + \frac{R_2}{R_1}\right)V_T \ln(n)$$

The drawback of the above circuit is that $V_{DS1}\#V_{DS2}$. Therefore I_{D1} is not accurately identical to I_{D2}.

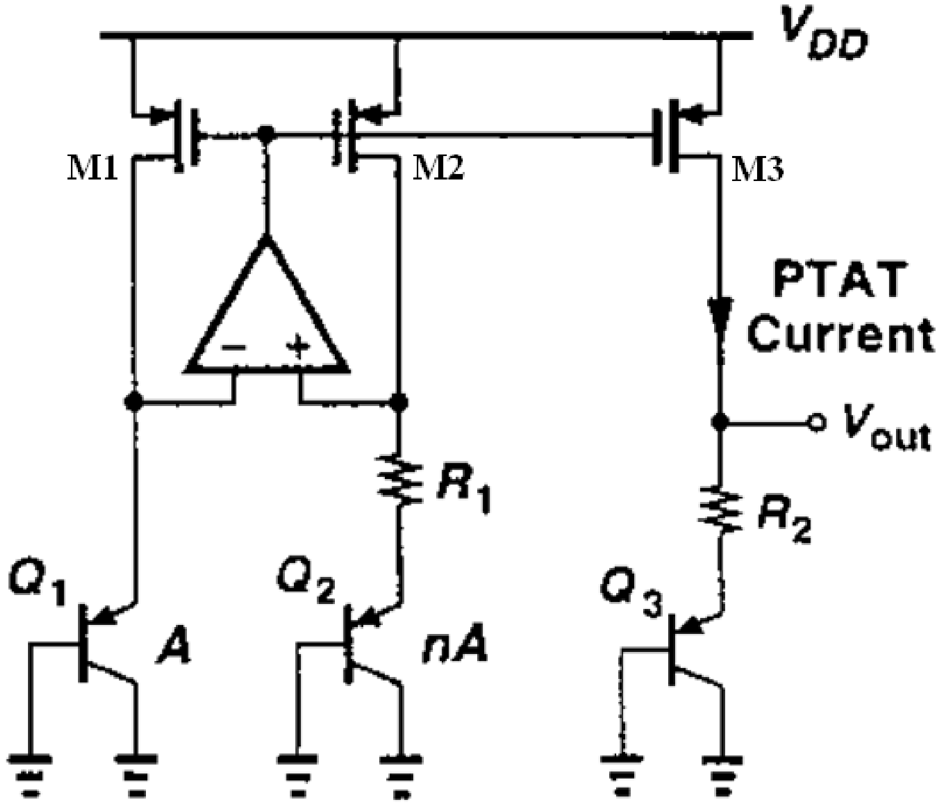
PTAT Current Generation



$$I = \frac{V_T \ln(n)}{R_1}$$

The advantage of the above circuit is that $V_{DS1}=V_{DS2}$. Therefore I_{D1} is accurately identical to I_{D2}.

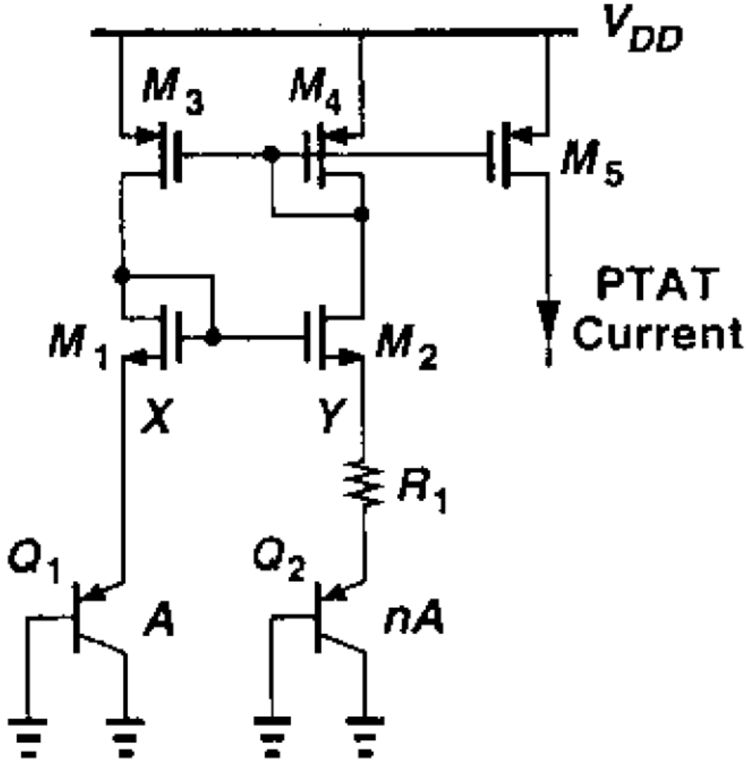
Employing PTAT to Generate Temperature-Independent Voltage



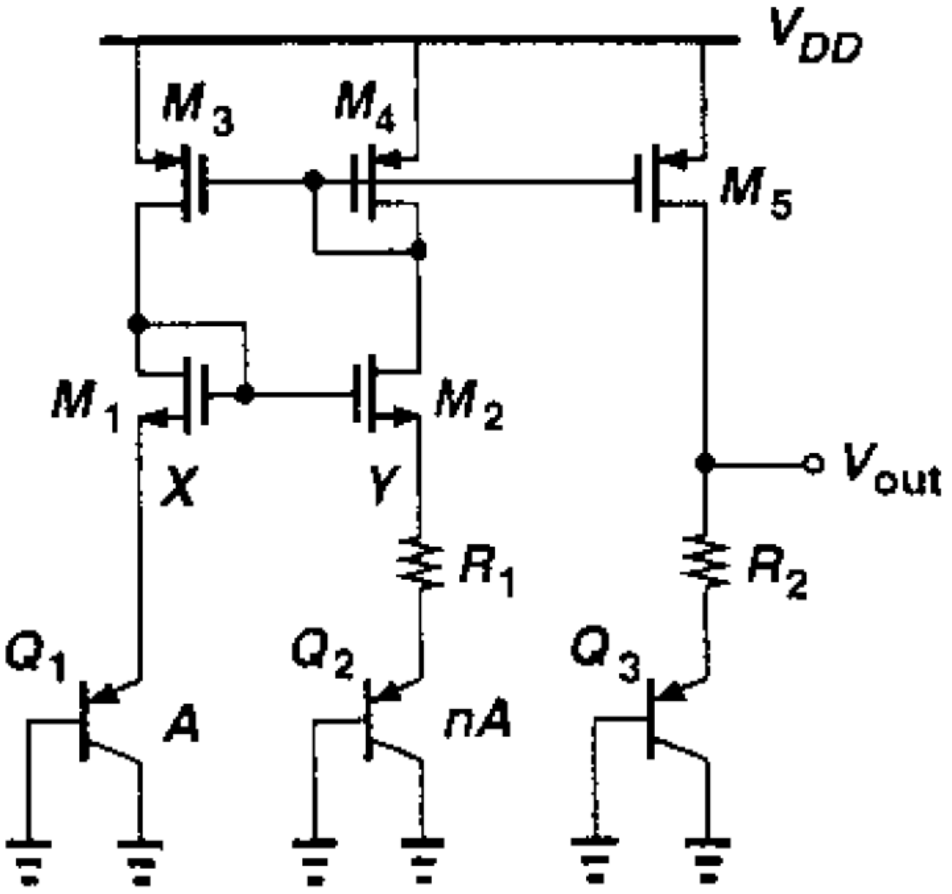
$$V_{out} = V_{EB3} + R_2 \frac{V_T \ln(n)}{R_1}$$

The advantage of the above circuit is that $V_{DS1}=V_{DS2}$. Therefore I_{D1} is accurately identical to I_{D2}.

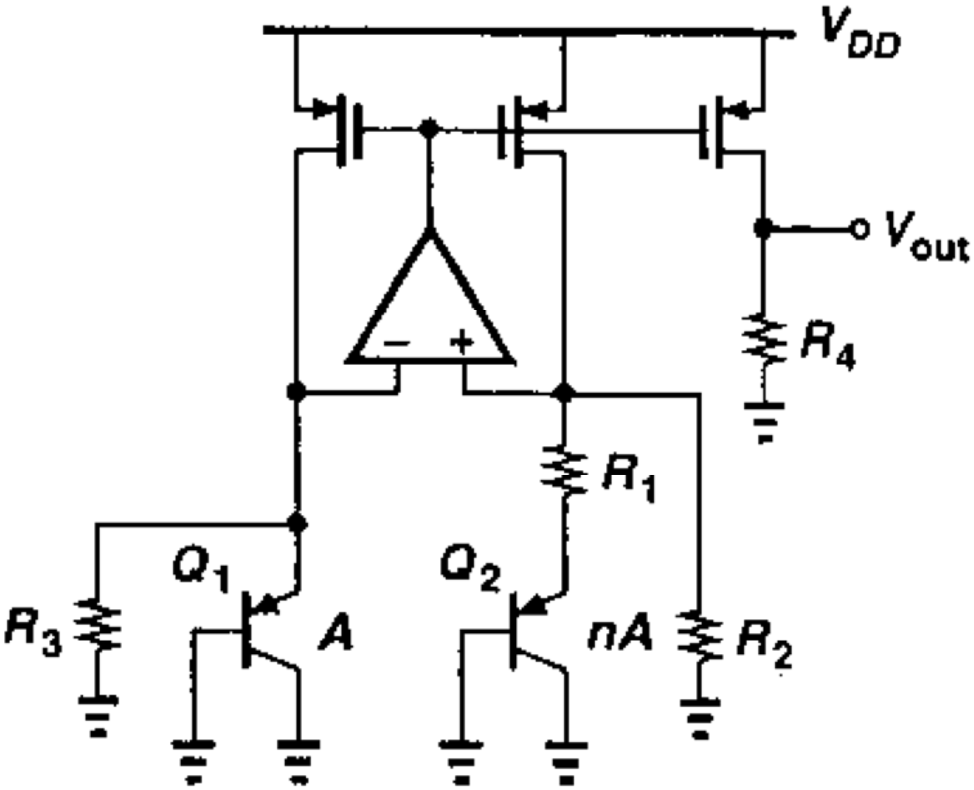
Generation of a PTAT Current Using a Simple Amplifier



Generation of a Temperature-Independent Voltage



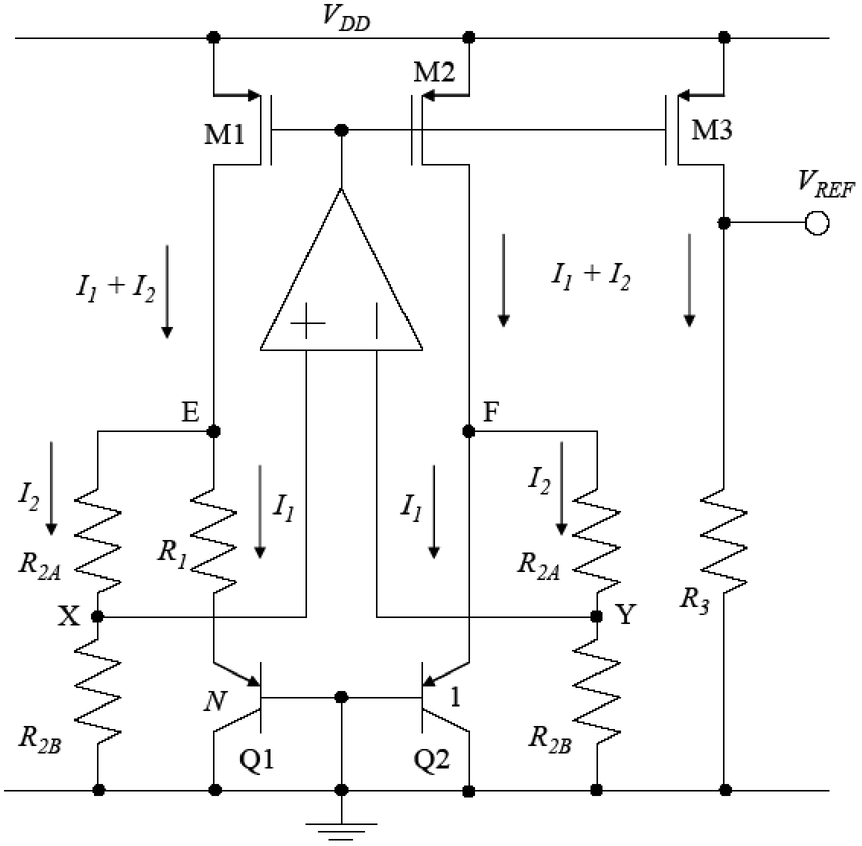
Generation of a Temperature-Independent Voltage



$$V_{out} = \frac{R_4}{R_2} V_{EB1} + \frac{R_4}{R_1} V_T \ln(n)$$

This circuit is useful to generate low reference voltages.

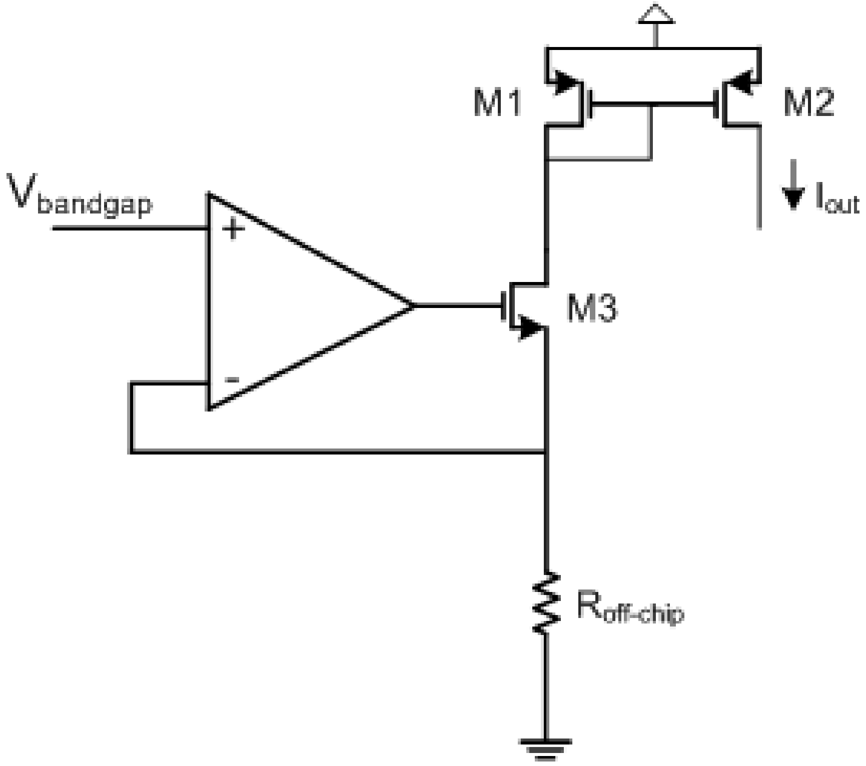
Generation of a Temperature-Independent Voltage



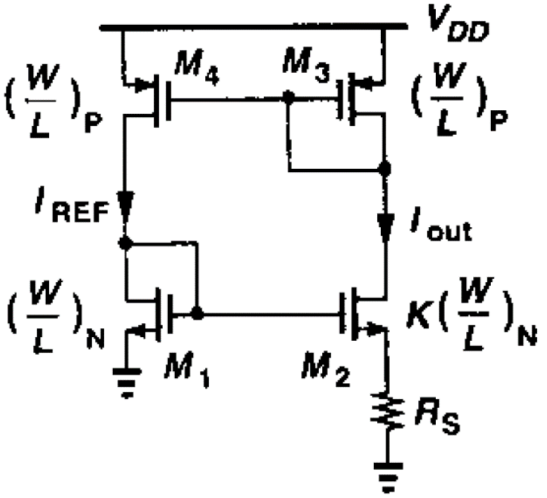
$$V_{REF} = \frac{R_3}{R_2}\left(V_{EB2} + \frac{R_2}{R_1} V_T \ln(N)\right)$$

This circuit is useful to generate low reference voltages.

Temperature-independent Current Generation



Constant-Gm Biasing



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

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

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

The resistor Rs is an off-chip resistor.

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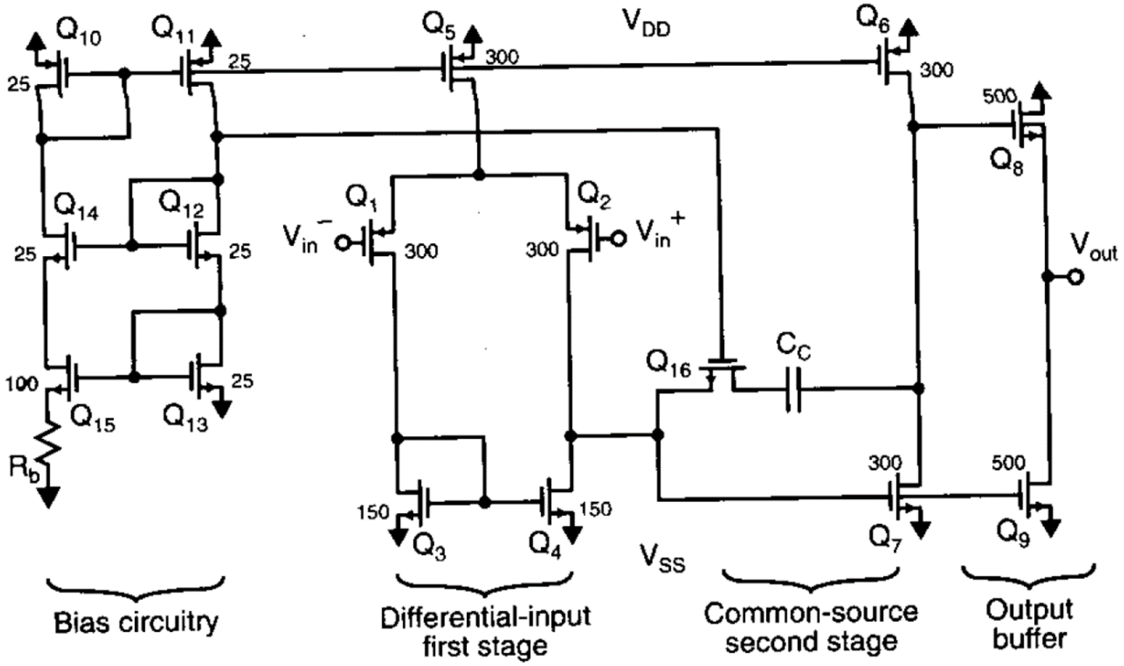

$$I_{D10} = \frac{2}{\mu_n C_{ox}\left(\frac{W}{L}\right)_{13}} \frac{1}{{R_b}^2}\left(1 - \frac{1}{\sqrt{K}}\right)^2, \quad K = \frac{\left(\frac{W}{L}\right)_{15}}{\left(\frac{W}{L}\right)_{13}}$$

This opamp utilizes the constant-G_m biasing. Rb is an off-chip resistor.