Bandgap Reference: Basics

Thanks for the help provided by M. Mobarak ,Faramarz Bahmani
and Heng Zhang

Outline

- Introduction
- Temperature-independent reference
- PTAT generator
- Supply insensitive current source
- Design example

Introduction

- Conditions to be satisfied for an IC in production:
  - Work even when Vcc changes (Supply variation):
    - eg: Vcc: 2.7V→3.0V
  - Work even when temperature changes (Temperature variation):
    - eg: T: -25C→0→25C→75C
  - Work even when physical properties change (Process variation):
    - BJTs: β: ±30%
    - MOS: μ: ±10%, V_{th}: ±100mV
    - Resistors: R: ±20%
    - Capacitors: C: ±5%
    - Inductors: L: ±1%
- All combinations of supply voltage (Vcc), temperature (T) and process (P) variations have to be considered in design. This is often referred to as PVT (process, voltage and temperature)

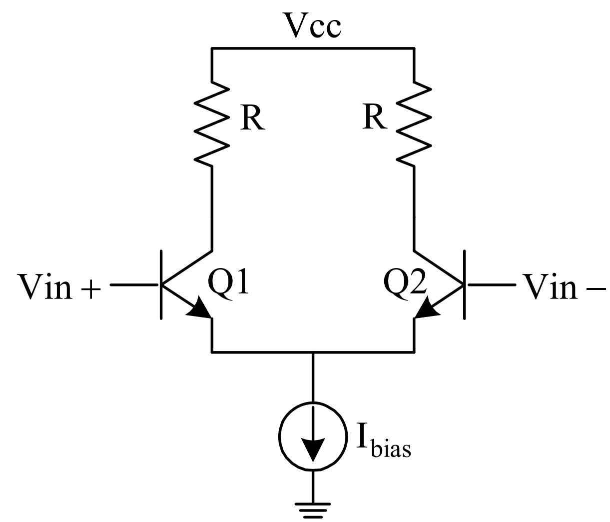
Introduction: Case study

Small signal gain variation with PVT:

- Supply variation: low frequency gain almost insensitive to V_{CC} variation (assuming Q in active region)

- Temperature variation: g_m is changing (decreasing) with T (assuming I_{CQ} independent of T) → gain is dependent on temperature.
  - Solution: Make I_{CQ} a function of T (increases with T) → gain remains insensitive to T.

- Process variations: In BJTs, V_T=KT/q is almost insensitive to process variation (assuming I_{CQ} insensitive to process variations) → gm remained intact. However, variations in resistor R results in gain variation.



$$\text{Gain} = \frac{V_{out}}{V_{in}} = g_m R$$

$$g_m = \frac{I_{CQ}}{V_T} = \frac{I_{CQ}}{\left.\frac{KT}{q}\right| \uparrow}$$

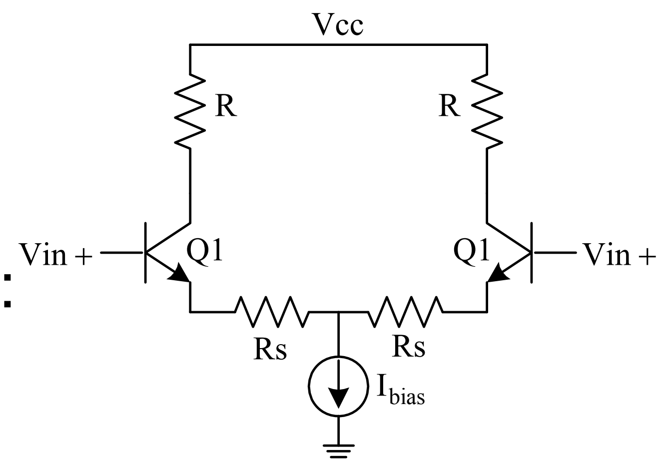
Introduction: Case study

Small signal gain variation with PVT:

- **Supply variation**: low frequency gain almost insensitive to V_{CC} variation (assuming Q in active region)

- **Temperature and Process variations**: Holding R/Rs constant→ low frequency gain is held constant.
  can be easily accomplished by
  – using the same type of resistors for R & Rs
  – following the standard layout practices to achieve good component matching

- **Bad news**: The gain has significantly reduced!



$$\text{Gain} = \frac{V_{out}}{V_{in}} \approx \frac{R}{Rs}$$

Temperature-Independent Reference

- Reference voltages and/or currents with little dependence to temperature prove useful in many analog circuits.

- Key idea: add two quantities with opposite temperature coefficient with proper weighting→ the resultant quantity exhibits zero temperature coefficient.

Eg: V1 and V2 have opposite temperature dependence, choose the coefficients c1 and c2 in such a way that:

$$V_{ref} = c_1 V_1 + c_2 V_2$$

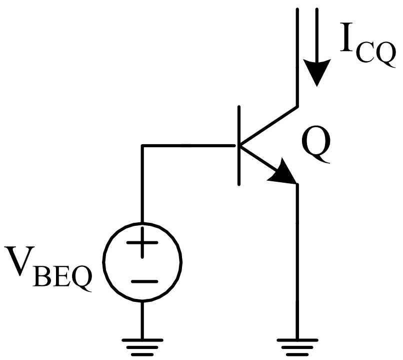
$$\frac{\partial V_{ref}}{\partial T} = c_1 \frac{\partial V_1}{\partial T} + c_2 \frac{\partial V_2}{\partial T} = 0 \qquad \Rightarrow \text{if } c_1,\, c_2 > 0 \Rightarrow \begin{cases} \dfrac{\partial V_1}{\partial T} < 0 : \text{ NTC} \\ \dfrac{\partial V_2}{\partial T} > 0 : \text{ PTC} \end{cases}$$

Thus, the reference voltage V_{ref} exhibits zero temperature coefficient.

Bandgap Voltage Reference

- Target: A fixed dc reference voltage that does not change with temperature.
  - Useful in circuits that require a stable reference voltage. E.g. ADC
- The characteristics of BJT have proven the most well-defined quantities providing positive and negative TC
- kT/q has a positive temperature coefficient
  - "PTAT" proportional to absolute temperature
- V_{BE} of a BJT decreases with temperature
  - "CTAT" complementary to absolute temperature
- Can combine PTAT + CTAT to yield an approximately zero TC voltage reference

Thermal behavior of BJT



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

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

Even though KT/q increases with temperature, V_{BE} decreases because I_S itself strongly depends on temperature

$$V_{BE} \cong \frac{kT}{q} ln\left(\frac{I_C}{I_0} e^{V_{G0}/(kT/q)}\right)$$

$$\cong V_{G0} - \frac{kT}{q} ln\left(\frac{I_0}{I_C}\right)$$

Assuming both I_0 and I_C are constant over T:

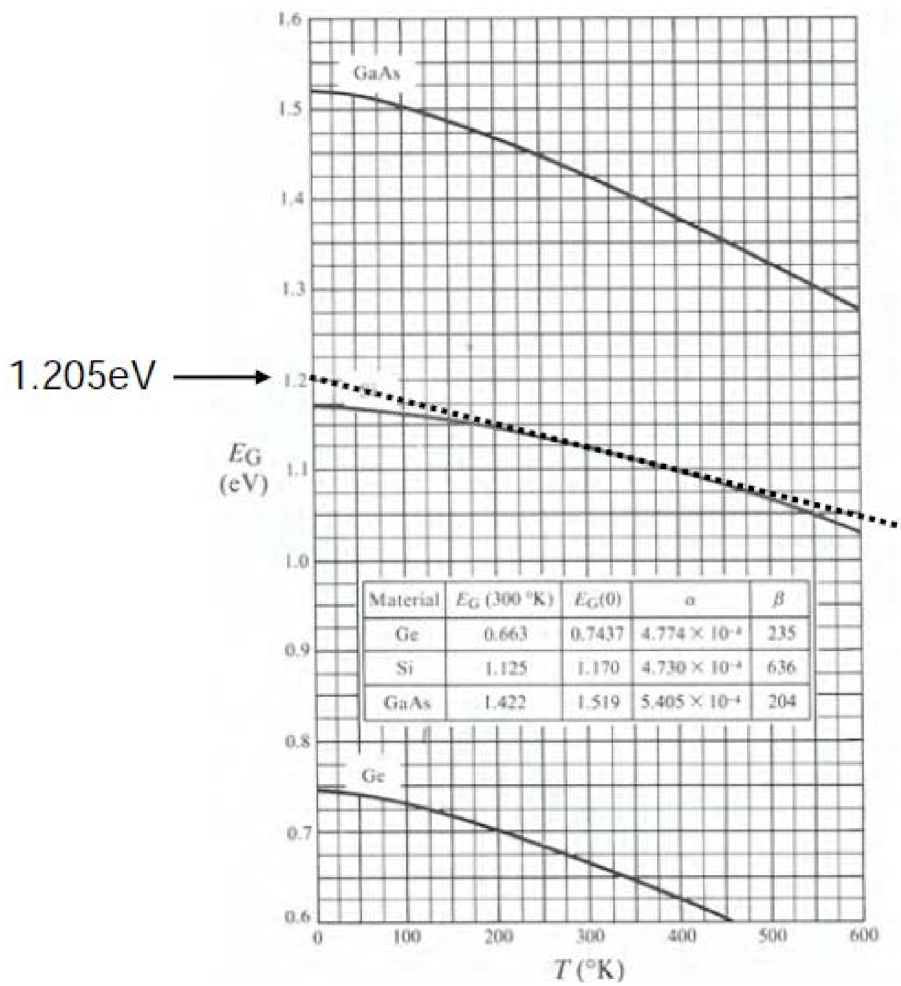
$$\frac{dV_{BE}}{dt} \cong -\frac{k}{q} ln\left(\frac{I_0}{I_C}\right) = \frac{V_{BE} - V_{G0}}{T}$$

- I_0 is a device parameter, which also depends on temperature

– We'll ignore this for now

- V_{G0} is the bandgap voltage of silicon "extrapolated to 0° K"

Extrapolated Bandgap



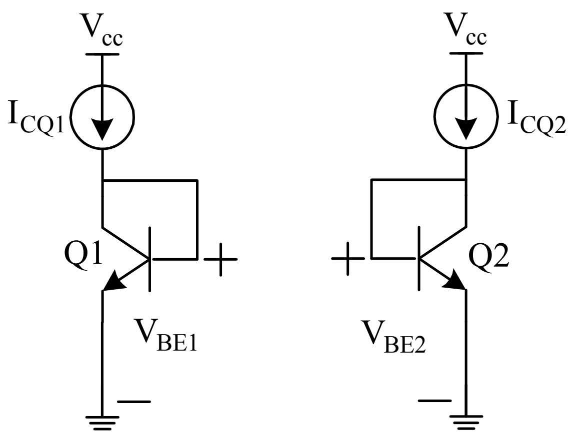
Material	E_G (300 °K)	$E_G(0)$	α	β
Ge	0.663	0.7437	4.774×10^{-4}	235
Si	1.125	1.170	4.730×10^{-4}	636
GaAs	1.422	1.519	5.405×10^{-4}	204

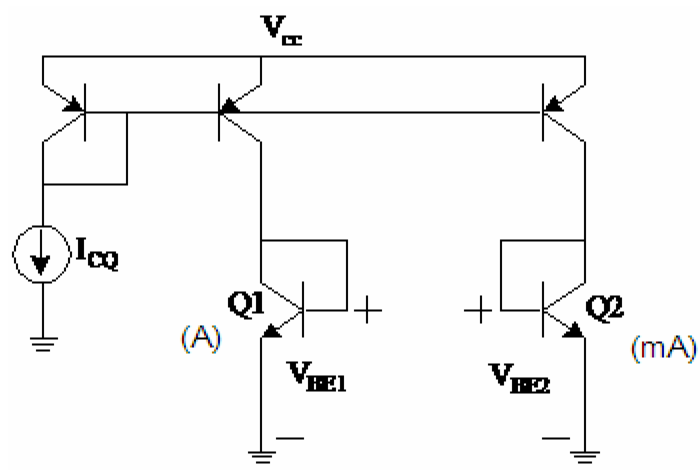
[Pierret, Advanced Semiconductor Fundamentals, p.85]

$$V_{G0} = \frac{1.205eV}{q} = 1.205V$$

PTAT Generator

- Amplifying the difference in V_{BE} of two BJTs→ PTAT term
- Different V_{BE} voltages can be obtained by:
  - Applying different I_{CQ}
  - Using two BJT's with different emitter areas but equal I_{CQ}





$$\Delta V_{BE} = V_{BE1} - V_{BE2} = \frac{KT}{q}\ln\left(\frac{I_{CQ1}}{I_{CQ2}}\right)$$

$$\text{if } \frac{I_{CQ1}}{I_{CQ2}} > 1 \Rightarrow \frac{\partial \Delta V_{BE}}{\partial T} > 0$$

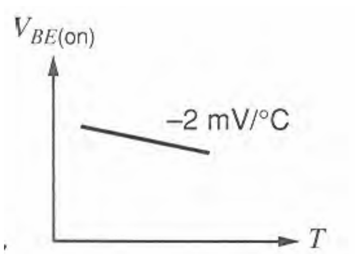
$$V_{BEQ1} = \frac{KT}{q}\ln\left(\frac{I_{CQ}}{\alpha A}\right),\ V_{BEQ2} = \frac{KT}{q}\ln\left(\frac{I_{CQ}}{\alpha m A}\right)$$

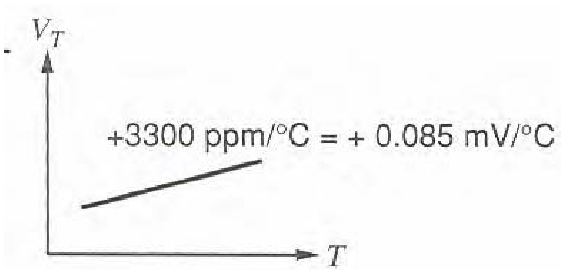
$$\Delta V_{BEQ} = V_{BEQ1} - V_{BEQ2} = \frac{KT}{q}\ln(m)$$

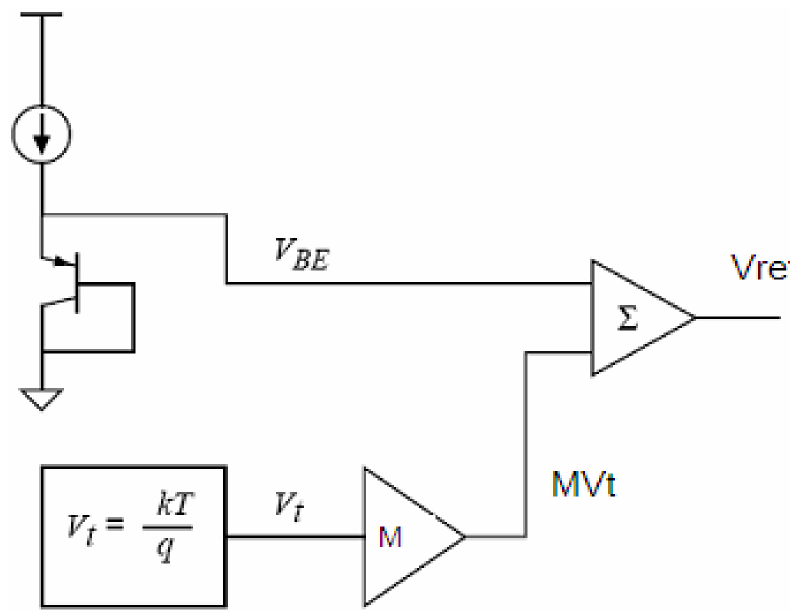
Bandgap Voltage Reference

- Generate an inverse PTAT and a PTAT and sum them appropriately.
  - V_{BE} is inverse PTAT at roughly -2.2 mV/°C at room temperature
  - $V_t = kT/q$ is PTAT that has a temperature coefficient of +0.085 mV/°C at room temperature.
- Multiply V_t by a constant M and summed with the V_{BE} to get

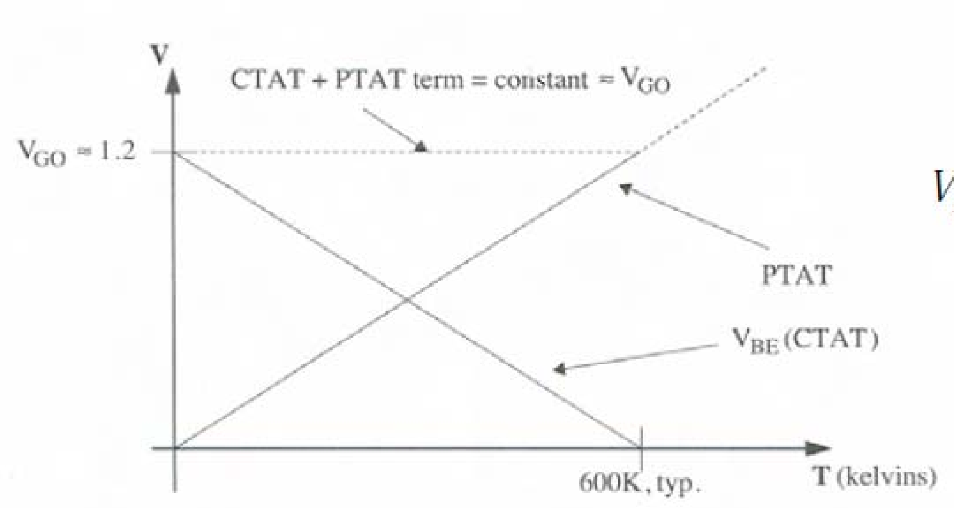
$$V_{REF} = V_{BE} + MV_t$$







Bandgap Voltage Reference



$$V_{BE} + M\frac{kT}{q} \cong V_{G0} - \frac{kT}{q} ln\left(\frac{I_0}{I_C}\right) + M\frac{kT}{q}$$

$$\cong V_{G0} + \frac{kT}{q}\left(M - ln\left(\frac{I_0}{I_C}\right)\right)$$

Combining V_{BE} and an appropriately scaled version of kT/q produces a temperature independent voltage, equal to V_{G0}

PTAT Generator

- How do we generate a voltage that is the difference of two V_{BE}?

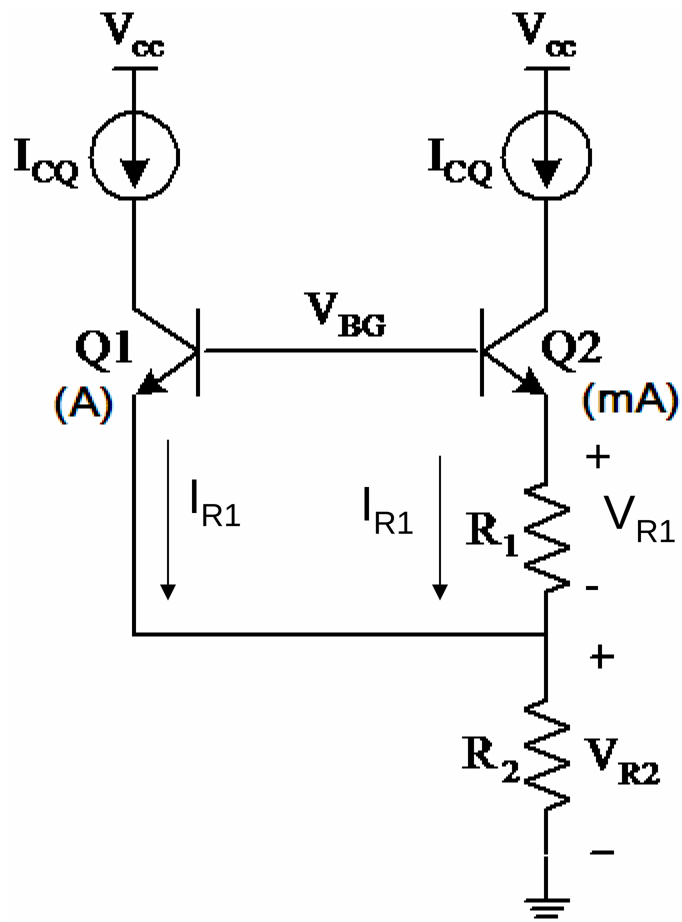
$$V_{BE1} = \frac{KT}{q}\ln(\frac{I_{CQ}}{\alpha A}) \text{ , } V_{BE2} = \frac{KT}{q}\ln(\frac{I_{CQ}}{\alpha mA})$$

$$V_{R1} = \Delta V_{BE} = V_{BE1}\text{-}V_{BE2} = \frac{KT}{q}\ln(m)$$

$$I_{R1} = \frac{V_{R1}}{R_1} = \frac{V_t}{R_1}\ln(m)$$

$$V_{R2} = 2R_2 I_{R1} = \frac{2R_2}{R_1}V_t \ln(m)$$

$$\Rightarrow \frac{\partial V_{R2}}{\partial T} = \frac{2R_2}{R_1}\frac{K}{q}\ln(m) > 0 \text{ ; PTC!}$$



Bandgap Voltage Reference

- More to come!

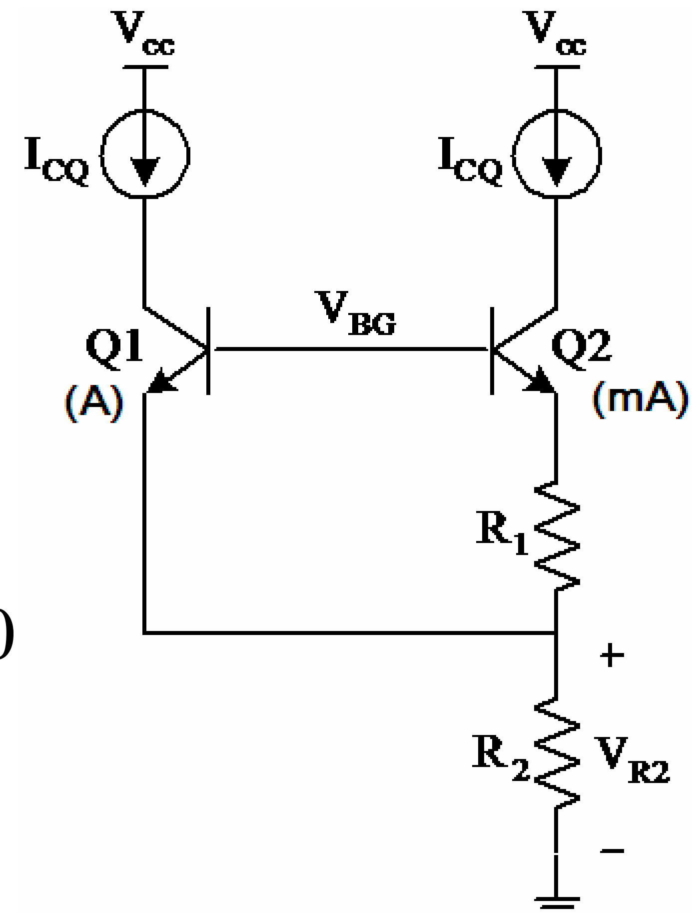
$$V_{BG} = V_{BE1} + V_{R2}$$

$$\frac{\partial V_{BE1}}{\partial T} < 0$$

(NTC)

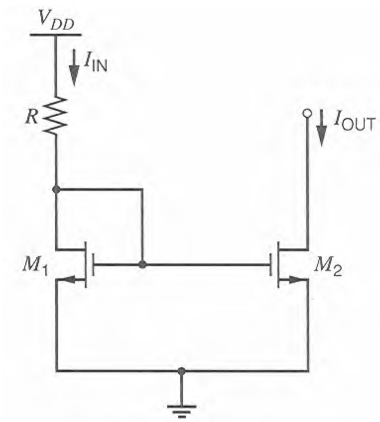
$$\frac{\partial V_{R2}}{\partial T} > 0$$

(PTC)



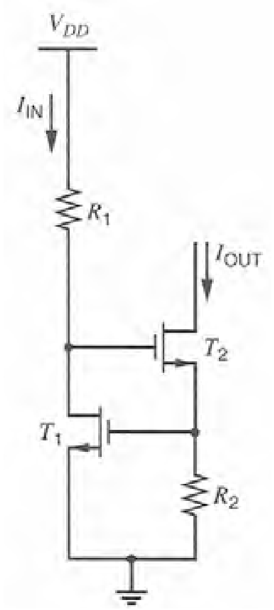
Supply Insensitive Current Source

- How can we generate the bias currents I_{CQ}?
  - Conventional current mirror:
    - Current is essentially proportional to V_{DD}
    - E.g. if V_{DD} varies by X%, bias current will roughly vary by the same amount.



  - Supply insensitive current source:

$$I_{OUT} = \frac{V_{GS1}}{R_2} \cong \frac{V_t + V_{OV}}{R_2} \cong \frac{V_t + \sqrt{\frac{2I_{IN}}{\mu C_{ox}\frac{W}{L}}}}{R_2}$$

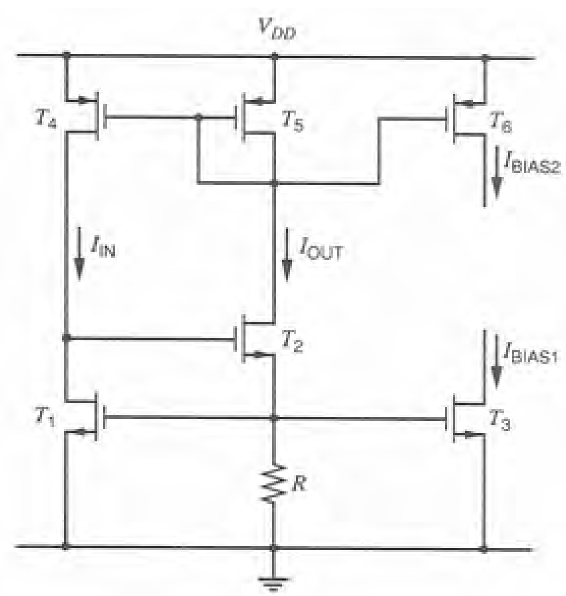


By using a sufficiently large device, we can make $V_{OV} << V_t$, and achieve:

$$I_{OUT} \cong \frac{V_t}{R_2}$$

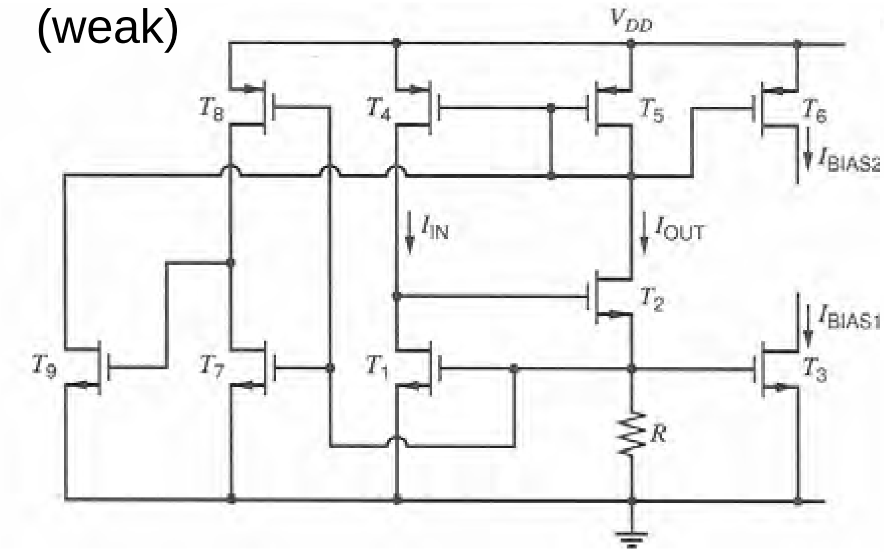
Supply Insensitive Current Source

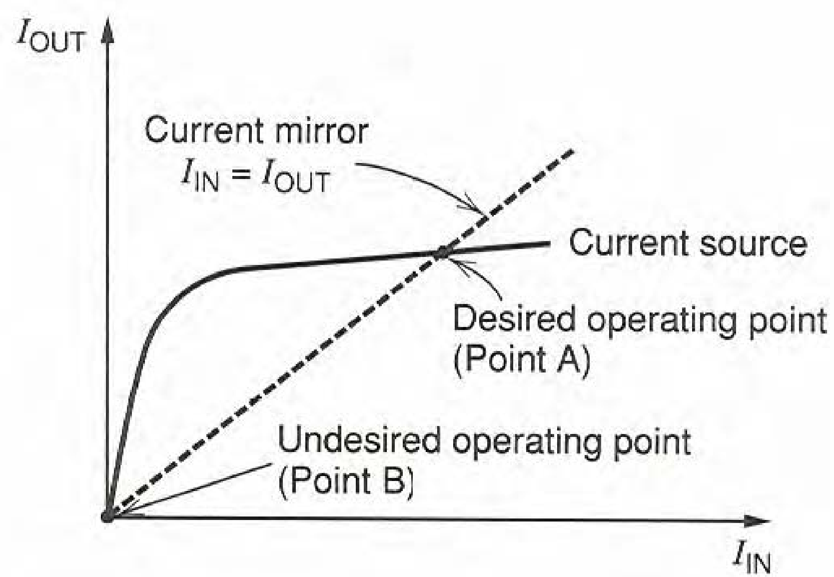
- In the above discussed bias generator circuits, the supply sensitivity is still fairly high, because I_{IN} is essentially directly proportional to V_{DD}
- Idea: Mirror output current back to input instead of using supply dependent input current!



Start-up Circuit

(weak)

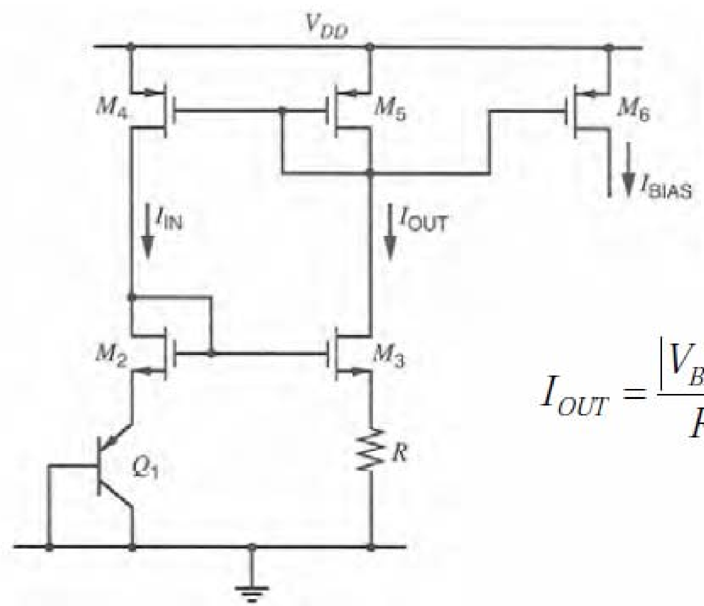




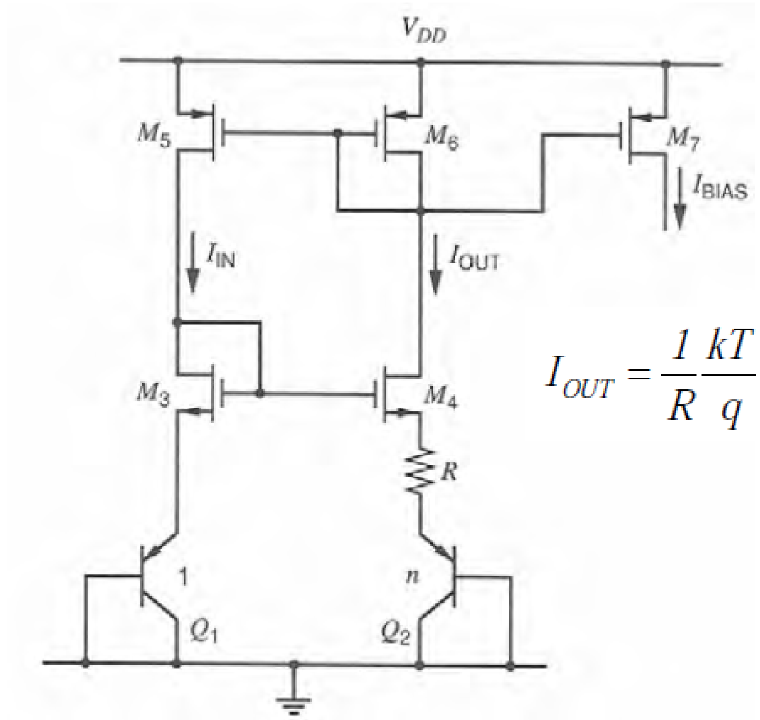
There exists a stable operating point with all currents =0

Can use a simple start-up circuit to solve this problem

PTAT Current Generation



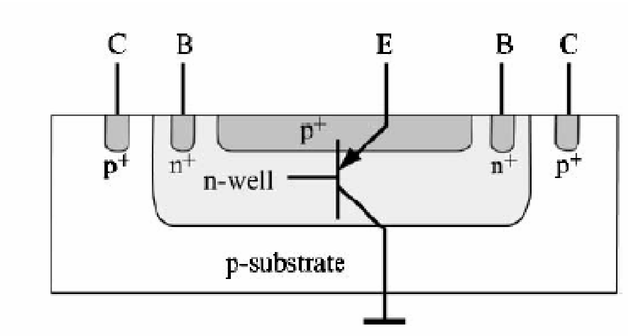
$$I_{OUT} = \frac{|V_{BE1}|}{R}$$



$$I_{OUT} = \frac{1}{R}\frac{kT}{q} ln(n)$$

Compatibility with CMOS Technology

- In CMOS technologies, where the independent bipolar transistors are not available, parasitic bipolar transistors are used.
- Realization of PTAT voltage from the difference of the source-gate voltages of two MOS transistors biased in weak inversion is also reported in the literature.



"parasitic" substrate PNP transistor available in any CMOS technology

CMOS Bandgap Reference With Substrate PNP BJTs

Operation:

The cascode mirror (M5-M8) keeps the currents in Q1, Q2, and Q3 identical.

Thus,

$$V_{BE1} = I_2 R + V_{BE2}$$

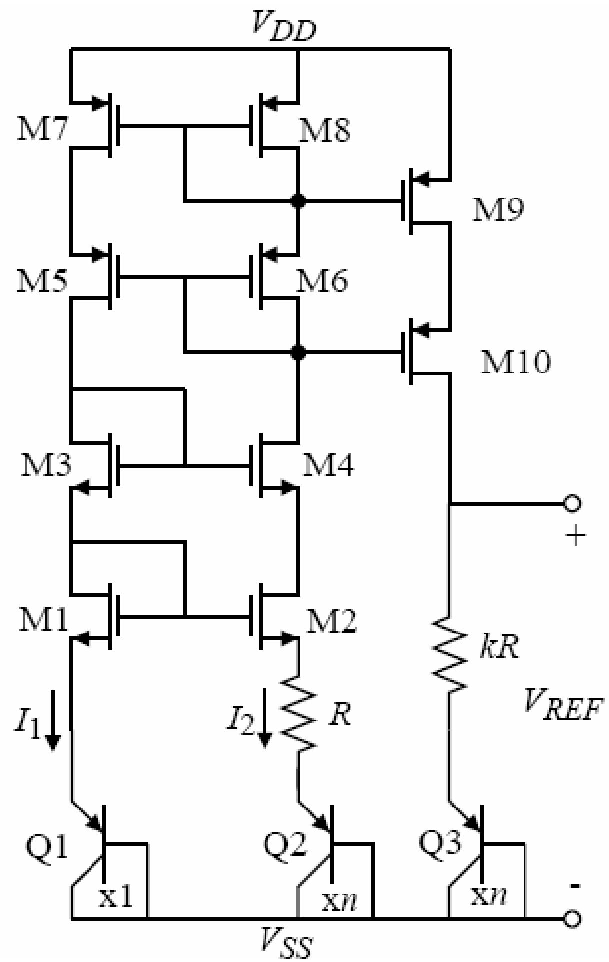
or

$$I_2 = \frac{V_t}{R} \ln(n)$$

Therefore,

$$V_{REF} = V_{BE3} + I_2(kR) = V_{BE3} + kV_t \cdot \ln(n)$$

Use k and n to design the desired value of K (n is an integer greater than 1).



Design example

Specifications:

Vsupply: 5V, 0.5um CMOS process
Vref : 1.2V
Temperature dependence: < 60ppm/C

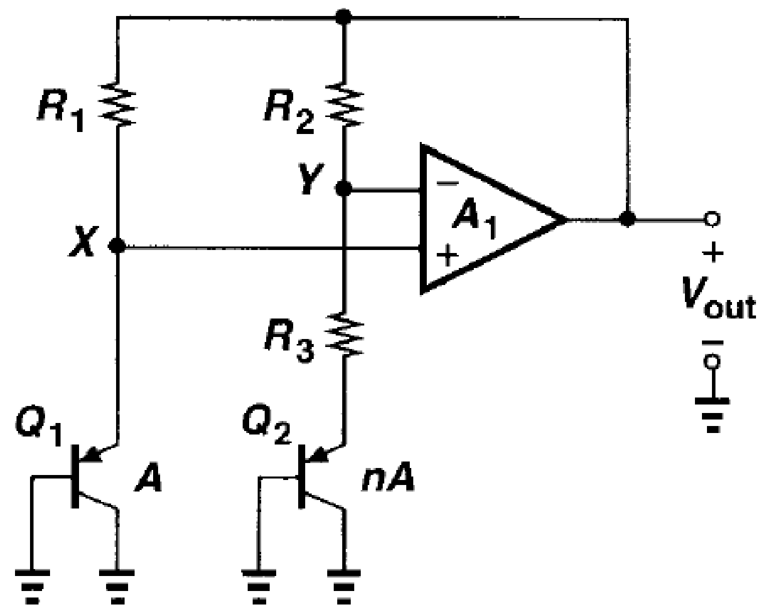
$$V_X = V_Y,\ R_1 = R_2,\ A_{EQ2} = nA_{EQ1}$$

$$\Rightarrow \frac{J_{C2}}{J_{C1}} = \frac{1}{n};\ V_{out} = V_{EB2} + V_{R2} + V_{R3};$$

$$V_{R3} = V_{EB1} - V_{EB2} = \Delta V_{EB} = V_T \ln(n)$$

$$V_{R2} = R_2 I_{R2} = R_2 \frac{V_{R3}}{R_3} = \frac{R_2}{R_3} V_T \ln(n)$$

$$\Rightarrow V_{out} = V_{EB2} + \left(1 + \frac{R_2}{R_3}\right) V_T \ln(n)$$

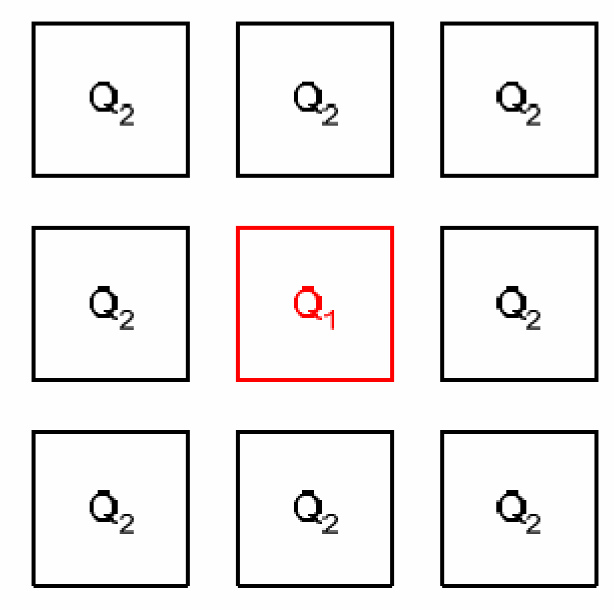


A critical point: DC output of Op Amp should be > 700mV for start up

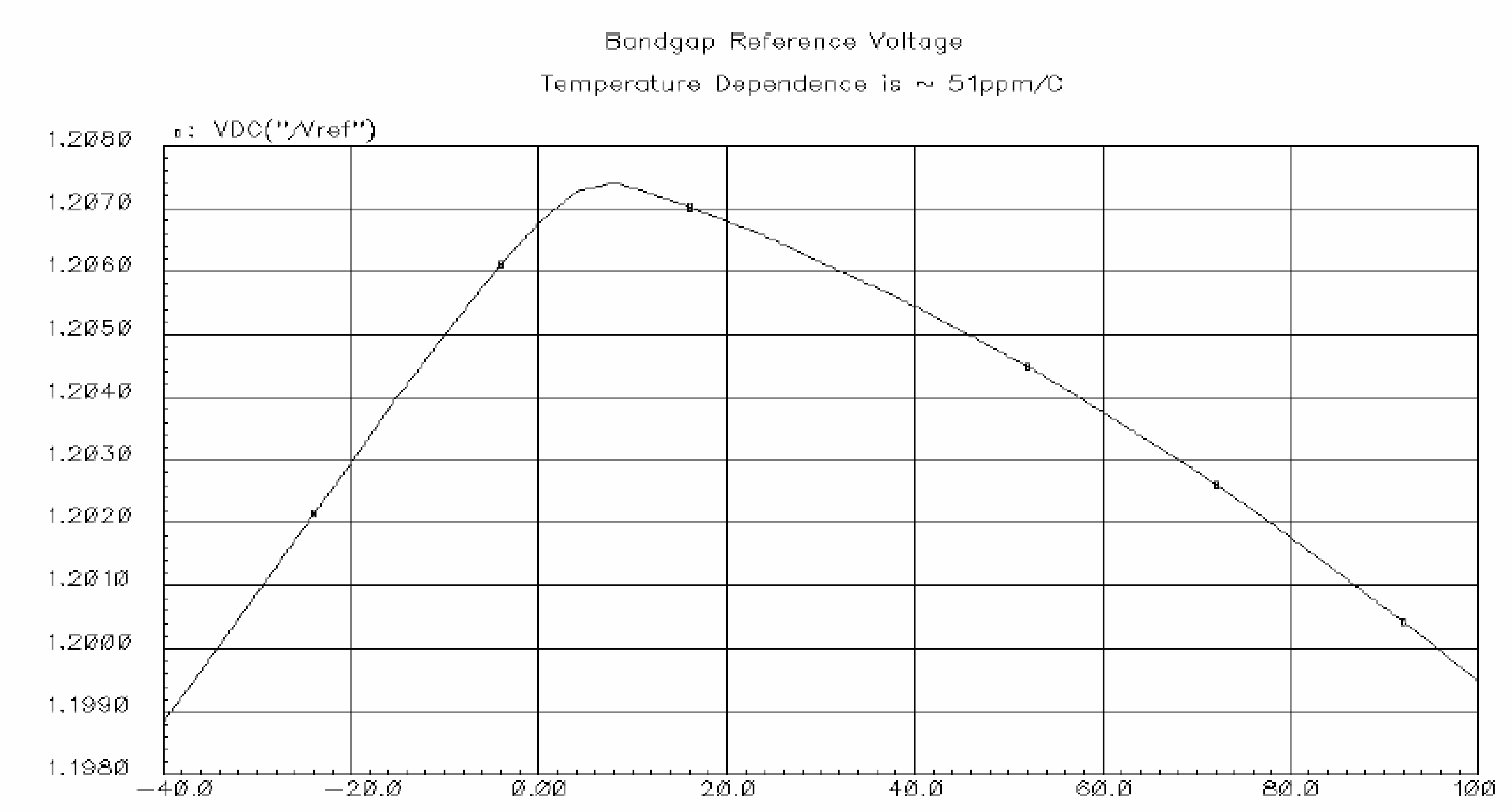
Choice of n

- Usually make $n = \text{integer}^2 - 1$, e.g. n=8

  Layout:

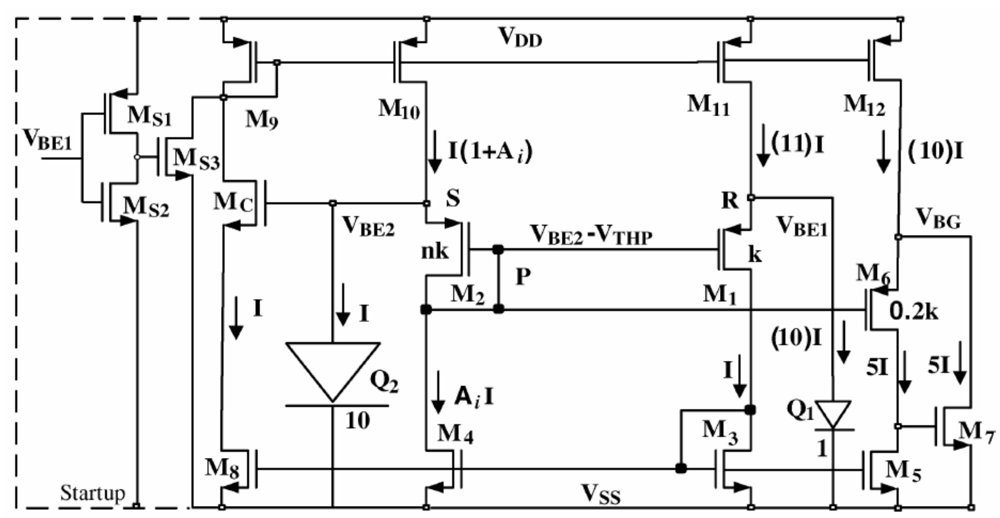


Simulations Result



A Low-Supply-Voltage CMOS Sub-Bandgap Reference

- Low supply voltage
- No resistor or op-amp is used, thus it is compatible with digital processes



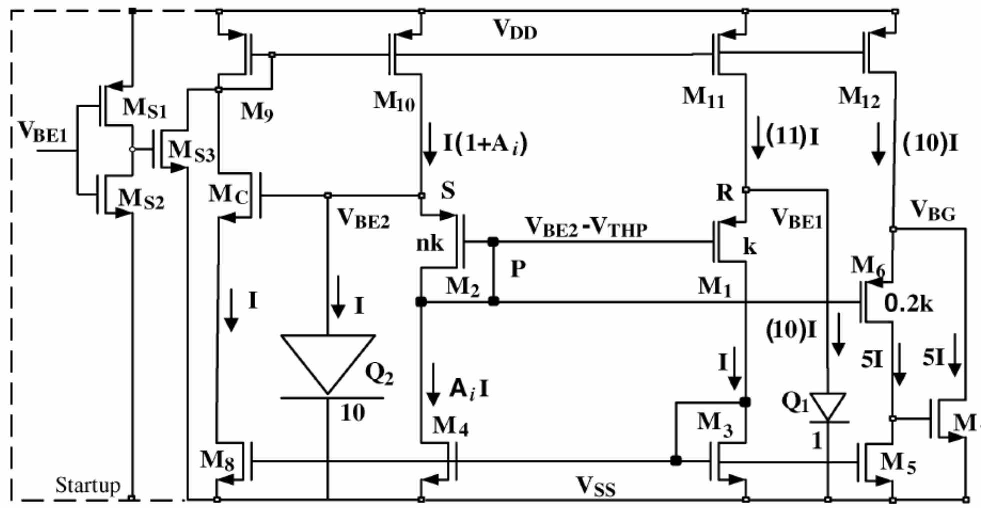
Ref: A. Becker-Gomez, T. L. Viswanathan, T.R. Viswanathan, "A Low-Supply-Voltage CMOS Sub-Bandgap Reference," *IEEE Transactions on Circuits and Systems II: Express Briefs*, vol.55, no.7, pp.609-613, July 2008

A Low-Supply-Voltage CMOS Sub-Bandgap Reference

$$V_{PTAT} = V_{BE1} - V_{BE2} = V_T \ln\left(\frac{I_{C1} I_{02}}{I_{C2} I_{01}}\right) = V_T \ln(100) = 4.6 V_T$$

$$V_{PTAT} = V_{SG1} - V_{SG2} = \sqrt{I/k} - \sqrt{A_i I/nk}$$

$$\Rightarrow I = \frac{k V_{PTAT}^2}{\left(1 - \sqrt{A_i/n}\right)^2}$$



$$V_{BG} - V_{BE2} = V_{SG6} - V_{SG2} = \sqrt{mI/rk} - \sqrt{A_i I/nk}$$

$$\Rightarrow V_{BG} = V_{BE2} + V_{PTAT} \frac{\sqrt{m/r} - \sqrt{A_i/n}}{1 - \sqrt{A_i/n}} \approx V_{BE2} + \sqrt{m/r} V_{PTAT}$$

- r is the ratio between M_6/M_1
- m is the ratio between M_5/M_1

- For A_i <<1, n>>1

Summary

How to Build a Bandgap.-

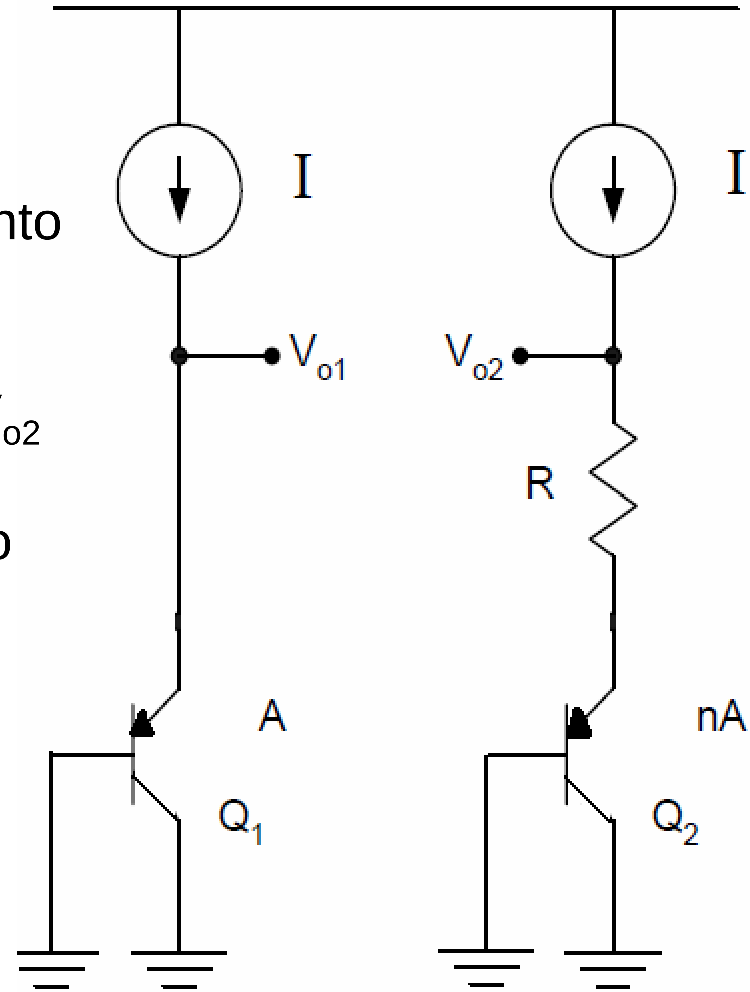
1. Generate two currents and dump into the transistors

2. Add a mechanism to force $V_{o1} = V_{o2}$

3. Add a scale factor to generate zero TC output

4. Startup circuit, some tweaking

Done!!!



References

- First bandgap voltage reference:

  R. J. Widlar, "New developments in IC voltage regulators," IEEE J. Solid-State Circuits, pp. 2-7, Feb. 1971.

- A classic implementation:

  A. P. Brokaw, "A simple three-terminal IC bandgap reference,“ IEEE J. Solid-State Circuits, pp. 388-393, Dec. 1974.

- Design of Analog Integrated Circuits, Behzad Razavi
- Analysis and Design of Analog Integrated Circuits, P.R. Gray, P. Hurst