EECS 240
Analog Integrated Circuits

Lecture 8: References

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Outline

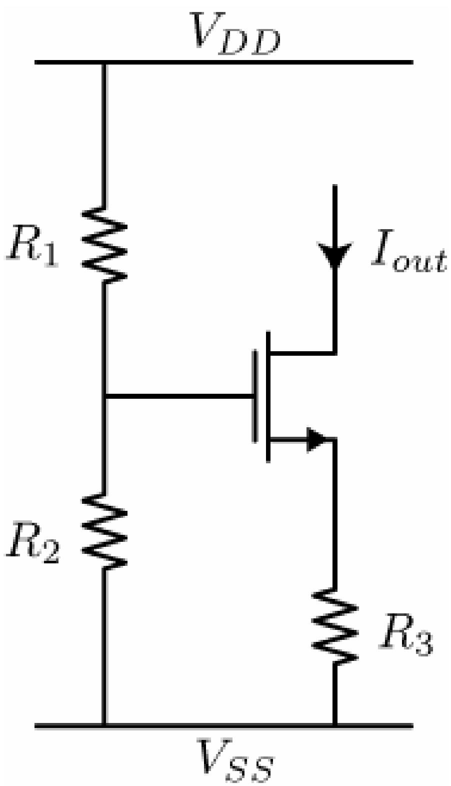
- Objectives
- CMOS implementations
- Startup circuits
- Typical performance
- Constant XXX references

References

- Applications
  - Bias current
  - ADC / DAC references
- Solutions
  - Voltage references:
    - PTAT ($V_t = kT/q$)
    - Bandgap
    - Threshold voltage, V_{TH}, ΔV_{TH}
  - Special purpose:
    - Constant g_m
  - No “direct” current reference

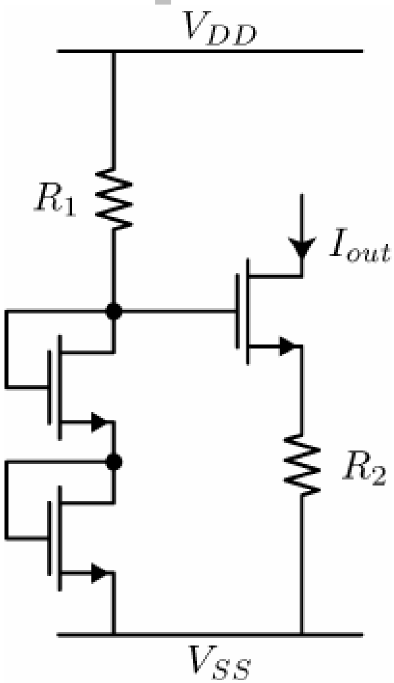
- Specifications
  - Accuracy: σ of $\Delta V_{out}/V_{out}$
  - Temperature coefficient, TC_F
  - Power rejection ratio, PSRR
  - Trimming
  - Supply voltage
  - Power dissipation

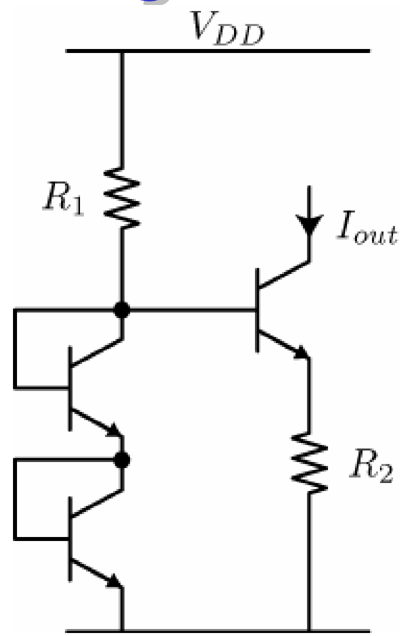
Supply Dependent Biasing



- Okay for test circuits, especially if resistors are off-chip. But output current is inaccurate and varies with supply/temperature.
- Realization of small (nA) currents requires big resistors (too much area).

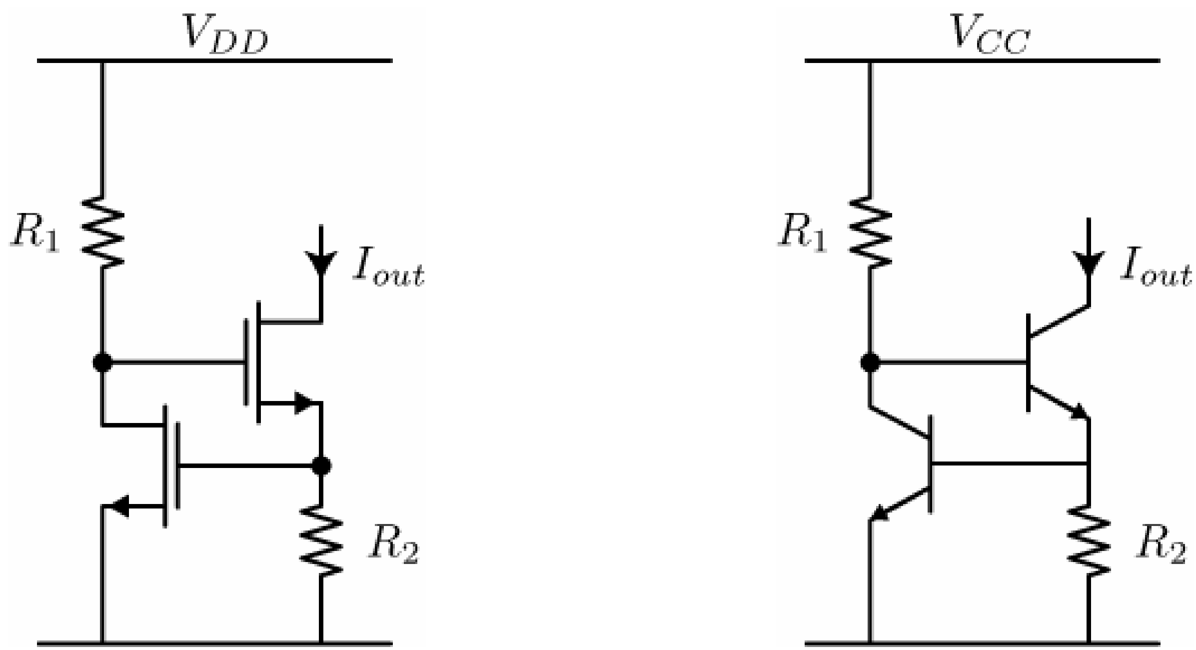
Simple Supply Rejection





- Use a V_{GS} or even better a V_{BE} as a reference. V_{BE} is very insensitive (logarithmically) to current variations.

Improved V_{GS}/V_{BE} Reference



- Now we have only one V_{BE} (V_{GS}) as the reference. If the overdrive of the MOS is small relative to V_T, this is a threshold reference.

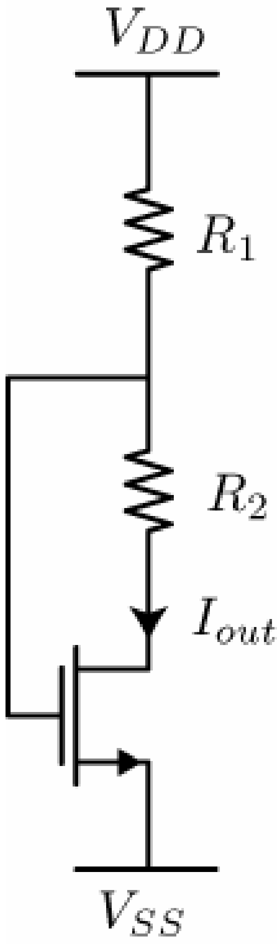
Peaking Current Source

$$V_o = V_{GS} - IR_2$$

$$\frac{dV_o}{dI} = \frac{dV_{GS}}{dI} - R_2$$

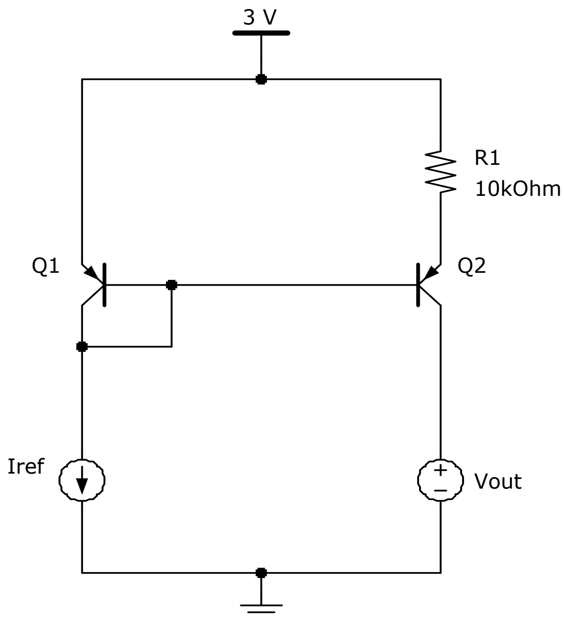
$$\frac{dV_o}{dI} = \frac{1}{g_m} - R_2 = 0 \qquad R_2 = \frac{1}{g_m}$$

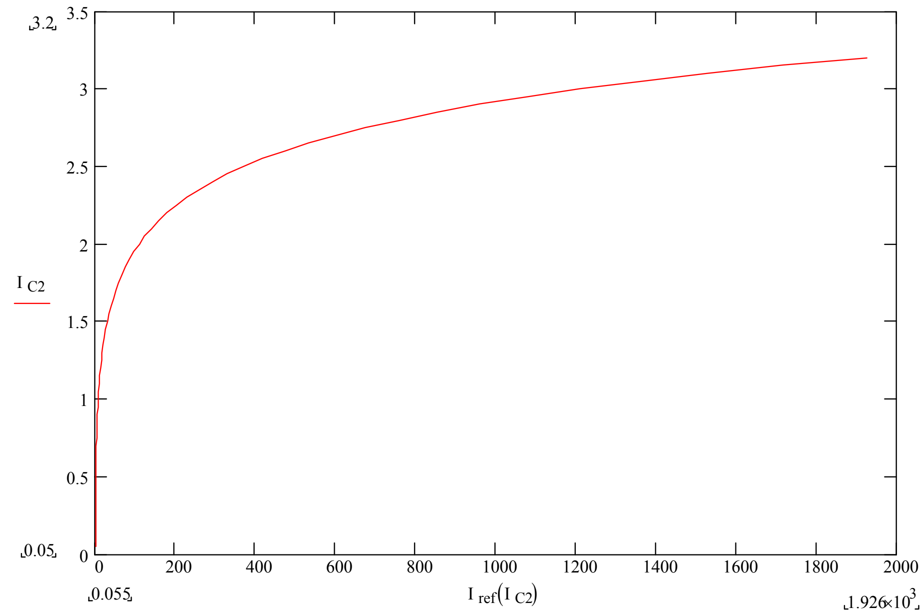
- Useful for very small (nA) current levels.
- Can compensate for variations in V_{GS} with a resistor to produce first order supply independent.



Widlar Reference

DC Analysis DC1
Device Iref
sweep from 0 to 300u (200 steps)



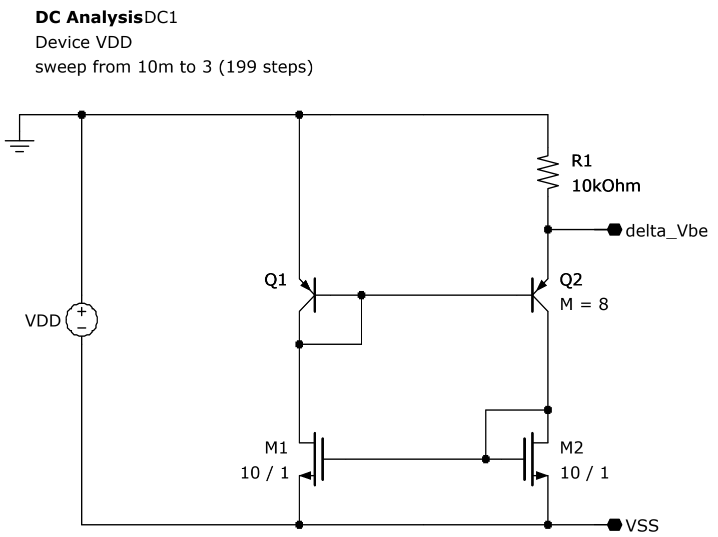


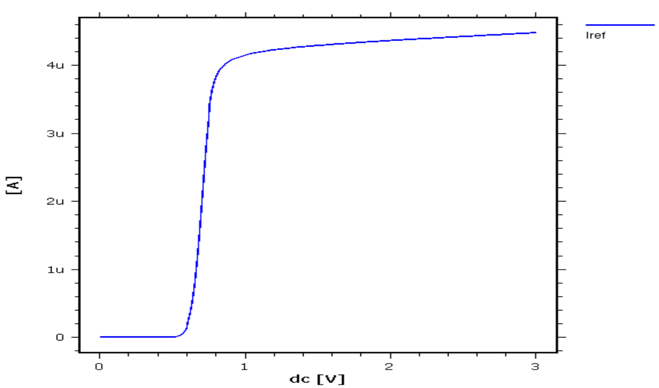
$$V_{BE1} = V_{BE2} + R_1 I_{C2}$$

$$V_t \ln\left(\frac{I_{ref}}{I_{s1}}\right) = V_t \ln\left(\frac{I_{C2}}{I_{s2}}\right) + R_1 I_{C2}$$

- I_{C2} is “relatively” insensitive to I_{ref}
- → first order supply independence

PTAT Reference





$$\Delta V_{BE} = V_t \ln\left(\frac{I_{s2}}{I_{s1}}\frac{I_{C1}}{I_{C2}}\right)$$

$$= V_t \ln\left(M\frac{I_{C1}}{I_{C2}}\right)$$

$$\propto T$$

Issues:

- Cascoding
- Self-biasing
- Temperature Coefficient
- Vertical BJT
- Startup

Temperature Coefficient

TC of Reference Voltage:

$$TC_F = \frac{1}{\Delta V_{BE}} \frac{d\Delta V_{BE}}{dT}$$
$$= \frac{1}{\Delta V_{BE}} \frac{\Delta V_{BE}}{T}$$
$$= \frac{1}{T}$$
$$\cong 3300\text{ppm/K} \quad \text{at room temperature } (300^{\circ}\text{K})$$

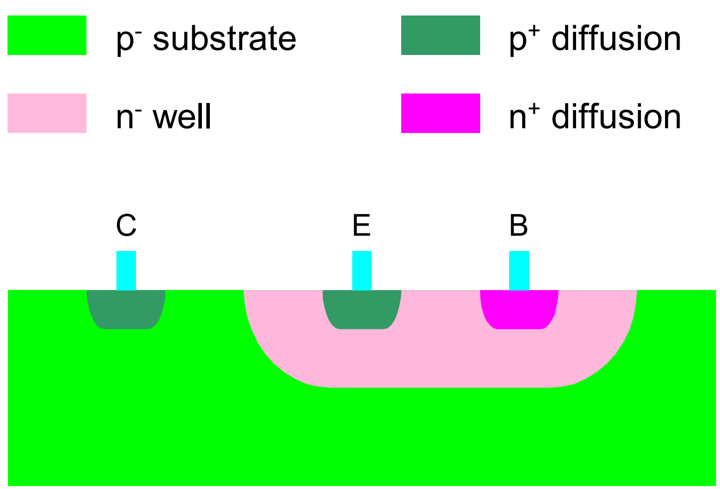
TC of Reference Current:

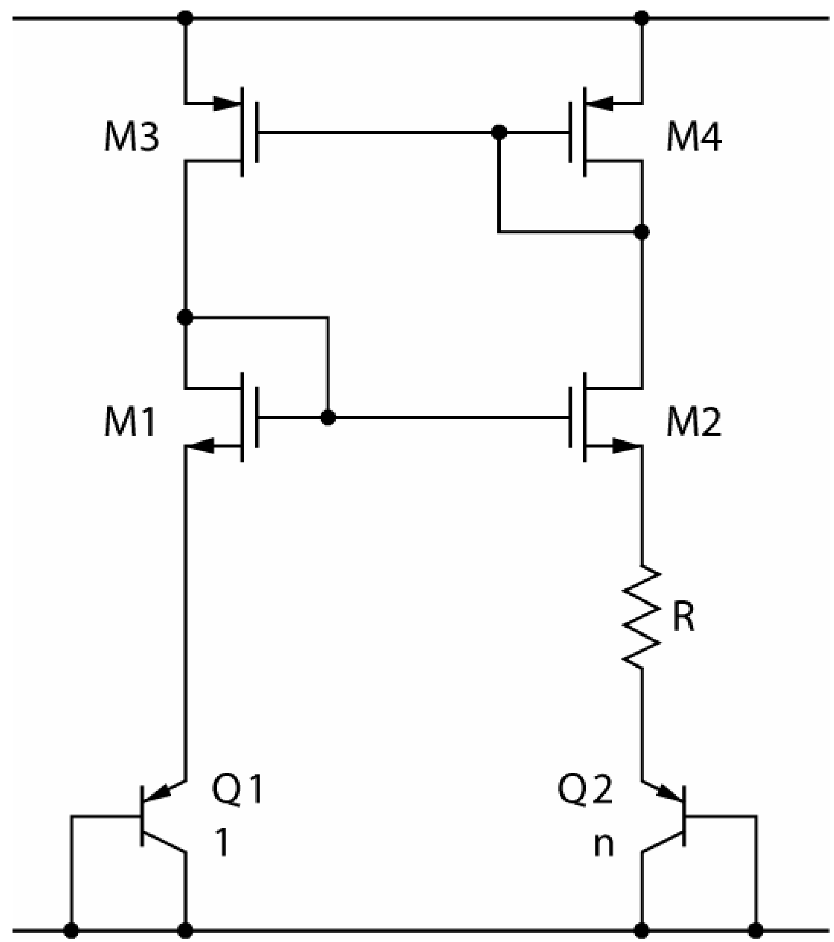
$$I_{out} = \frac{\Delta V_{BE}}{R_1}$$
$$TC_F = \frac{1}{I_{out}} \frac{dI_{out}}{dT}$$
$$= \frac{1}{\Delta V_{BE}} \frac{d\Delta V_{BE}}{dT} - \frac{1}{R_1} \frac{dR_1}{dT}$$
$$= 3300\text{ppm/K} - 1500\text{ppm/K} = 1800\text{ppm/K}$$

for n + diffusion resistor

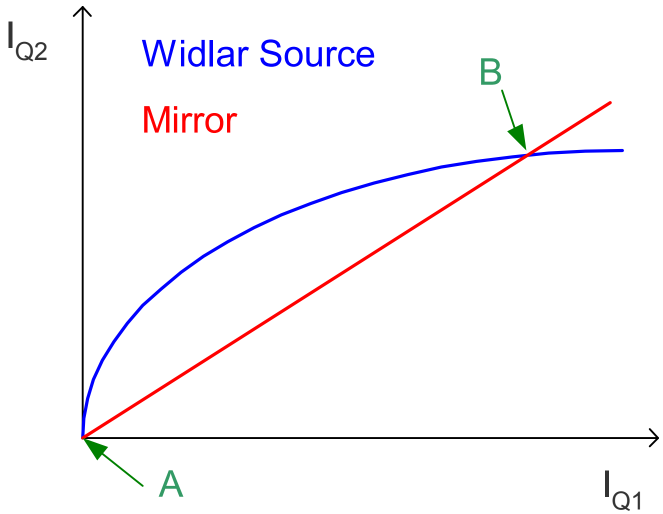
CMOS PTAT Reference

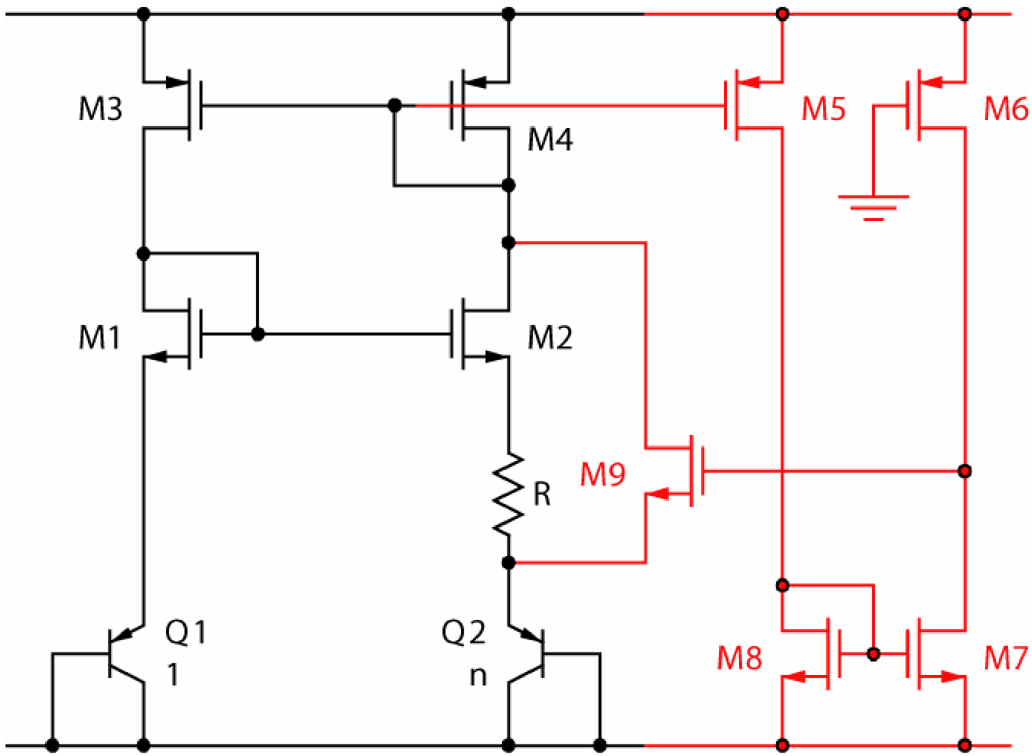
Vertical PNP





Startup Circuit





Parasitic operating point A:

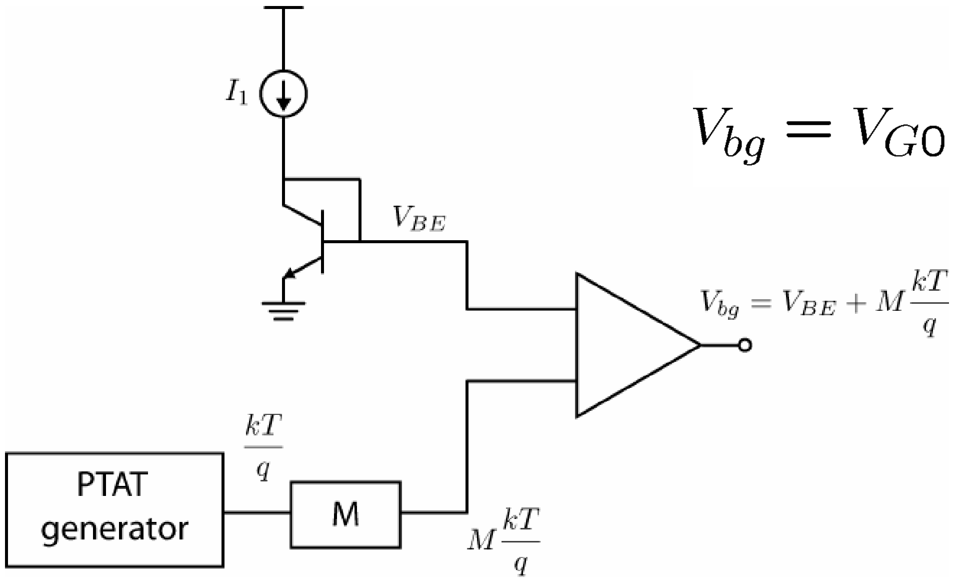
- Positive feedback → unstable
- Noise drives circuit away from A (and to B)
- Problem: gain at A too small ($I_Q = 0$)

Bandgap Reference

- Supply and temperature insensitive
- $V_{BG,Si} = 1.205V$
- Curvature correction
- References:
  - R. Widlar, JSSC 2/1971, pp. 2
    first report
  - G. Nicollini, JSSC 1/1991, pp. 41
    offset compensated amplifier
  - K. Tham, JSSC 5/1995, pp. 586
    self-regulated supply for improved PSRR
  - A. Boni, JSSC 10/2002, pp. 1339
    bandgap reference for $V_{DD} < V_{BG}$
  - P. Malcovati, JSSC 7/2001, pp. 1076
    curvature corrected CMOS bandgap reference

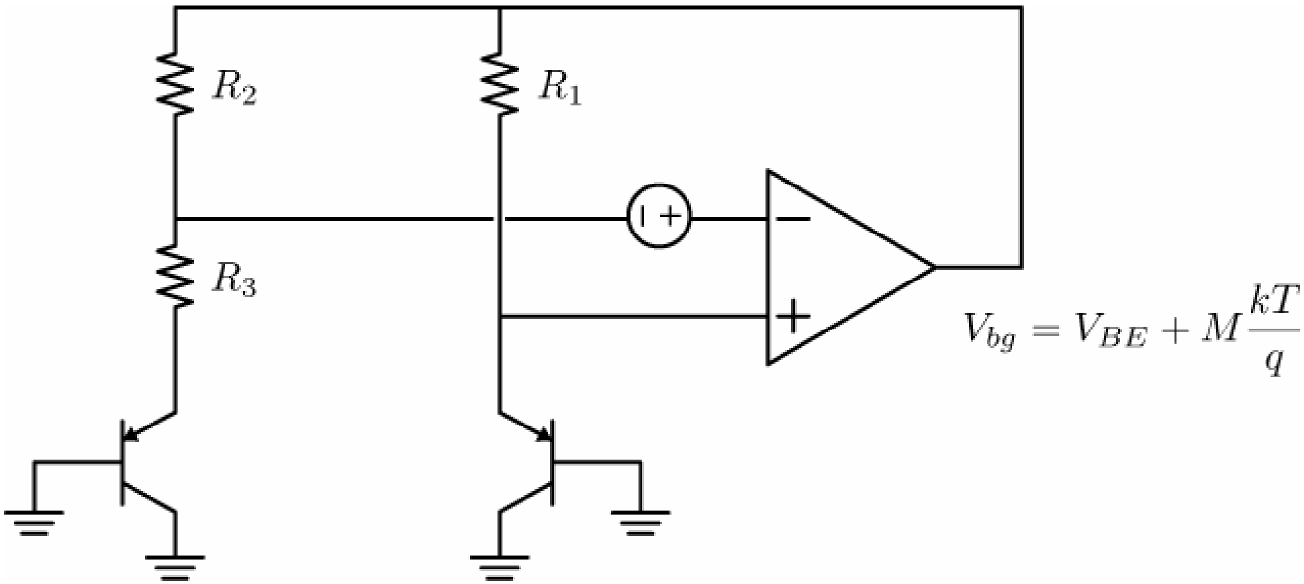
Hypothetical Band-Gap

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



- V_{BE} has a tempco of -2 mV/°C. If we add this to a multiple of the thermal voltage with positive tempco of 0.085 mV /°C, we can achieve temperature independence.

"CMOS" Bandgap



$$V_{R3} = V_{EB1} - V_{EB2} + V_{OS} = \Delta V_{EB} + V_{OS}$$

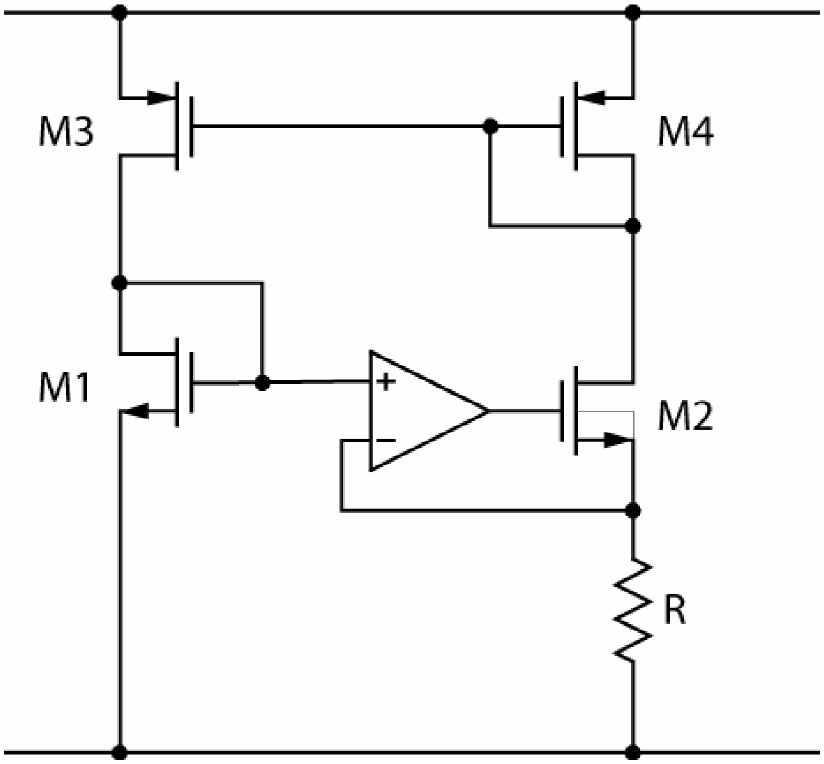
$$V_{R2} = \frac{R_2}{R_3} V_{R3} = \frac{R_2}{R_3} (\Delta V_{EB} + V_{OS})$$

$$V_{BG} = \left(1 + \frac{R_2}{R_3}\right) (\Delta V_{EB} + V_{OS}) + V_{EB2}$$

Bandgap Performance

	[Nicollini]	[Tham]	[Malcovati]
Supply	+/- 5V	3V	1V
Output voltage	6.2V	1.24V	0.54V
Accuracy (σ)	24mV	20mV	
TC_F	15ppm/^{o}C	85ppm/^{o}C	7.5ppm/^{o}C
PSRR	86dB	80dB @ 10kHz 40dB @ 500kHz	212ppm/V at DC
Power dissipation	4.8mW	1mW	92μW

Constant g_m Reference



$$\omega_u \propto \frac{g_m}{C_L}$$

$$g_{m1} = \frac{1}{R}$$

Reference Distribution

- Single shared reference
- Current distribution:
  - Many wires
  - Increase power dissipation
- Voltage distribution:
  - Susceptible to mismatch
  - → use large V_{GS} in distribution network
  - Careful supply routing to avoid poor PSRR
  - Avoid loops in analog supply