Voltage references

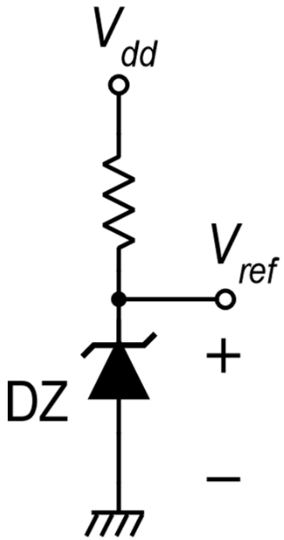
Voltage references are blocks that produce an output voltage that is independent of **PVT** variations:
V: Supply voltage
T: Temperature
P: Process errors

Voltage references are used for:

- Providing an absolute reference voltage for ADCs and DACs
- Providing an absolute reference voltage for stimulating sensors or other external devices that require precise control voltages and/or currents.
- Creating constant bias voltages (and currents) when required

Possible reference voltage sources

- Zener Diodes



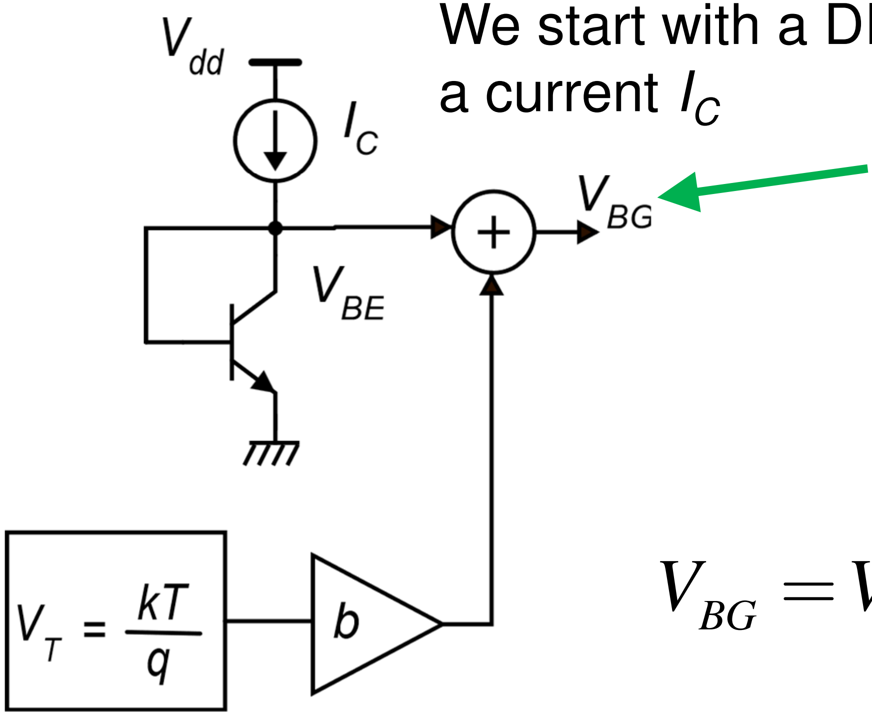
Problems:

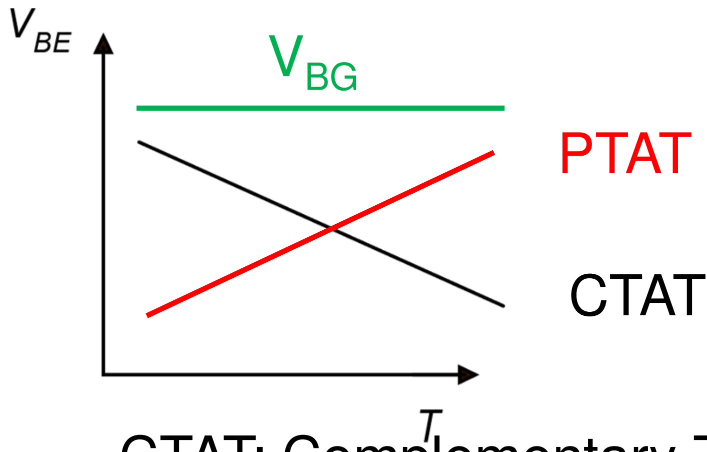
- **Require additional process steps**, but only a small number of components are required for each chip (not convenient)
- **Available voltages are > 3 V**
- Temperature stability is poor for $V_Z \neq$ 5-6 V
- The reference voltage generated by a Zener diode is noisy (very wide band noise)

- Band-gap circuits

Band-gap voltage reference: principle of operation

We start with a DIODE (BJT) biased with a current I_C





$$V_{BG} = V_{BE} + bV_T$$

$$\frac{dV_{BE}}{dT} \cong -2 \text{ mV/K} \ ..... -3 \text{ mV/K}$$

CTAT: Complementary To Absolute Temperature

PTAT: Proportional To Absolute Temperature

Band-gap voltage reference: determination of parameter *b* and estimate of the output voltage

$$V_{BG}=V_{BE}+bV_T$$

We have to determine the value of *b*, for which: $\dfrac{dV_{BG}}{dT}=0$

$$\frac{dV_{BG}}{dT}=\frac{dV_{BE}}{dT}+b\frac{dV_T}{dT}=0$$

$$b=\frac{-\dfrac{dV_{BE}}{dT}}{\dfrac{dV_T}{dT}}$$

Good news! This voltage is compatible with low-supply voltage circuits

$$\frac{dV_T}{dT}=\frac{k}{q}\cong 8.56\times10^{-5}\ \ V/K$$

Example:

$$\frac{dV_{BE}}{dT}\cong -2\ \ \text{mV/K}\ \ \Rightarrow b\cong 23$$

V_{BE} $\quad$ V_T (290 K)

$$V_{BG}\cong 0.65+0.025\times 23\ =1.225\ \ \text{V}$$

Band-Gap voltage reference: theory

$$V_{BE}=V_T\ln\left(\frac{I_C}{I_S}\right)$$

$$I_S=\frac{qA_E n_i^2 D_n}{Q_B}=F\cdot n_i^2 D_n$$

constant (F)

$$n_i^2\propto T^3 e^{-\frac{E_{g0}}{kT}}$$

$$D_n=\mu_n\frac{kT}{q}$$

$$\mu_n\propto T^{-\alpha_\mu}$$

$$\frac{E_{g0}}{kT}=\frac{E_{g0}}{q}\frac{q}{kT}=\frac{V_{G0}}{V_T}$$

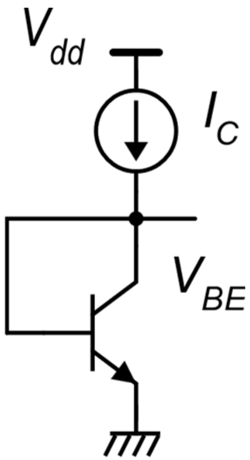
V_{G0} ($=\frac{E_{g0}}{q}$)

$$I_S=BT^{\gamma}e^{-\frac{V_{G0}}{V_T}}\qquad \gamma=4-\alpha_\mu$$

$$\alpha_\mu\cong 1.5$$

constant (B)

constant (G)



$$I_C=GT^{\alpha}$$

It is not necessary that I_C is temperature-independent

$$E=\frac{1}{B}$$

$$V_{BE}=V_T\ln\left(\frac{GT^{\alpha}}{BT^{\gamma}\exp\left(\frac{-V_{GO}}{V_T}\right)}\right)=V_{GO}+V_T\left[\ln\left(G\cdot E\right)-\left(\gamma-\alpha\right)\ln\left(T\right)\right]$$

$$\frac{G}{B}T^{-(\gamma-\alpha)}$$

Gray, Hurst, Lewis, Meyer, "Analysis and design of analog integrated circuits" 4th edition, 2001 J.Wiley & Sons

Band-Gap voltage reference: theory

$$V_{BE} = V_{GO} + V_T\left[\ln(G \cdot E) - (\gamma - \alpha)\ln(T)\right] \qquad V_{BG} = V_{BE} + bV_T$$

$$V_{BG} = V_{GO} + V_T\left[\ln(G \cdot E) + b - (\gamma - \alpha)\ln(T)\right]$$

The name **"band-gap"** of this reference voltage comes from V_{GO}, which is the dominant part

$$V_{G0} = \frac{E_{g0}}{q}$$

V_{GO} is numerically equivalent to E_{g0} measured in eV

$$E_{g0} \cong 1.2\ eV \quad \Rightarrow \quad V_{G0} \cong 1.2\ \mathrm{V}$$

Let us calculate the derivative of V_{BG} with respect to temperature

$$\frac{dV_{BG}}{dT} = \frac{k}{q}\left[\ln(G \cdot E) + b - (\gamma - \alpha)\ln(T)\right] - (\gamma - \alpha)V_T\frac{1}{T}$$

$$V_T\frac{1}{T} = \frac{k}{q}$$

$$\frac{dV_{BG}}{dT} = \frac{k}{q}\left[\ln(G \cdot E) + b - (\gamma - \alpha) - \underline{\underline{(\gamma - \alpha)\ln(T)}}\right]$$

The derivative of V_{BG} depends on temperature

Band-Gap voltage reference: theory

We impose that the derivative of V_{BG} is zero at a given temperature T_0

This is possible, since b is a free parameter that can be chosen to obtain this result.

$$\frac{k}{q}\left[\ln(G\cdot E)+b-(\gamma-\alpha)-(\gamma-\alpha)\ln(T_0)\right]=0$$

$$\ln(G\cdot E)+b=(\gamma-\alpha)+(\gamma-\alpha)\ln(T_0)$$

$$V_{BG}=V_{GO}+V_T\left[\ln(G\cdot E)+b-(\gamma-\alpha)\ln(T)\right]$$

$$V_{BG}=V_{GO}+V_T\left[(\gamma-\alpha)+(\gamma-\alpha)\ln(T_0)-(\gamma-\alpha)\ln(T)\right]$$

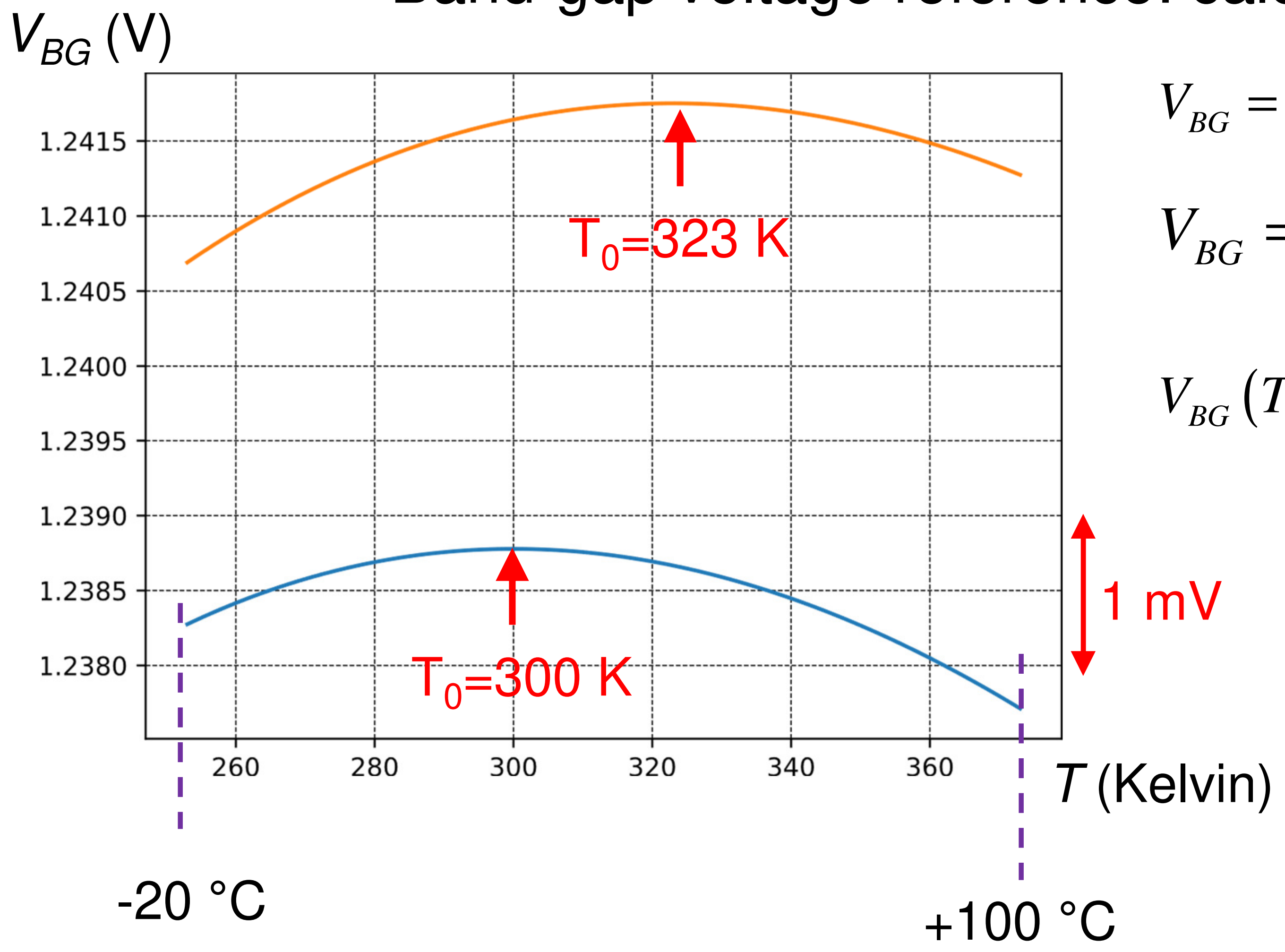
Typically: α=1

$$V_{BG}=V_{G0}+V_T(\gamma-\alpha)\left(1+\ln\left(\frac{T_0}{T}\right)\right)$$

$$V_{BG}(T_0)=V_{G0}+\frac{kT_0}{q}(\gamma-\alpha)\cong 1.24\ \text{V}$$

$$\gamma\cong 2.5$$

Band-gap voltage reference: calculation result

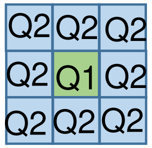


$$V_{BG} = V_{BE} + bV_T$$

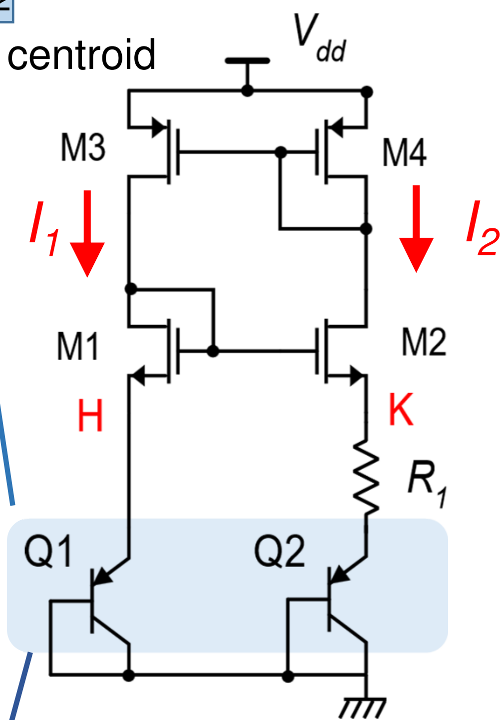
$$V_{BG} = V_{G0} + V_T(\gamma - \alpha)\left(1 + \ln\left(\frac{T_0}{T}\right)\right)$$

$$V_{BG}(T_0) = V_{G0} + \frac{kT_0}{q}(\gamma - \alpha)$$

Band-Gap voltage: a CMOS compatible Circuit



Common centroid layout
For n=8



$$\frac{area_2}{area_1} = n > 1$$

Substrate PNPs

Part 1: PTAT current generator

$$M3 = M4 \Rightarrow I_1 = I_2 = I$$

$$M1 = M2$$

neglecting the effects of V_{DS} on I_D :

$$V_{GS1} = V_{GS2}$$

$$V_H - V_K = (V_{G1} - V_{GS1}) - (V_{G2} - V_{GS2}) = V_{GS2} - V_{GS1}$$

$$V_H = V_K$$

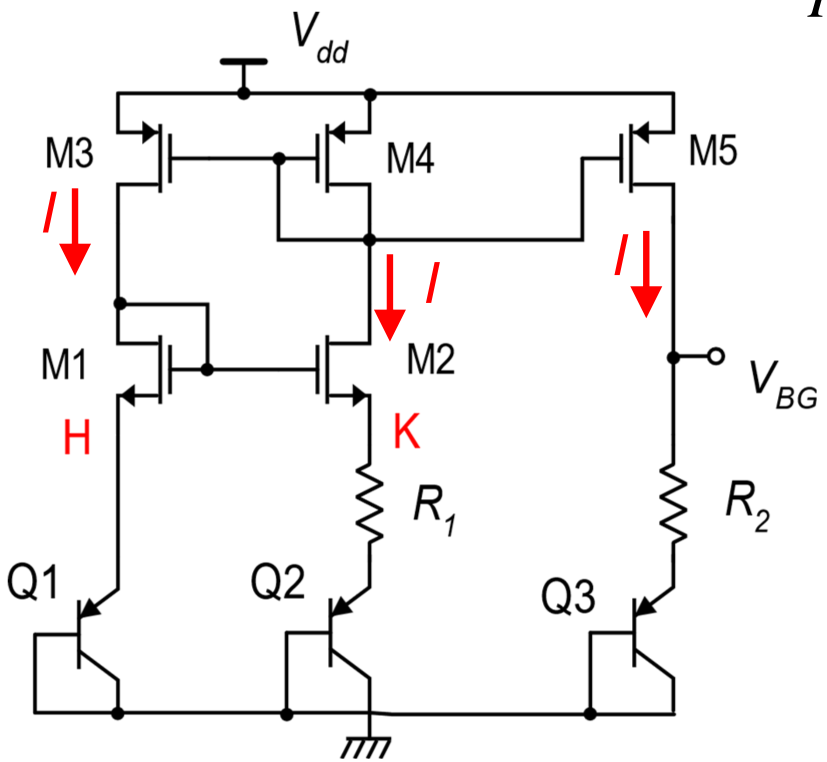
$$V_H = |V_{BE1}| \qquad V_K = |V_{BE2}| + R_1 I$$

$$R_1 I = |V_{BE1}| - |V_{BE2}| = V_T \ln\left(\frac{I_{C1}}{I_{S1}} \frac{I_{S2}}{I_{C2}}\right) = V_T \ln(n)$$

$$I = \frac{1}{R_1} \frac{kT}{q} \ln(n)$$

I is proportional to *T* (PTAT) and independent of V_{dd}.

Band-Gap voltage: a CMOS compatible Circuit



$$I = \frac{1}{R_1}\frac{kT}{q}\ln(n)$$

$$V_{BG} = |V_{BE3}| + IR_2$$

Biased with *I*

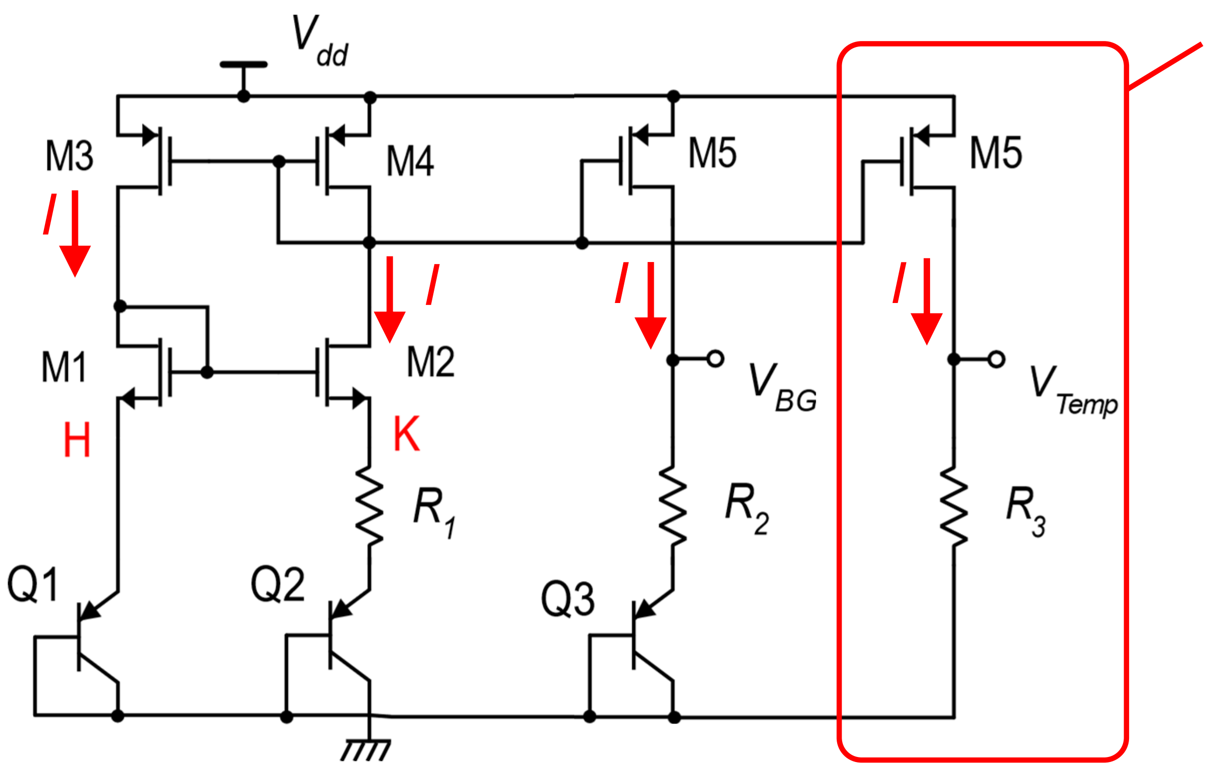
α=1

$$V_{BG} = |V_{BE3}| + \frac{R_2}{R_1}\frac{kT}{q}\ln(n)$$

$$V_{BG} = |V_{BE3}| + V_T \frac{R_2}{R_1}\ln(n)$$

$$V_{BG} = V_{BE} + bV_T$$

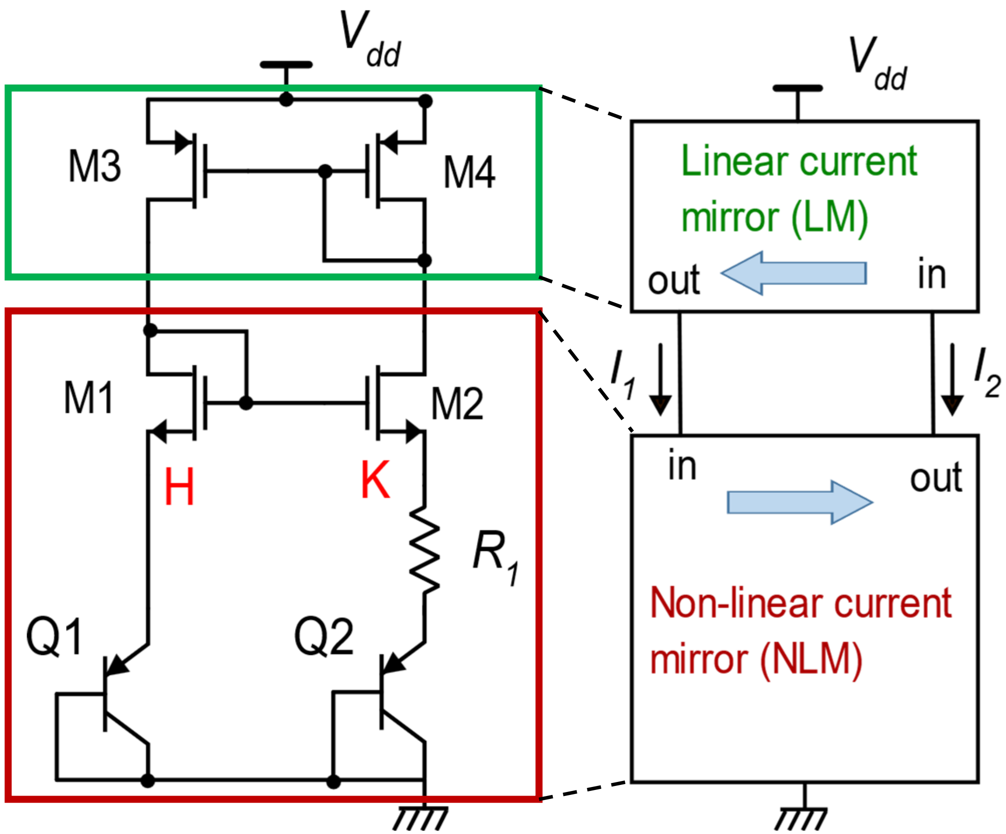
Deriving a temperature sensor from the Band-Gap circuit



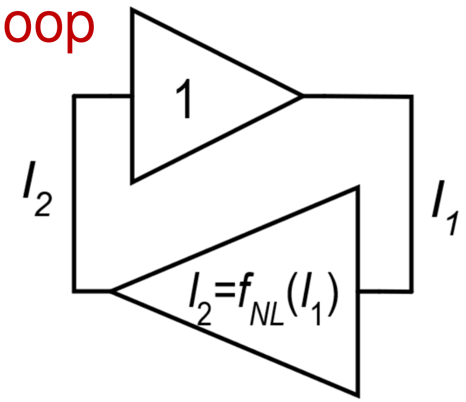
Adding this branch, we can obtain a voltage proportional to the absolute temperature, which can be conveniently used to monitor the chip temperature.

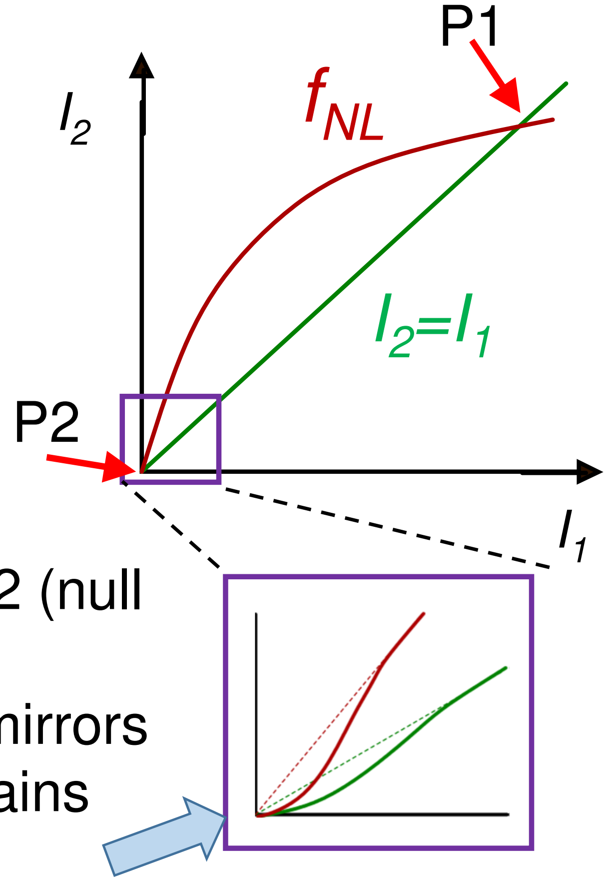
$$V_{Temp} = R_3 I = \frac{R_3}{R_1} \frac{kT}{q} \ln(n)$$

PTAT current generator: multiple stable states



Positive feedback loop

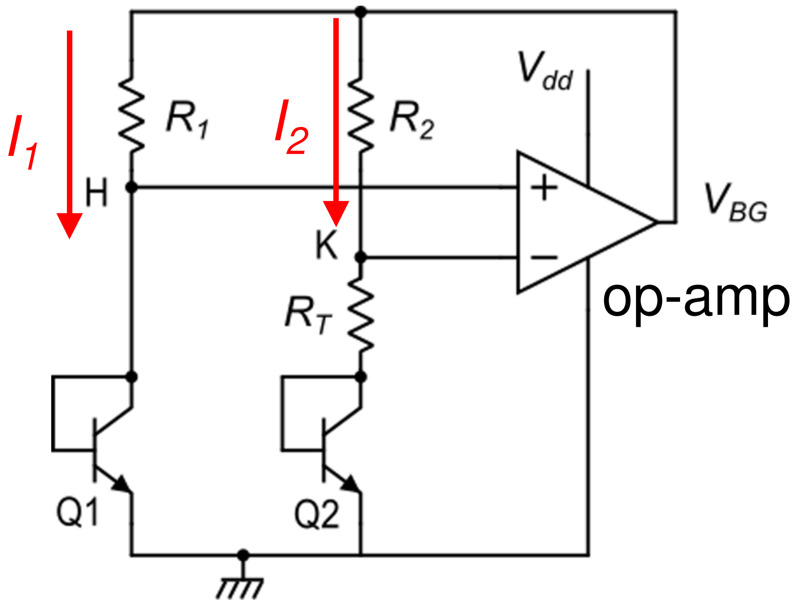




P1 is the correct operating point. P2 (null currents) is stable because the two mirrors have very small gains around the origin.

A start-up circuit is necessary to prevent the circuit from being trapped into P2

Mention to another very popular bandgap circuit



Due to virtual short circuit:

$$V_H = V_K \;\Rightarrow V_{R1} = V_{R2}$$ (voltages across R_1 and R_2)

We choose R_1=R_2 $\Rightarrow I_1 = I_2$

$$V_H = V_K \;\Rightarrow V_{BE1} = V_{BE2} + I_2 R_T$$

$$I_2 R_T = V_{BE1} - V_{BE2} = V_T \ln\left(\frac{I_{C1}}{I_{S1}}\frac{I_{S2}}{I_{C2}}\right)$$

$$I_{C1} \cong I_1 \qquad I_{C2} \cong I_2 \qquad n = \frac{I_{S2}}{I_{S1}}$$

$$I_2 = I_1 = \frac{V_T \ln(n)}{R_T} \qquad V_{BG} = V_{BE1} + I_1 R_1 = V_{BE1} + \frac{V_T \ln(n)}{R_T} R_1$$