Voltage references

[Razavi]

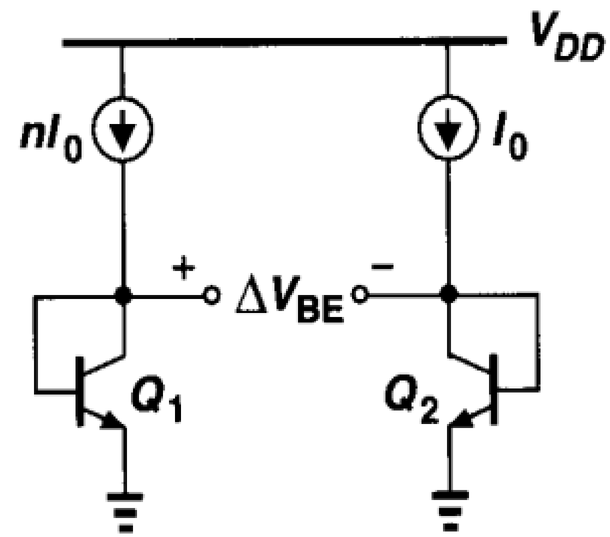
Temperature independent voltage references

- The idea is to add two quantities having opposite temperature coefficients (TCs) with proper weighting
- BJTs are good in building both positive and negative TC references

Positive TC voltage references (PTAT, proportional to absolute temperature)

- If two identical BJTs operate at different current *densities*, the difference of their V_{be} is proportional to absolute *T:*
- from $I_C = I_S \exp(V_{BE}/V_T)$, neglecting I_b

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



- so that

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

- with $k/q = 0.087$ mV/K

Negative TC voltage references (CTAT, complementary to absolute temperature)

- A forward biased *pn* junction can be used
- With constant $I_C = I_S \exp(V_{BE}/V_T)$ it may be found that

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

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

- with E_g the energy gap of silicon, and $\mu \propto \mu_0 T^m$ with $m \approx -3/2$
- With $V_{BE} \approx 750$ mV we find $\partial V_{BE}/\partial T \approx -1.5 \text{ mV/ K}$

Bandgap reference

- Summing a negative- and a positive- TC voltage we can build a (nominally) zero TC reference
- $V_{REF}=V_{BE}+V_T \ln n$
- With

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

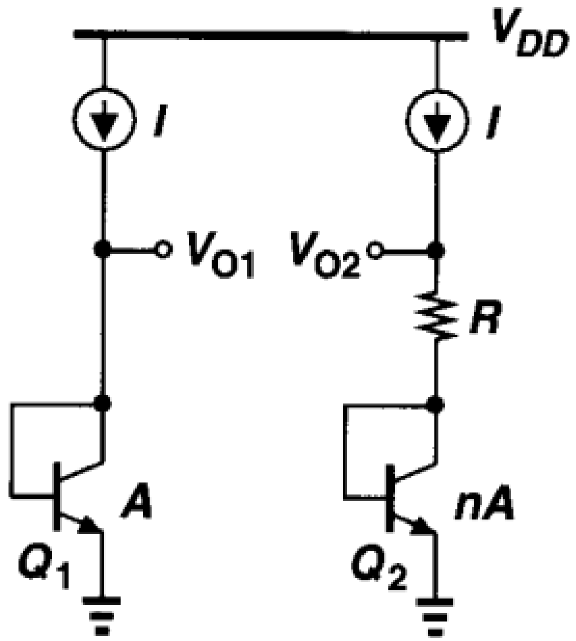
$$\partial V_T/\partial T \approx +0.087\ \mathrm{mV/\ K},$$

- we find that for zero TC we must have $\ln n \sim 17.2$
  as -1.5m+0.087m*17.2 ~ 0
- And we get

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

Bandgap reference

- Q_1 is a unit transistor, Q_2 are n unit transistors in parallel
- Let us neglect base current
- and somehow keep $V_{O1} = V_{O2}$
- From $$RI = V_{BE1} - V_{BE2} = V_T \ln n$$
- we get $V_{O2} = V_{BE2} + RI = V_{BE2} + V_T \ln n$
- which has zero TC when $\ln n \approx 17.2$



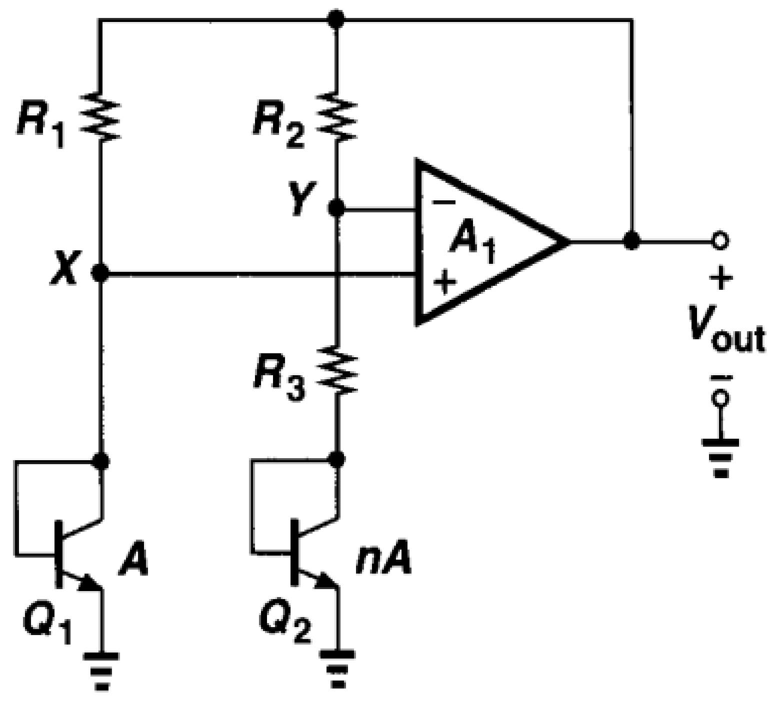
Bandgap reference

- For a pratical realization
  - something is needed to keep $V_{O1} = V_{O2}$
  - the term $RI = V_T \ln n$ must be scaled in order to avoid an exceedingly large n

- e.g. (here $R_1 = R_2$; note that V_{REF} is taken at the output of the opamp):

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

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



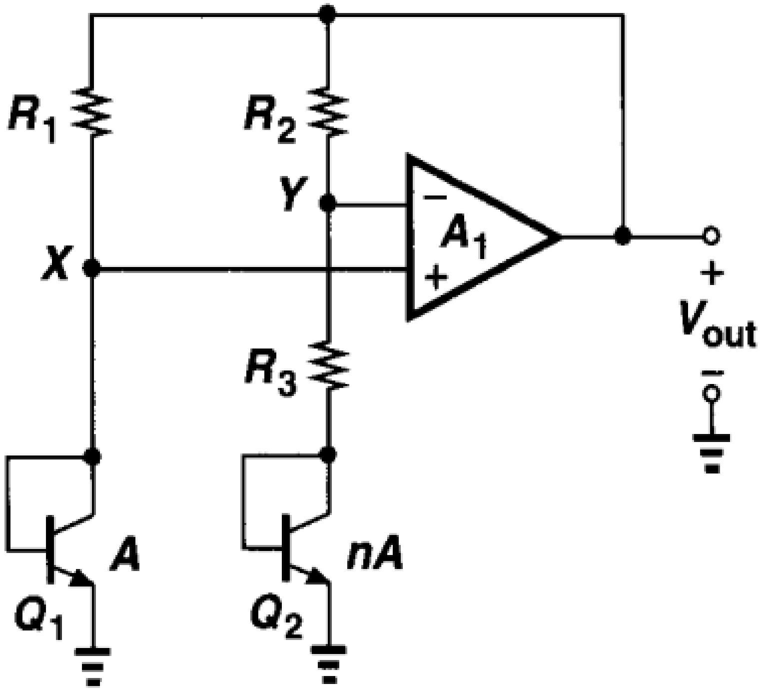
- with $\ln n\,(1 + R_2/R_3) = 17.2$
- i.e. $n = 31$ and $R_2/R_3 = 4$

Bandgap reference

- Actually, here the I_C's are not constant: $I_{C1} = I_{C2} \approx (V_T \ln n)/R_3$
- It may be found that

$$\frac{\partial V_{BE}}{\partial T} = \frac{V_{BE} - (3+m)V_T - E_g/q}{T}$$

- i.e. TC is slightly less negative that 1.5 mV/K



Bandgap reference

- It can be found that the output voltage $V_{REF} = V_{BE} + V_T \ln n$

  can be written, in the zero TC condition, as

$$V_{REF} = \frac{E_g}{q} + (4+m)V_T$$

- $V_{REF} \sim E_g / q$
  - hence the name *bandgap reference*

- Actually, V_{REF} slightly depends on T