# CH8

## 8.2 Bias circuit

# 8.2 Bias circuit

Ideal voltage or current source : no PVT dependence

(PVT: process voltage temperature)

1. Supply voltage dependence of bias circuit
2. Self-bias circuit
3. CMOS band-gap reference

# 8.2.1 Supply dependence

Simple current source (use VDD as reference voltage):
VDD increase ➔ Iout increase

$$\Delta I_{out} = \frac{\Delta V_{DD}}{R_1 + 1/g_{m1}} \cdot \frac{(W/L)_2}{(W/L)_1}$$

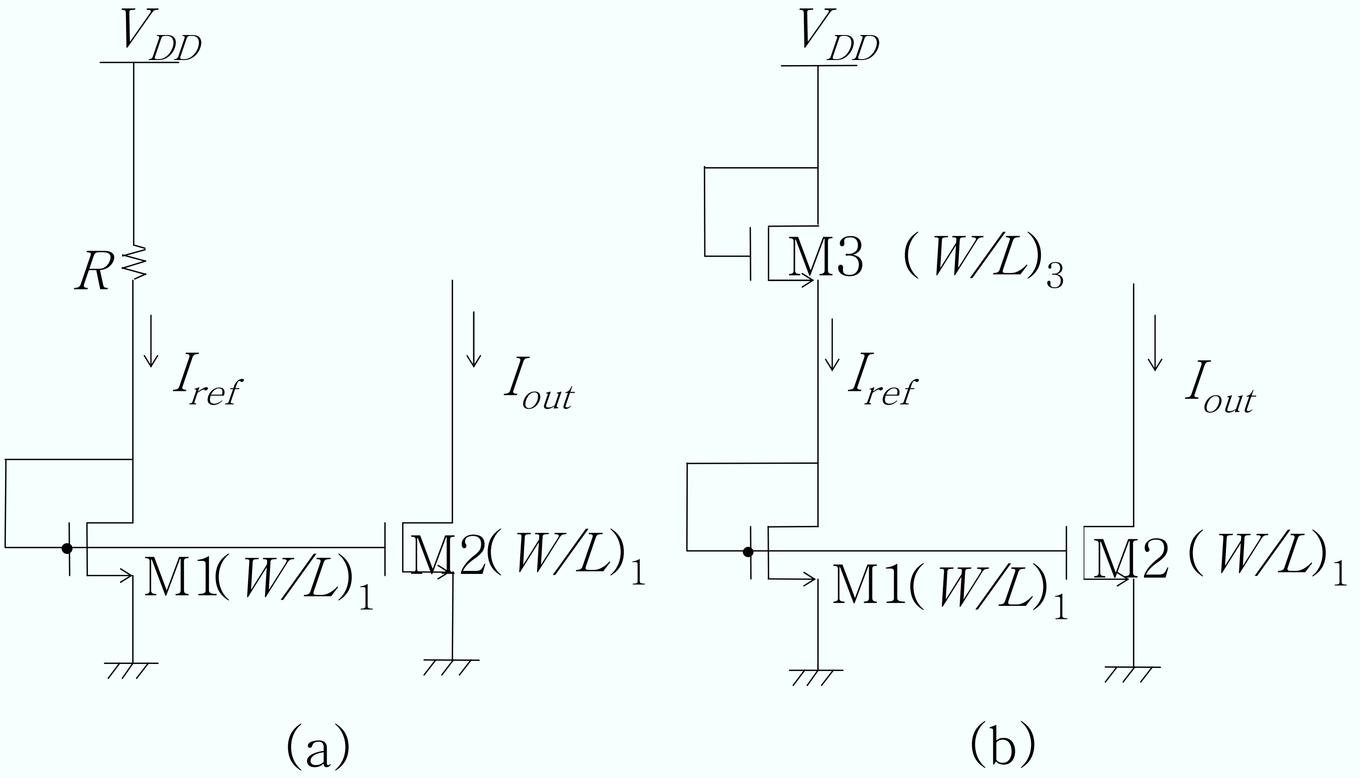
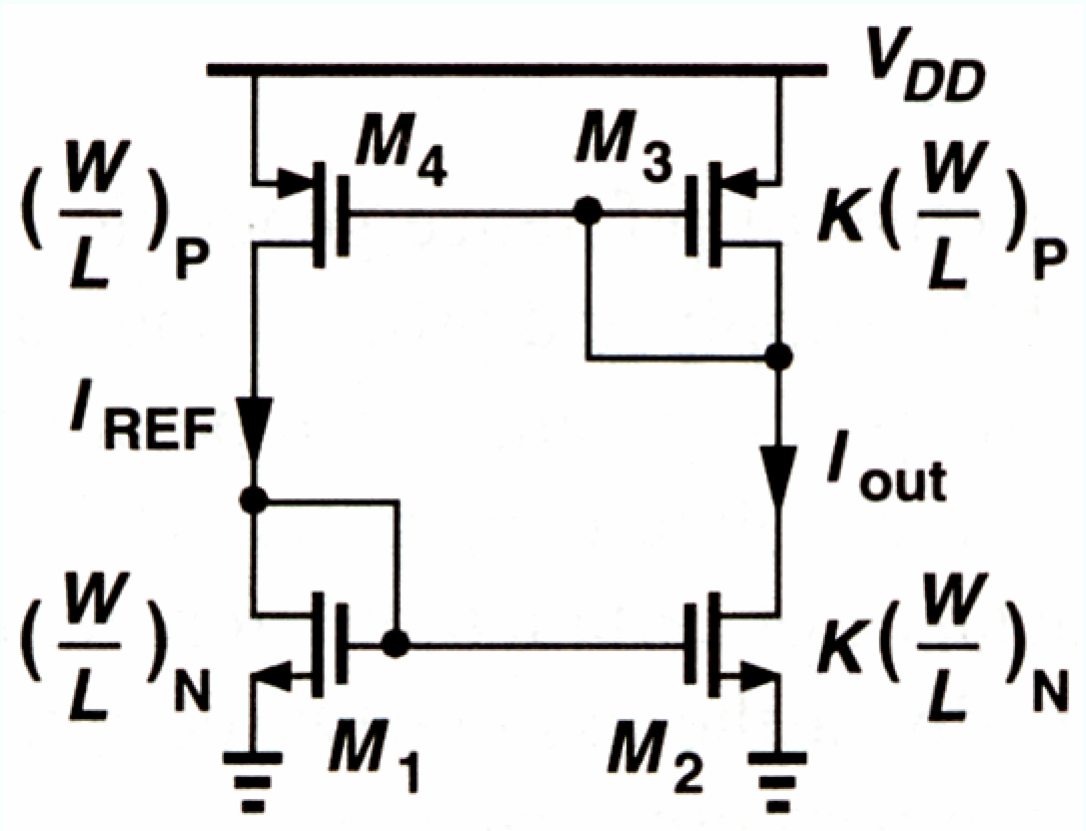


**Fig 8.2.1** Simple current bias circuits

# Self-bias circuit

## A simple self-bias circuit

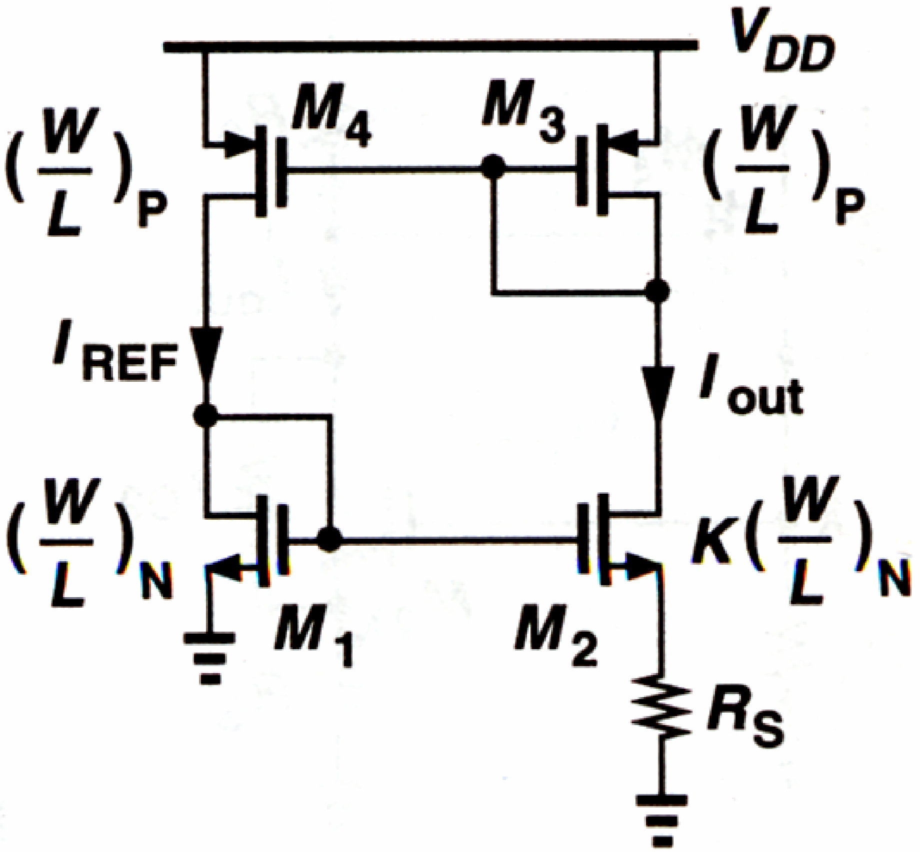


$$I_{out} = K I_{REF}$$

Iout can be any value (including 0),
Cannot be used

Razavi

# Self-bias circuit



Iout determined to be a single value

M3, M4 ➔ Iref = Iout

M1, M2, Rs ➔
VGS1 = VGS2 + Iout x Rs

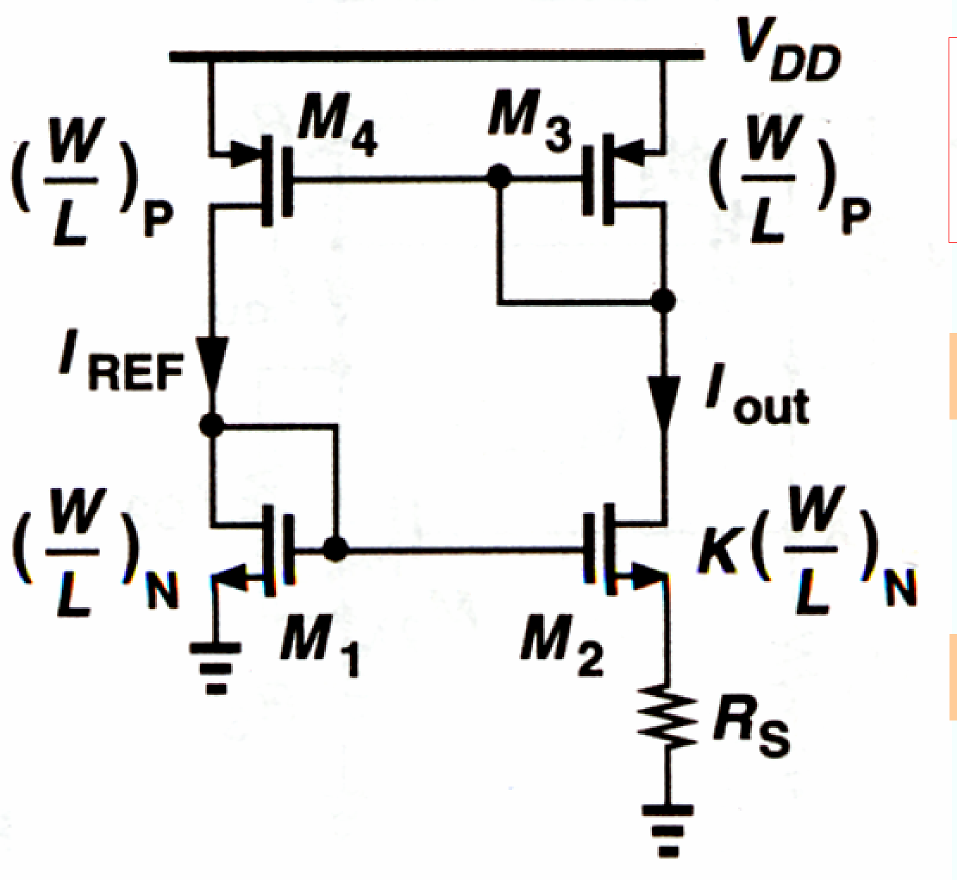
$$\sqrt{\frac{2I_{out}}{\mu_n C_{ox}(W/L)_N}} + V_{TH1} = \sqrt{\frac{2I_{out}}{\mu_n C_{ox} K (W/L)_N}} + V_{TH2} + I_{out} R_S$$

Iout can be 0

$$\boxed{I_{out} = \frac{2}{\mu_n C_{ox}(W/L)_N} \cdot \frac{1}{R_S^2}\left(1 - \frac{1}{\sqrt{K}}\right)^2}$$

Razavi

# Self-bias circuit

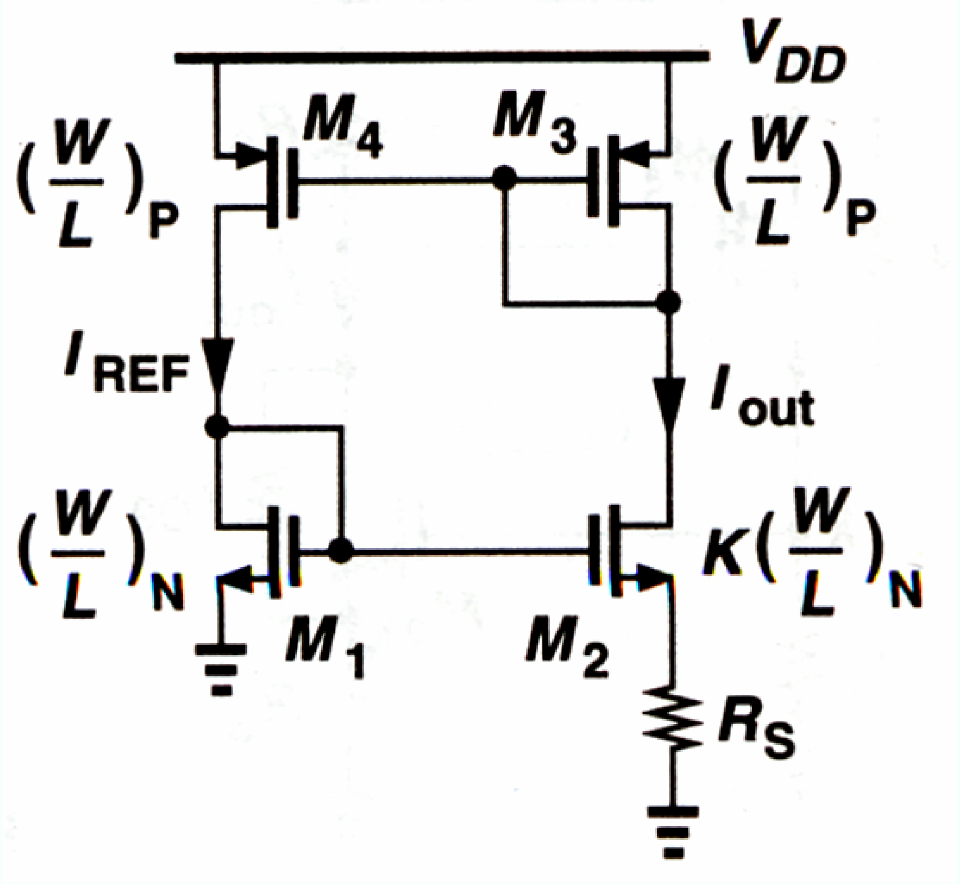


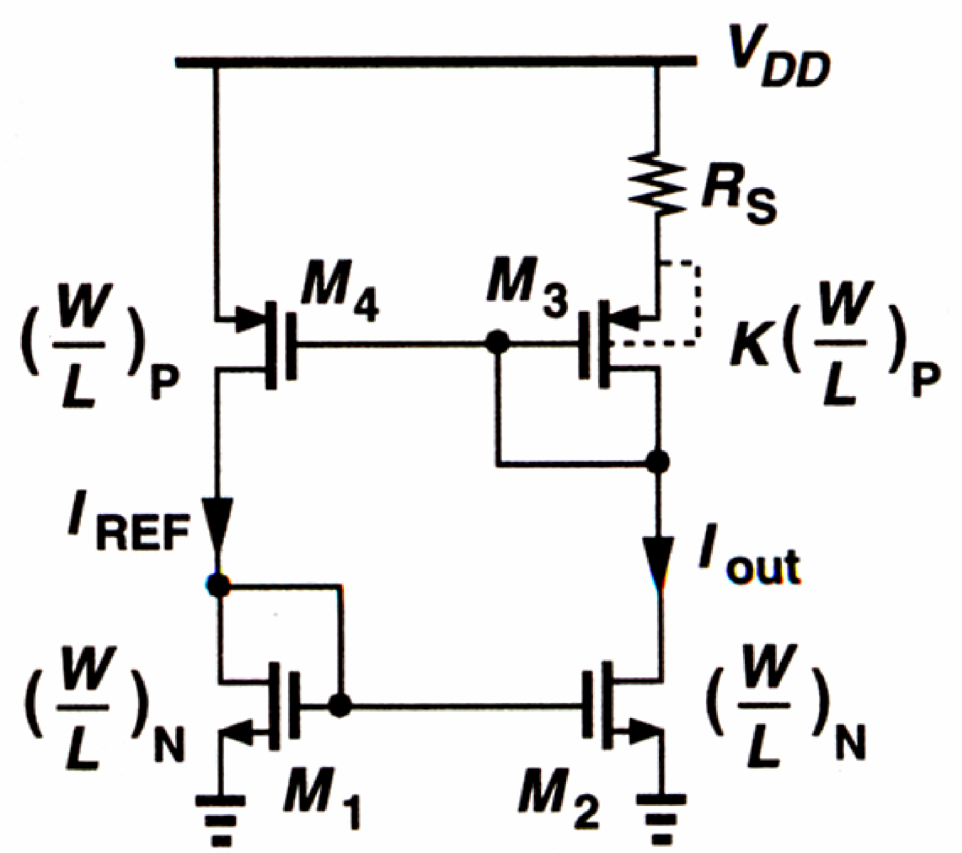
$$I_{out} = \frac{2}{\mu_n C_{ox}(W/L)_N} \cdot \frac{1}{R_S^2}\left(1 - \frac{1}{\sqrt{K}}\right)^2$$

Iout can be 0 ➔ needs start-up ckt

Body effect on M2 ➔ inaccuracy

# Self-bias circuit

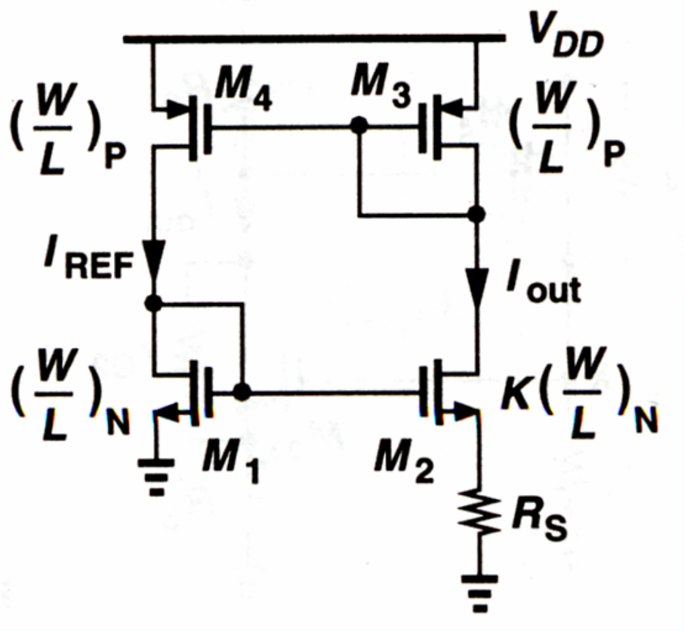




Body effect eliminated

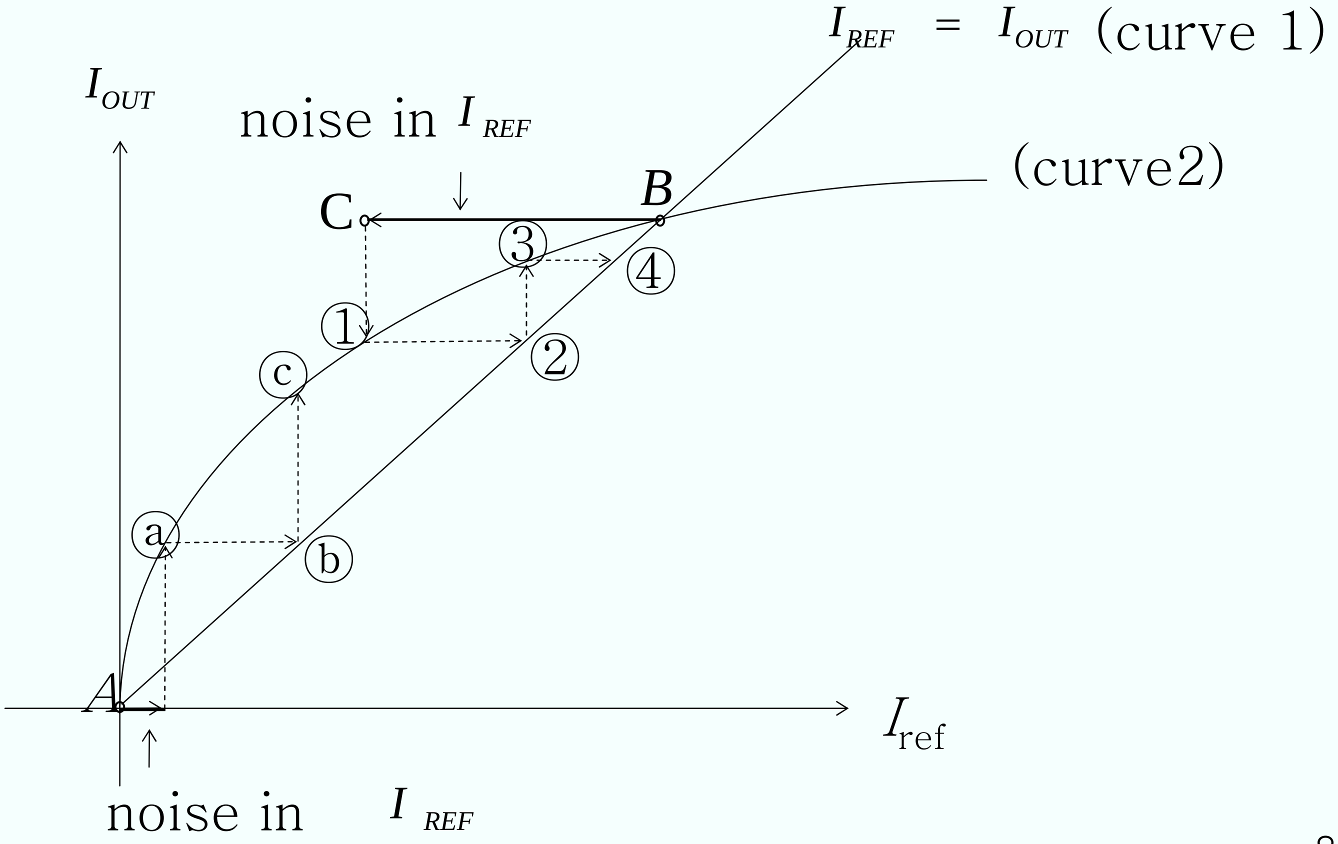
Errata: M4, M2 in diode
M3, M1 Not in diode

Razavi

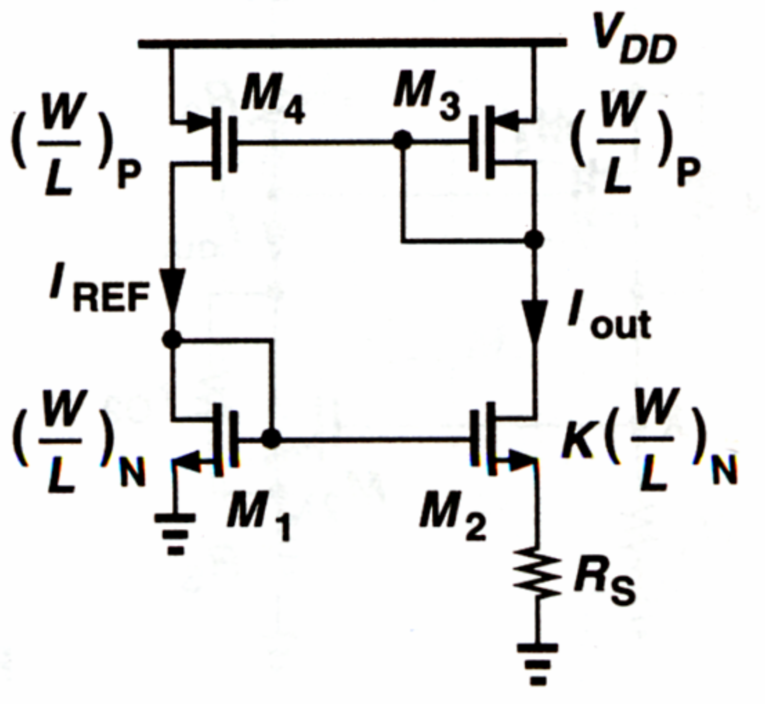


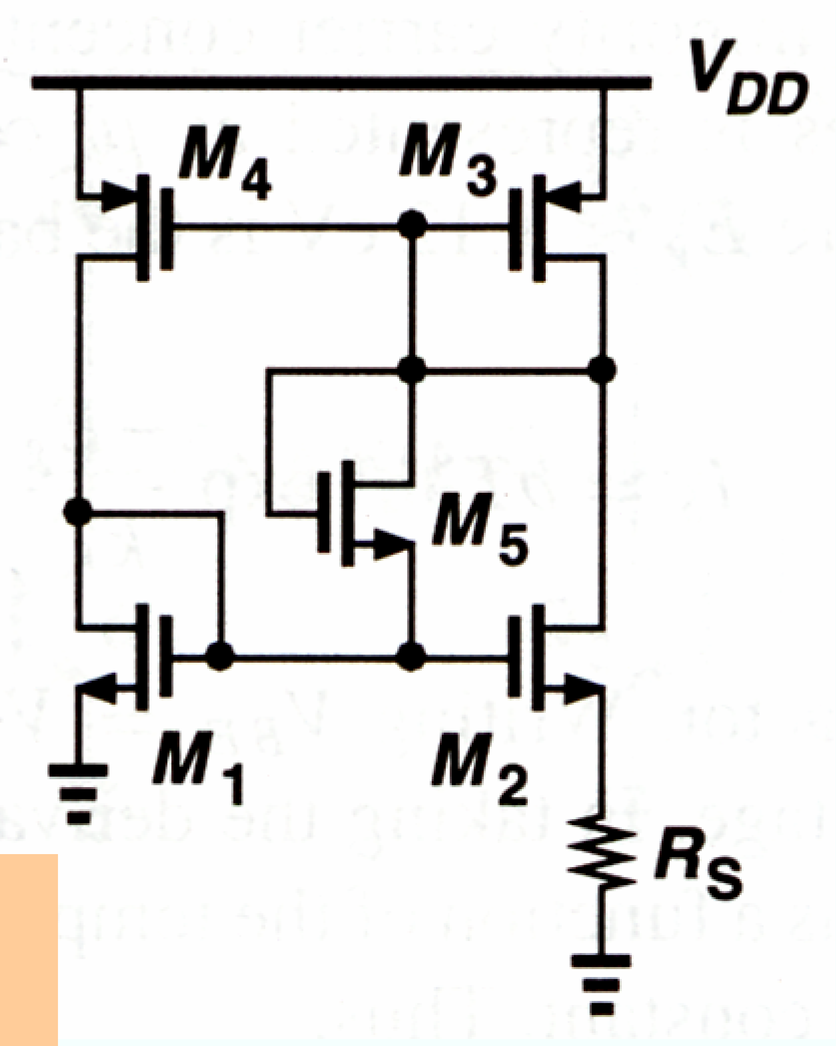
# Iref = Iout (curve 1)

$$\sqrt{\frac{2I_{out}}{\mu_n C_{ox}(W/L)_N}} + V_{TH1} = \sqrt{\frac{2I_{out}}{\mu_n C_{ox}K(W/L)_N}} + V_{TH2} + I_{out}R_S$$



# Self-bias circuit with start-up





Eliminate the operating point of Iout=0

Constraints:

(1) $V_{TH1} + V_{TH5} + |V_{TH3}| < V_{DD}$

(2) $V_{GS1} + V_{TH5} + |V_{GS3}| > V_{DD}$

➔ Not a good start-up ckt

Razavi

# Supply voltage dependence

Supply–insensitive biasing :

cannot use VDD as reference

Use one of the following three as reference instead

(1) BJT VBE

(2) MOS threshold voltage

(3) Thermal voltage VT

➔ self bias circuit

Band gap reference : PVT insensitive voltage source(~1.2V)

# 8.2.5 CMOS band gap reference

$$V_{out} = V_{BE} + K \cdot V_T$$

$$\frac{\partial V_{out}}{\partial T} = \frac{\partial V_{BE}}{\partial T} + \frac{K \cdot V_T}{T}$$

$$K = \left(1.65\, mV / {}^\circ C\right) / \left(0.083\, mV / {}^\circ C\right) = 19.9$$

➔ 0 TC

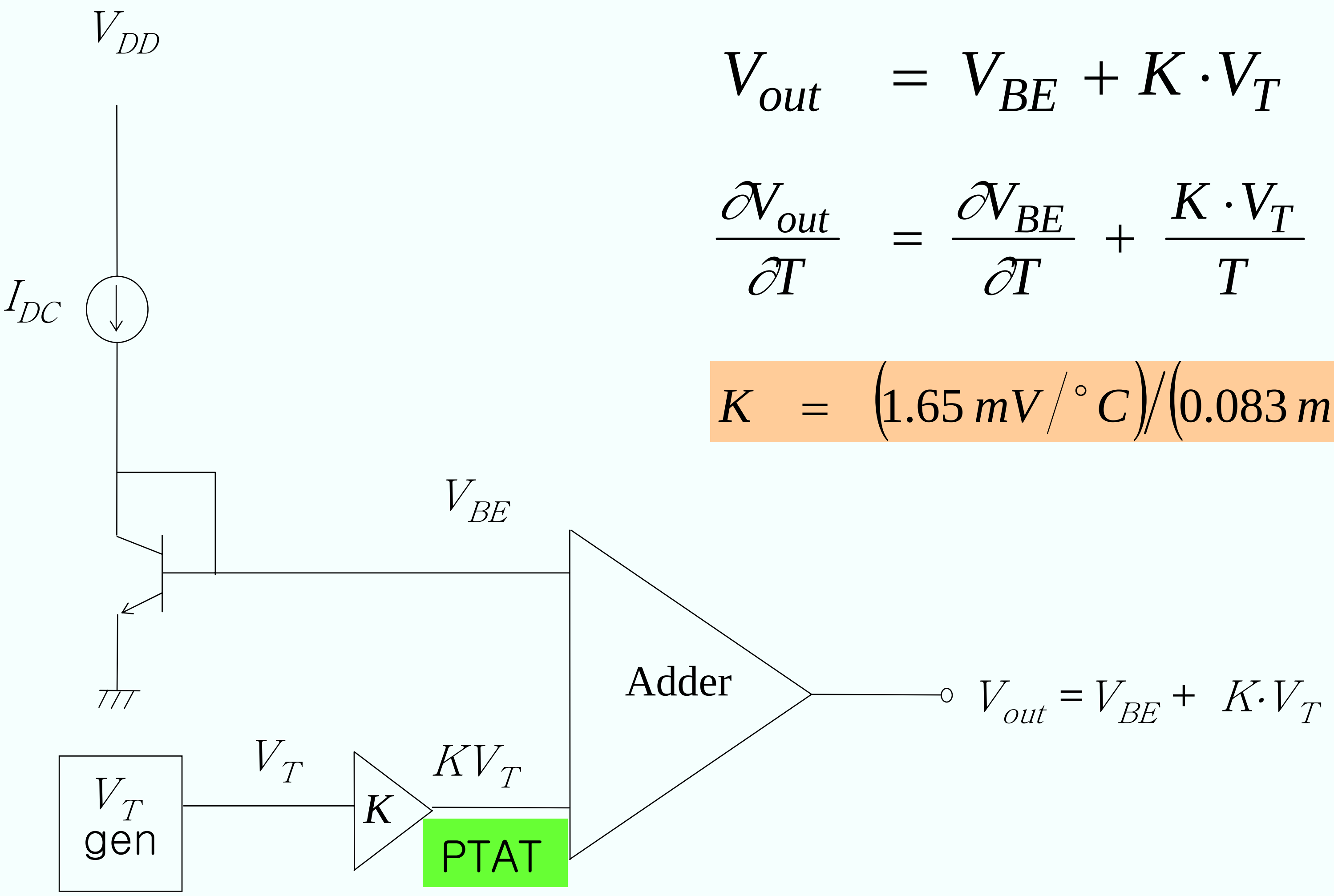


**Fig 8.2.9** Band gap reference voltage source

# Temp. dependence of BJT base-emitter voltage

$$V_{BE}(T) = V_T \cdot \ln\left\{\frac{I_{DC}}{I_S(T)}\right\}$$

➔Assumed DC collector current (constant and PVT independent)

$$I_S = \frac{qA_E D_n n_i^2}{N_A \cdot W_B}$$

$$n_i^2 = 4 \cdot \left(\frac{2\pi k\sqrt{m_n^* m_p^*}}{h^2}\right)^3 \cdot T^3 \cdot e^{-\frac{E_G}{kT}}$$

$$n_i^2(T) = (1.45\times 10^{10})^2 \cdot \left(\frac{T}{300}\right)^3 \cdot e^{-\frac{E_G(T)}{kT}} \cdot e^{+\frac{E_G(300)}{300\,k}}$$

$$I_S(T) = I_S(300)\cdot\left(\frac{T}{300}\right)^{4+m} \cdot e^{-\frac{E_G(T)}{kT}} \cdot e^{+\frac{E_G(300)}{300\,k}}$$

**M = -1.5 due to Temperature dependence of mobility (un)**

# Temp. dependence of BJT base-emitter voltage

$$V_{BE}(T) = V_T \cdot \ln\left\{\frac{I_{DC}}{I_S(T)}\right\} = V_T \cdot \ln\left\{\frac{I_{DC}}{I_S(300)\cdot\left(\frac{T}{300}\right)^{4+m}\cdot e^{-\frac{E_G(T)}{kT}}\cdot e^{+\frac{E_G(300)}{300k}}}\right\}$$

$$= V_T \cdot \ln\left(\frac{I_{DC}}{I_S(300)}\right) - (4+m)\cdot V_T \cdot \ln\left(\frac{T}{300}\right) + \frac{E_G(T)}{q} - V_T \cdot \frac{E_G(300)}{300\,k}$$

$$= \frac{T}{300}\cdot\left\{V_{BE}(300) - \frac{E_G(300)}{q} - (4+m)\cdot V_{T300}\cdot\ln\left(\frac{T}{300}\right) + \frac{300}{T}\cdot\frac{E_G(T)}{q}\right\}$$

$$\frac{\partial V_{BE}(T)}{\partial T} = \frac{1}{300}\left\{V_{BE}(300) - \frac{E_G(300)}{q} - (4+m)\cdot V_{T300}\cdot\left\{\ln\frac{T}{300}+1\right\} + \frac{300}{q}\cdot\frac{\partial E_G(T)}{\partial T}\right\}$$

$$\left.\frac{\partial V_{BE}(T)}{\partial T}\right|_{T=300^\circ K} = \frac{1}{300}(0.75-1.12-0.0625-0.051) = -1.61\,mV/^\circ C$$

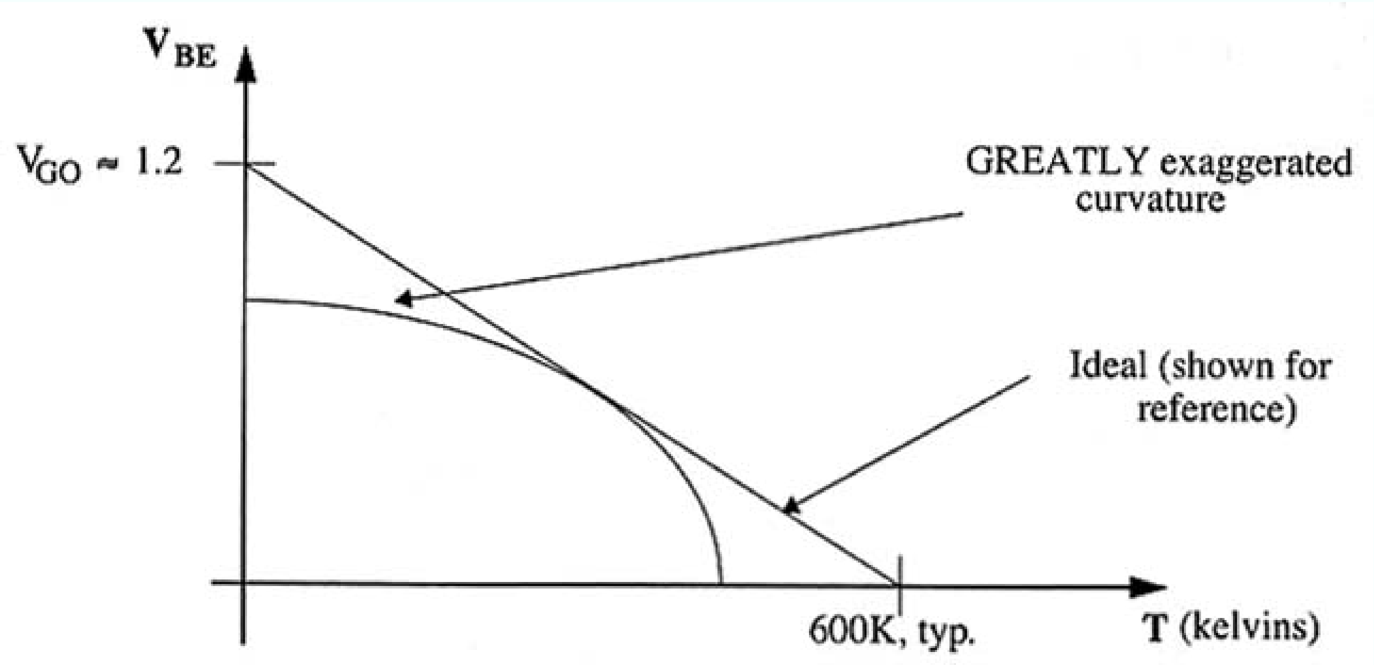
# Temp. dependence of BJT base-emitter voltage

$$\frac{\partial V_{BE}(T)}{\partial T} = \frac{1}{300}\left\{V_{BE}(300) - \frac{E_G(300)}{q} - (4+m)\cdot V_{T300}\cdot\left\{\ln\frac{T}{300}+1\right\} + \frac{300}{q}\cdot\frac{\partial E_G(T)}{\partial T}\right\}$$

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

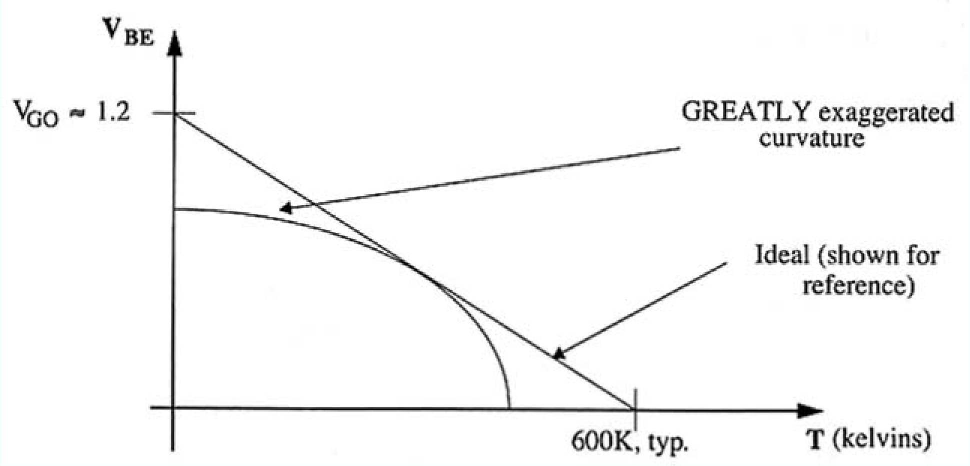
Razavi

**Constant IC assumed**



$V_{BE}$ versus temperature

# Temp. dependence of BJT base-emitter voltage

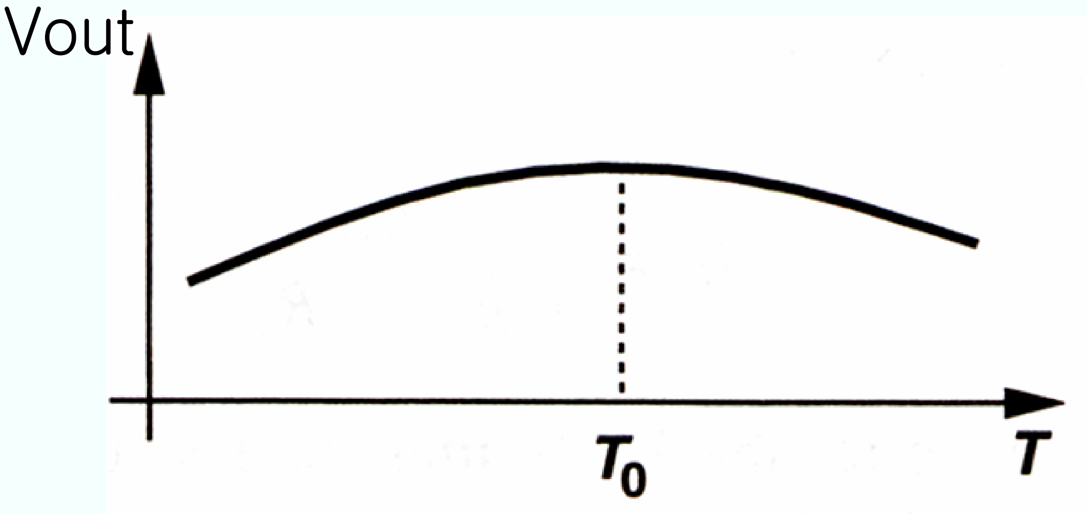


$V_{BE}$ versus temperature

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

**Vout = VBE + K T**

**dVout / dT = d VBE / dT + K**
**Changes from negative to 0 and to positive**

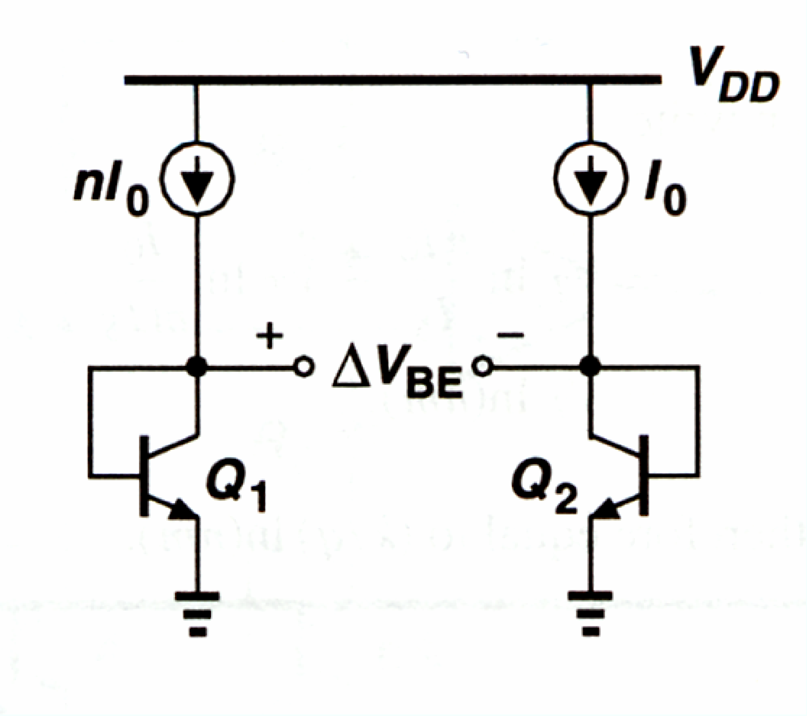


**Curvature in temperature characteristics**
**Of Vout ( = VBE + K T )**

Razavi

# PTAT voltage source

PTAT voltage (PTAT : proportional to absolute temperature)



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

PTAT voltage

PTAT voltage : difference between 2 VBEs of PN junctions with different current density

Razavi

# CMOS band gap reference

Bandgap reference : Vref = VBE + K VT

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

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

$$\begin{aligned} V_{REF} &\approx V_{BE} + 17.2 V_T \\ &\approx 1.25\ \mathrm{V}. \end{aligned}$$

Close to bandgap of silicon

# CMOS band gap reference

$$V_{REF} = V_{BE} + V_T \ln n$$

$$\frac{\partial V_{REF}}{\partial T} = \frac{\partial V_{BE}}{\partial T} + \frac{V_T}{T} \ln n$$

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

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

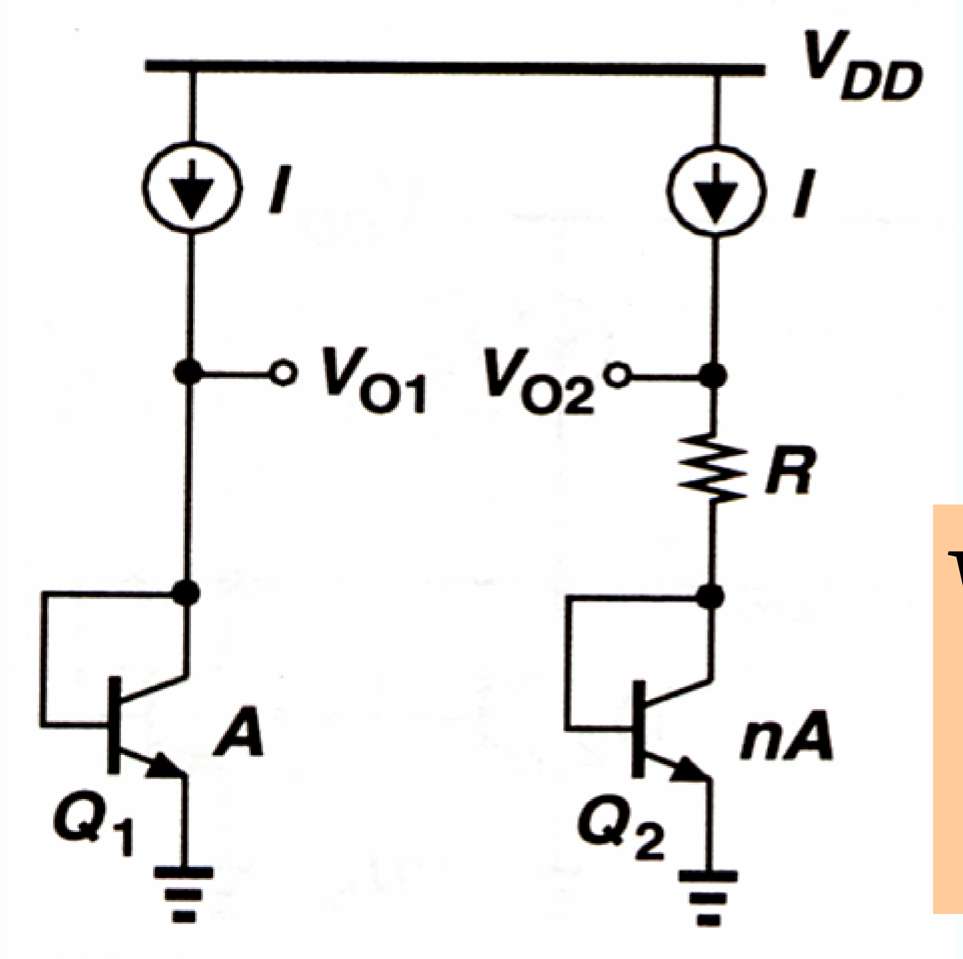
For 0 TC

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

Close to bandgap

# CMOS band gap reference

Conceptual band gap reference :
enforce Vo1 and Vo2 to be the same



$$V_{BE1} = RI + V_{BE2}$$

$$RI = V_{BE1} - V_{BE2} = V_T \ln n.$$

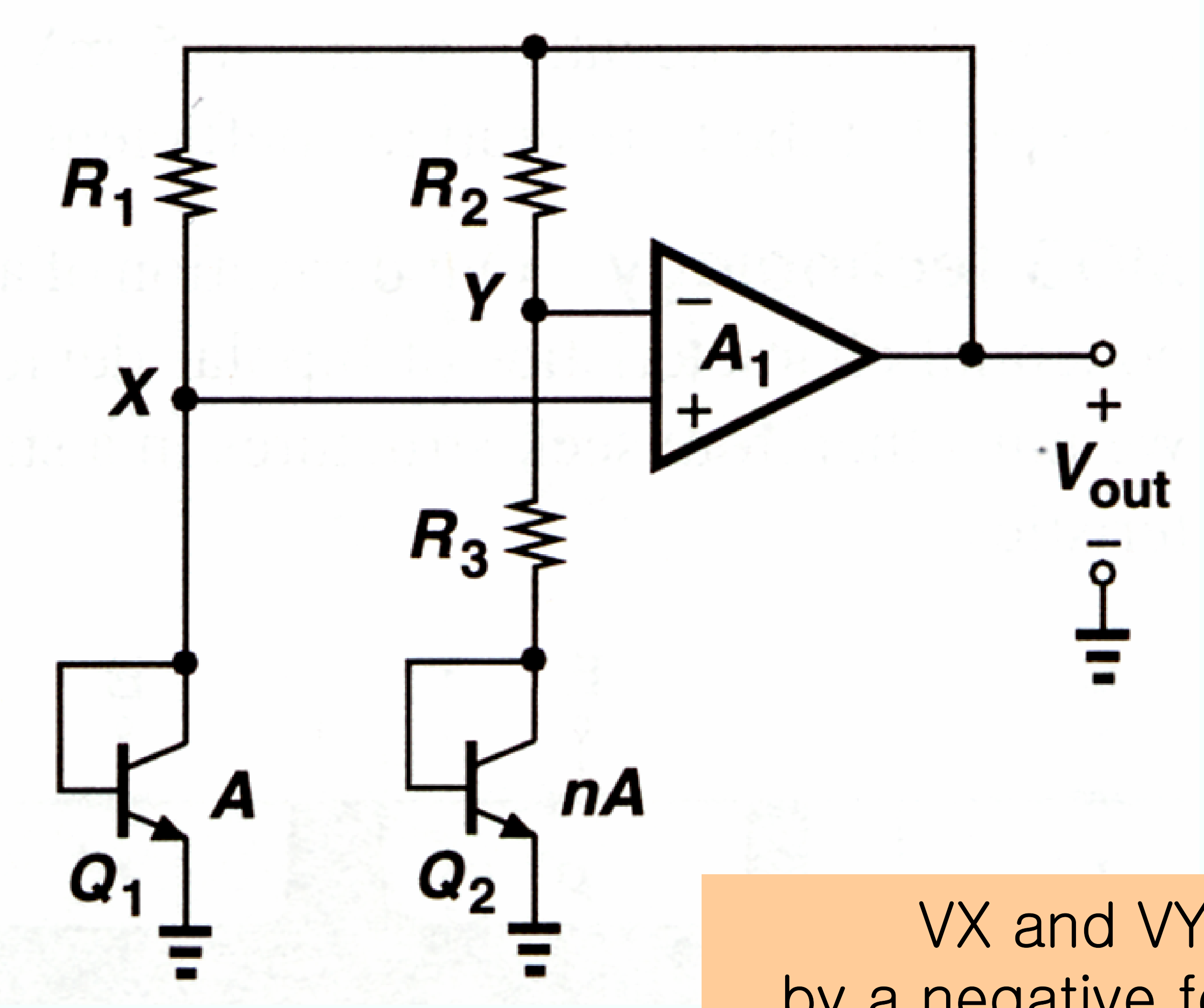
$$V_{o2} = R\,I + V_{BE2}$$
$$= V_T \cdot \ln n + V_{BE2}$$

ln (n) = 17.2 ➔ n=2.95e7 (too large, impractical)

Razavi

# CMOS band gap reference

## Basic band gap reference ckt

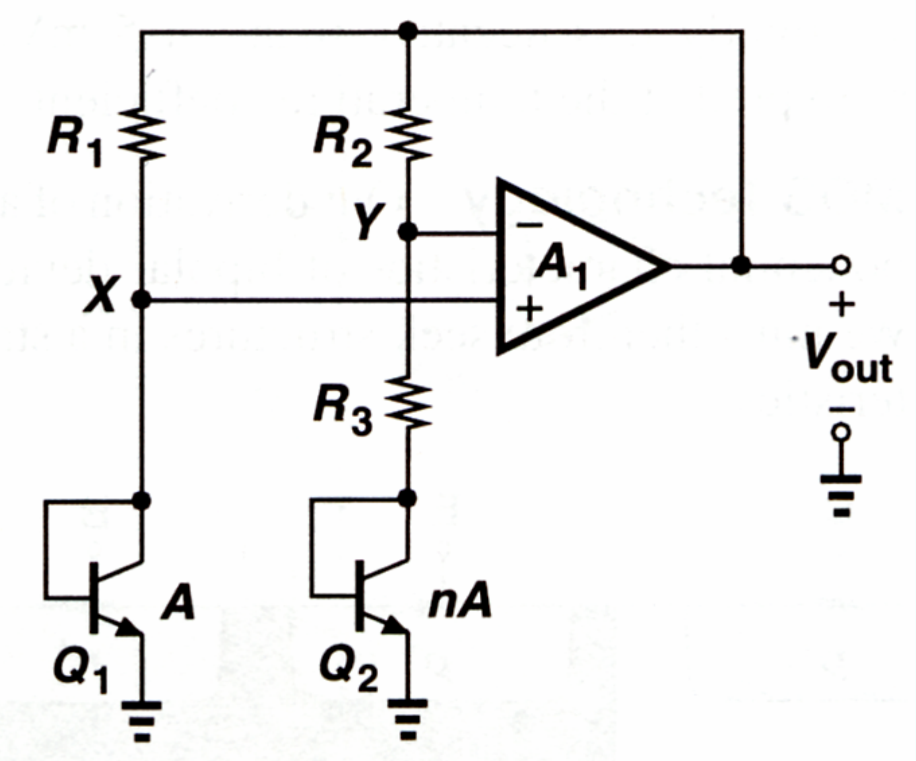


VX and VY: kept the same
by a negative feedback OP amp ckt

Razavi

# CMOS band gap reference

## Basic band gap reference ckt



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

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

R1=R2 ➔ the same current at Q1, Q2
R2 > R3 to decrease *n*

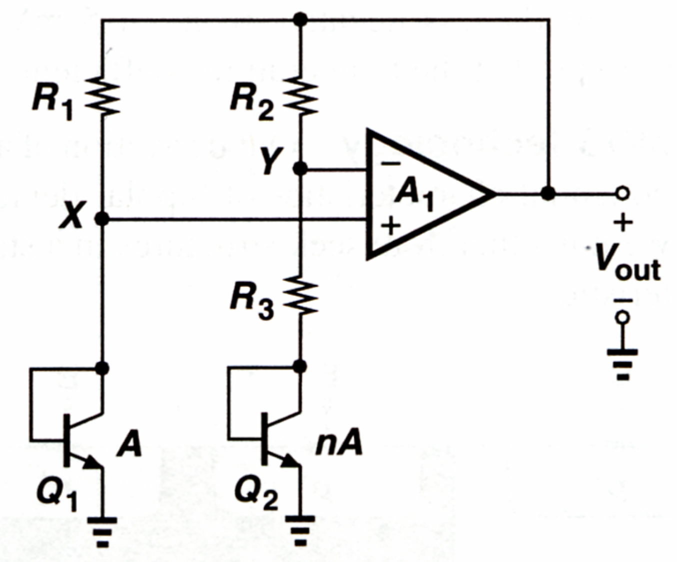
$$\ln n \cdot (1 + \frac{R_2}{R_3}) = 17.2$$

Example: R1=R2, R2/R3=4, n=31

Razavi

# CMOS band gap reference

## Basic band gap reference ckt



$$I_{C1} = I_{C2} \approx (V_T \ln n)/R_3$$

$$\frac{\partial V_{BE}}{\partial T} = \frac{\partial V_T}{\partial T} \ln \frac{I_C}{I_S} + V_T \left( \frac{1}{I_C} \frac{\partial I_C}{\partial T} - \frac{1}{I_S} \frac{\partial I_S}{\partial T} \right)$$

$$\frac{\partial V_{BE}}{\partial T} = \frac{\partial V_T}{\partial T} \ln \frac{I_C}{I_S} + \frac{V_T}{T} - \frac{V_T}{I_S} \frac{\partial I_S}{\partial T}$$

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

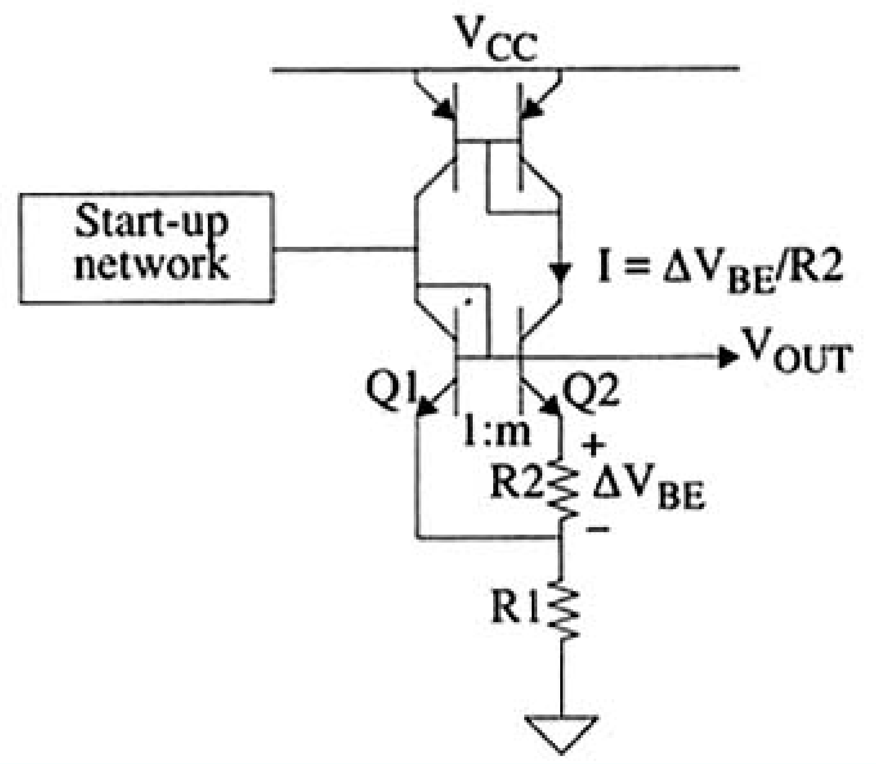
**PTAT IC**

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

**Constant IC**

Razavi

# Classic Brokaw bandgap reference circuit



Let m=8 and VBE=0.65V at IC=100uA, 300K

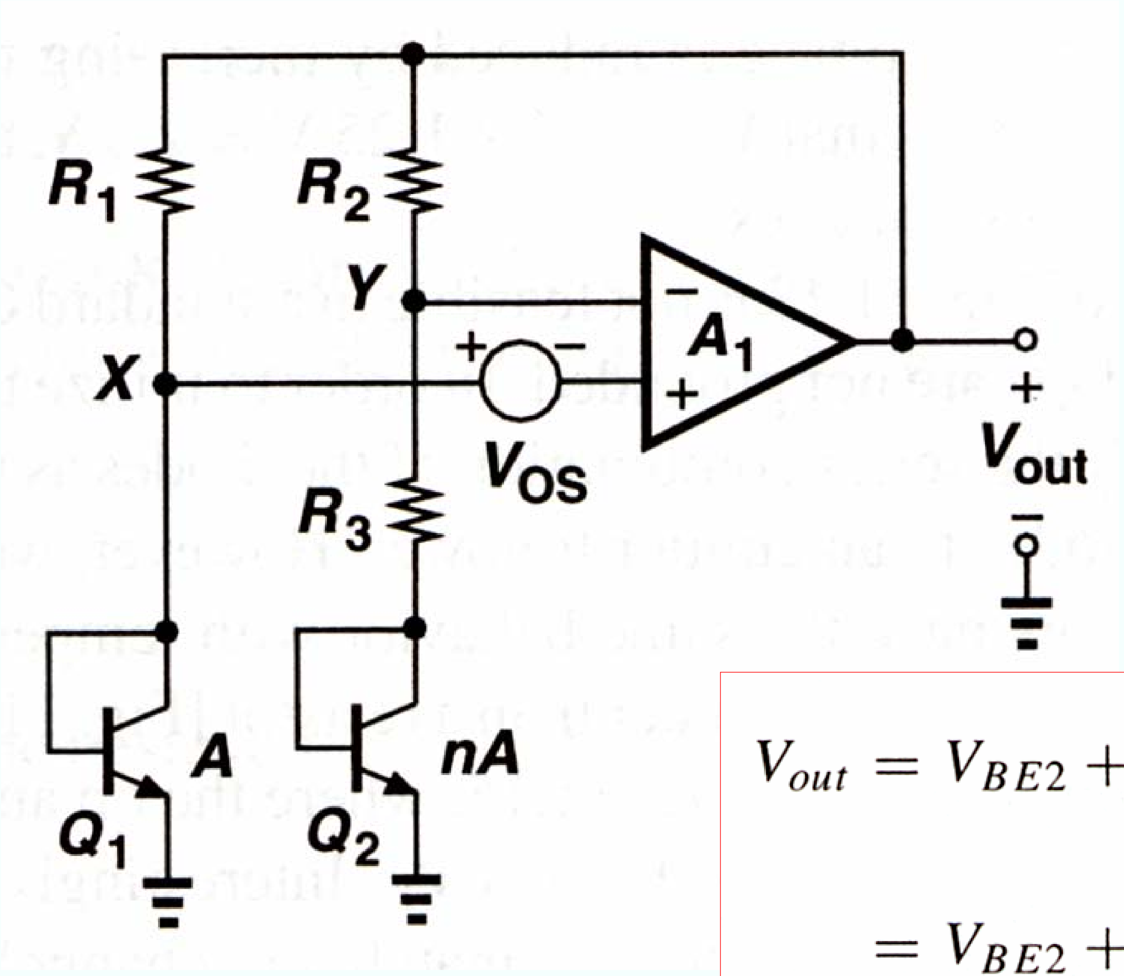
DELTA VBE = VT x ln(8) = 53.8mV >> offset

R2 = 53.8mV / 100uA = 538 ohm

R1 = (1.2 – 0.65 – 0.0538) / 200uA = 0.496V / 200uA = 2.48Kohm

# CMOS band gap reference

## Effect of Vos (input offset voltage)



$$V_{BE1} - V_{OS} \approx V_{BE2} + I_{C2} \cdot R_3$$

$$I_{C2} = (V_{BE1} - V_{BE2} - V_{OS}) / R_3$$
$$= (V_T \cdot \ln n - V_{OS}) / R_3$$

$$V_{out} = V_{BE2} + (R_3 + R_2) I_{C2}$$

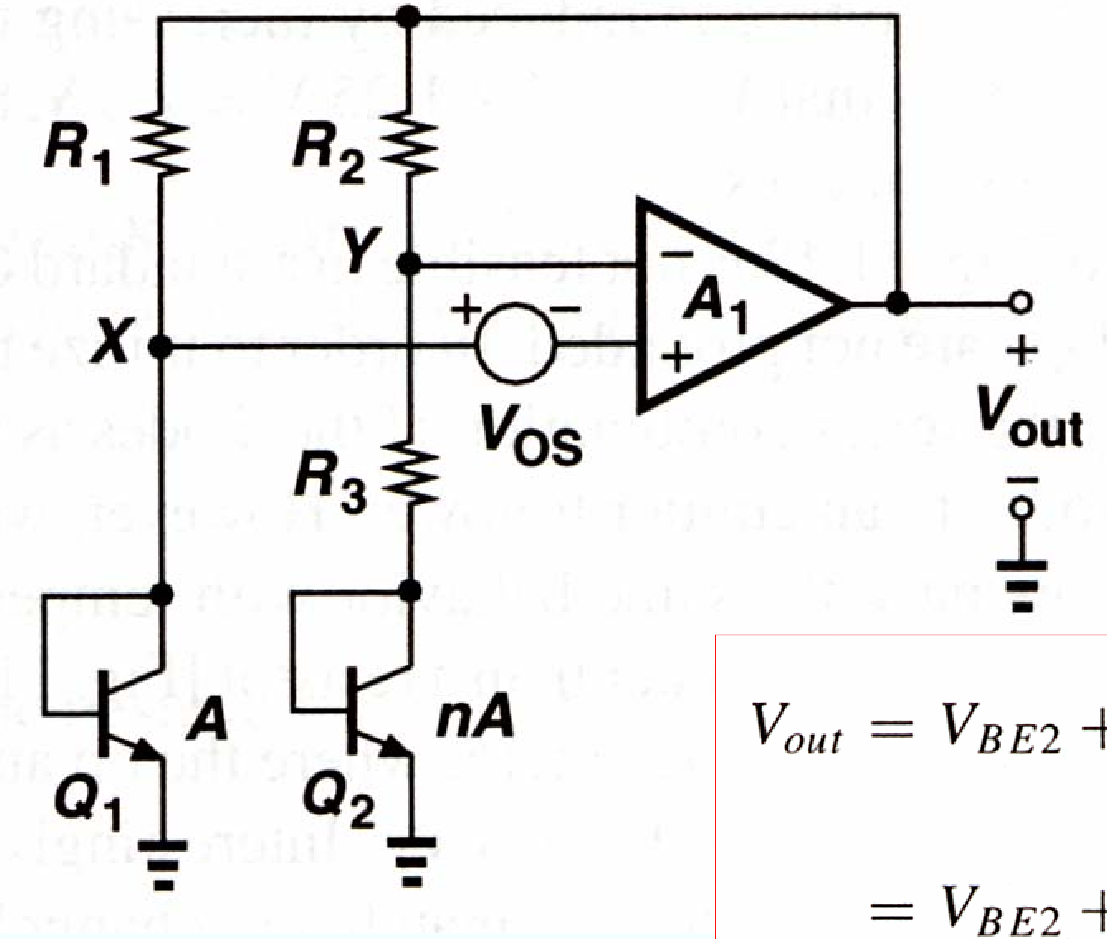
$$V_{out} = V_{BE2} + (R_3 + R_2)\frac{V_{BE1} - V_{BE2} - V_{OS}}{R_3}$$
$$= V_{BE2} + \left(1 + \frac{R_2}{R_3}\right)(V_T \ln n - V_{OS}),$$

Vos amplified, Vos varies with temperature

Razavi

# CMOS band gap reference

## Effect of Vos (input offset voltage), R1=R2



$$V_{BE1} - V_{OS} \approx V_{BE2} + I_{C2} \cdot R_3$$

$$I_{C2} = (V_{BE1} - V_{BE2} - V_{OS}) / R_3$$
$$= (V_T \cdot \ln n - V_{OS}) / R_3$$

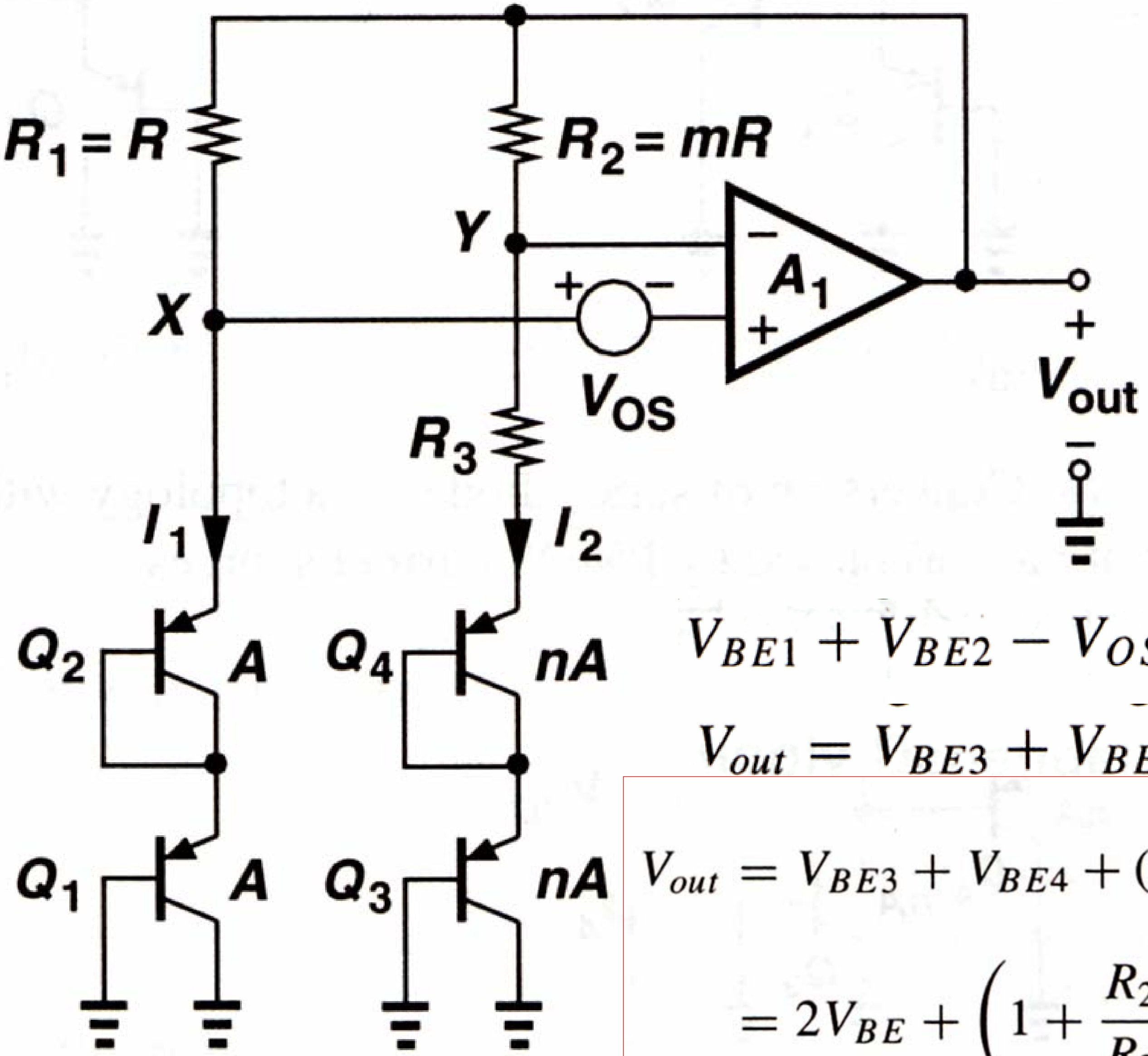
$$V_{out} = V_{BE2} + (R_3 + R_2) I_{C2}$$

$$V_{out} = V_{BE2} + (R_3 + R_2)\frac{V_{BE1} - V_{BE2} - V_{OS}}{R_3}$$
$$= V_{BE2} + \left(1 + \frac{R_2}{R_3}\right)(V_T \ln n - V_{OS}),$$

Vos amplified, Vos varies with temperature

Razavi

# Bandgap reference to improve Vos effect



$$I_1 \approx mI_2.$$

$$V_{BE1} + V_{BE2} - V_{OS} = V_{BE3} + V_{BE4} + R_3 I_2$$

$$V_{out} = V_{BE3} + V_{BE4} + (R_3 + R_2) I_2$$

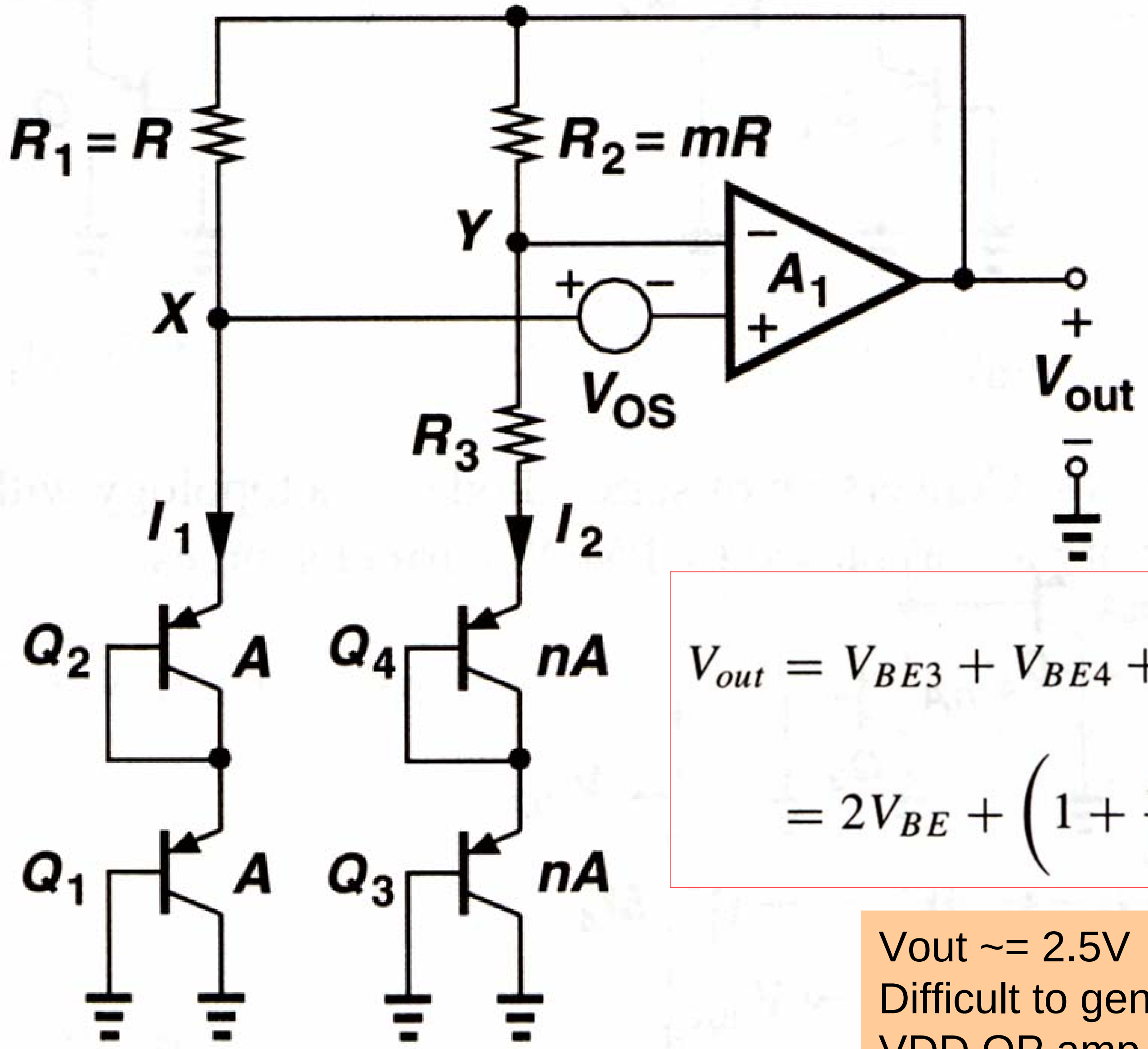
$$V_{out} = V_{BE3} + V_{BE4} + (R_3 + R_2)\frac{2V_T \ln(mn) - V_{OS}}{R_3}$$

$$= 2V_{BE} + \left(1 + \frac{R_2}{R_3}\right)[2V_T \ln(mn) - V_{OS}].$$

Razavi

Vos effect decreased by half

# Bandgap reference to improve Vos effect



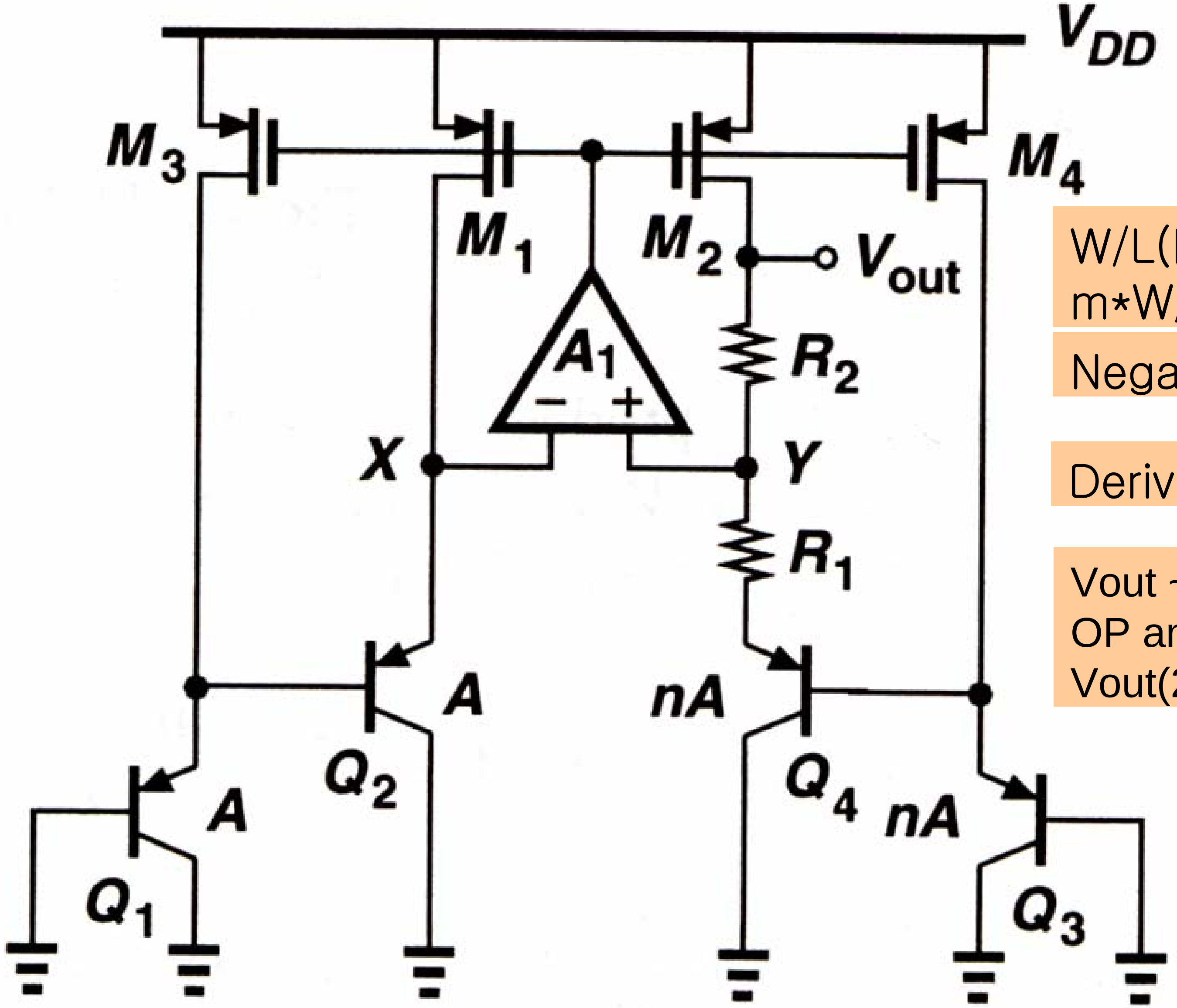
$$V_{out} = V_{BE3} + V_{BE4} + (R_3 + R_2)\frac{2V_T \ln(mn) - V_{OS}}{R_3}$$

$$= 2V_{BE} + \left(1 + \frac{R_2}{R_3}\right)[2V_T \ln(mn) - V_{OS}].$$

Vout ~= 2.5V
Difficult to generate 2.5V output using low-VDD OP amp ➔ No good at low VDD

Razavi

# Bandgap reference to improve Vos effect



W/L(M1)=W/L(M3)=m*W/L(M2)= m*W/L(M4)

Negative feedback

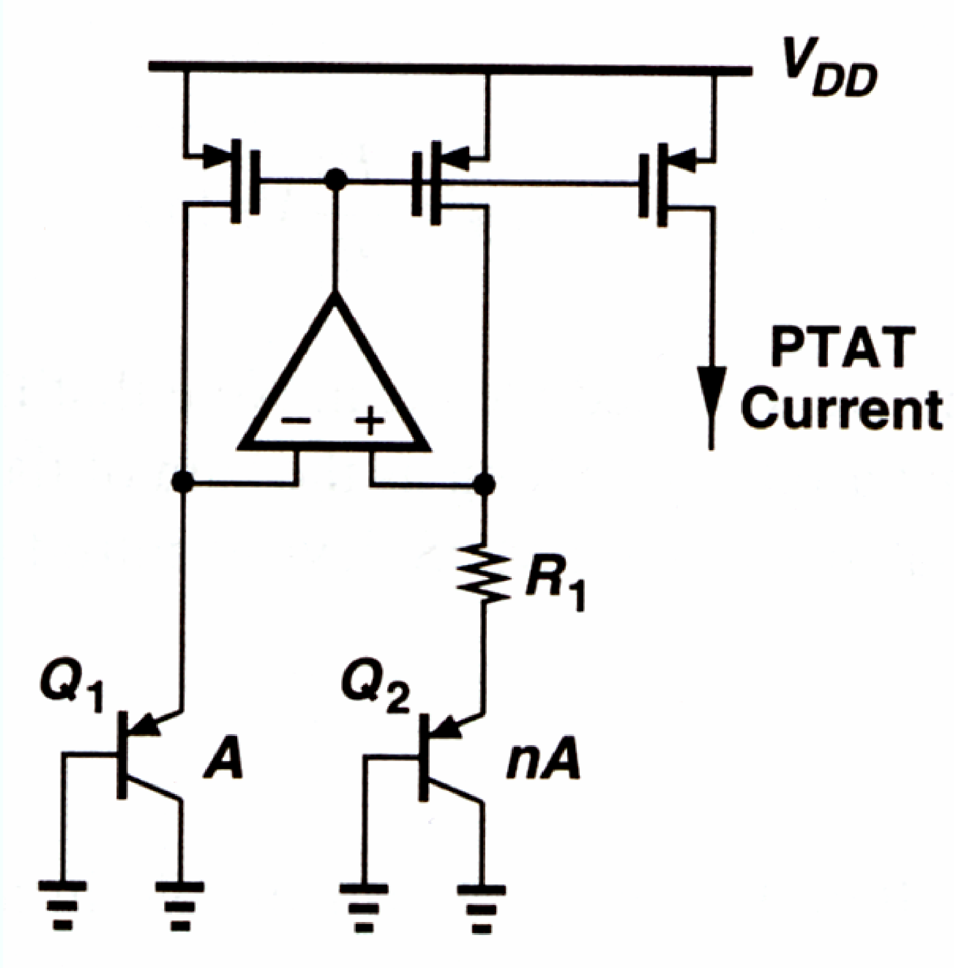
Derive Vout eq. including Vos

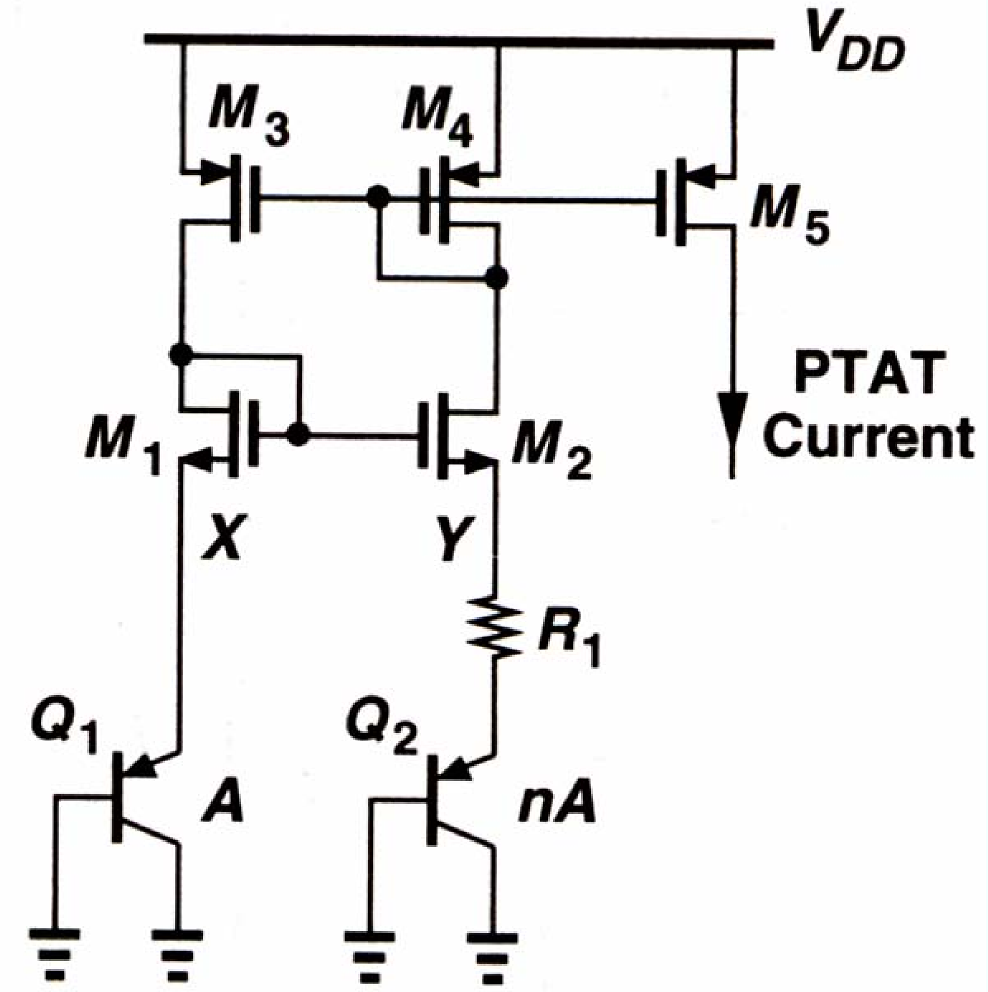
Vout ~= 2.5V
OP amp does not generate
Vout(2.5V) ➔ OK at low VDD

Razavi

# Bandgap reference

## PTAT current

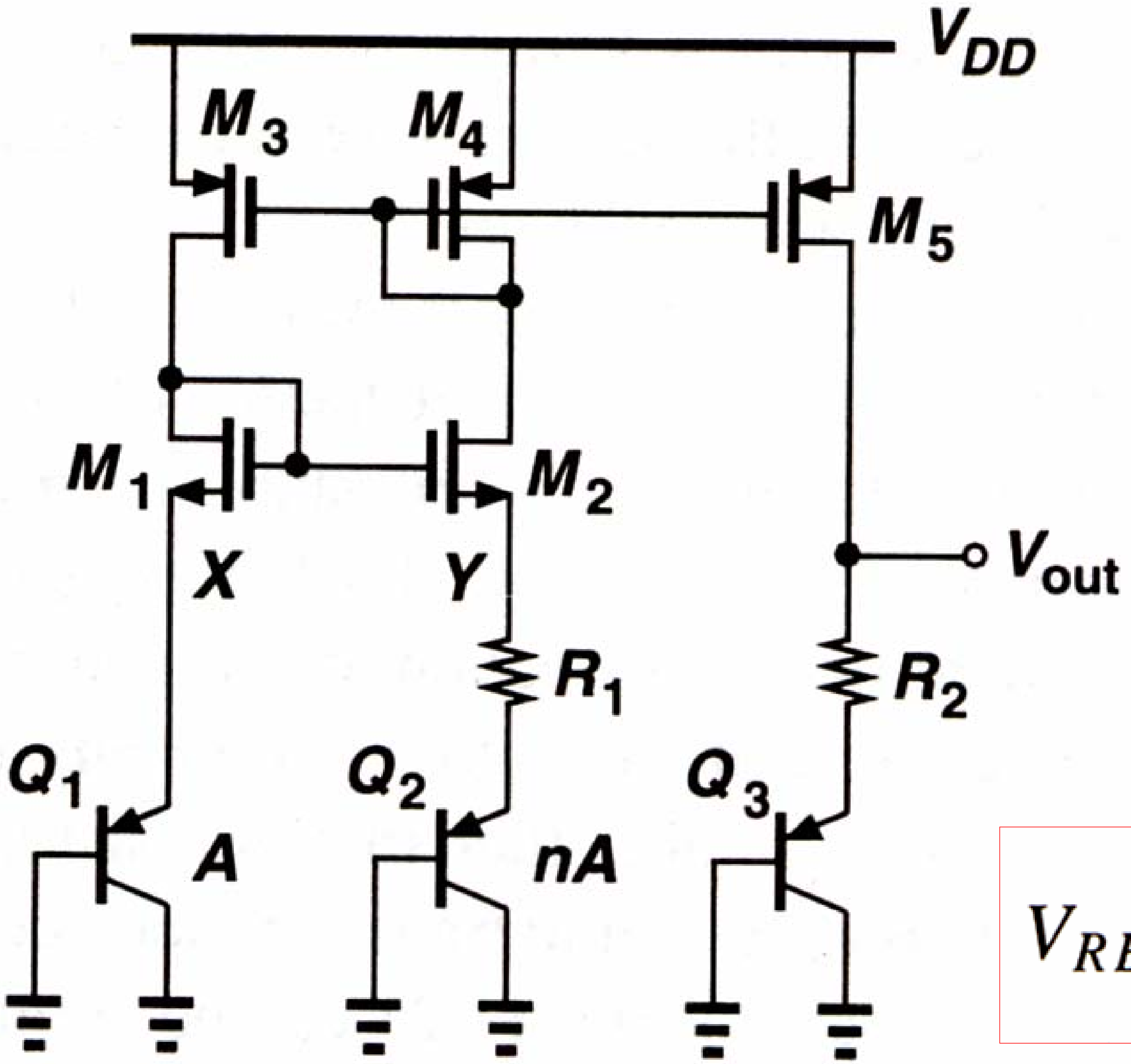




Implementation using simple amp

Razavi

# Bandgap voltage reference using simple amp



$$V_{REF} = V_{BE3} + \frac{R_2}{R_1} V_T \ln n$$

Razavi

# CMOS band gap reference circuit

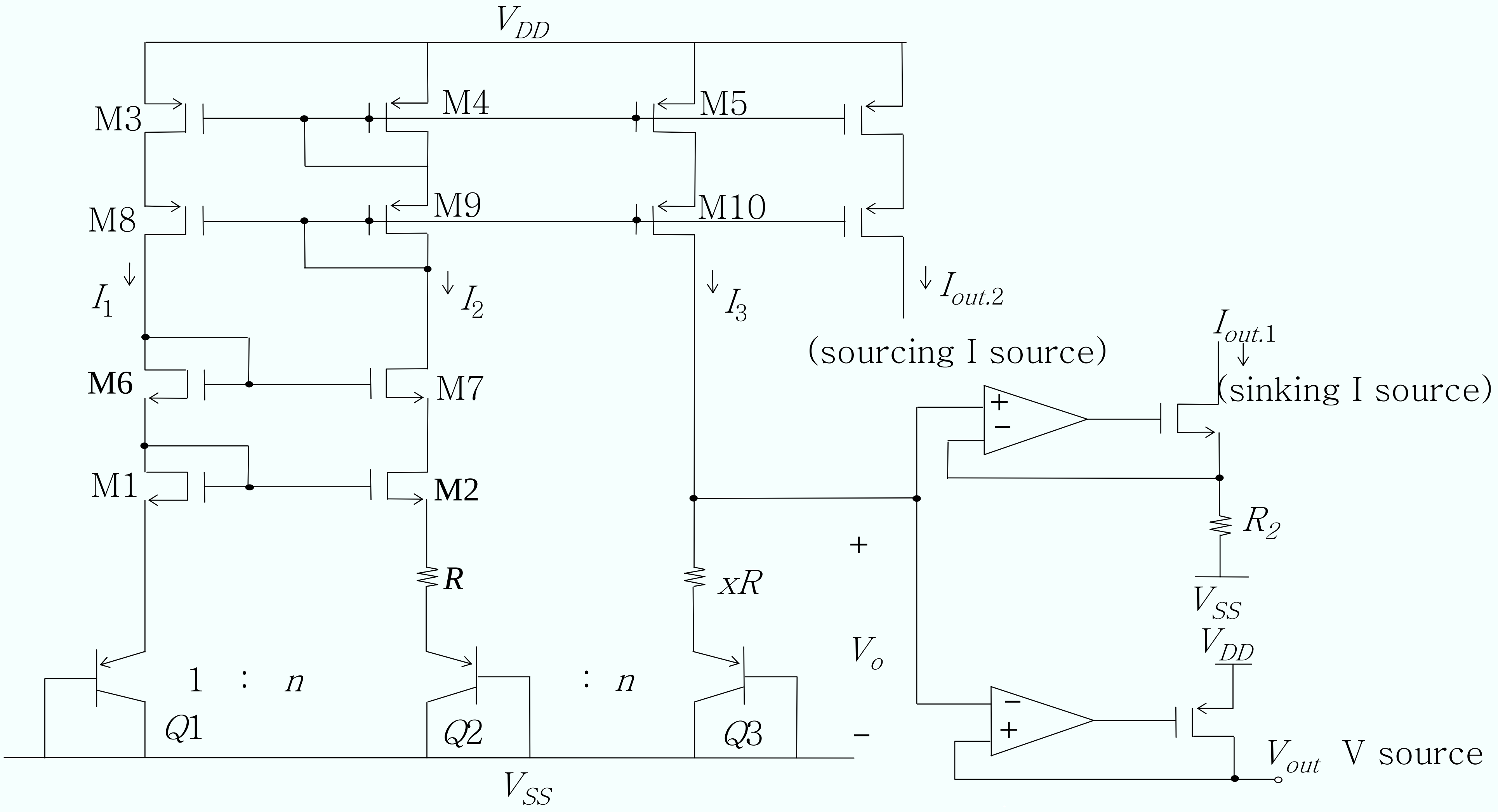
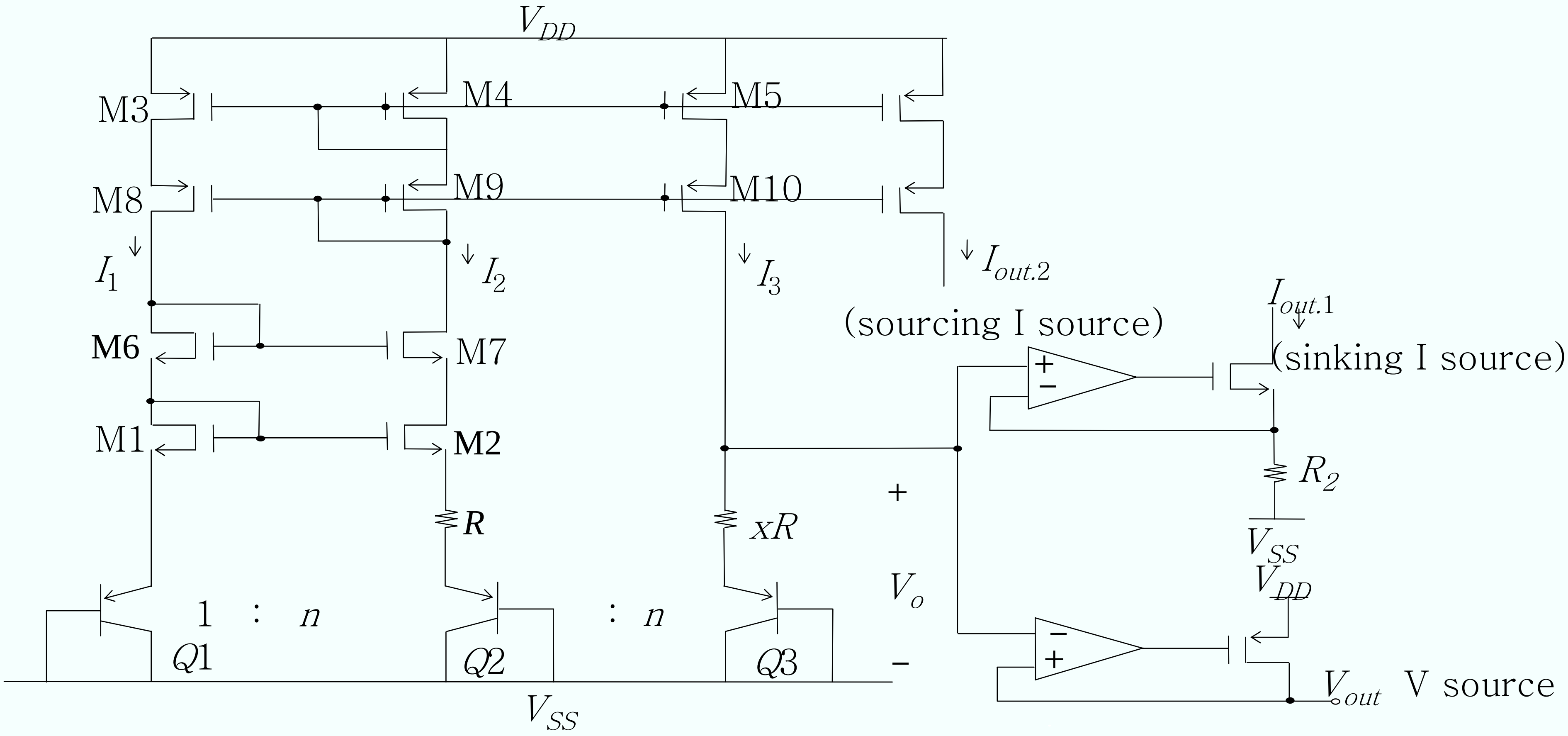


**Fig 8.2.10** CMOS band gap reference circuit

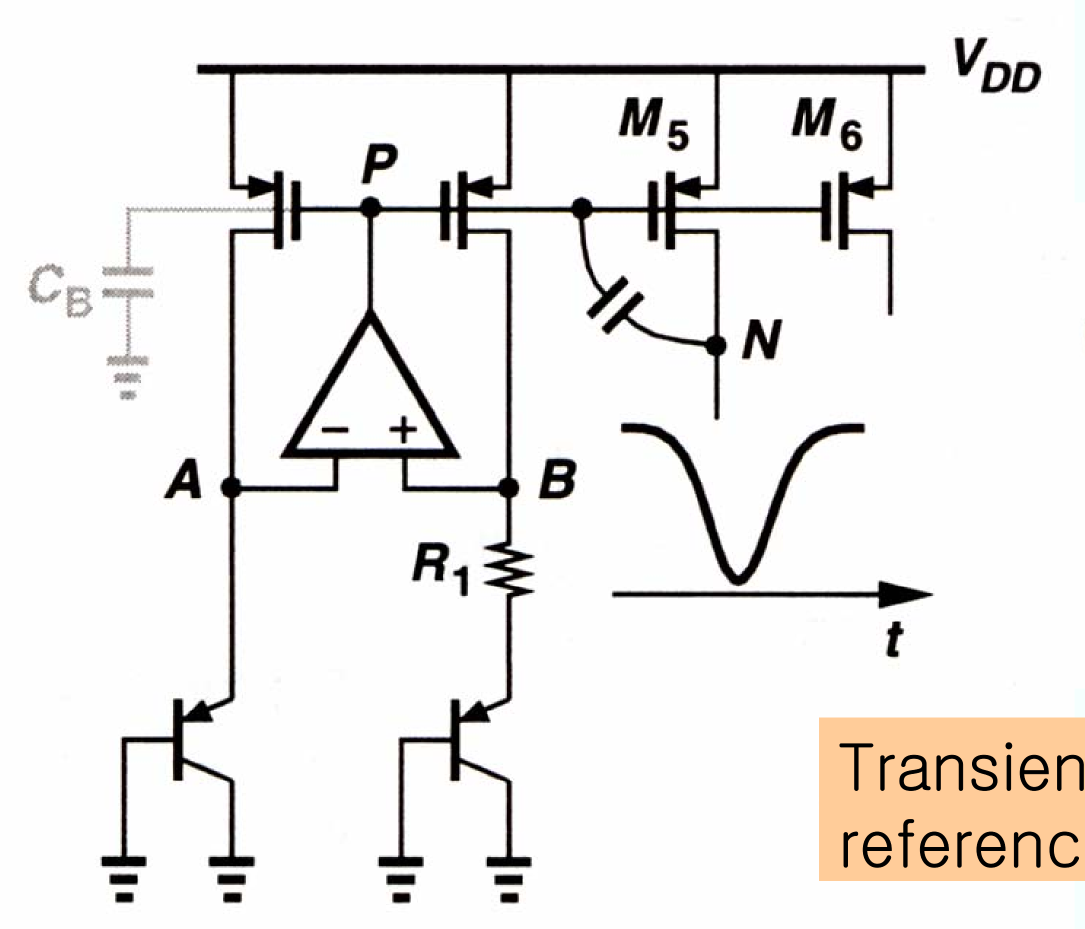
# CMOS band gap reference circuit

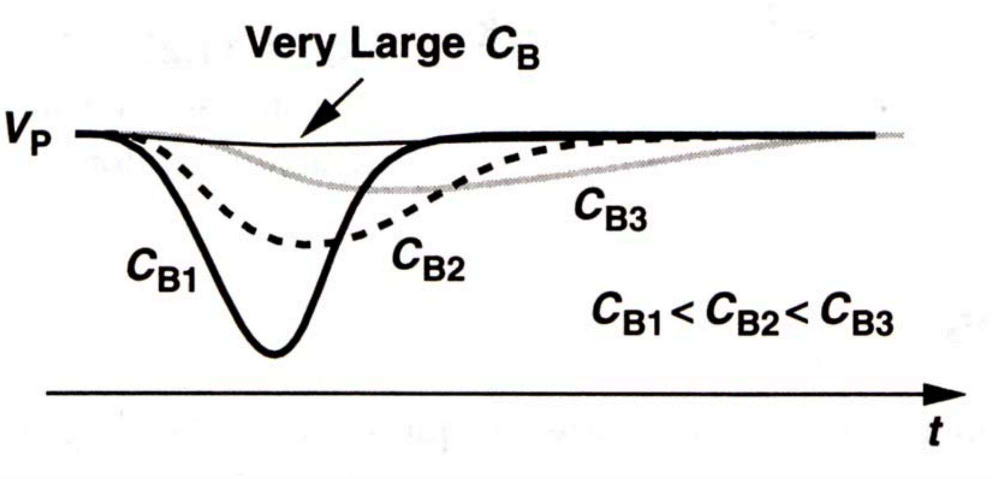


$$I_1 = I_2 \qquad I_3 = I_2 \qquad I_3 = I_2 = I_1 \approx \frac{V_T \cdot \ln(n)}{R}$$

$$V_o = I_3 \cdot xR + V_{EB3} = V_T \cdot x \cdot \ln(n) + V_{EB3}$$

# Transients on reference voltage



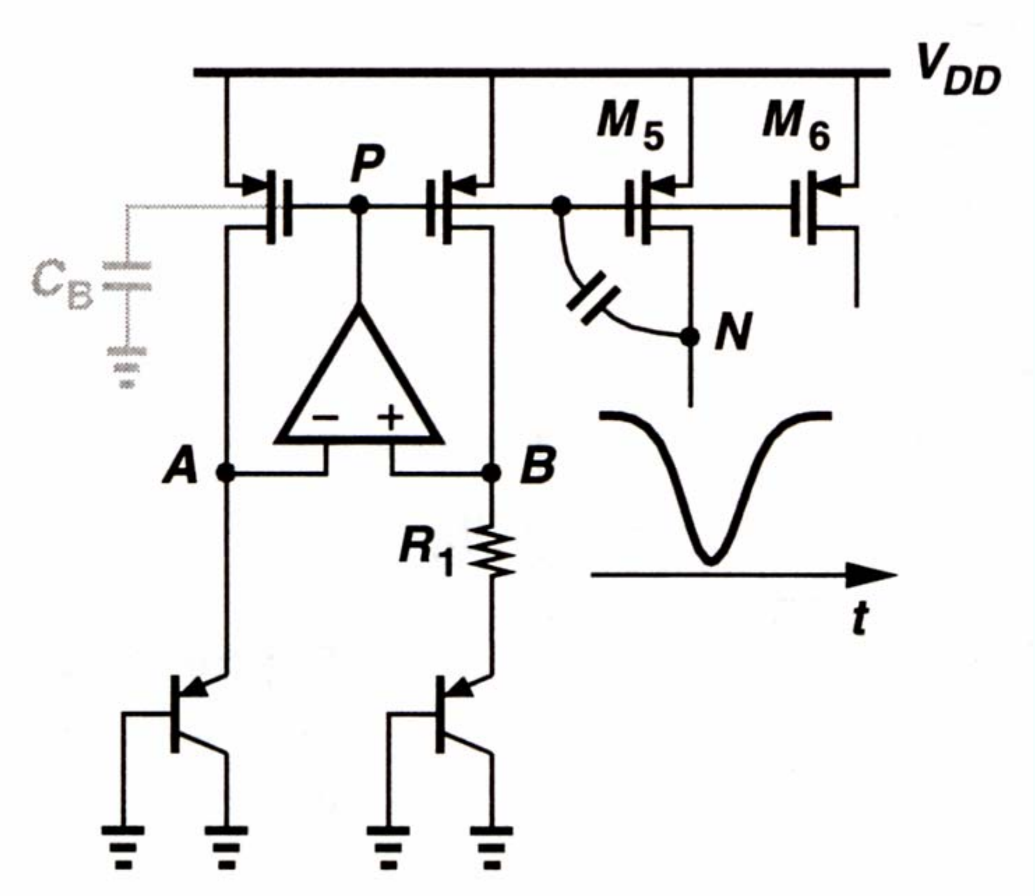


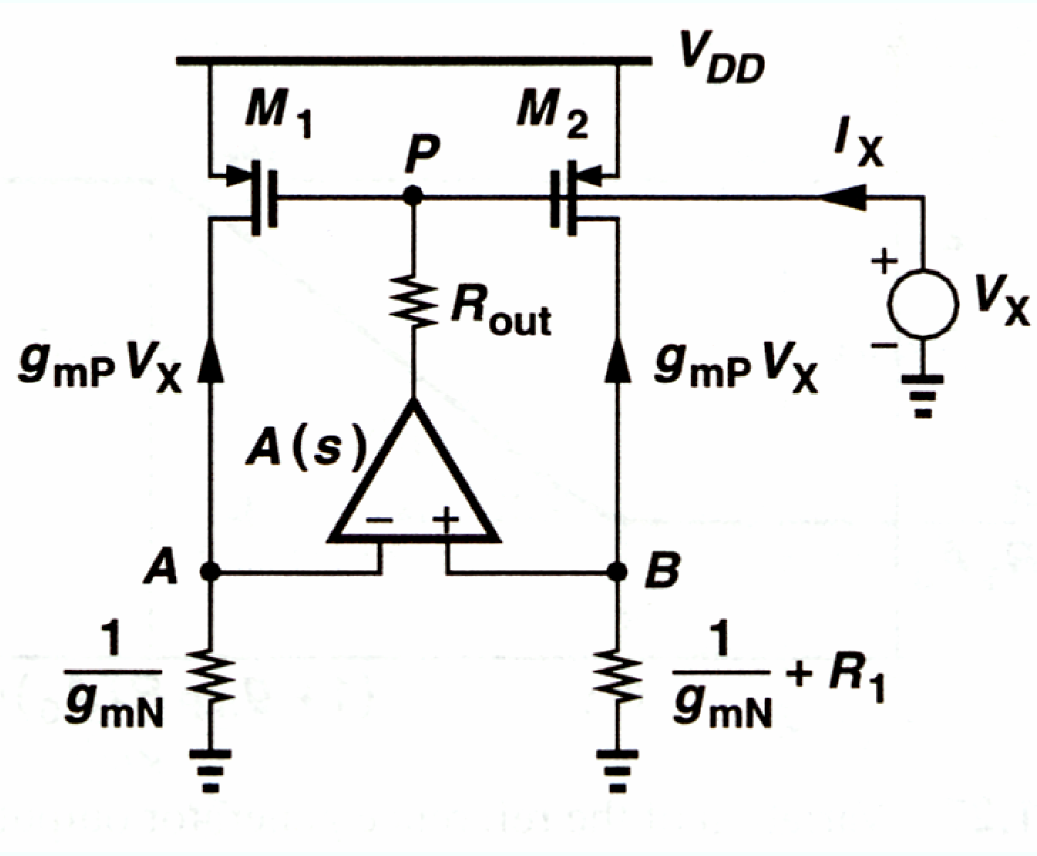
Transients in ckts ➔ transients in reference ➔ broadcast in circuits

Due to finite Rout of reference

# Transients on reference voltage

## Calculation of Rout

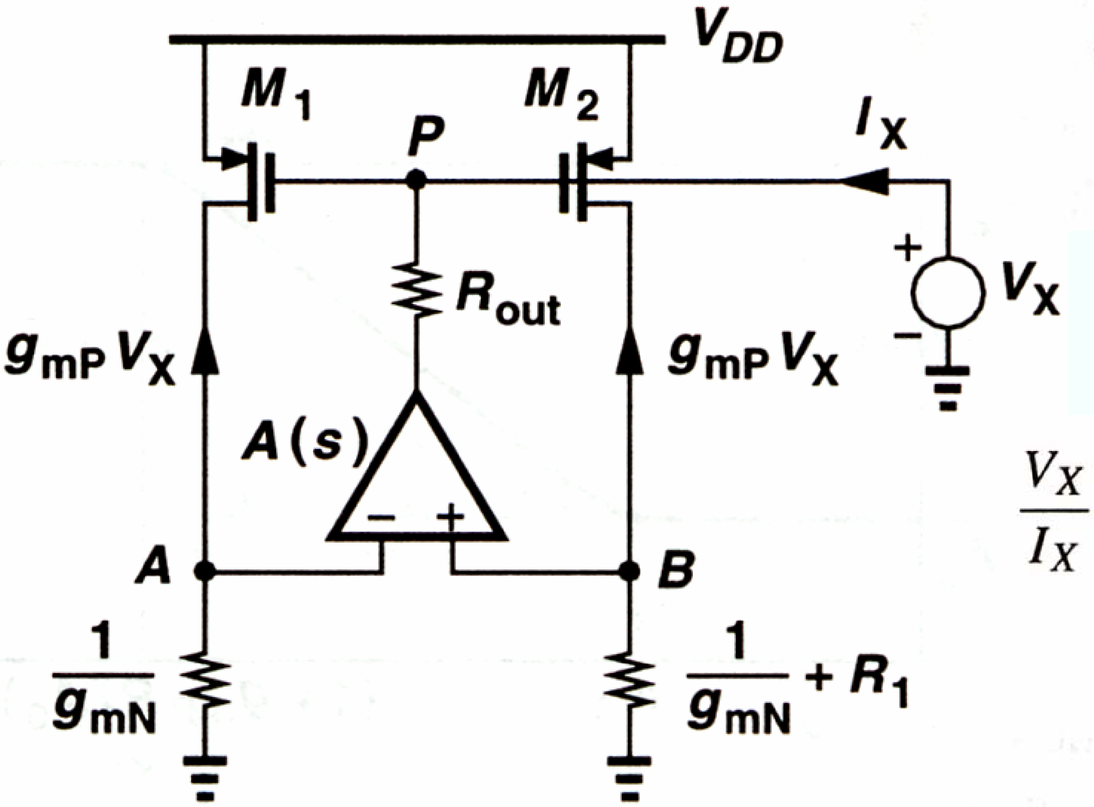




Razavi

# Transients on reference voltage

## Calculation of Rout



$$V_{AB} = -g_{mP}V_X\frac{1}{g_{mN}} + g_{mP}V_X\left(\frac{1}{g_{mN}}+R_1\right)$$
$$= g_{mP}V_XR_1.$$

$$I_X = \frac{V_X + g_{mP}V_XR_1A(s)}{R_{out}}$$

$$\frac{V_X}{I_X} = \frac{R_{out}}{1+g_{mP}R_1A(s)}$$

$$= \frac{R_{out}}{1+g_{mP}R_1\dfrac{A_0}{1+s/\omega_0}}$$

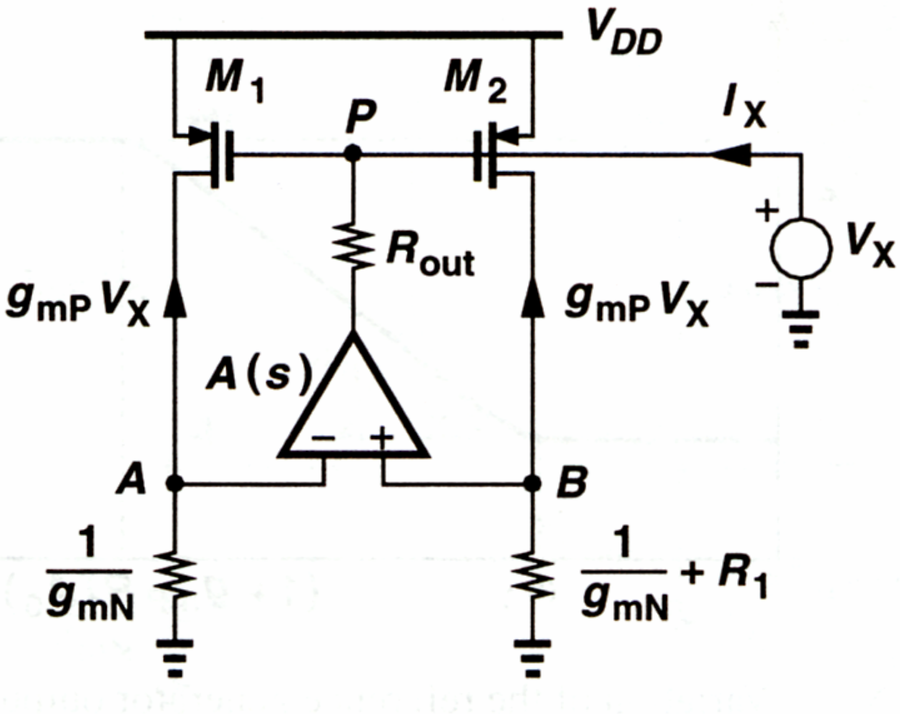
$$= \frac{R_{out}}{1+g_{mP}R_1A_0}\,\frac{1+\dfrac{s}{\omega_0}}{1+\dfrac{s}{(1+g_{mP}R_1A_0)\omega_0}}$$

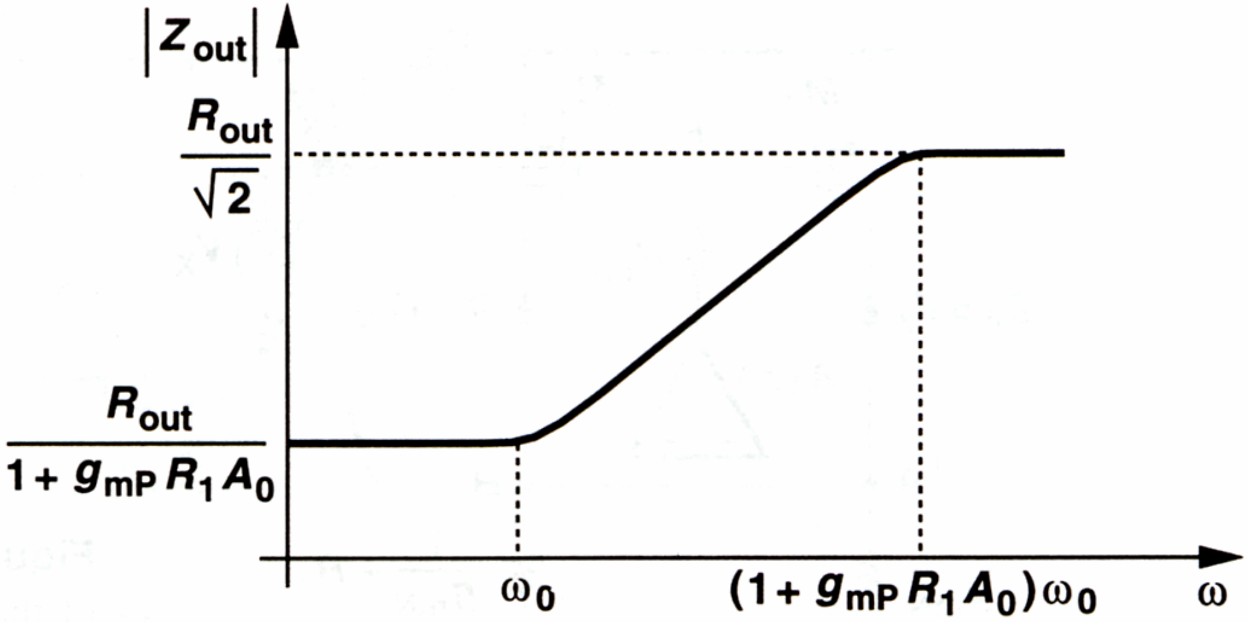
Razavi

# Transients on reference voltage

## Calculation of Rout =

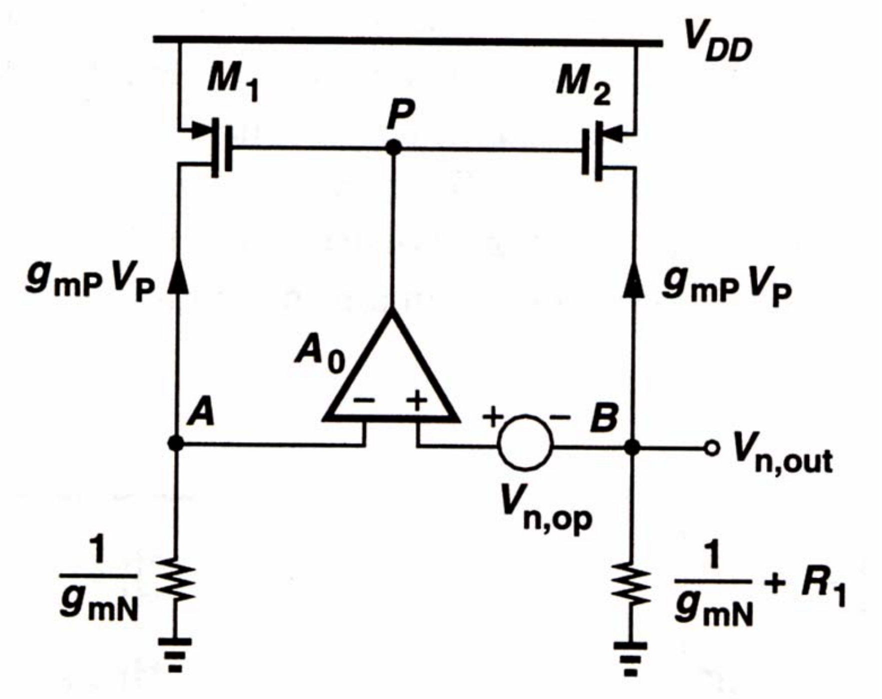
$$= \frac{R_{out}}{1+g_{mP}R_1A_0}\,\frac{1+\dfrac{s}{\omega_0}}{1+\dfrac{s}{(1+g_{mP}R_1A_0)\omega_0}}$$





|Zout| large at high frequency ➔ easier coupling

# Bandgap reference: Effect of noise



$$V_P = -g_{mP}^{-1} V_{n,out}/(R_1 + g_{mN}^{-1})$$

$$\frac{V_{n,out}}{R_1 + g_{mN}^{-1}} \cdot \frac{1}{g_{mN}} - \frac{V_{n,out}}{g_{mP}A_0(R_1 + g_{mN}^{-1})} = V_{n,op} + V_{n,out}$$

$$g_{mP}A_0 \gg g_{mN} \gg R_1^{-1}$$

$$V_{n,out}\left[\frac{1}{R_1 + g_{mN}^{-1}}\left(\frac{1}{g_{mN}} - \frac{1}{g_{mP}A_0}\right) - 1\right] = V_{n,op}$$

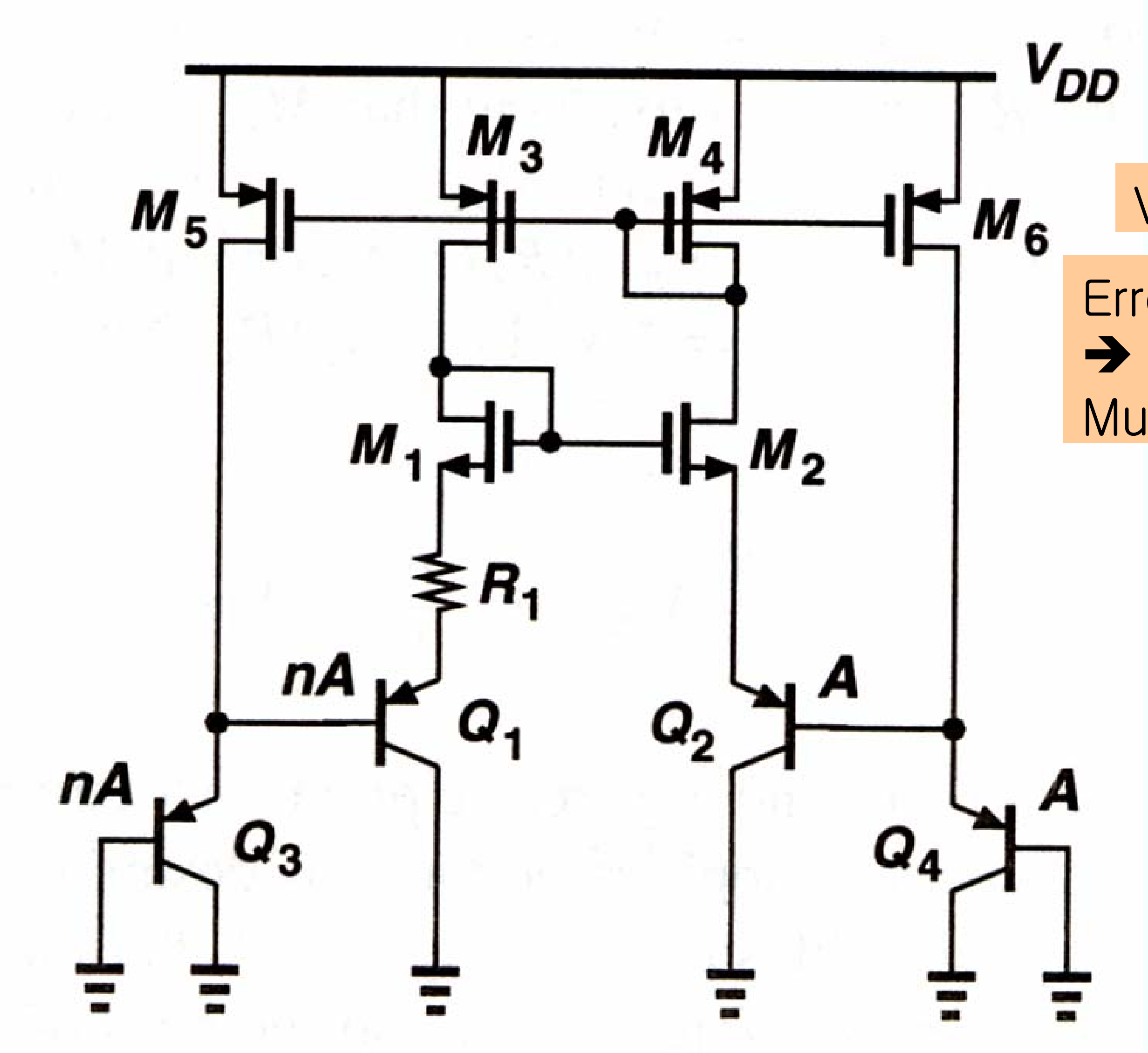
$$\boxed{|V_{n,out}| \approx V_{n,op}}$$

Input noise of amp ➔ directly reference out

Razavi

# Bandgap reference: Case studies

2 VBE used to reduce MOSFET mismatches



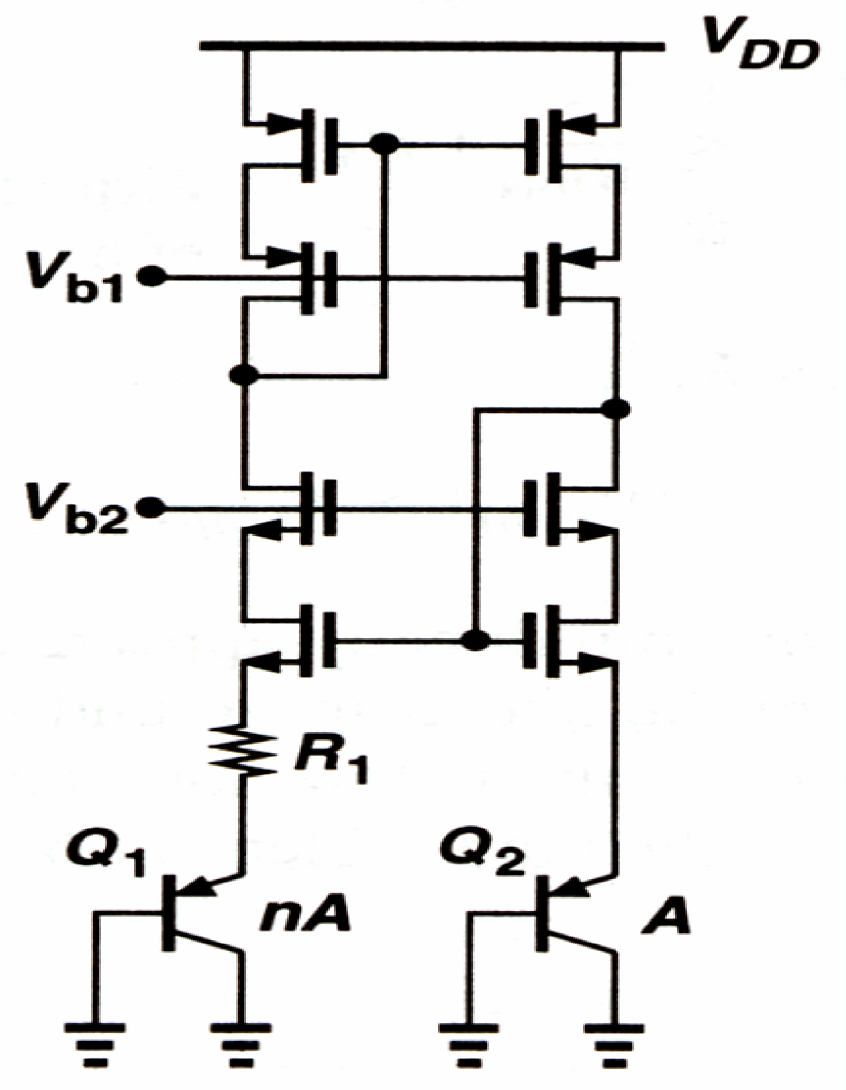
VOUT = 2 x EGO/q ~= 2.5V

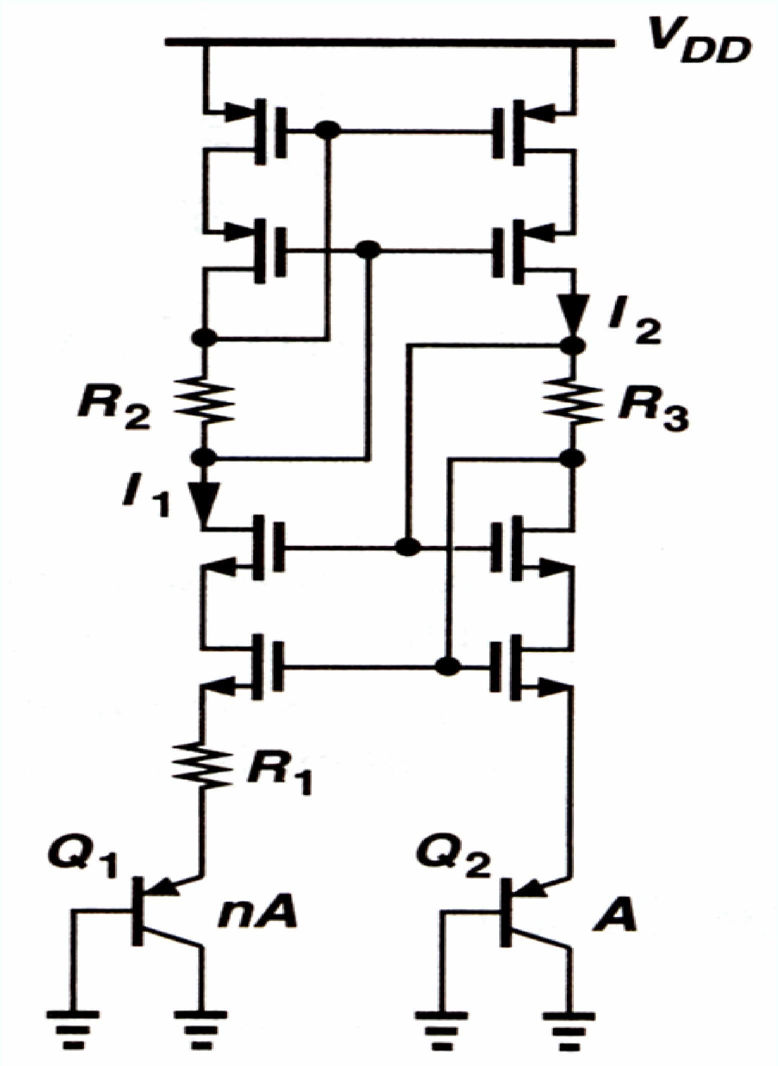
Errors in MOS diode connections
➔ M2,M3 instead of M1,M4
Must be MOS diodes

Razavi

# Bandgap reference: Case studies

## Channel length modulation of MOSFET ➔ supply dependence

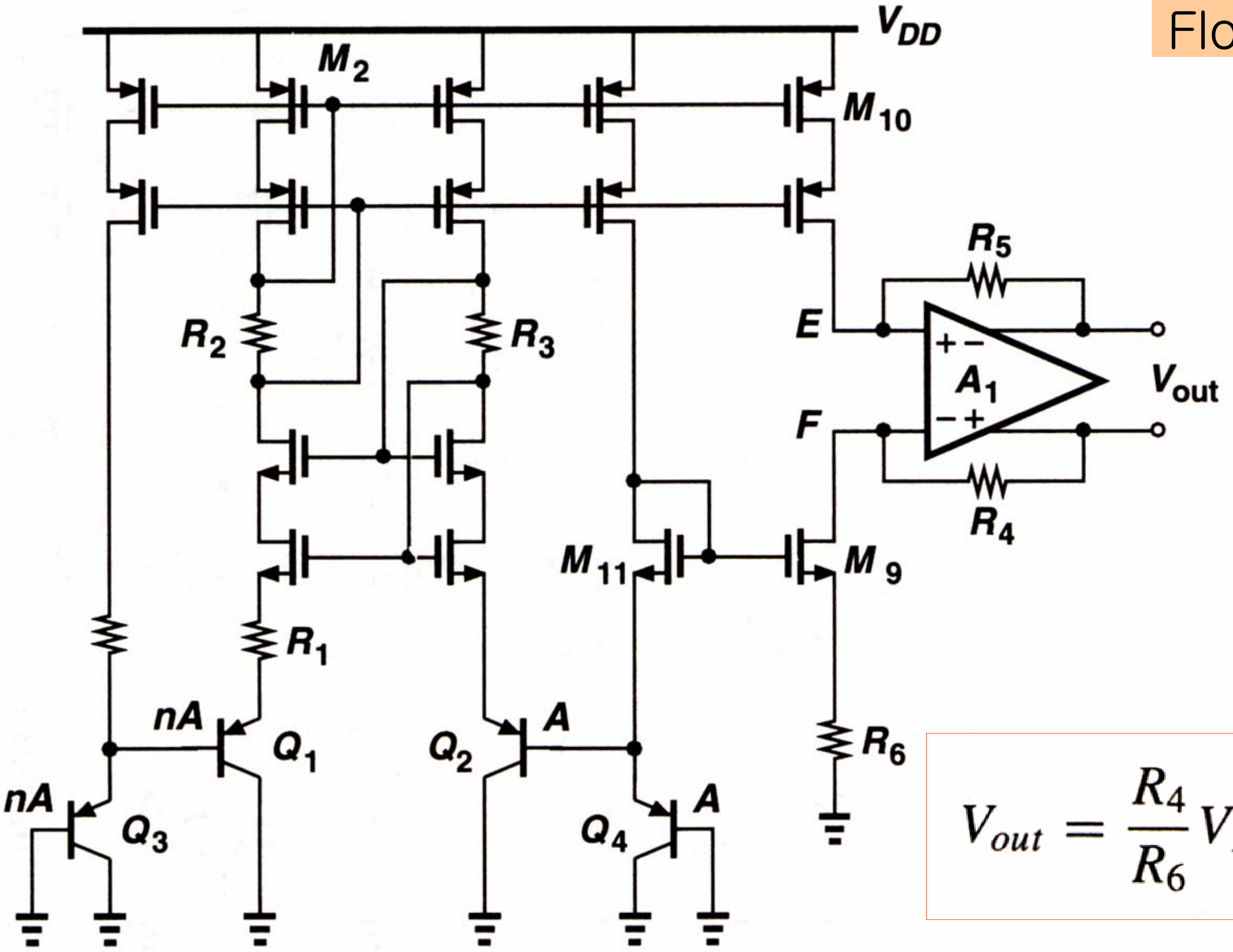




Razavi

# Bandgap reference: Case studies

## Floating reference



$$V_{out} = \frac{R_4}{R_6} V_{BE4} + 2\frac{R_5}{R_1} V_T \ln n.$$

Razavi

# Bandgap reference: Case studies

## Core: floating bandgap reference

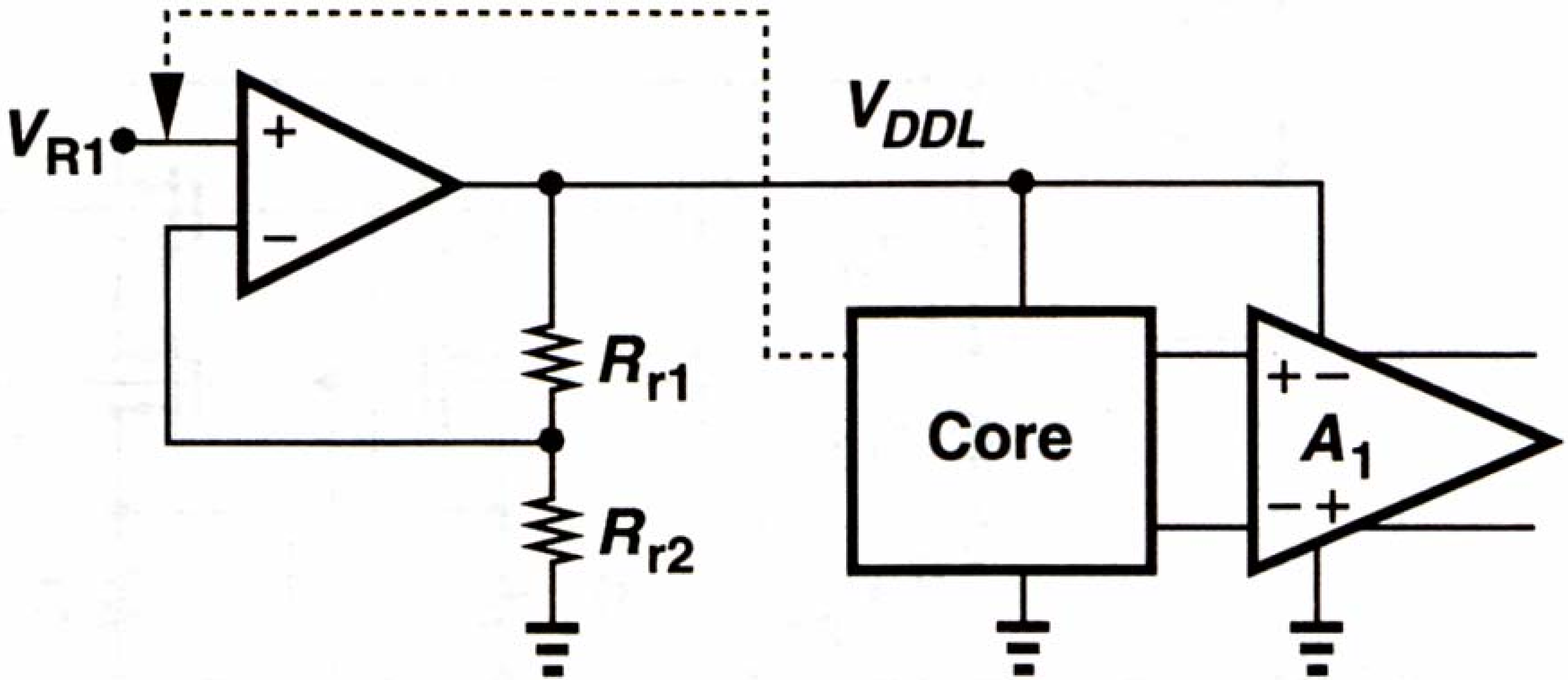
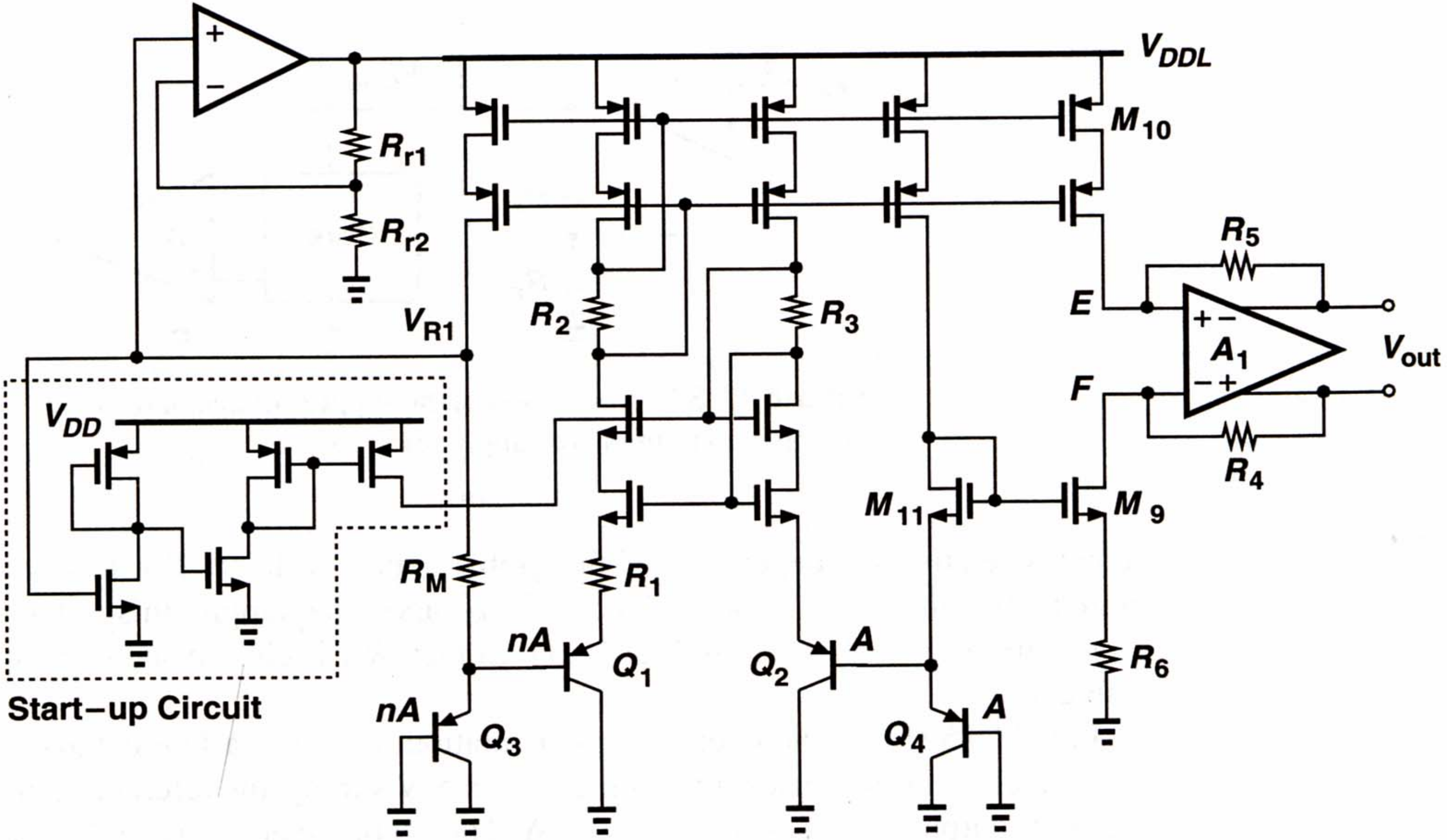


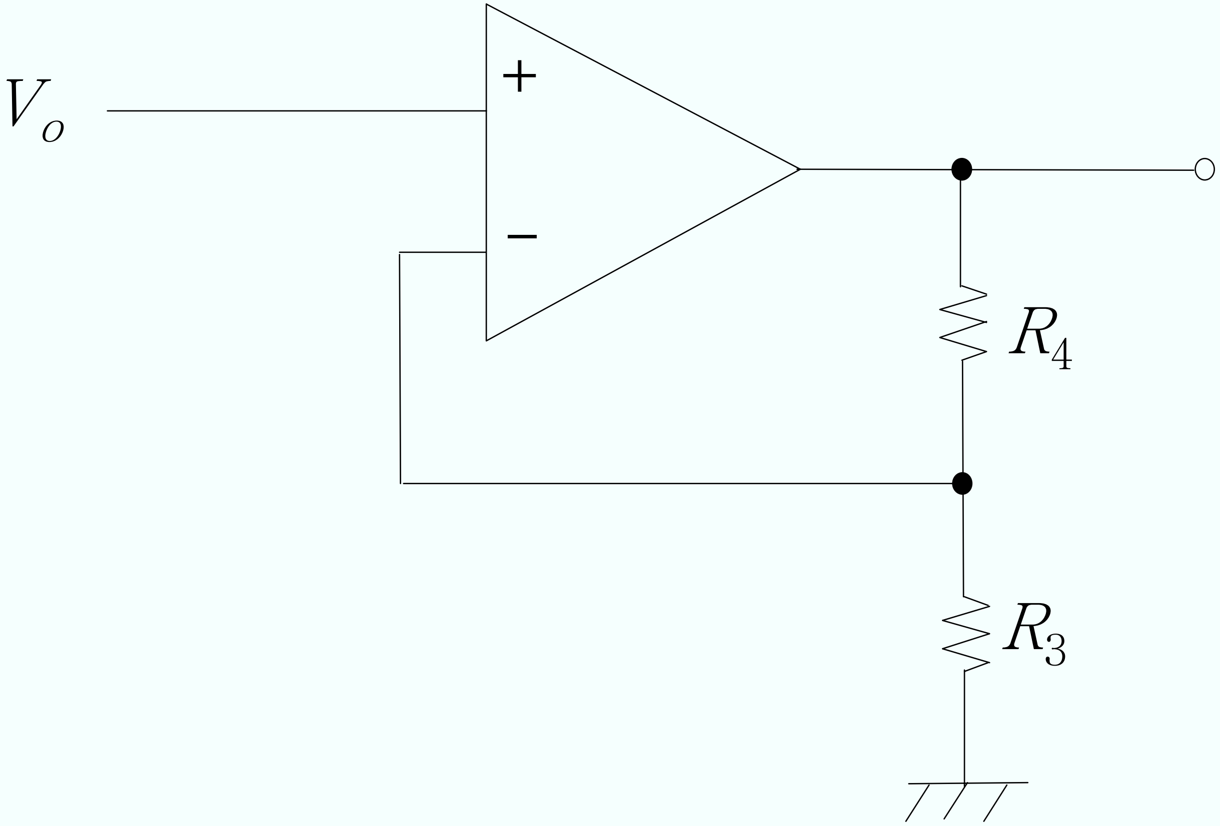
**Figure 11.33** Regulation of the supply voltage of the core and op amp to improve supply rejection.

Razavi

# Bandgap reference: Case studies



Razavi

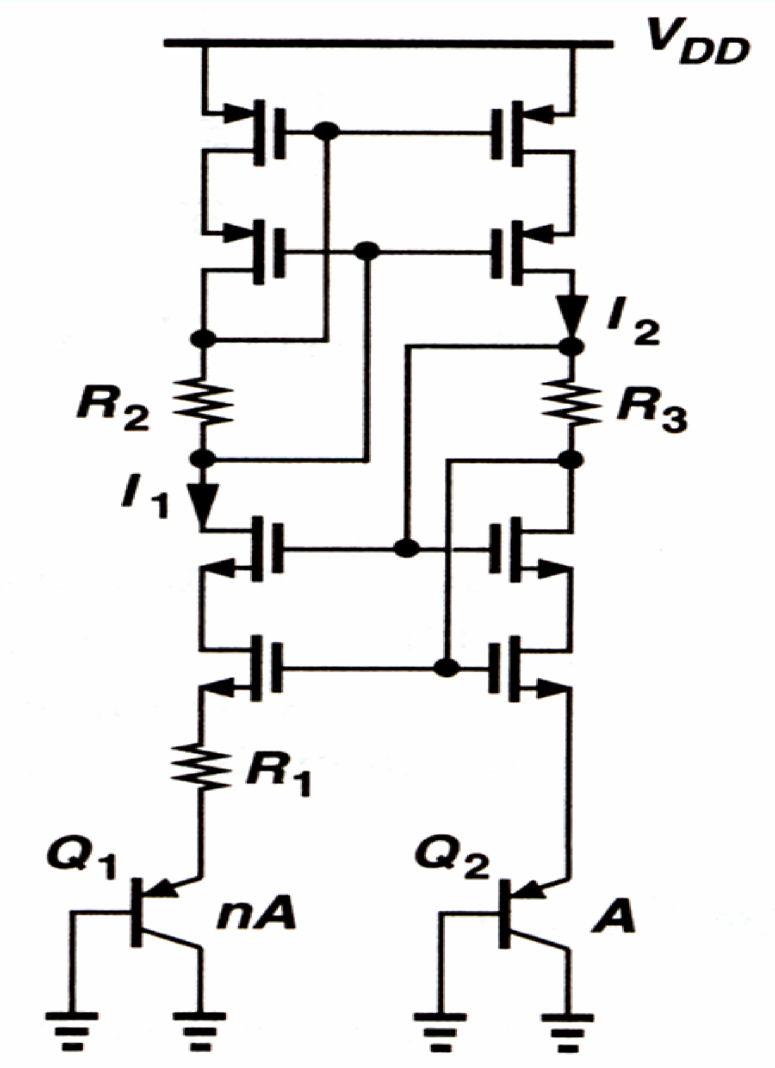


$$V_{out} = V_o \cdot \frac{R_3 + R_4}{R_3}$$

**PVT sensitivity of OP amp input offset voltage (Vos) ➔ causes problem**

**Fig 8.2.11** Arbitrary voltage generator from a bandgap source

# Excercise



What is the range of I1 x R2 in terms of VDSAT and VTH (PMOS), so that PMOSFETs are in saturation Region.