Bandgap Voltage Reference

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Voltage Reference

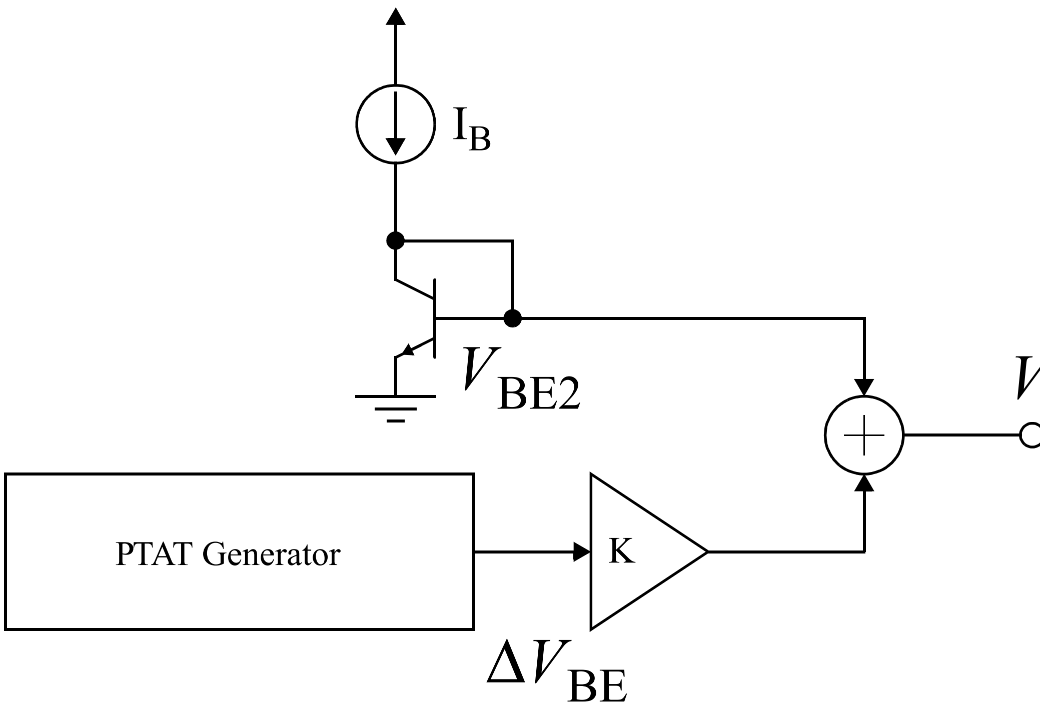
Basic Goal

- To create an on-chip voltage reference that does not vary with process, temperature, aging, etc.
- Bandgap voltage reference most common
- Cancels negative temp of pn diode with positive temp of PTAT (Proportional To Absolute Temp) circuit

Approaches other than bandgap

- Zener diode (p+/n+) — usually too high a voltage nowadays, 6.7volts
- Threshold difference between enhance and depletion transistors — no depletion nowadays

Basic Concept



$$V_{ref} = V_{BE2} + K\Delta V_{BE}$$
$$= 1.26\text{V}$$

- V_{BE2} has negative temperature coefficient
- ΔV_{BE} has positive temperature coefficient
- K is a multiplying factor to get zero temp coeff

Equations

$$I_C = I_s e^{V_{\mathrm{BE}}/((kT)/q)} \tag{1}$$

- where for a constant I_C, V_{BE} has a temperature coefficient of approximately

$$-2\ \mathrm{mV}/°\mathrm{K} \tag{2}$$

- Also need to define collector current density, J_C, as

$$I_C = A_E J_C \tag{3}$$

- where A_E is the area of base-emitter junction
- Can write V_{BE} as a function of collector current and temperature.
- It has been shown to be ...

Equations

$$V_{BE} = V_{G0}\left(1 - \frac{T}{T_0}\right) + V_{BE0}\frac{T}{T_0} + \frac{mkT}{q}\ln\left(\frac{T_0}{T}\right) + \frac{kT}{q}\ln\left(\frac{J_C}{J_{C0}}\right) \quad (4)$$

- V_{G0} is bandgap voltage of silicon at 0 °K (about 1.206 V)
- T_0 is a reference temperature, T is true temp
- V_{BE0} is base-emitter voltage at temp T_0
- J_{C0} is collector current density at temp T_0
- J_C is collector current density at temp T
- m is a constant (approximately 2.3)

Equations

$$\Delta V_{BE} = V_2 - V_1 = \frac{kT}{q} \ln\left(\frac{J_2}{J_1}\right) \qquad (5)$$

- while V_{BE} has negative temp coeff, ΔV_{BE} has a positive temp coeff since ...
- ΔV_{BE} is ***proportional to absolute temperature*** (as long as ratio J_2/J_1 remains constant) (PTAT voltage)

Example

- Assuming ratio of $J_2/J_1 = 10$ and $T = 300\ °K$

$$\Delta V_{BE} = \frac{kT}{q}\ln\left(\frac{J_2}{J_1}\right) = \frac{1.38\times10^{-23}(300)}{1.602\times10^{-19}}\ln(10) = 59.5\text{ mV} \tag{6}$$

- so temperature dependence is ...

$$59.5\text{ mV}/300\ °K = 0.198\text{ mV}/°K \tag{7}$$

- Need $K \cong 10$ to cancel temp dependence of V_{BE} which is $-2\text{ mV}/°K$

Equations

- We now make the assumption that junction currents are PTAT (will be true if resistors are temp independent)

$$\frac{J_i}{J_{i0}} = \frac{T}{T_0} \qquad (8)$$

- and we can now find

$$V_{\text{ref}} = V_{\text{BE2}} + K\Delta V_{\text{BE}} \qquad (9)$$

$$= V_{\text{G0}} + \frac{T}{T_0}(V_{BE0\text{-}2} - V_{G0}) + (m-1)\frac{kT}{q}\ln\left(\frac{T_0}{T}\right) + K\frac{kT}{q}\ln\left(\frac{J_2}{J_1}\right)$$

Equations

- Take derivative of (9) wrt temperature to give

$$\frac{\partial V_{ref}}{\partial T} = \frac{1}{T_0}(V_{BE0\text{-}2} - V_{G0}) + K\frac{k}{q}\ln\left(\frac{J_2}{J_1}\right) + (m-1)\frac{k}{q}\ln\left(\frac{T_0}{T} - 1\right) \quad (10)$$

- and setting (10) equal to zero at $T = T_0$ gives

$$V_{BE0\text{-}2} + K\frac{kT_0}{q}\ln\left(\frac{J_2}{J_1}\right) = V_{G0} + (m-1)\frac{kT_0}{q} \quad (11)$$

- Left side is output voltage V_{ref} at $T = T_0$ so we need

$$V_{ref\text{-}0} = V_{G0} + (m-1)\frac{kT_0}{q} \quad (12)$$

Equations

- In case where $T_0 = 300\ °K$ and $m = 2.3$

$$V_{ref\text{-}0} = 1.24\ \mathrm{V} \tag{13}$$

- Value is independent of current densities used --- thus the reason for name "**Bandgap** voltage reference".
- From (11), we find K as

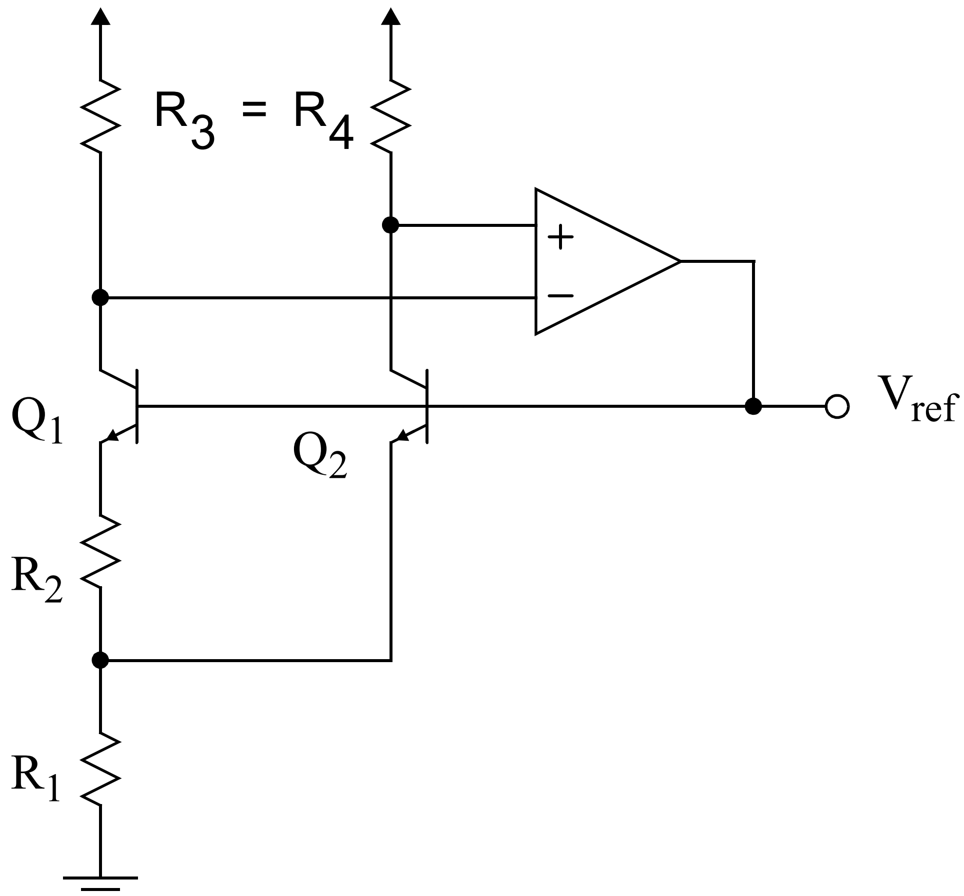
$$K = \frac{V_{\mathrm{G0}} + (m-1)\dfrac{kT_0}{q} - V_{BE0\text{-}2}}{\dfrac{kT_0}{q}\ln\left(\dfrac{J_2}{J_1}\right)} = \frac{1.24 - V_{BE0\text{-}2}}{0.0258\ \ln\left(\dfrac{J_2}{J_1}\right)} \tag{14}$$

- at $T_0 = 300\ °K$

Bipolar Circuit

$A_{E1} = 8A_{E2}$

$$\frac{J_2}{J_1} = 8$$



Bipolar Circuit

$$V_{\mathrm{ref}} = V_{BE2} + V_{\mathrm{R1}} \tag{15}$$

$$\begin{aligned} V_{\mathrm{R1}} &= I_{R1}R_1 \\ &= 2I_{R2}R_1 \end{aligned} \tag{16}$$

$$I_{R_2} = \frac{V_{R2}}{R_2} = \frac{\mathrm{V}_{BE2} - V_{BE1}}{\mathrm{R}_2} = \frac{\Delta V_{\mathrm{BE}}}{R_2} \tag{17}$$

$$\mathrm{V}_{\mathrm{ref}} = \mathrm{V}_{BE2} + \frac{2R_1}{R_2}\,\Delta\mathrm{V}_{\mathrm{BE}} \tag{18}$$

$$K = \frac{2R_1}{R_2} \tag{19}$$

Bipolar Circuit

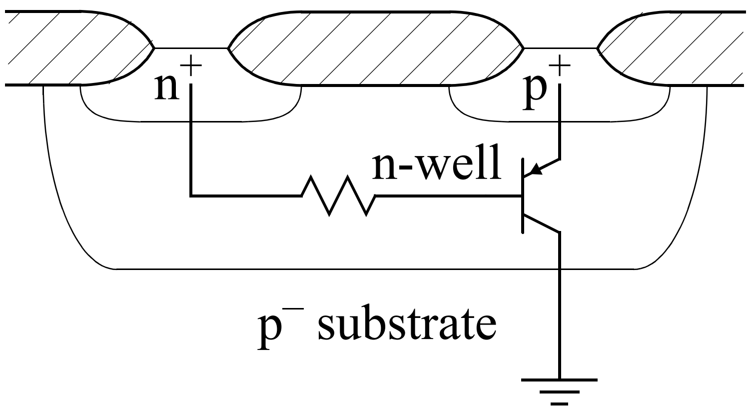
- And if $V_{\mathrm{BE2}} = 0.65$ at ref temp

$$\frac{R_1}{R_2} = \frac{1}{2} \times \frac{1.24 - 0.65}{0.0258 \times \ln(8)} = 5.5 \tag{20}$$

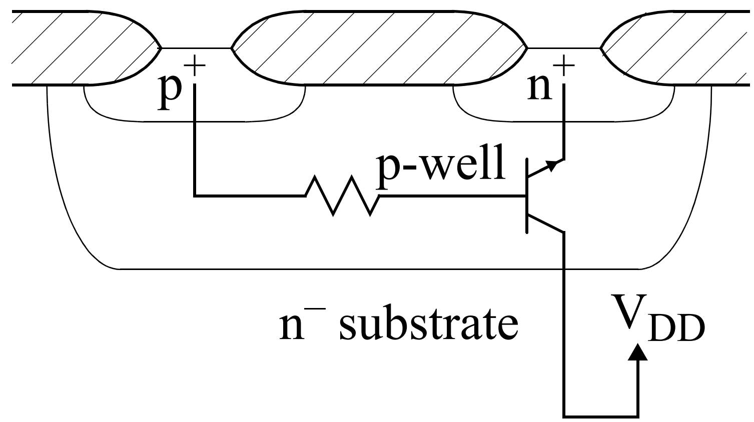
- If possible, R_1 or R_2 would be trimmed to obtain correct reference voltage
- Note that as assumed, we have

$$I_{E1} = I_{E2} = I_{R2} = \frac{\Delta V_{\mathrm{BE}}}{R_2} = \frac{\frac{kT}{q}\ln\left(\frac{J_2}{J_1}\right)}{R_2} \tag{21}$$

CMOS Circuit



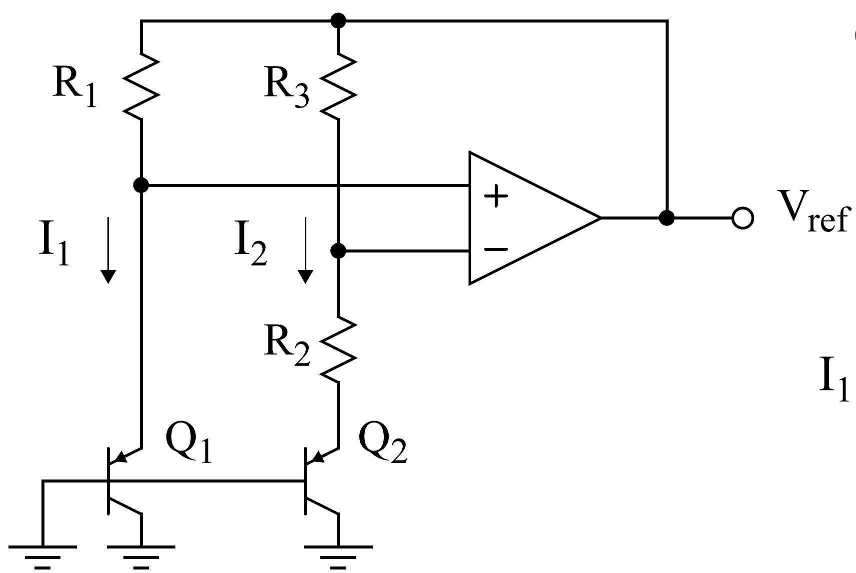
n-well



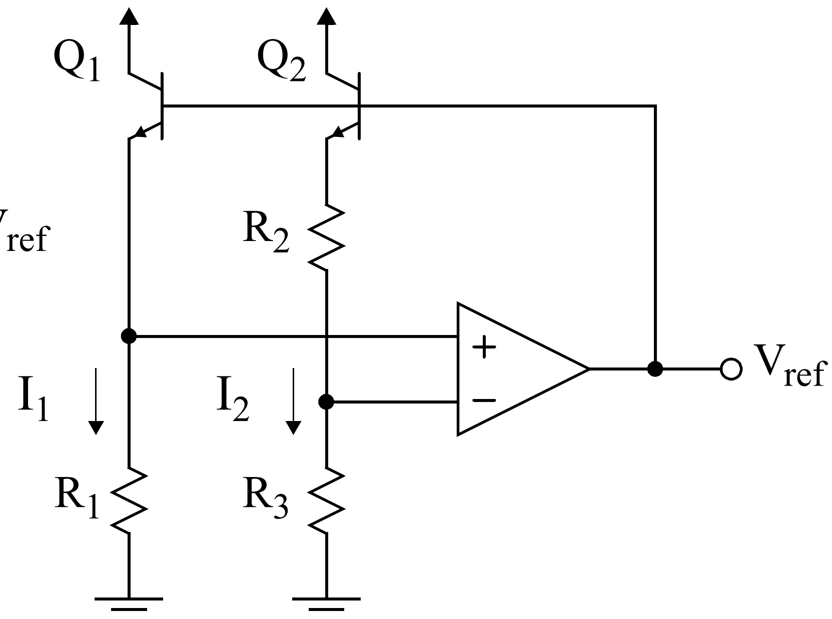
p-well

- Parasitic vertical bipolar transistors exist in CMOS

CMOS Circuit



n-well



p-well

CMOS Circuit

- Equations for n-well circuit

$$V_{ref} = V_{EB1} + V_{R1} \tag{22}$$

$$V_{R2} = V_{EB1} - V_{EB2} = \Delta V_{EB} \tag{23}$$

$$V_{R3} = \frac{R_3}{R_2} V_{R2} = \frac{R_3}{R_2} \Delta V_{EB} \tag{24}$$

$$V_{ref} = V_{EB1} + \frac{R_3}{R_2} \Delta V_{EB} \tag{25}$$

$$\frac{J_1}{J_2} = \frac{R_3}{R_1} \tag{26}$$

CMOS Circuit

$$\Delta V_{EB} = V_{EB1} - V_{EB2} = \frac{kT}{q}\ln\left(\frac{J_1}{J_2}\right) \tag{27}$$

$$V_{ref} = V_{EB1} + \frac{R_3}{R_2}\frac{kT}{q}\ln\left(\frac{R_3}{R_1}\right) \tag{28}$$

$$K = \frac{R_3}{R_2} \tag{29}$$

CMOS Example

- Find resistances for above when $I_1 = 80\ \mu A$, $I_2 = 8\ \mu A$, and $V_{EB1\text{-}0} = 0.65\ V$ at $T = 300\ °K$.
- First, we note that

$$V_{ref\text{-}0} = 1.24\ V \tag{30}$$

- which leads to

$$V_{R1} = V_{ref\text{-}0} - V_{EB1\text{-}0} = 0.59\ V \tag{31}$$

- This allows us to find R_1 and R_3

$$R_1 = \frac{V_{R1}}{I_1} = \frac{0.59\ V}{80\ \mu A} = 7.38\ k\Omega \tag{32}$$

$$R_3 = \frac{V_{R3}}{I_2} = \frac{0.59\ V}{8\ \mu A} = 73.8\ k\Omega \tag{33}$$

- To find R_2, we first find K to be

$$K = \frac{1.24 - 0.65\ \mathrm{V}}{0.0258 \times \ln(10)} = 9.93 \tag{34}$$

$$R_2 = \frac{R_3}{K} = 7.43\ \mathrm{k\Omega} \tag{35}$$