Dallas, February 19, 2001

CURVATURE COMPENSATED BICMOS BANDGAP WITH 1 V SUPPLY VOLTAGE

F. Maloberti

Texas A&M University

franco@ee.tamu.edu

OUTLINE

- **Introduction**
- **Bandgap references**
- **Low-Voltage Bandgap**
- **Operational Amplifier**
- **Startup Circuit**
- **Curvature Compensation**
- **Experimental Results**
- **Conclusions**

INTRODUCTION

- Voltage references generators with a minimum (or zero) variation with temperature are important element for precise electronics
- A voltage reference is normally based on a given ingredient; it can have a positive or a negative voltage coefficient
- V_T has positive coefficient
- V_{BE} has negative coefficient
- Properly combining V_T and V_{BE} it is possible to compensate the positive coefficient of one constituent with the negative coefficient of the other one
- The voltage achieved by a bandgap is typically 1.2 V

- ❒ Evolution of IC ➜ Submicron technologies (reduced oxide thickness) and low-power low-voltage applications
  - ➥ Reduced power supply voltages (1.8 V down to 1.2 V)
  - ✗ The threshold voltage of transistors scales less than the supply
  - ✌ New circuit techniques for the design of analog building blocks
- ❒ Bandgap voltage generator
  - ➥ Reference voltage ➜ 1.2 V
  - ✗ If the supply voltage is lower than 1.5 V ➜ Conventional implementations of the bandgap reference circuit cannot be used
- ❒ Proposed bandgap reference circuit in standard BiCMOS technology
  - ✌ Output voltage ➜ 0.65 V with 0.5 mV variation from 0° C to 80 ° C
  - ✌ Supply voltage ➜ 1 V with 0.8 V MOS threshold voltages

BANDGAP REFERENCES

- The band-gap operates on the principle of compensating the negative temperature coefficient of V_{BE} with the positive temperature coefficient of the thermal voltage V_T.
- The temperature coefficient of V_{BE}, at room temperature, is *- 2.2 mV/°C*; while, the positive coefficient of the thermal voltage is *0.086 mV/°C*.
- A full compensation at room temperature is obtained by combining the term with positive temperature coefficient and the one with negative temperature coefficient to give

$$V_{BG} = V_{BE} + nV_T = V_{BE} + n\frac{kT}{q}$$

where *n* must be equal to *25.6 (=2.2/0.086)*.

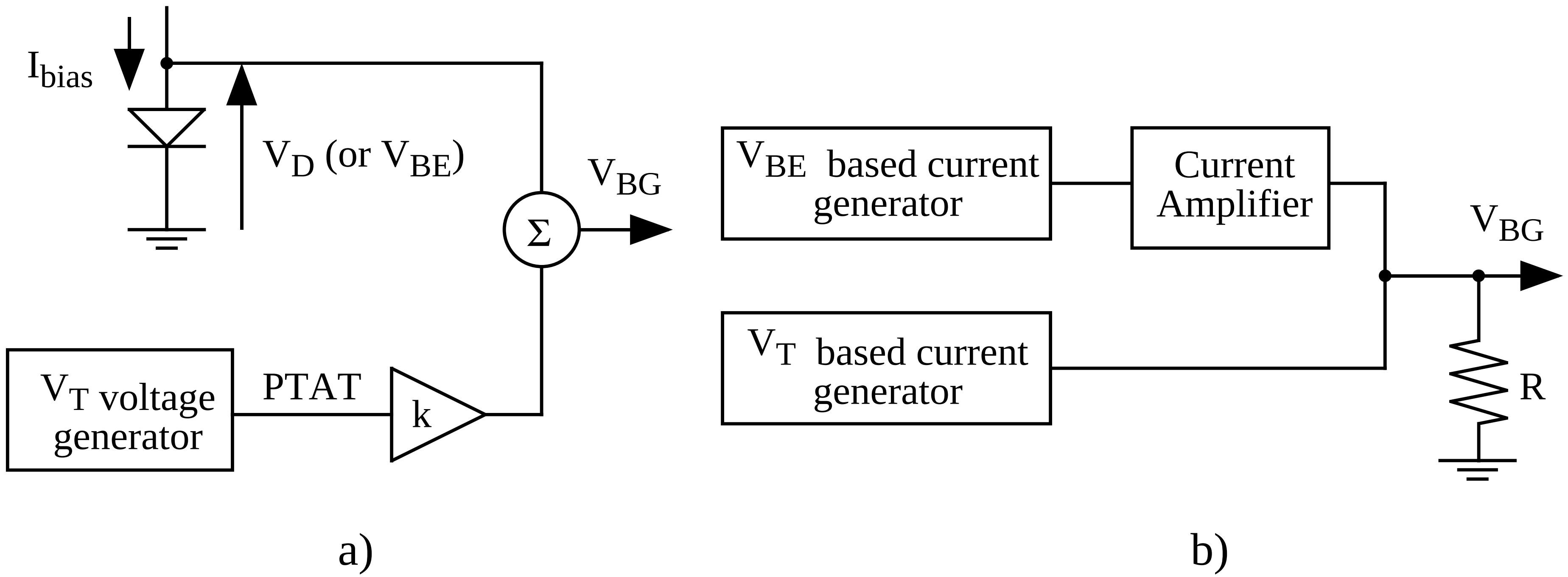
WHY THE NAME: BANDGAP?

- ❒ Since the value of V_{BE} for low currents is close to *0.650V,* and V_T at room temperature is *25.8 mV*, the value of V_{BG} is *1.26 V*. Such a value is just slightly more than the silicon energy gap (expressed in volts it is *1.21 V*). Therefore, we normally call the circuits that achieve temperature compensation *band-gap reference*.

NOTE: The name bandgap can be misleading: what is generated it is not a physical constant.

➥ Since $V_T = kT/q$ is proportional to the absolute temperature, we often refer to it using the acronym *PTAT*.

CONCEPTUAL IMPLEMENTATIONS

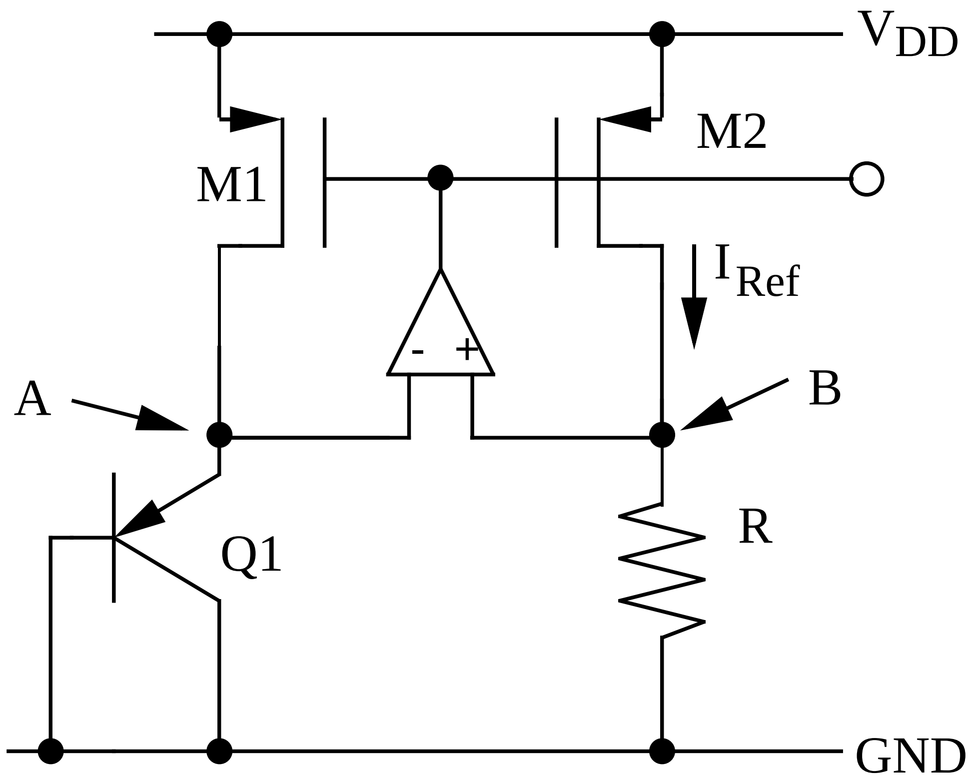


a) Voltage mode approach

b) Current mode approach

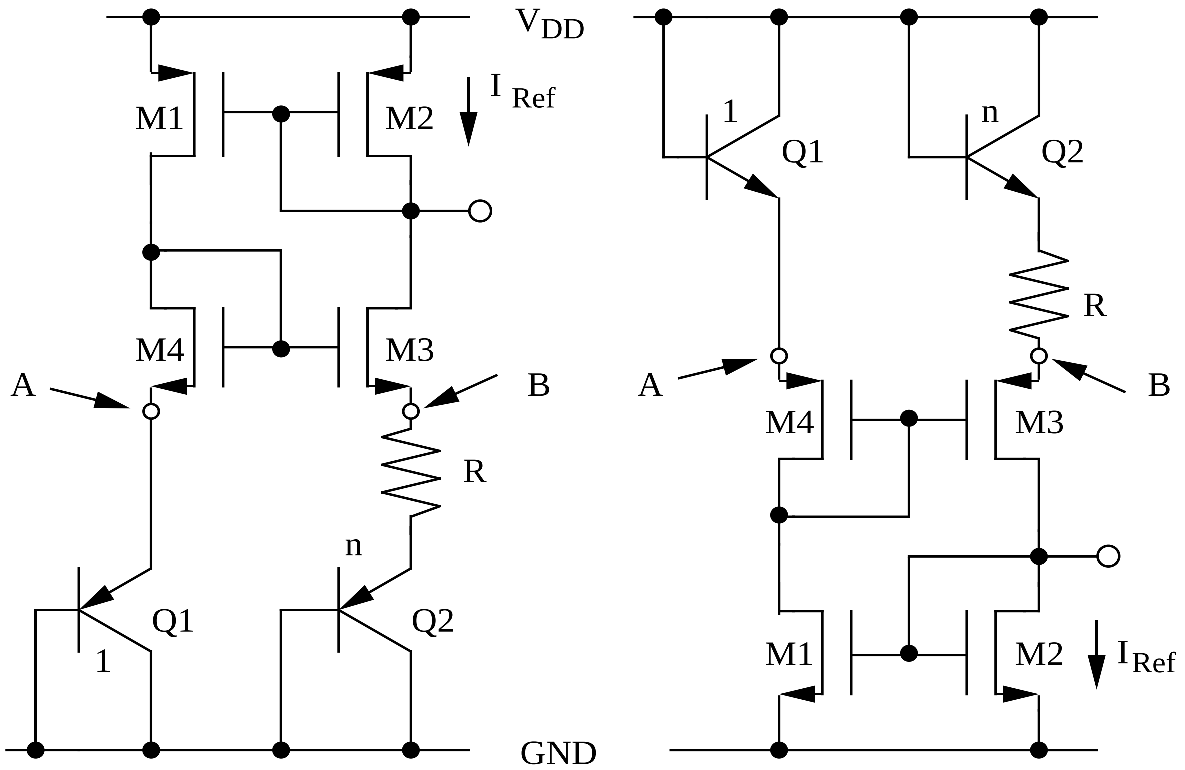
BASIC INGREDIENTS

- ❒ V_{BE} and V_{BE} based current generator



- ❒ Offset of the Op-amp can be a problem

❐ PTAT Current based generator

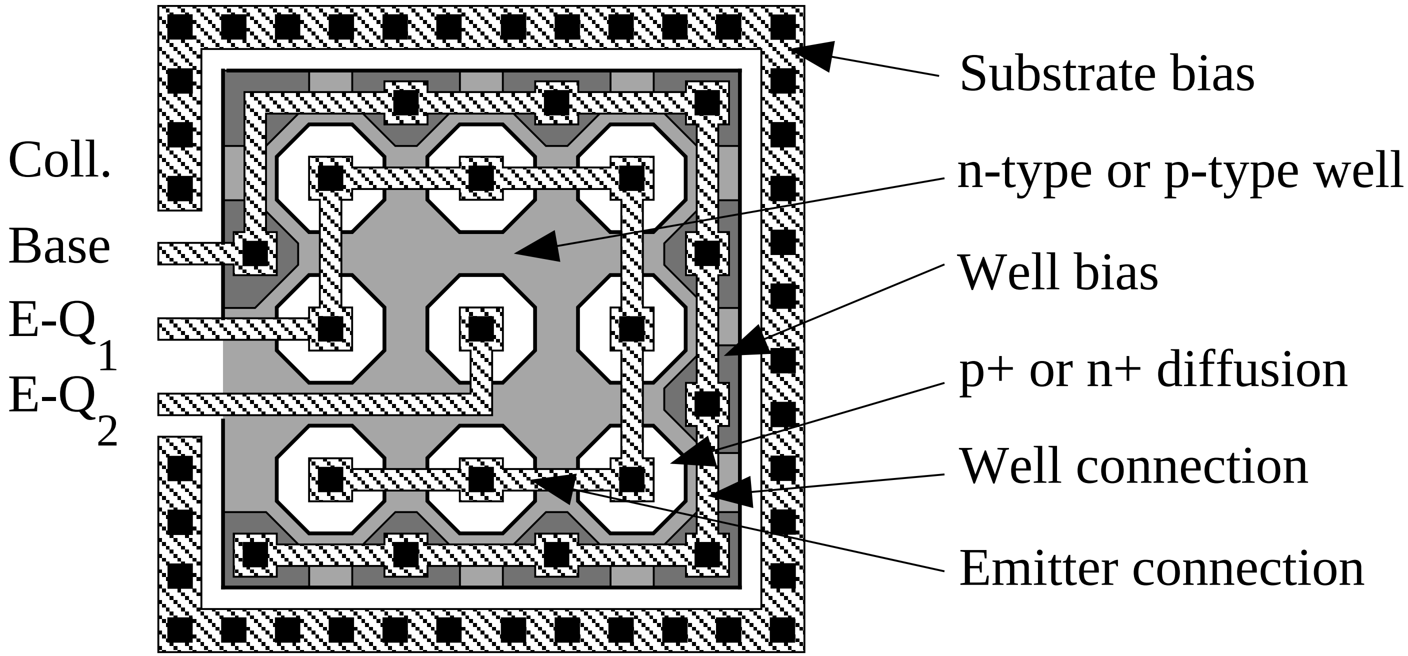


$$V_{BE1} = V_T \ln\frac{I_1}{AI_{SS}} \; ; \; V_{BE2} = V_T \ln\frac{I_1}{nAI_{SS}}$$

$$RI_1 = V_{BE1} - V_{BE2} = V_T \ln\frac{I_1}{AI_{SS}}\frac{nAI_{SS}}{I_1}$$

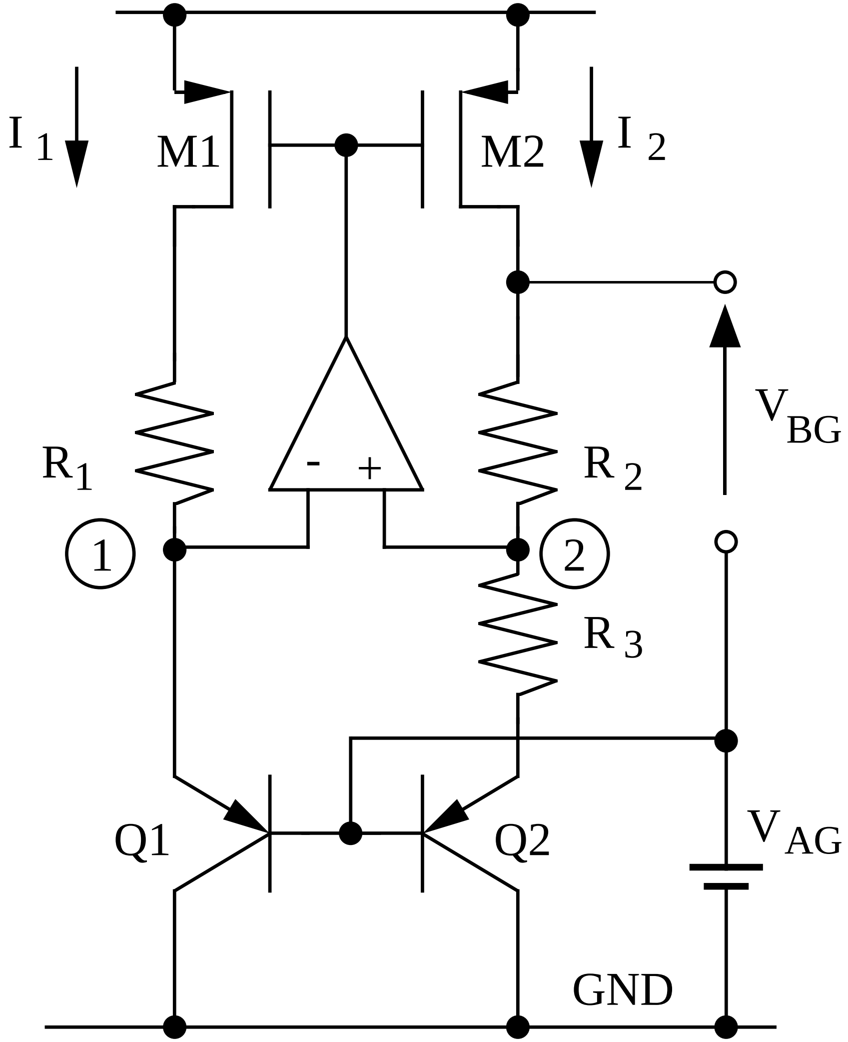
$$I_1 = \frac{V_T}{R}\ln(n)$$

VALUE OF “N” AND LAYOUT



❒ N= 8 or N=24 are good numbers for layout

VOLTAGE MODE BANDGAP



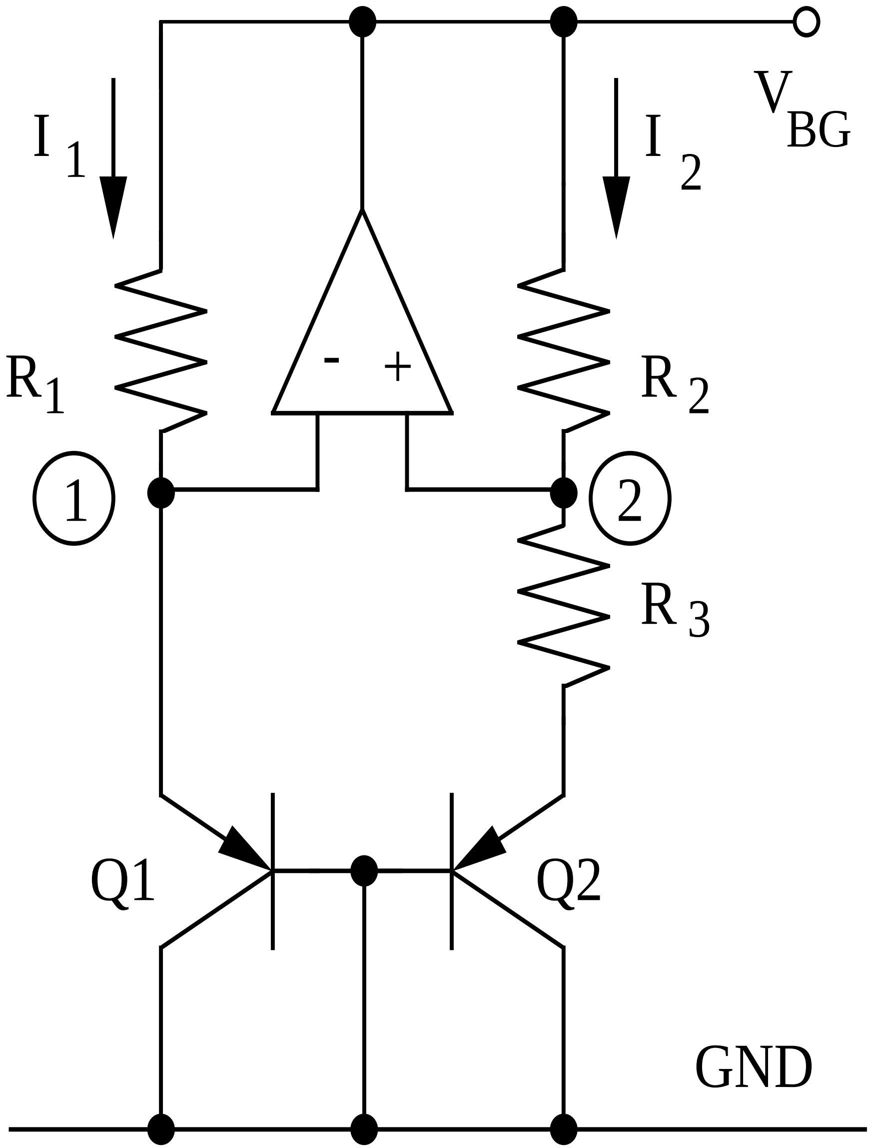
$$\frac{I_1}{I_2} = \left(\frac{W}{L}\right)_1 \Big/ \left(\frac{W}{L}\right)_2$$

$$V_{BG} = V_2 - V_{AG} + R_2 I_2 = V_{BE1} + \frac{R_2}{R_3}\Delta V_{BE}$$

$$V_{BG} = V_{BE1} + V_T \frac{R_2}{R_3} \ln \frac{(W/L)_1}{(W/L)_2}\frac{A_2}{A_1}$$

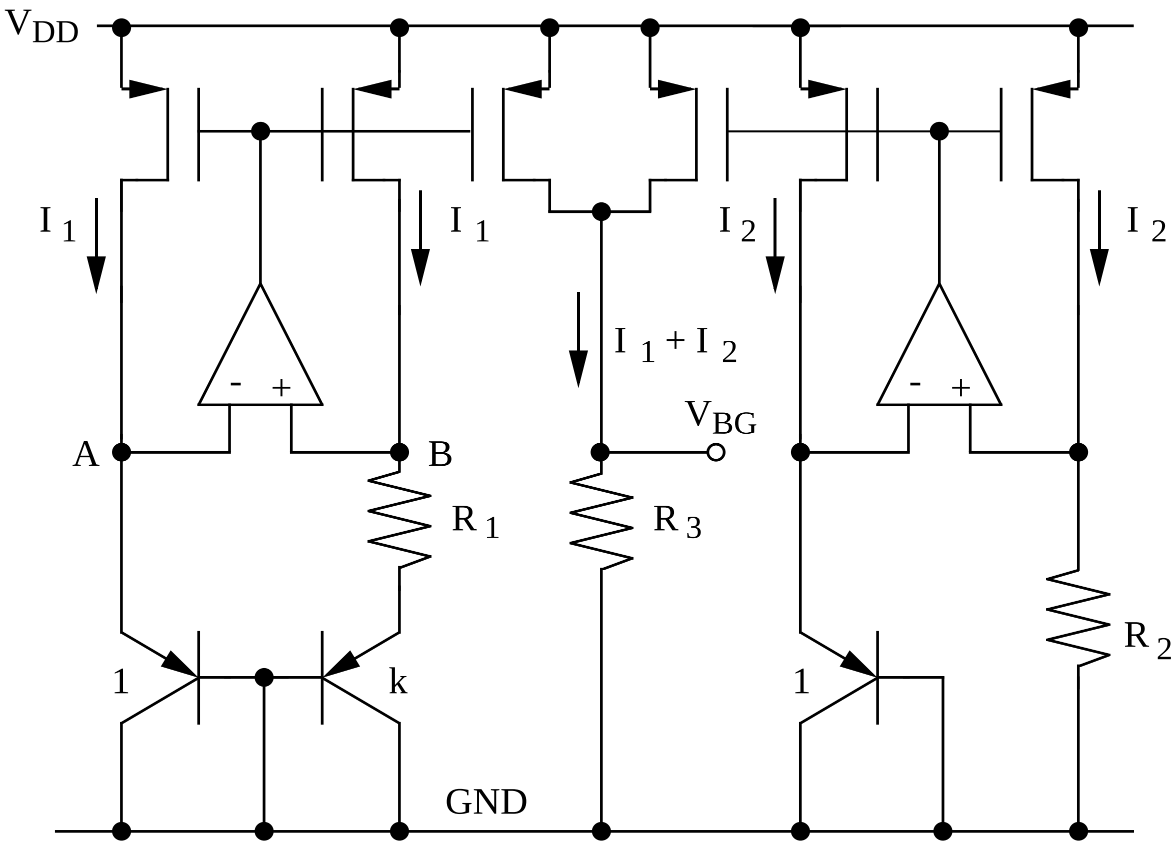
$$m = \frac{R_2}{R_1} \ln \frac{(W/L)_1}{(W/L)_2}\frac{A_2}{A_1}$$

ANOTHER VOLTAGE MODE SOLUTION



The matching of currents I_1 and I_2 depends on R_1 and R_2.

CURRENT MODE BANDGAP



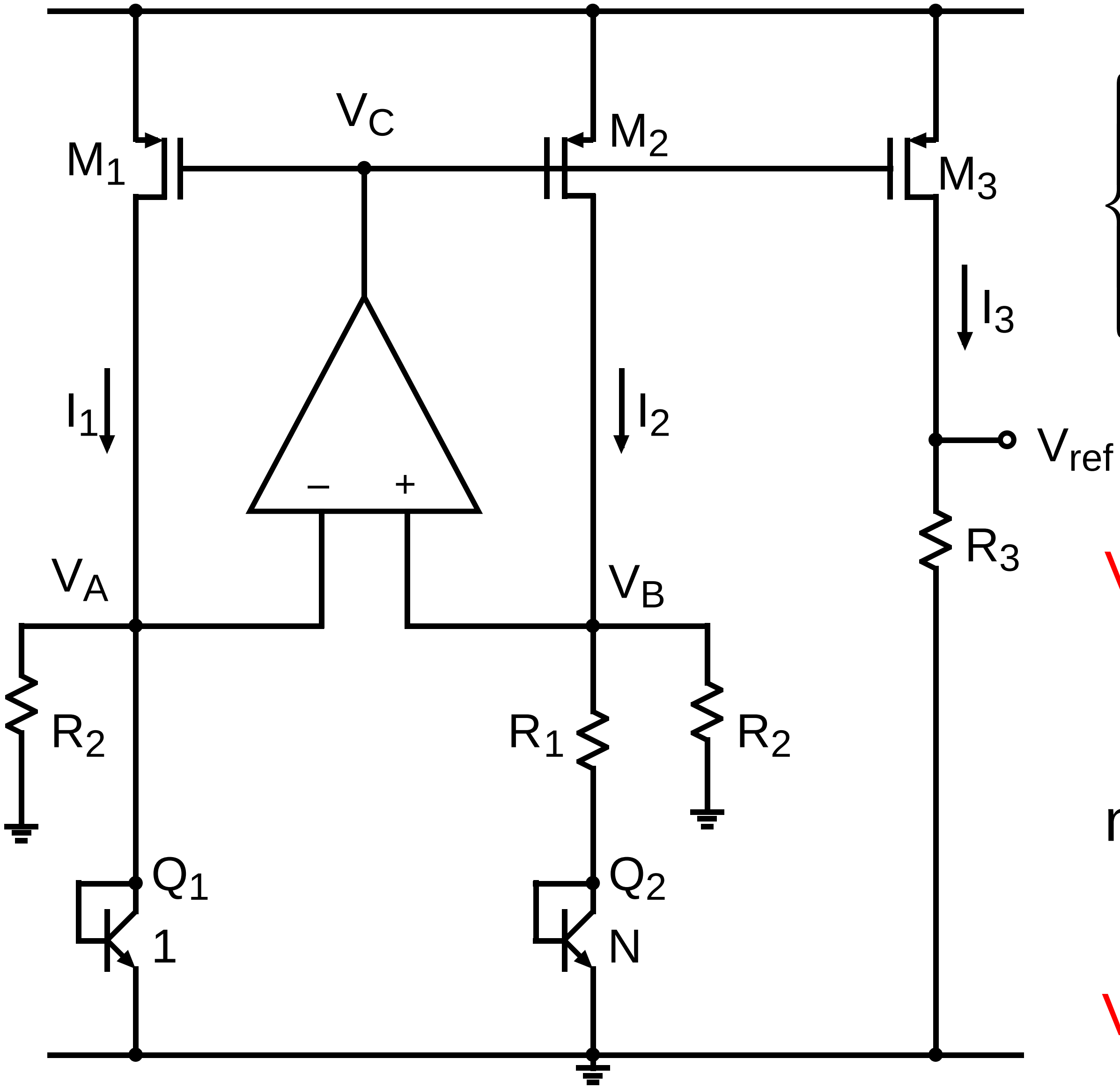
$$V_A = V_B = V_{BE}$$

$$I_1 = \frac{V_T \ln(N)}{R_1}$$

$$I_2 = \frac{V_{BE}}{R_2}$$

$$V_{BG} = \left(\frac{V_T \ln(N)}{R_1} + \frac{V_{BE}}{R_2}\right) \cdot R_3$$

MERGING THE TWO BRANCHES



$$\begin{cases} V_A = V_B = V_{BE} \\ I_1 = I_2 = \dfrac{V_T \ln(N)}{R_1} + \dfrac{V_{BE}}{R_2} = I_3 \end{cases}$$

$$V_{ref} = V_T\left(\frac{R_3 \ln(N)}{R_1}\right) + V_{BE}\left(\frac{R_3}{R_2}\right)$$

$$n = \frac{R_2 \ln(N)}{R_1} = 25 \text{ and } \alpha = \frac{R_3}{R_2}$$

V_{ref} ➜ Temperature independent

LOW-VOLTAGE OP-AMP

✌ The described architecture is good for generating low voltage band-gap

BUT

we need a LOW-VOLTAGE Op-Amp

❒ Band gap minimum supply voltage is $V_{DD} = V_{BE} + V_{sat,\,p}$
  - ✌ VDD = 1 V is sufficient to operate the circuit
  - ✗ The operational amplifier has to operate from $V_{DD} = 1$ V

THEREFORE

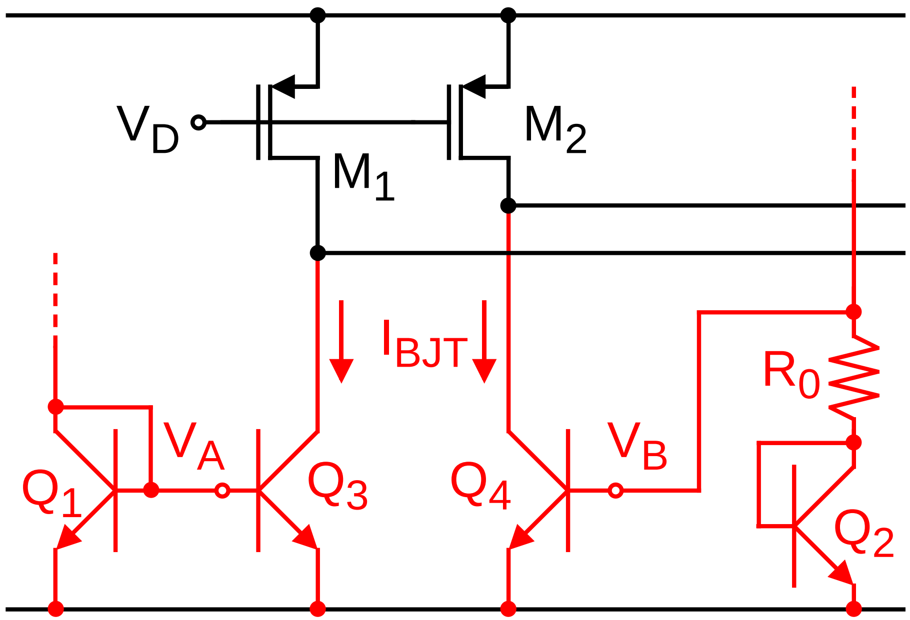
❒ The operational amplifier is the most critical block
  - ➥ Input common-mode voltage ➜ $V_{BE} \cong 0.65$ V
  - ➥ Output voltage ➜ $V_{Cut} = V_{DD} - V_{th,\,p} - V_{sat,\,p} \cong 0.15\ \text{V} \div 0.2\ \text{V}$

OP-AMP DESIGN CONSIDERATIONS

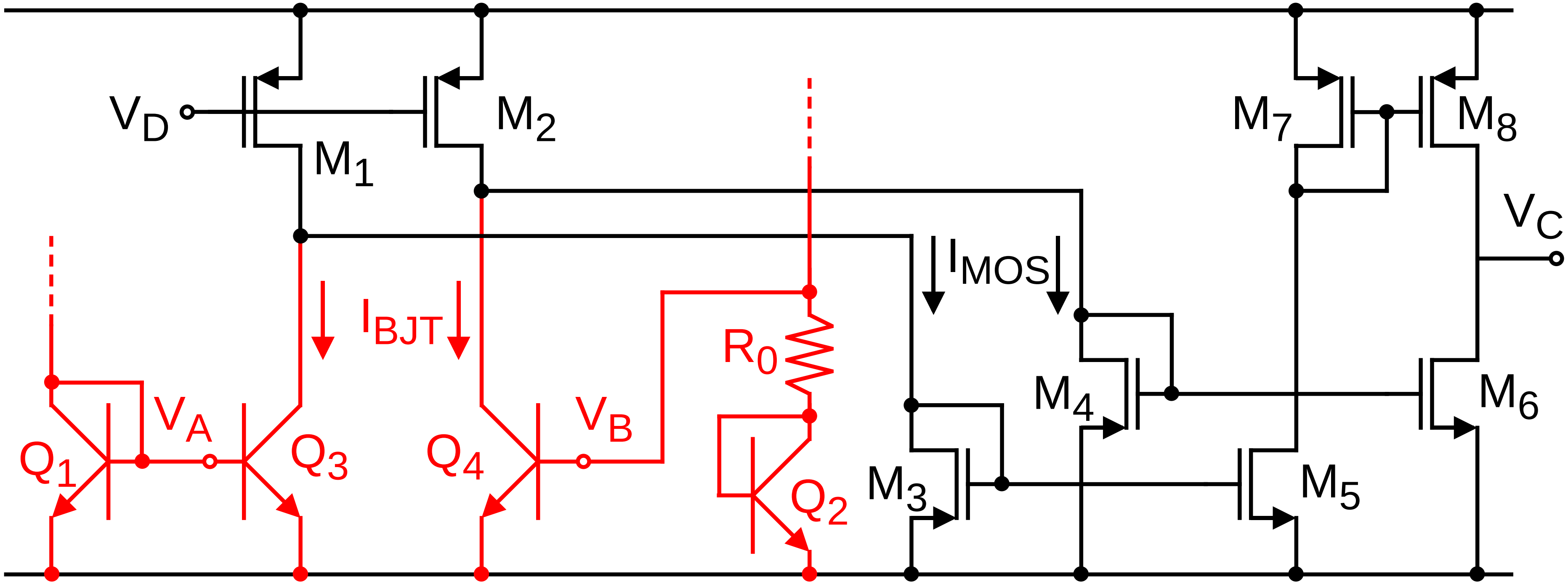
- ❐ Choice of architecture
  - ➥ No speed limitations
  - ➥ DC gain: around 60 dB
  - ➥ Very low offset
- ❐ Constrains
  - ✗ Input stage ➜ No MOS input differential pair
  - ✗ Output stage ➜ No cascode structures
- ❐ Observations
  - ➥ if $V_{th} < 0.5$ V @ $V_{DD} = 1$V ➜ all MOS operational amplifier
  - ➥ if $V_{th} > 0.5$ V @ $V_{DD} = 1$V ➜ use bipolar transistors
  - ➥ The input common mode voltage is V_{BE}

TECHNOLOGY AND OP-AMP

- ❒ Since the threshold of CMOS is high, we had to use BiCMOS
- ❒ Why using an input differential pair?
  - ➥ to control the tail current
  - ➥ to reject a common mode input component
  - ✌ Those requirements are not essential in our circuit

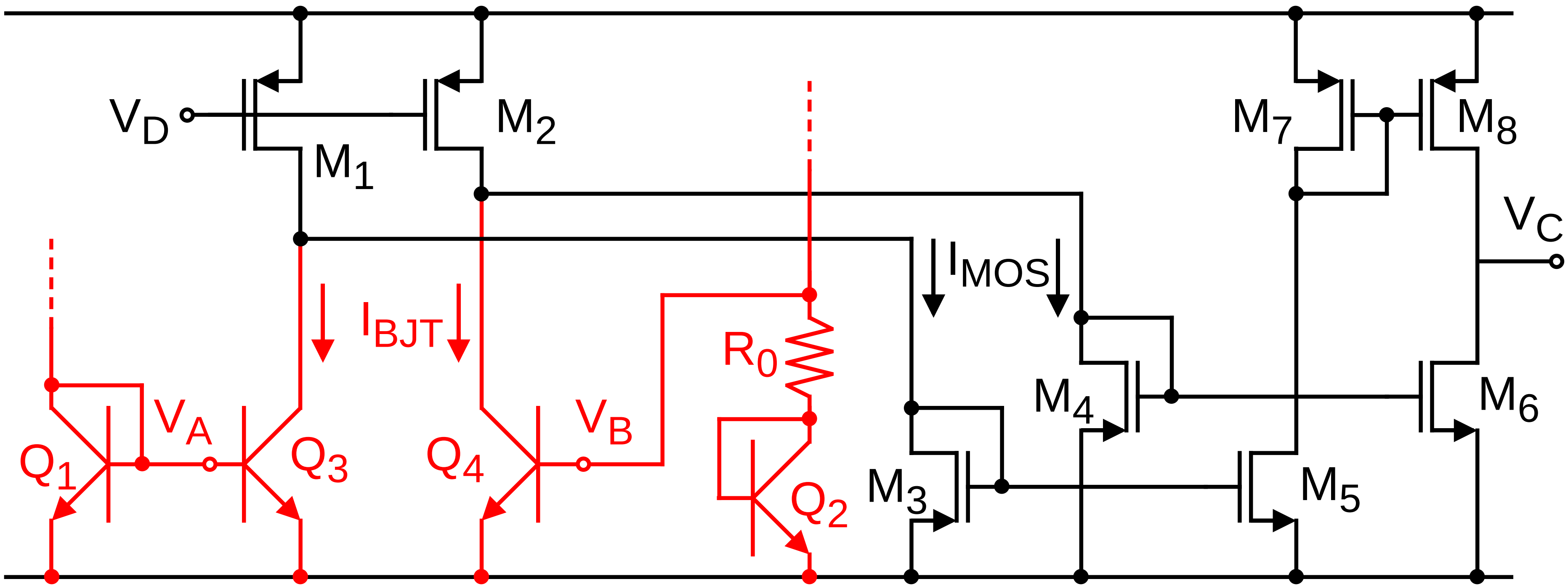


OPERATIONAL AMPLIFIER



- Two-stages operational amplifier
- Input stage with grounded bipolar transistors
  - No current source required to provide the bias current
- Bias current ➜ $V_A = V_B = V_{BE}$ ➜ $I_{Q3} = I_{Q4} = I_{BJT} = V_T \ln(N)/R_0$

OFFSET OF THE OP-AMP



- M3 and M4: matched conditions
- Output voltage ➜ $V_{Cut} = V_{DD} - V_{th,\,p} - V_{sat,\,p} \cong 0.15\ \mathrm{V} \div 0.2\ \mathrm{V}$
- Drain of M7 ➜ $V_{D7} = V_{DD} - V_{th,\,p} - V_{sat,\,p} \cong 0.15\ \mathrm{V} \div 0.2\ \mathrm{V}$

OPERATIONAL AMPLIFIER

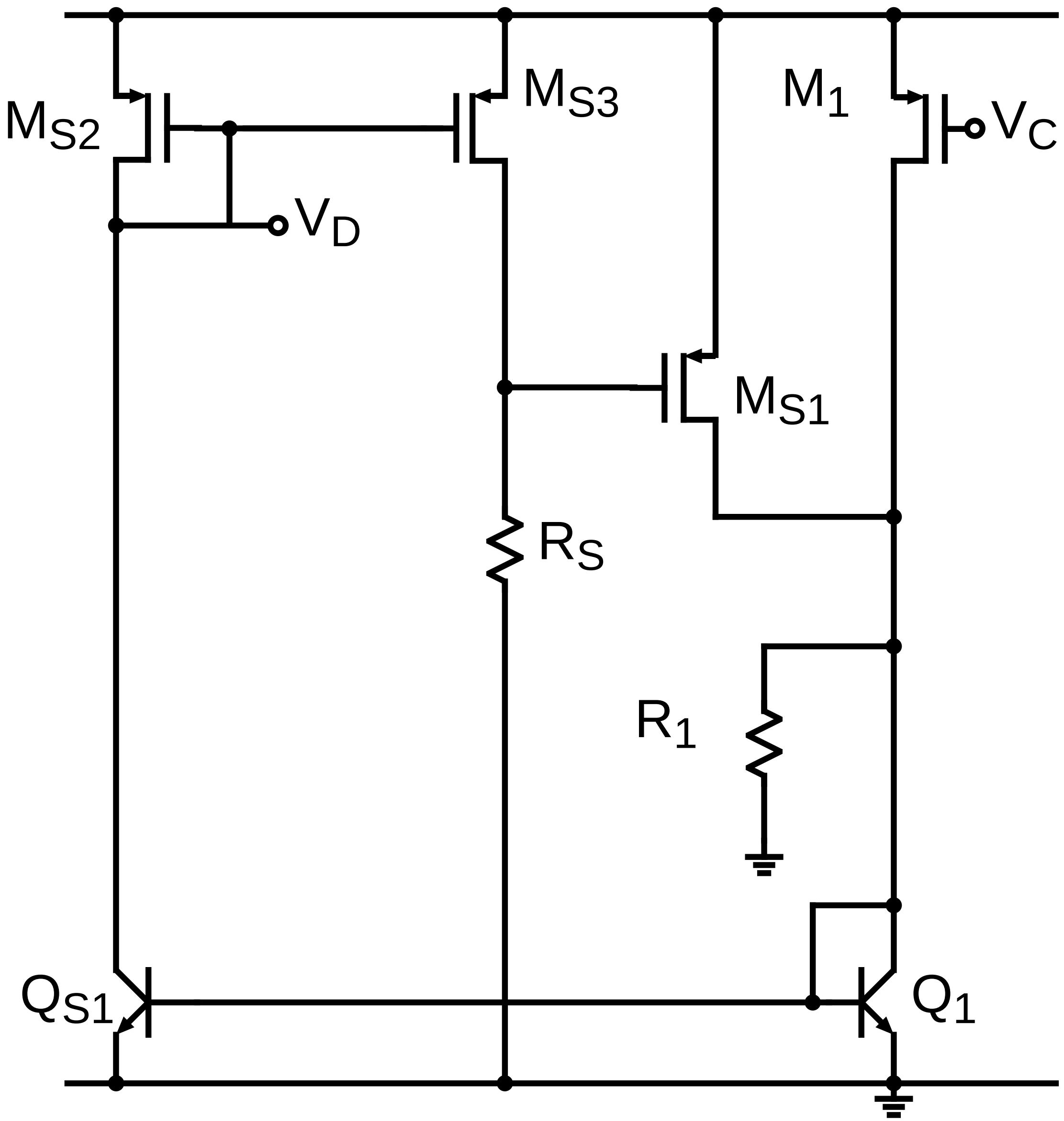
Simulated Performance	
Parameter	**Value**
Technology	0.8 µm BiCMOS
p-MOS Transistor Threshold Voltage n-MOS Transistor Threshold Voltage	840 mV 800 mV
DC Gain	60 dB
Gain-Bandwidth Product	1.2 MHz
Phase Margin	63˚
Systematic Offset Voltage	625 µV
Supply Voltage	1 V
Current Consumption @ T = 25˚ C	35 µA

STARTUP CIRCUIT

- ❒ In every bandgap circuit there are two stable operating points
  - ✌ Desired operating point ➜ $I_{Q_1} = I_{Q_2} = V_T \ln(N) / R_0$, $V_{ref} \neq 0$
  - ✗ Undesired operating point ➜ $I_{Q_1} = I_{Q_2} = 0$, $V_{ref} = 0$

- ❒ The operational amplifier systematic offset during the startup phase can cause metastability in the bandgap circuit
  - ➥ The operational amplifier has to startup at least as fast as the bandgap circuit
  - ✌ Operational amplifier bias current $I_{BJT} = I_{Q_1} = I_{Q_2}$
  - ✌ All of the currents in the operational amplifier and in the bandgap circuit are matched
  - ➥ No operational amplifier systematic offset during startup

STARTUP CIRCUIT



- $I_{Q_1} = 0 \rightarrow I_{Q_{S1}} = 0$
  - M_{S2} and M_{S3} are off
  - $V_{GS,\,M_{S1}} = V_{DD}$
  - $I_{M_{S1}}$ flows into Q_1 and R_1
  - The circuit leaves the undesired operating point
  - $I_{Q_1} \rightarrow \dfrac{V_T \ln(N)}{R_0}$
- In normal operating conditions
  - $I_{Q_1} \neq 0 \rightarrow I_{M_{S3}} R_S \cong V_{DD}$
  - M_{S1} switches off

CURVATURE COMPENSATION

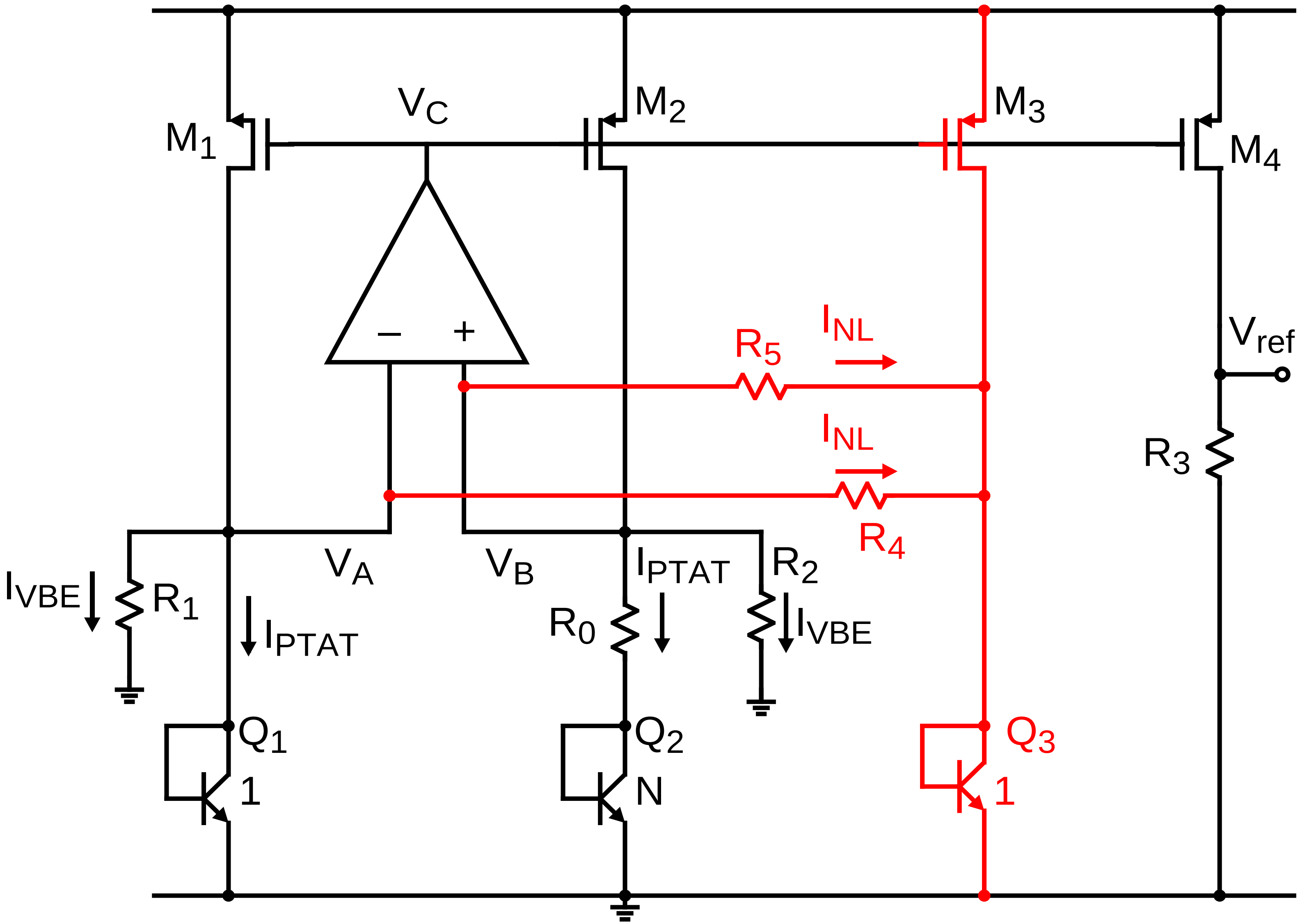
- ❒ Simple bandgap circuits: temperature compensation is at first order
  - L V_{BE} does not change linearly with temperature

$$V_{BE}(T) = V_{BG} - [V_{BG} - V_{BE0}]\frac{T}{T_0} - (\eta - \alpha)\ln\frac{T}{T_0}$$

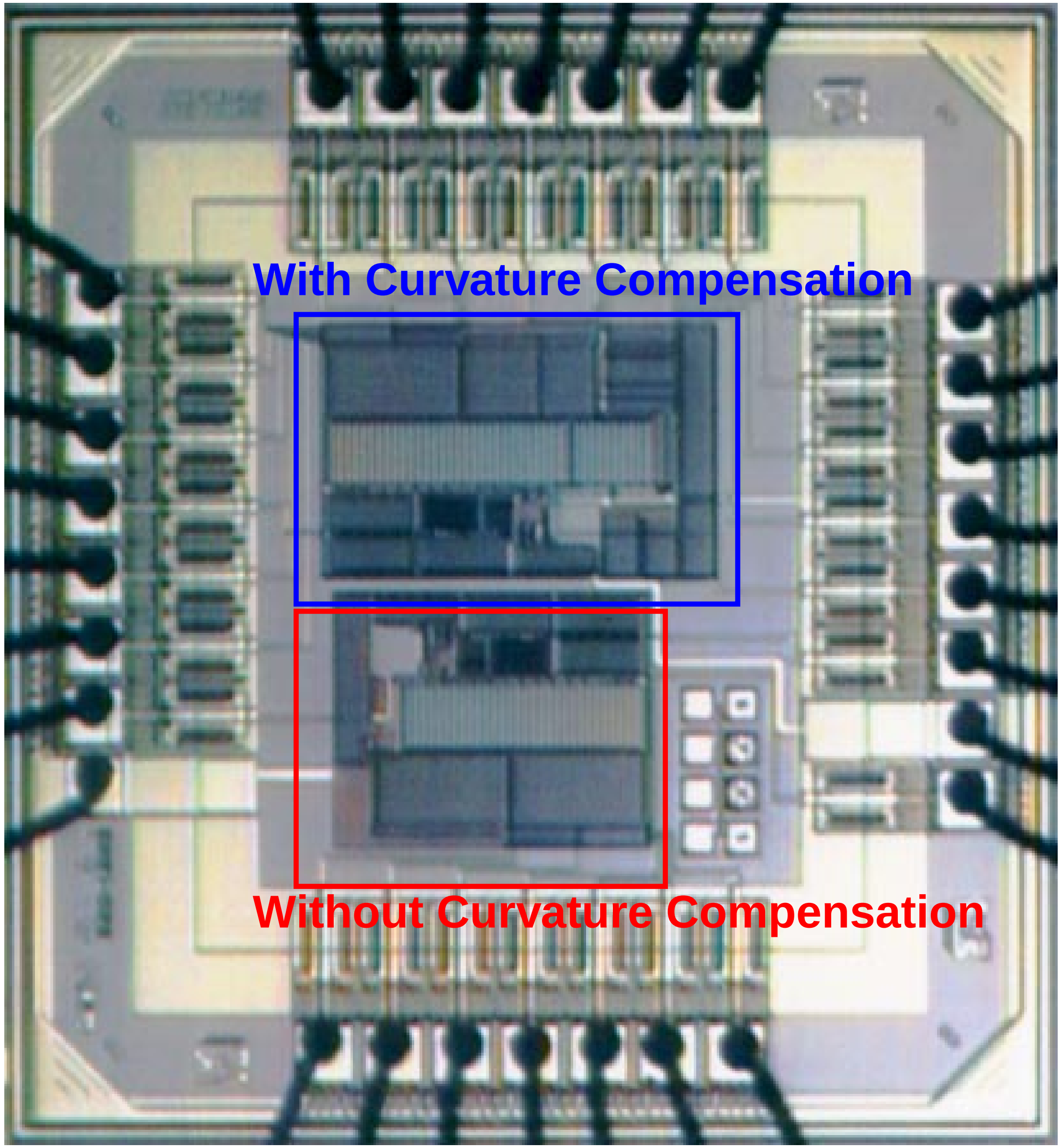
  - ➥ $\eta \cong 4$ ➜ Depends on the bipolar transistor structure
  - ➥ Temperature independent current (I_{TI}) in the transistor ➜ $\alpha = 0$
  - ➥ PTAT current (I_{PTAT}) in the transistor ➜ $\alpha = 1$

- ❒ $V_{BE@I_{TI}} - V_{BE@I_{PTAT}}$ ➜ Nonlinear term ➜ Correction
  - ➥ I_{Q_1} ➜ PTAT current
  - ➥ I_{M_1} ➜ Temperature independent current
  - ✌ Simple generation of the nonlinear term

CURVATURE COMPENSATION

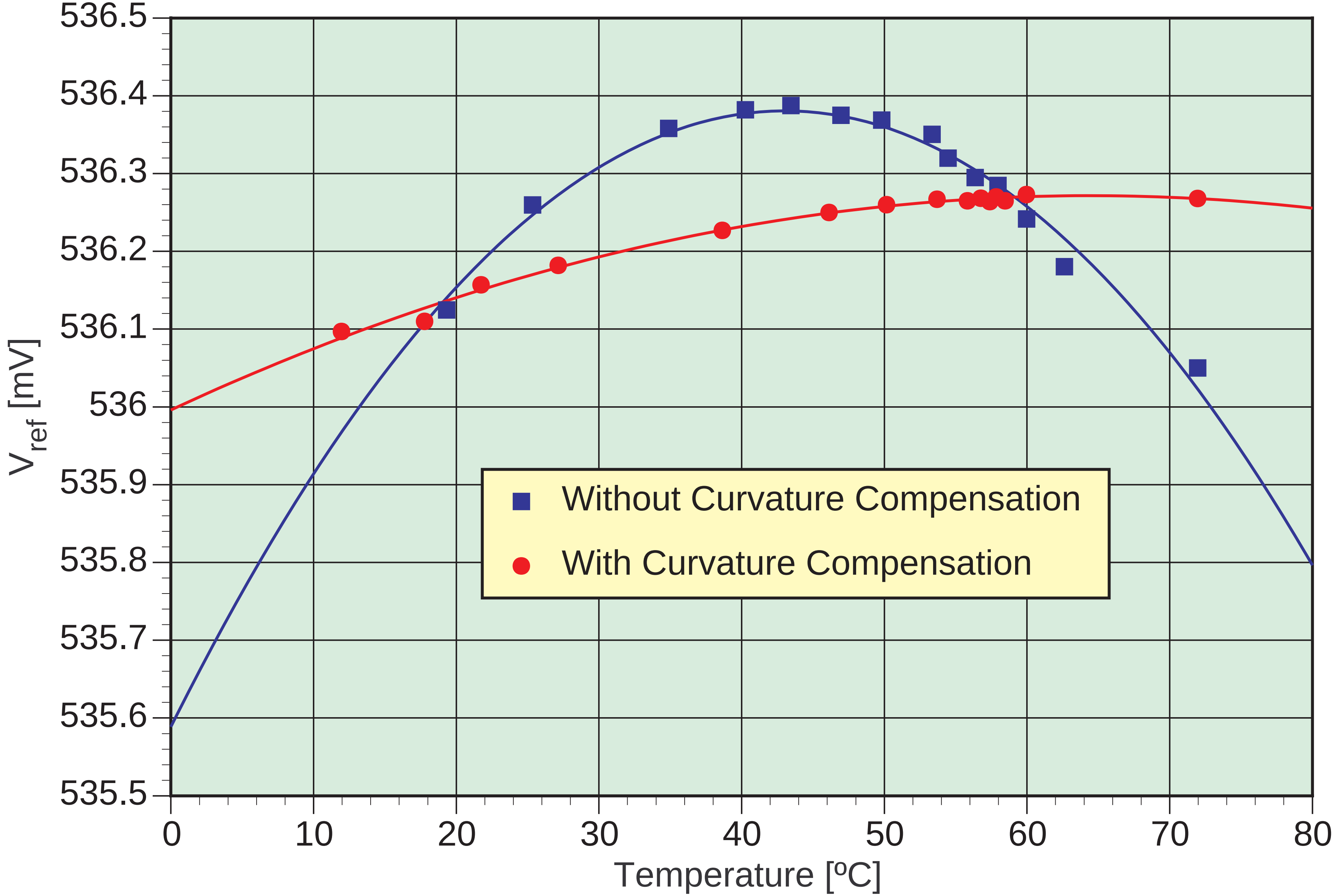


CHIP MICROGRAPH

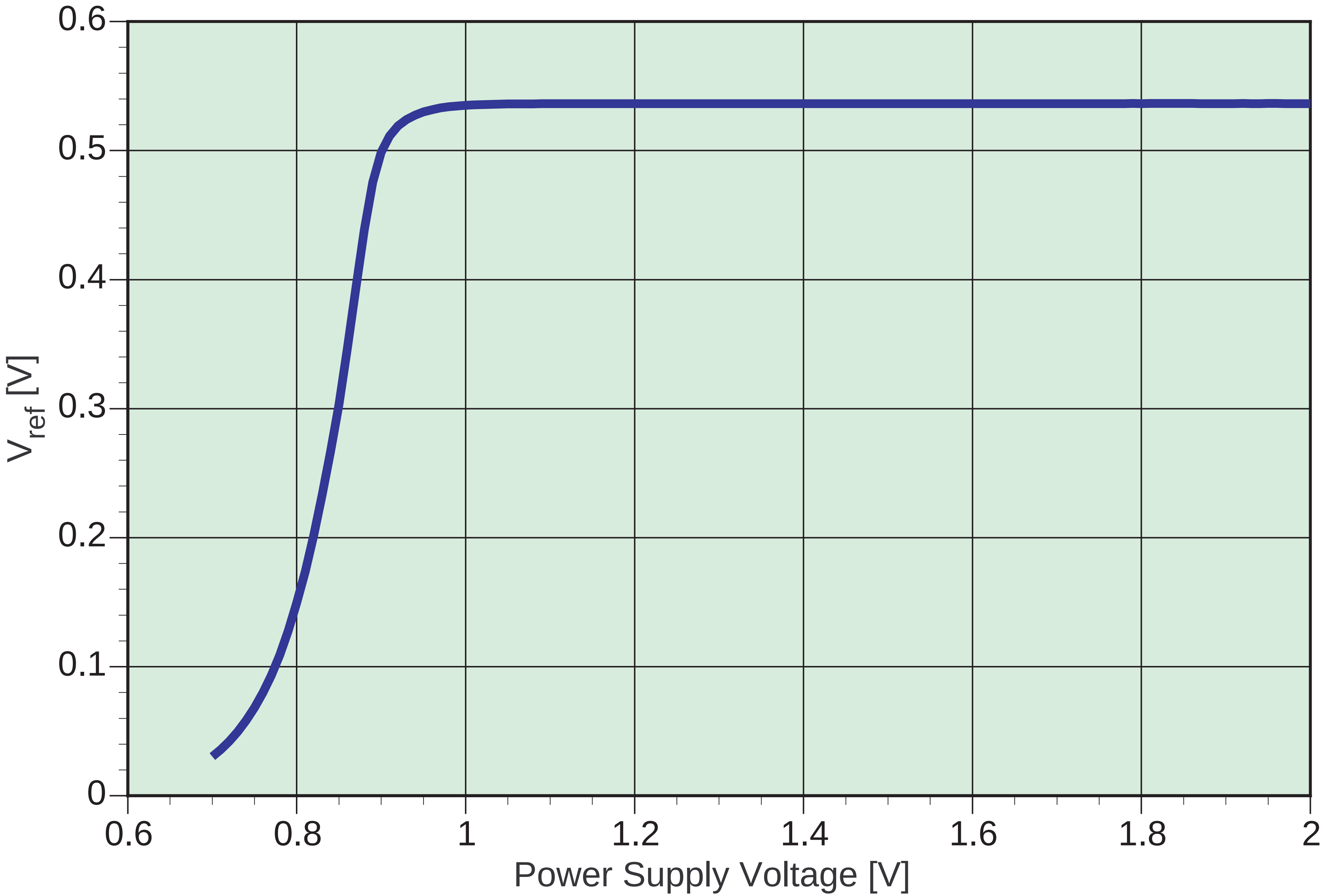


- Technology
  - 0.8 µm BiCMOS
  - Double poly
  - Double metal
- Total area including pads
  - 3 mm^2
- Core area
  - 0.20 mm^2
  - 0.25 mm^2
- Trimming of resistors
  - R_0, R_4 and R_5
  - 8 pins per resistor

EXPERIMENTAL RESULTS



EXPERIMENTAL RESULTS



PERFORMANCE SUMMARY

Parameter	Value
Power Supply Voltage	1 V
Technology	0.8 μm BiCMOS
Bandgap Cell Area Without Curvature Compensation With Curvature Compensation	 0.20 mm^2 0.25 mm^2
Power Consumption @ 25° C	92 μW
Reference Voltage @ 25° C	536 mV
Temperature Variation (0° C ÷ 80 ° C) Without Curvature Compensation With Curvature Compensation	 800 μV 300 μV
Voltage Coefficient	114 μV/V

CONCLUSIONS

- Low voltage (V_{DD} = 1 V) bandgap can be achieved with current-mode structures AND low voltage, low offset op-amps
- A current mode structure permits to achieve curvature compensation in a simple way (no extra op-amps
- Experimental results show that it is possible to achieve 0.5 V reference with 1 V supply and a well controlled temperature behavior.

THANK YOU!