Bandgap and current reference circuits

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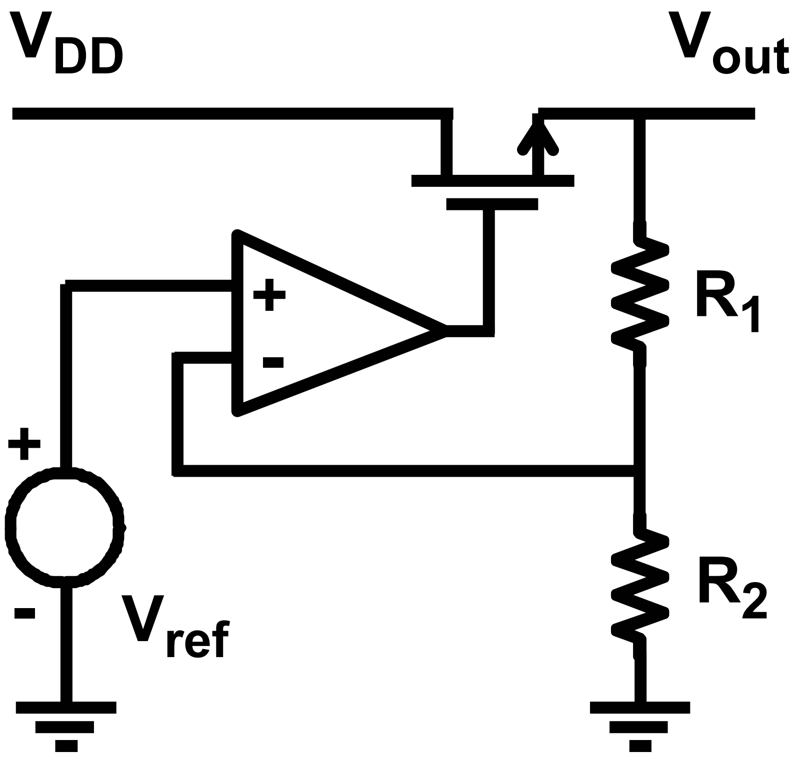
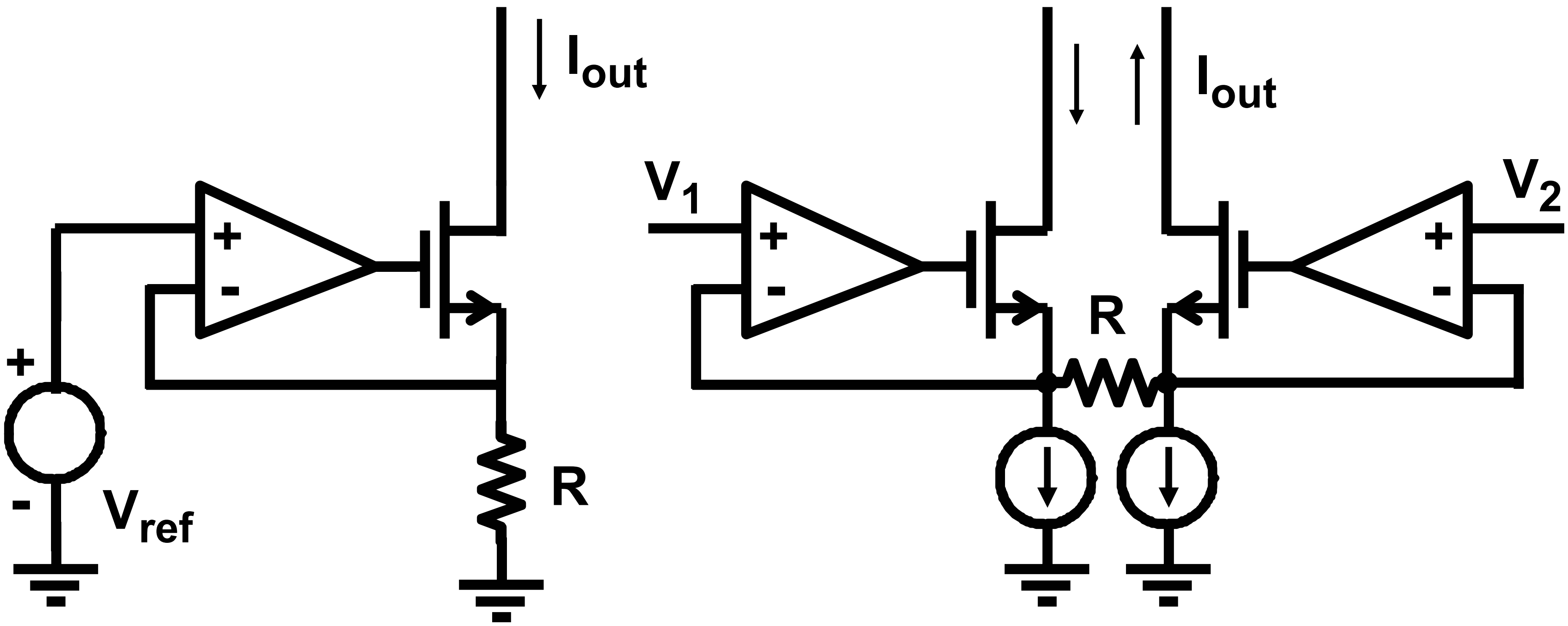
Voltage regulator



$$V_{out} = V_{ref} \frac{R_1 + R_2}{R_2}$$

Current regulator



$$I_{out} = \frac{V_{ref}}{R}$$

$$I_{out} = \frac{V_1 - V_2}{R}$$

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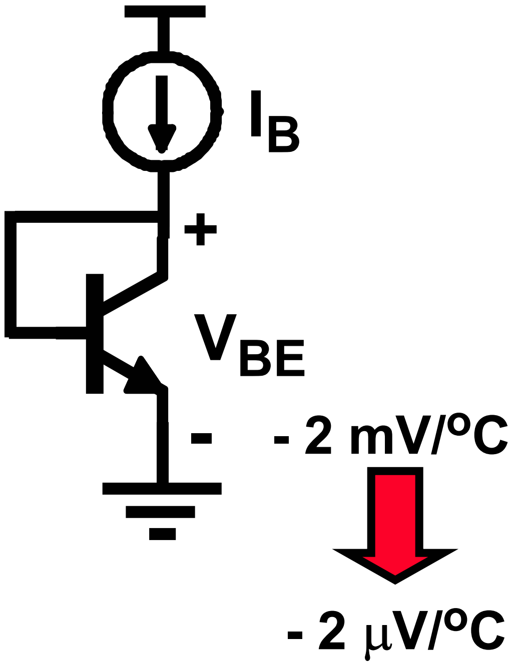
- CMOS bandgap references
- Bandgap references < 1 V
- Current references
- LDO Regulators

Ref.: B.Gilbert, G.Meijer, ACD , Kluwer 1995

Bipolar transistor equations



$$I_C = I_S \exp\left(\frac{V_{BE}}{kT/q}\right)$$

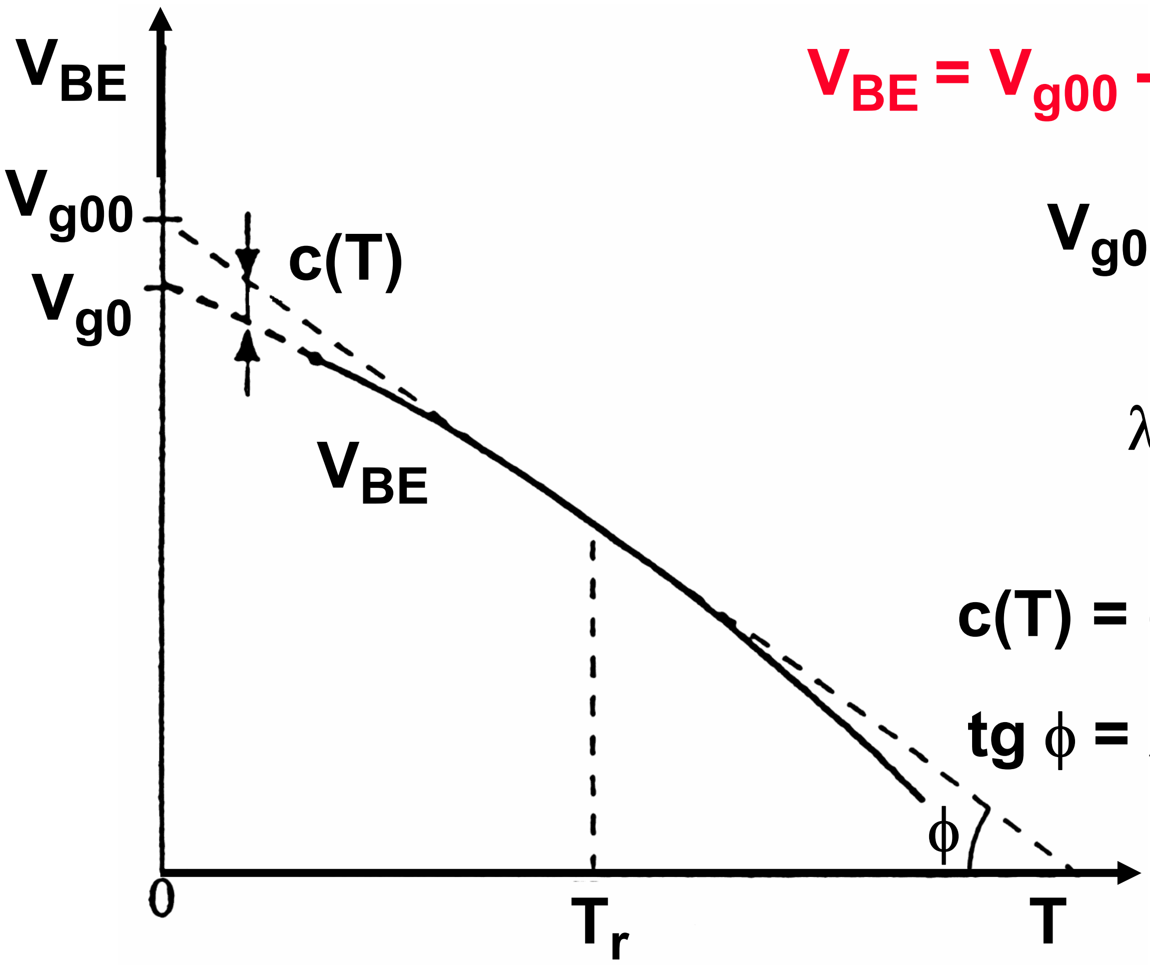
$$\text{or} \quad I_C = CT^{\eta} \exp\left(\frac{V_{BE} - V_{g0}}{kT/q}\right)$$

with $V_{g0} = 1268\ \text{mV} - \eta\ kT_r/q$

and $T_r = 323\ \text{K}$

which gives $V_{BE} = V_{g00} - \lambda T + c(T)$ for $I_C \sim T^m$

V_{BE} versus Temperature



$V_{BE} = V_{g00} - \lambda T + c(T)$ for $I_C \sim T^m$

$$V_{g00} = V_{g0} + (\eta - m)\, kT_r/q$$

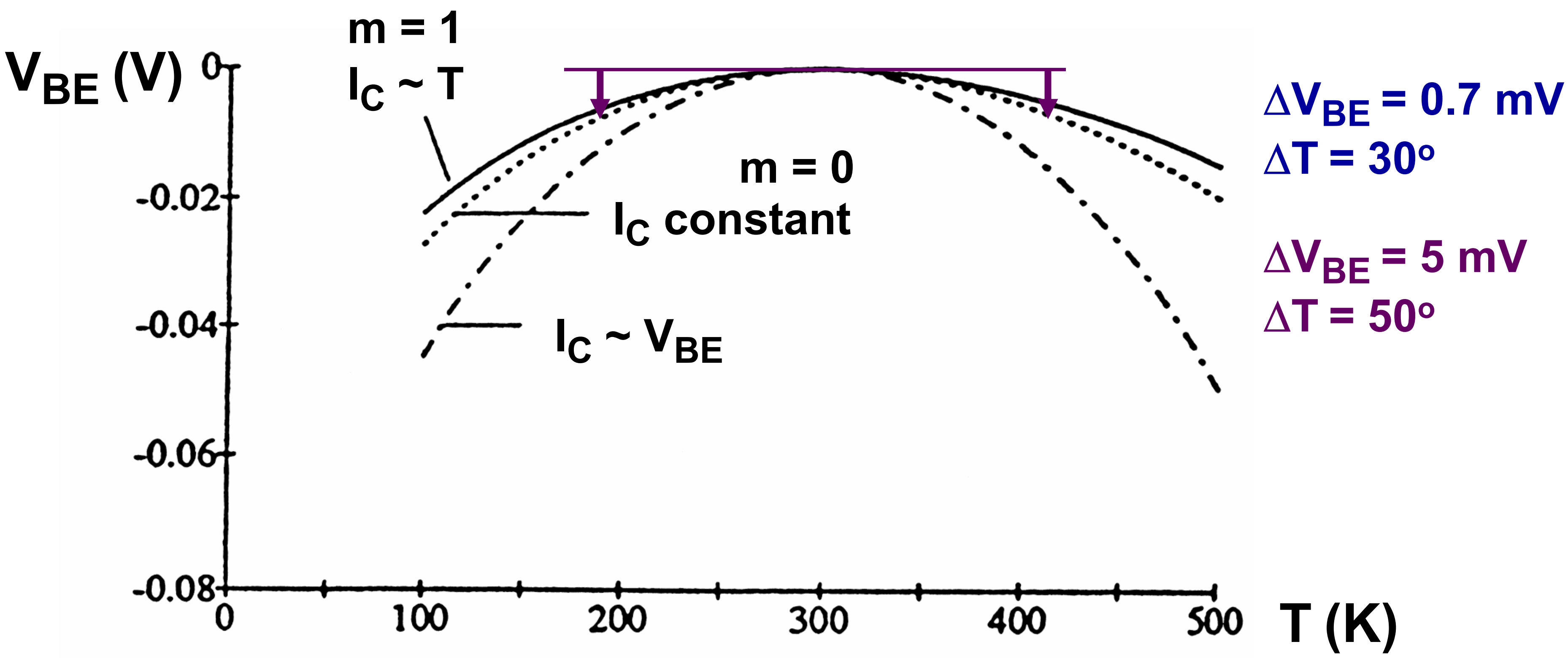
$$\lambda = \frac{V_{g00} - V_{BE}(T_r)}{T_r}$$

$$c(T) = (\eta - m)\frac{k}{q}\left(T - T_r - T \ln \frac{T}{T_r}\right)$$

$$\mathrm{tg}\,\phi = \lambda$$

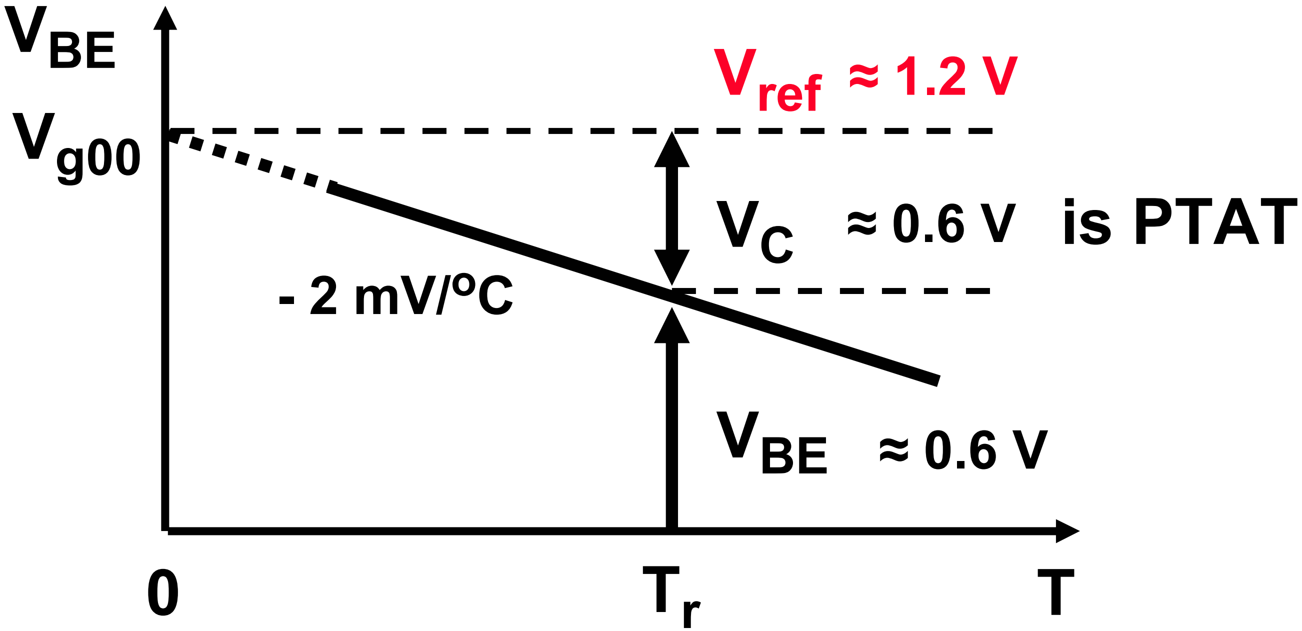
$V_{g0} = 1156$ mV
$\eta = 4$
$T_r = 300$ K
$V_{BE}(T_r) = 700$ mV

The curvature c(T)



m = 1	$I_C \sim T$	g_m constant
m = 0	I_C constant	$g_m \sim T^{-1}$
m = -	$I_C \sim V_{BE}$	$g_m \sim T^{-x}$

Bandgap reference Vref

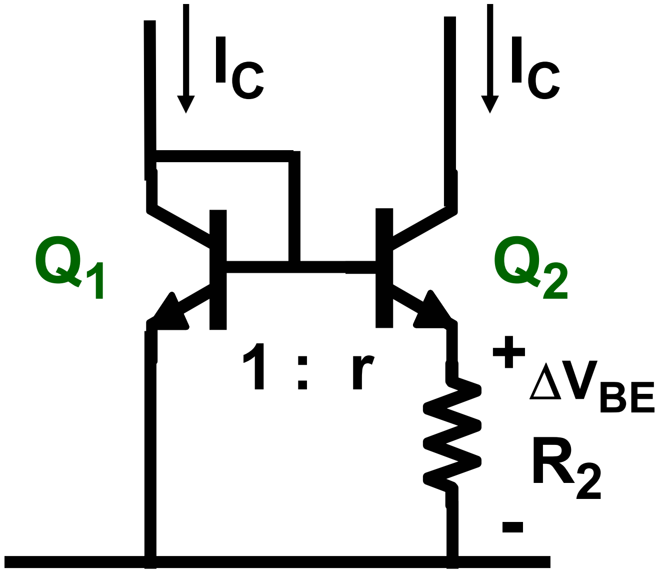


$$V_{ref} = V_{BE} + V_C \qquad V_C \sim \frac{kT}{q}$$

PTAT voltage and current

$$I_C = I_S \exp\left(\frac{V_{BE}}{kT/q}\right) \qquad V_{BE} = \frac{kT}{q} \ln \frac{I_C}{I_S}$$

$$\Delta V_{BE} = V_{BE1} - V_{BE2}$$

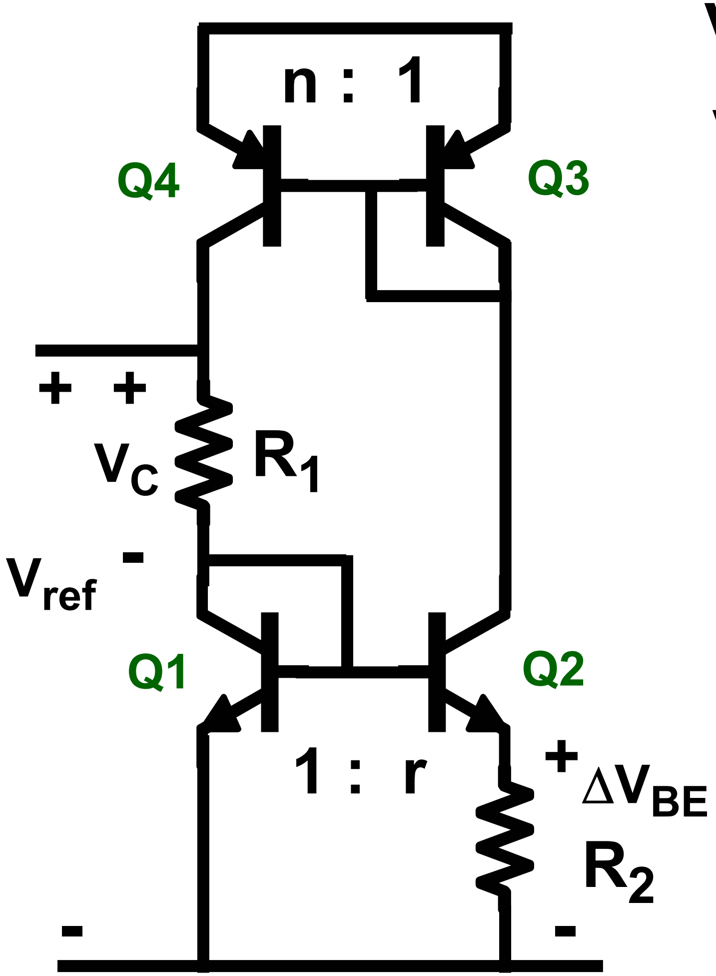


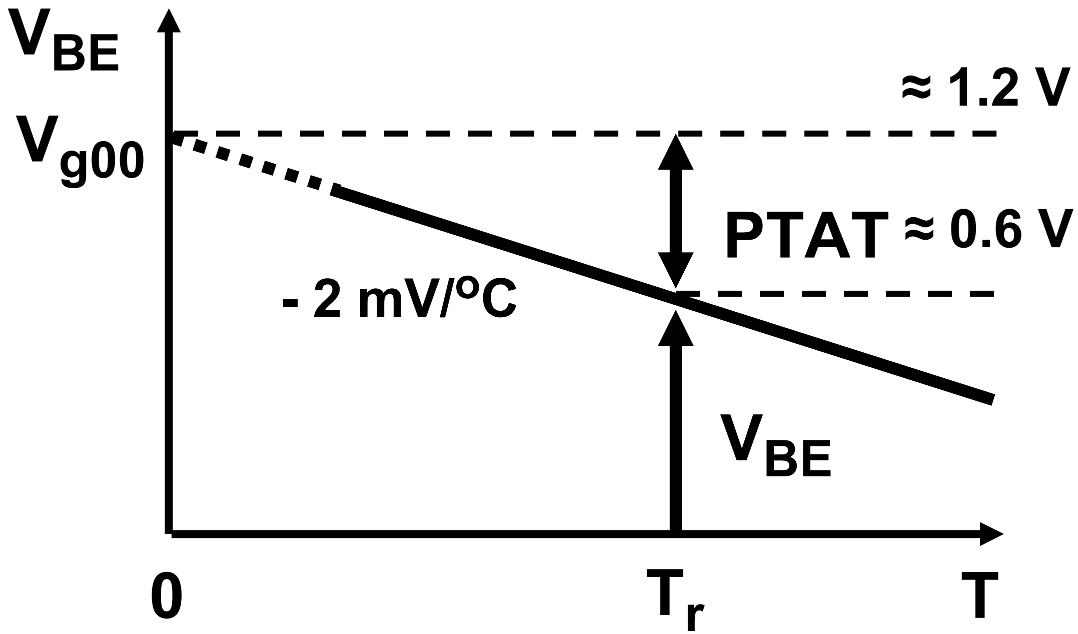
$$\Delta V_{BE} = \frac{kT}{q} \ln \frac{I_{S2}}{I_{S1}}$$

$$\Delta V_{BE} = \frac{kT}{q} \ln r \qquad I_C = \frac{kT}{qR_2} \ln r$$

r is 10-1000 !!

Bandgap reference circuit

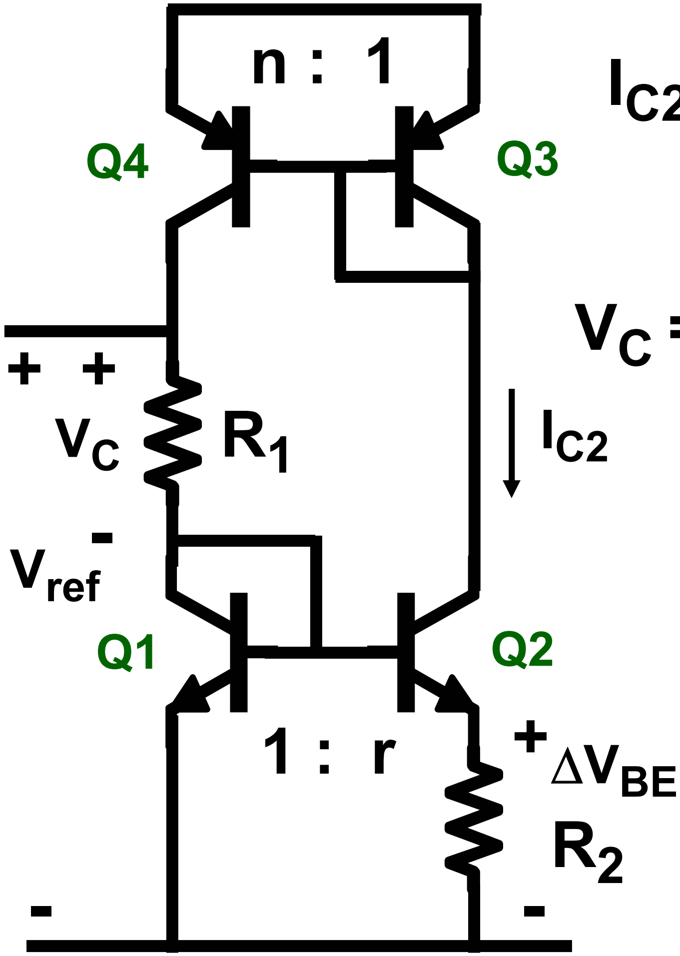




$$\Delta V_{BE} = \frac{kT}{q} \ln nr \qquad I_{C2} = \frac{kT}{qR_2} \ln nr = \frac{A}{R_2}$$

$$V_{ref} = V_{BE} + V_C \qquad V_C = n \frac{R_1}{R_2} \frac{kT}{q} \ln nr$$

Noise Bandgap reference - 1



$$I_{C2} = \frac{kT}{qR_2} \ln nr = \frac{A}{R_2} \qquad A = \frac{kT}{q} \ln nr \approx 0.12 \text{ V}$$

$$V_C = n \frac{R_1}{R_2} \frac{kT}{q} \ln nr = n \frac{R_1}{R_2} A = nR_1 I_{C2} \approx 0.6 \text{ V}$$

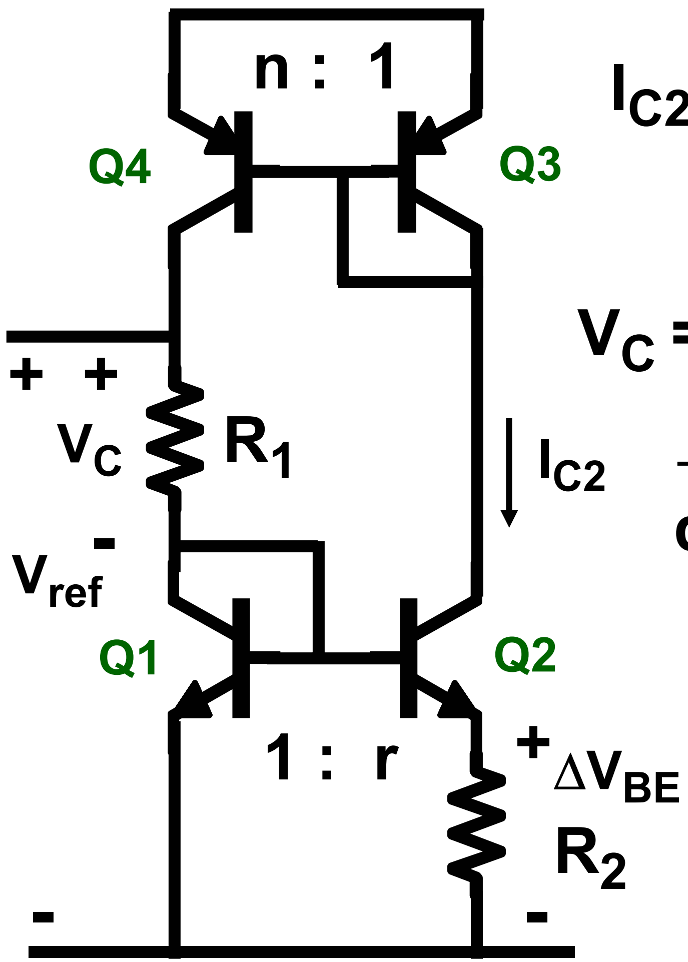
$R_1 >> 1/g_{m1}$ $\quad R_1 I_{C1} \approx 0.5$ V $\quad g_{m1}R_1 \approx 20$

$R_2 >> 1/g_{m2}$ $\quad R_2 I_{C2} \approx 0.06$ V $\quad g_{m2}R_2 \approx 2.3$

Noise sources : R_1 R_2

$g_{m3,4}$ negligible for large V_{GS} -V_T or R_E !!

Noise Bandgap reference - 2



$$I_{C2} = \frac{kT}{qR_2}\ln nr = \frac{A}{R_2} \qquad A = \frac{kT}{q}\ln nr \approx 0.12\ \mathrm{V}$$

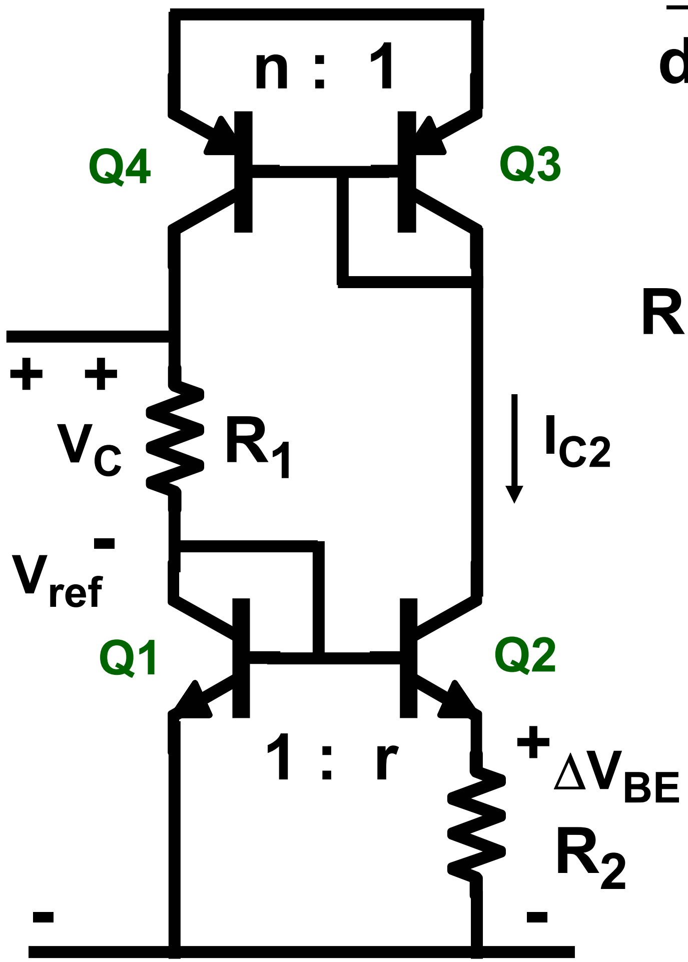
$$V_C = n\,\frac{R_1}{R_2}\,\frac{kT}{q}\ln nr = n\,\frac{R_1}{R_2}A = nR_1I_{C2} \approx 0.6\ \mathrm{V}$$

$$\overline{dV_{Ref}^2} = 4kT\,R_1\,df + R_1^2n^2\,4kT/R_2\,df$$

$$= 4kT\,R_1\,df\left(1 + \frac{R_1}{R_2}n^2\right)$$

$$\frac{R_1}{R_2}n^2 = \frac{n}{R_2}R_1n = \frac{n}{R_2}\,\frac{V_C}{I_{C2}} = \frac{nV_C}{\Delta V_{BE}} \gg 1$$

Noise Bandgap reference - 3



$$\overline{dV_{Ref}^2} = 4kT\, R_1 \frac{R_1}{R_2} n^2\, df$$

$$R_1 \frac{R_1}{R_2} n^2 = \frac{(R_1 n)^2}{R_2} = \frac{1}{R_2} \frac{V_C^2}{I_{C2}^2} = \frac{V_C^2}{I_{C2}\, \Delta V_{BE}}$$

$V_C \approx 0.6$ V :

>> Large I_{C2} : small R's

>> Large r : large ΔV_{BE}

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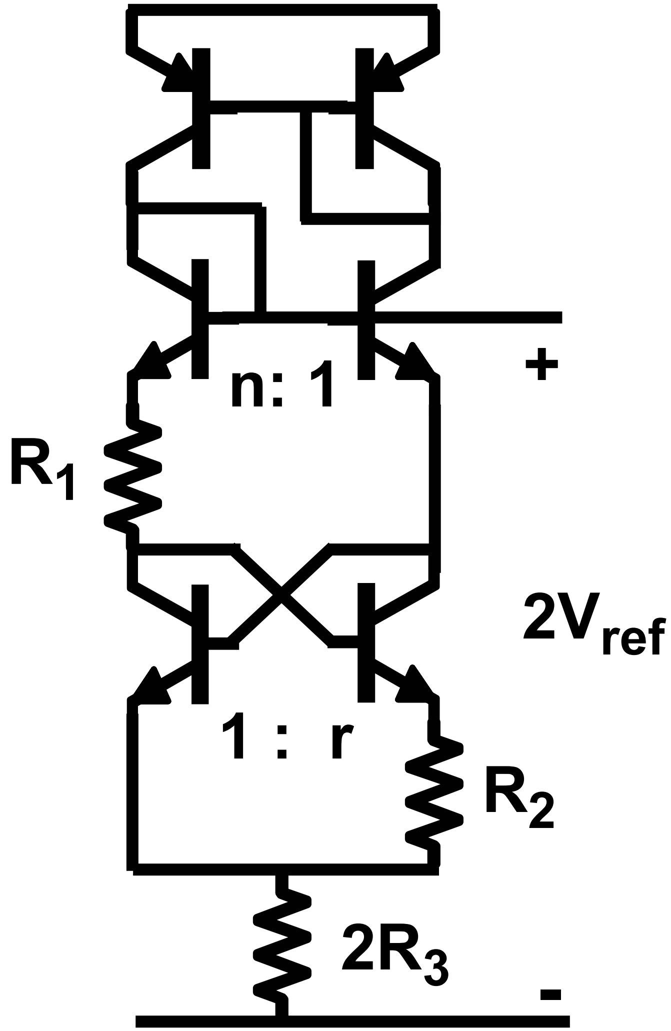
Ref.: B. Gilbert, G.Meijer, ACD , Kluwer 1995

Bandgap reference with bipolar transistors



Insensitive to β and V_E !

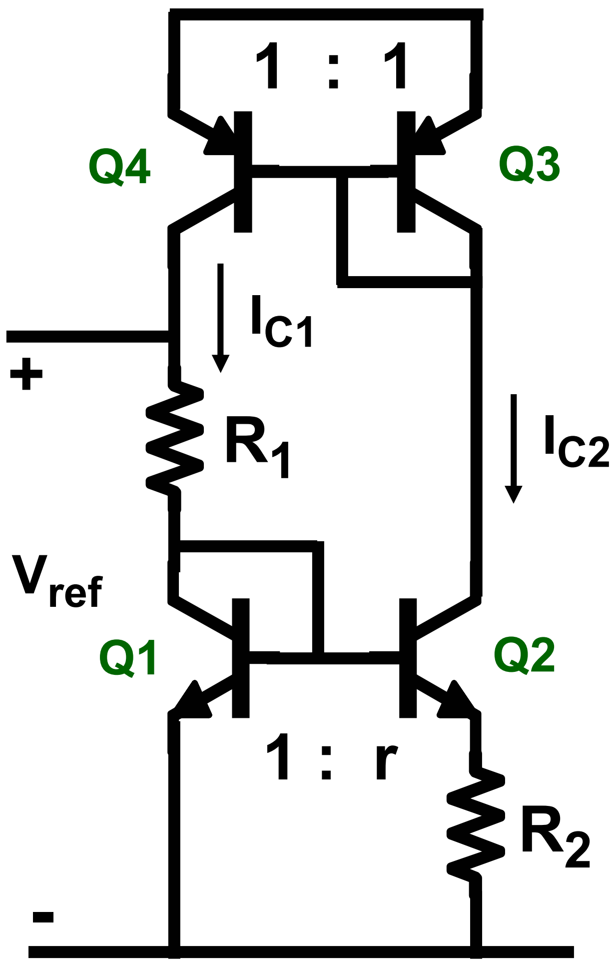
$$\Delta V_{BE} = \frac{kT}{q} \ln nr \qquad I_C = \frac{kT}{qR_2} \ln nr$$

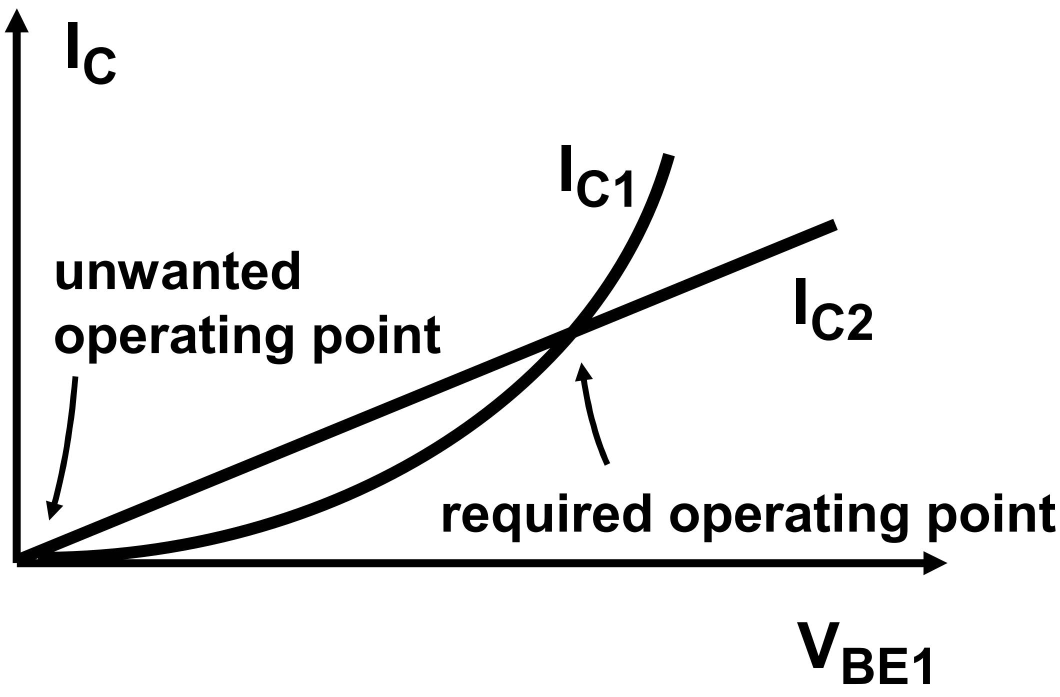
$$V_{ref} = 2V_{BE} + V_{R3}$$

$$V_{R3} = 2R_3 \left(\frac{1}{R_1} + \frac{1}{R_2}\right) \frac{kT}{q} \ln nr$$

Ref.: G.Meijer, ACD , Kluwer 1995

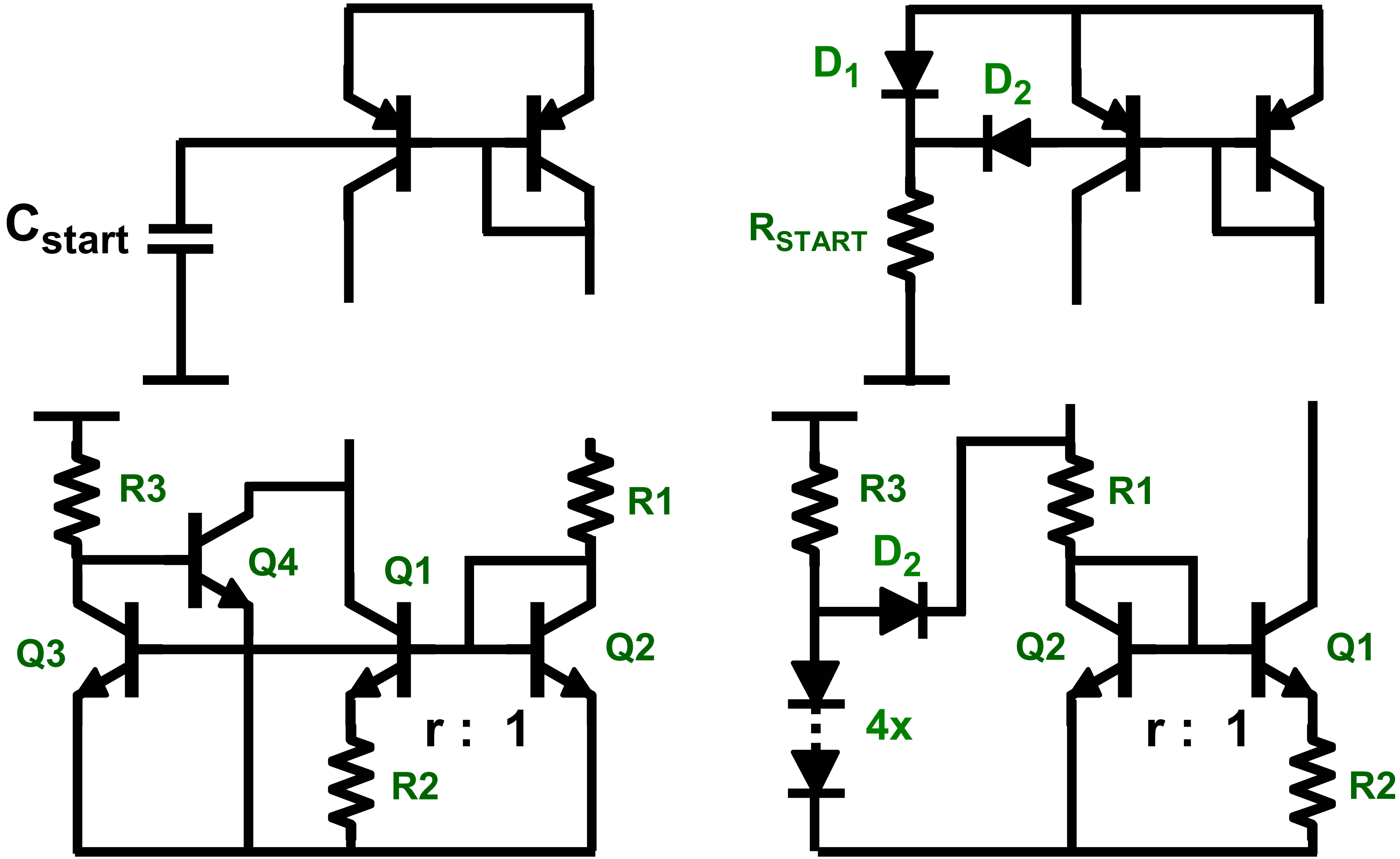
Start-up circuits required



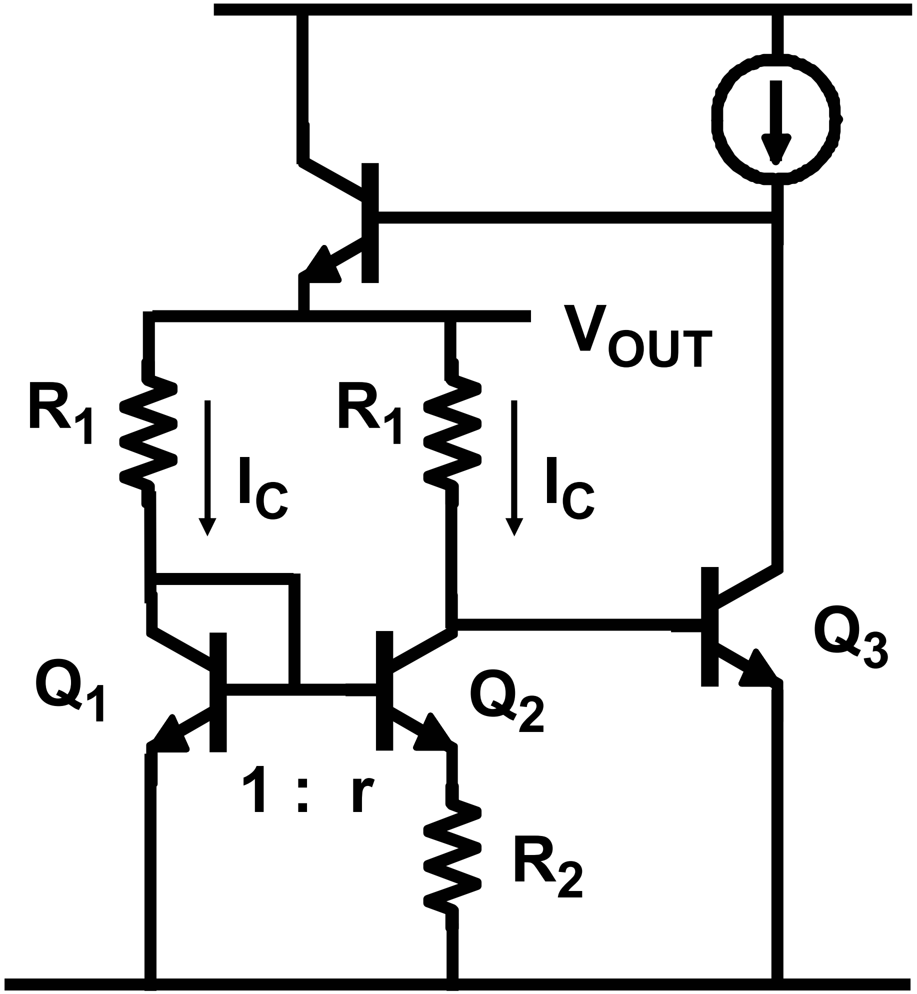


$$V_{ref} = V_{BE1} + \frac{R_1}{R_2}\frac{kT}{q}\ln r$$

Start-up circuits



Bipolar Bandgap reference without opamp

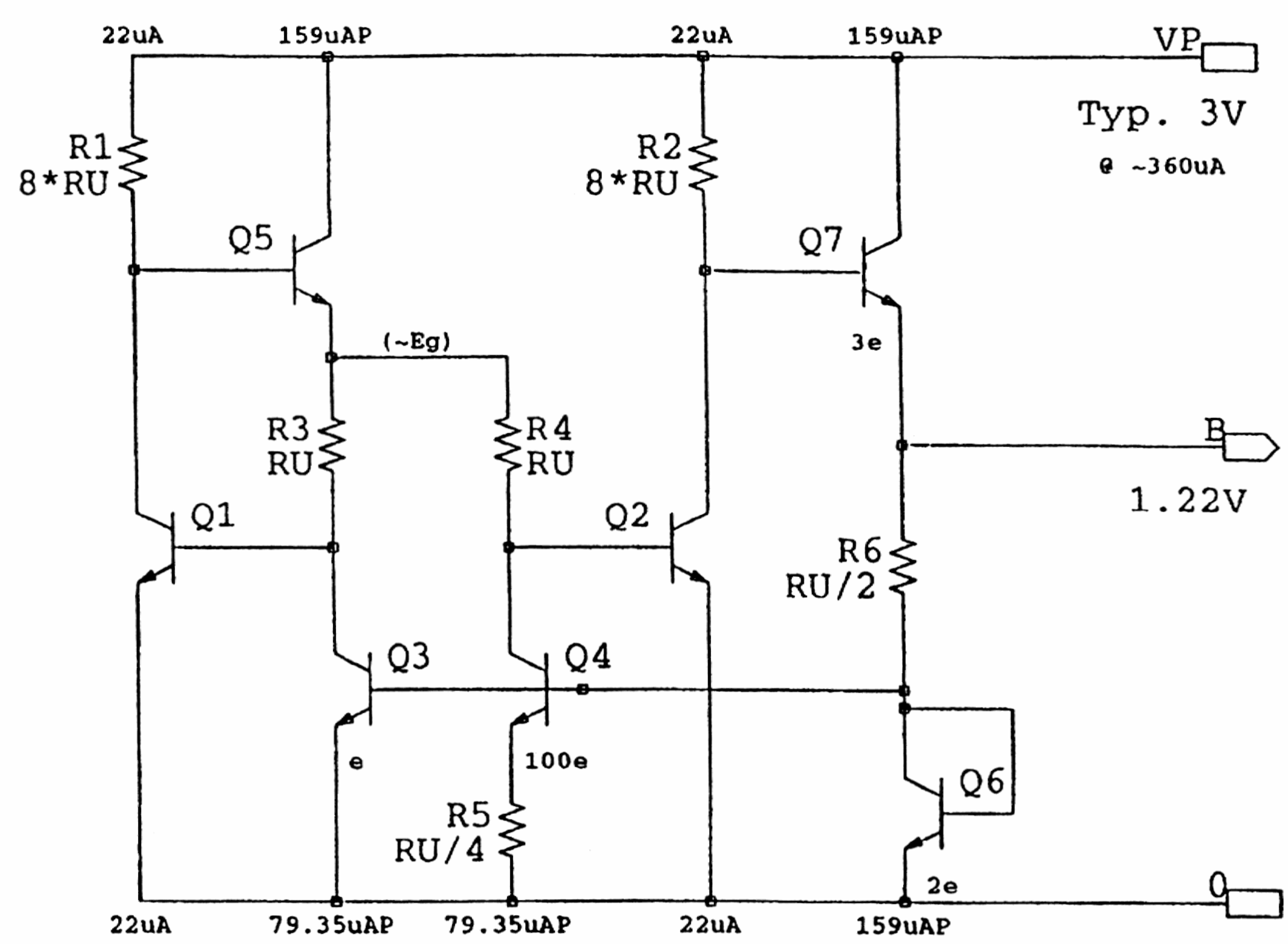


$$V_{OUT} = V_{BE1} + R_1\, I_C$$

$$= V_{BE1} + \frac{R_1}{R_2}\frac{kT}{q}\ln r$$

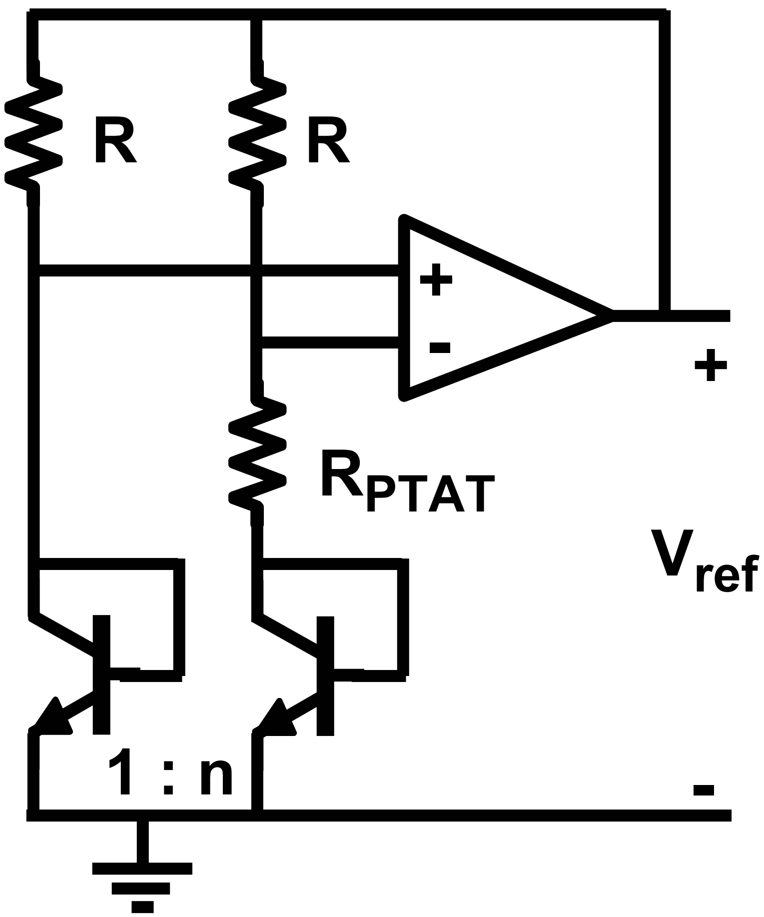
Ref. Widlar, JSSC Feb.1971, 2-7

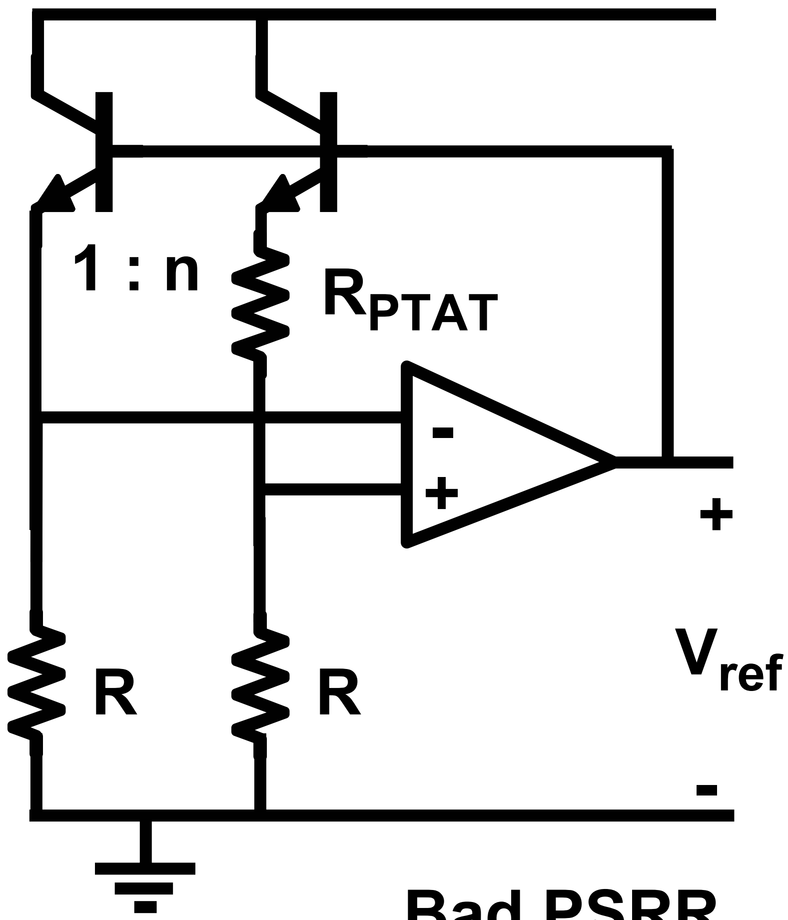
All NPN bipolar bandgap reference



Ref.: B.Gilbert, ACD , Kluwer 1995

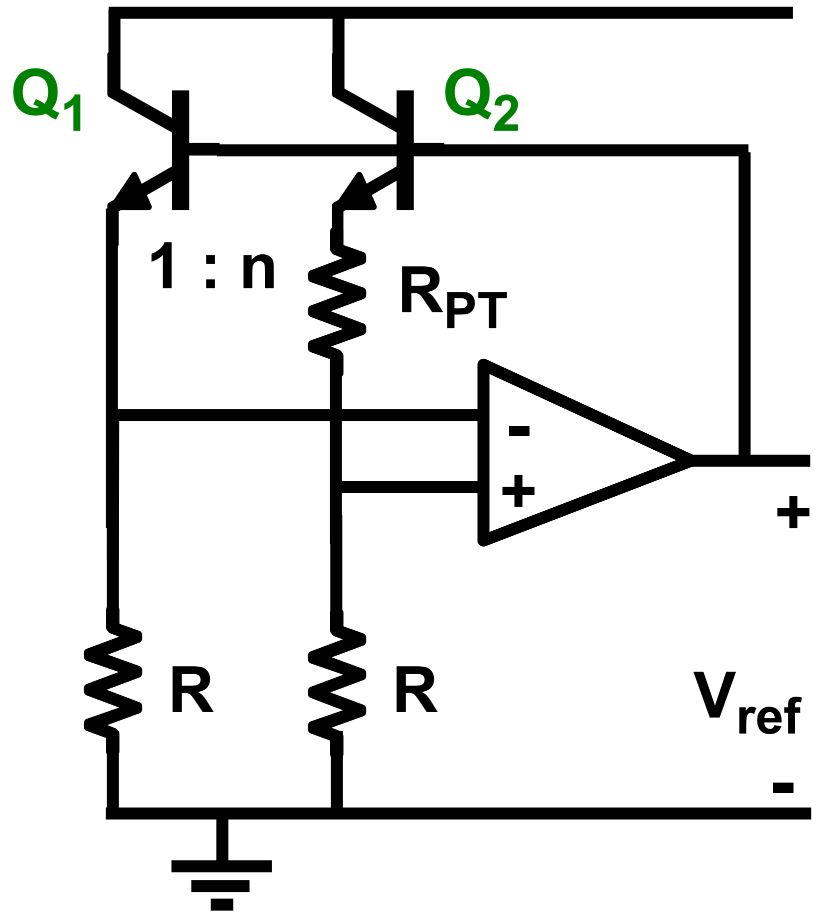
Bipolar Bandgap references with opamps





Bad PSRR

CMOS Bandgap ref.with opamp: error analysis 1



$$I_C = \frac{kT}{qR_{PT}} \ln n \qquad A = \frac{R}{R_{PT}}$$

$$V_{ref} = V_{BE} + A\,(V_{BE1} - V_{BE2})$$

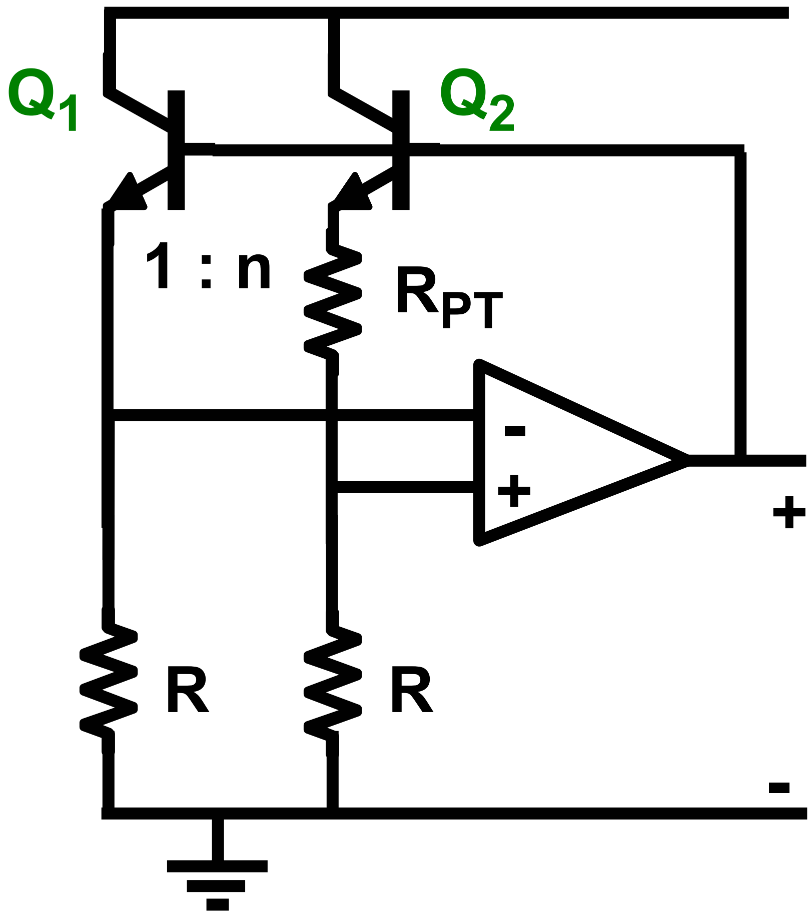
$$dV_{BE} = \frac{kT}{q}\left(\frac{dI_C}{I_C} - \frac{dI_S}{I_S}\right)$$

$$= \frac{kT}{q}\left(\frac{1}{\ln n}\frac{dn}{n} - \frac{dR_{PT}}{R_{PT}} - \frac{dI_S}{I_S}\right)$$

is PTAT !

= 26 mV (0.46 2% - 30 % - 20%) ≈ 13 mV (if n = 10)

CMOS Bandgap ref.with opamp: error analysis 2



$$V_{ref} = V_{BE} + A\,(V_{BE1} - V_{BE2})$$

$$V_{BE1} - V_{BE2} = \frac{kT}{q}\ \ln n$$

$$d(V_{BE1} - V_{BE2}) = \frac{kT}{q}\ \frac{dn}{n}$$

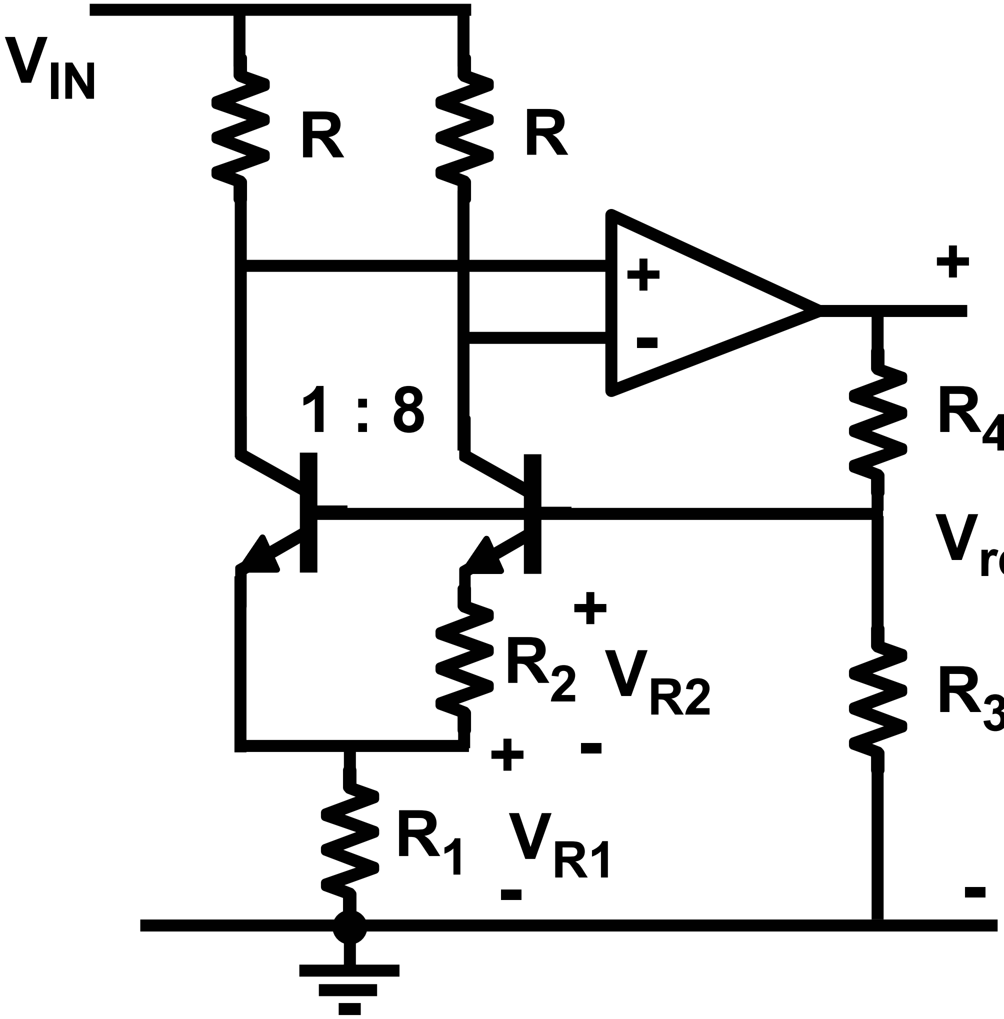
$$d[A(V_{BE1} - V_{BE2})] =$$

$$= A\,\frac{kT}{q}\ \ln n \left(\frac{dA}{A} + \frac{1}{\ln n}\ \frac{dn}{n} \right)$$

is PTAT !

= 600 mV (1 % + 0.46 2%) ≈ 11 mV ⇨ 24 mV or 2%

Bipolar Bandgap reference AD580



$$V_{OUT} = V_{ref}\ \frac{R_3 + R_4}{R_3}$$

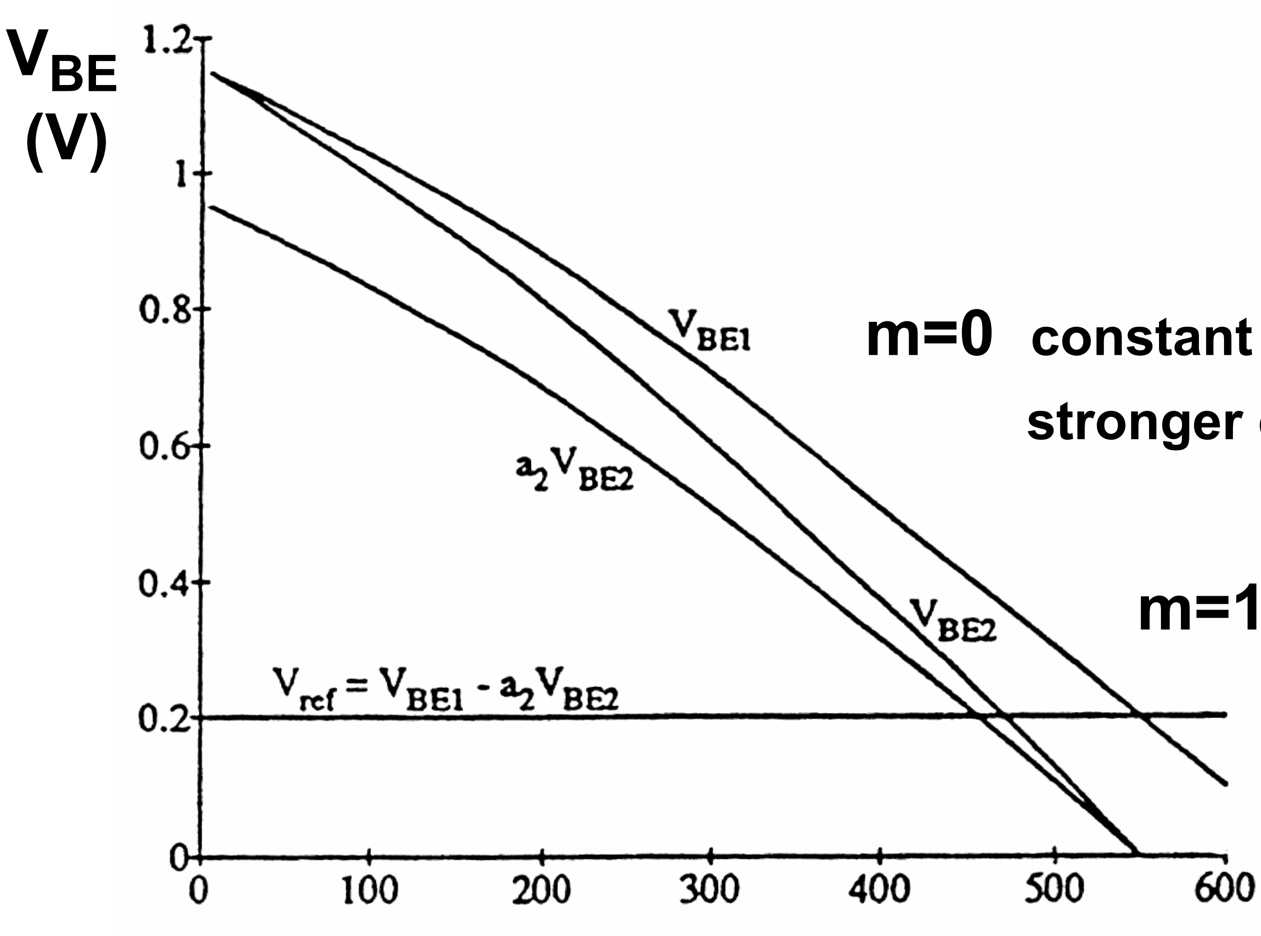
$$V_{ref} = V_{BE} + V_{R1}$$

$$= V_{BE} + 2\ \frac{R_1}{R_2} V_{R2}$$

$$= V_{BE} + 2\ \frac{R_1}{R_2}\frac{kT}{q}\ \ln 8$$

$$\approx 1.205\ V$$

Curvature correction with ΔV_{BE}



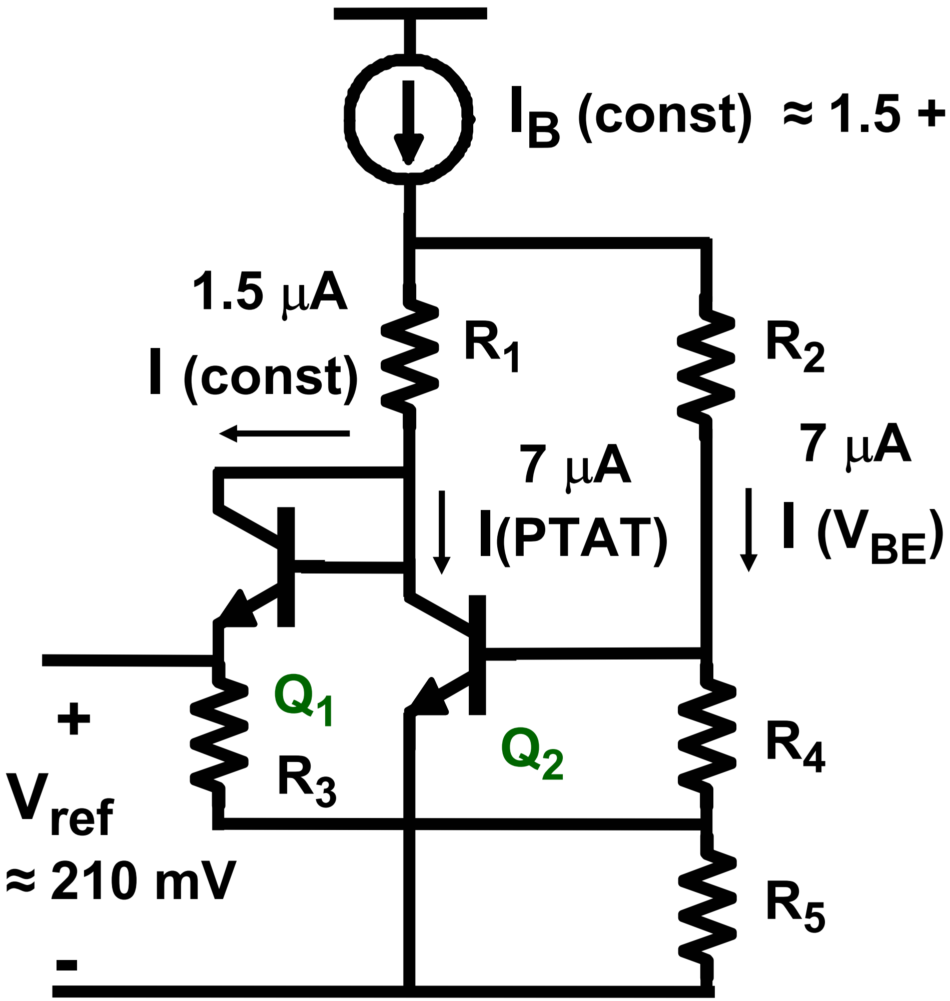
m=0 constant current
stronger curvature

m=1 PTAT current
ratio $\eta/(\eta-1)$ or $1/a_2$
$\eta = 3.5 \quad a_2 \approx 0.714$

$V_{ref} \approx 210$ mV

Ref. Widlar, Meijer, van Staveren

Curvature correction with ΔV_{BE}

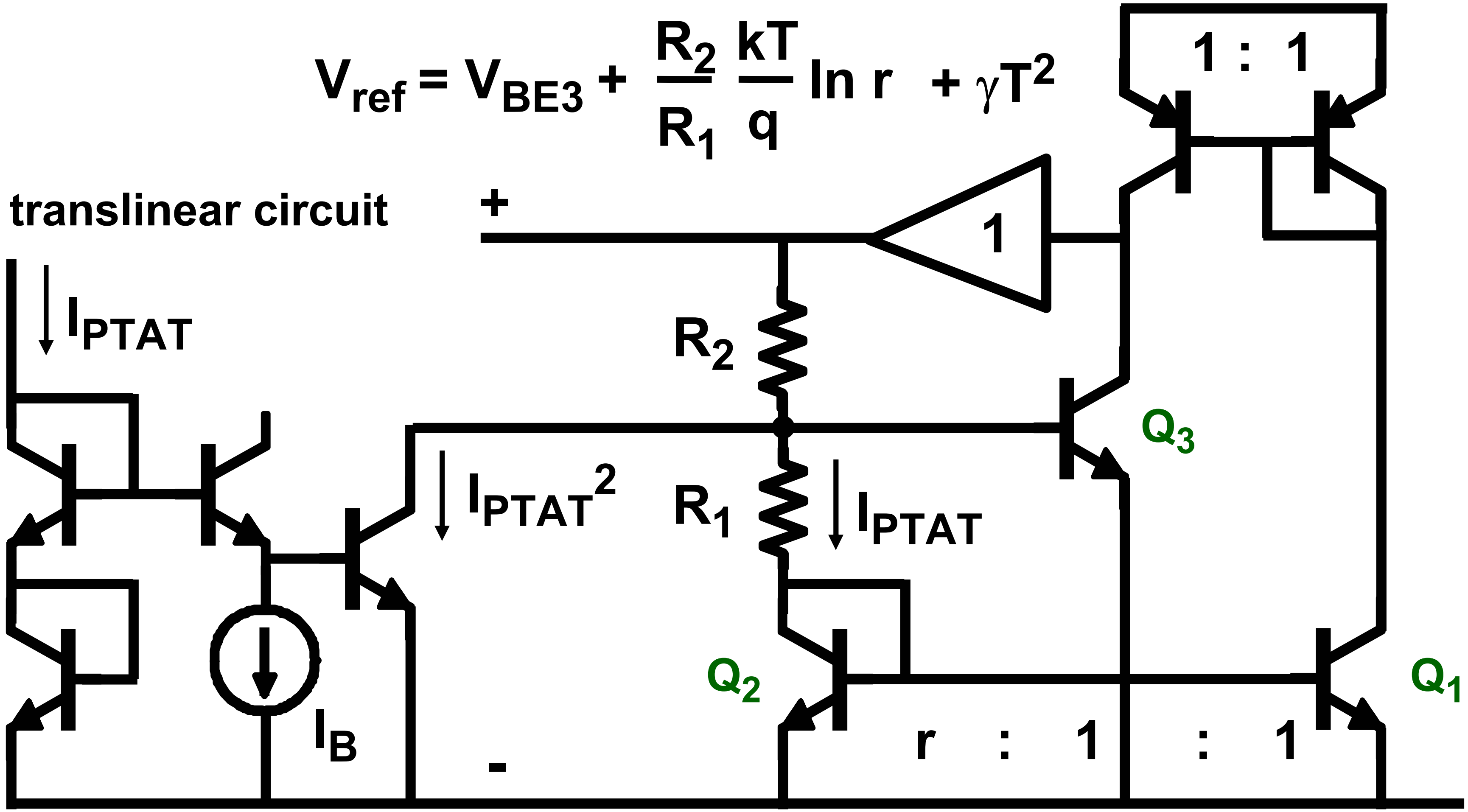


$$V_{ref} = V_{BE2} + R_2\, I\,(V_{BE})$$
$$- R_1(I\,(\text{const}) + I\,(\text{PTAT}))$$
$$- V_{BE1}$$
$$\approx V_{PTAT} + AV_{BE2}$$

Ref. Widlar JSSC Dec.78, 838-846

Curvature correction with PTAT²

$$V_{ref} = V_{BE3} + \frac{R_2}{R_1}\frac{kT}{q}\ln r \;\; + \gamma T^2$$



Ref. Song JSSC Dec.83, 634-643, Degrauwe ISSCC Febr.85, 142-143

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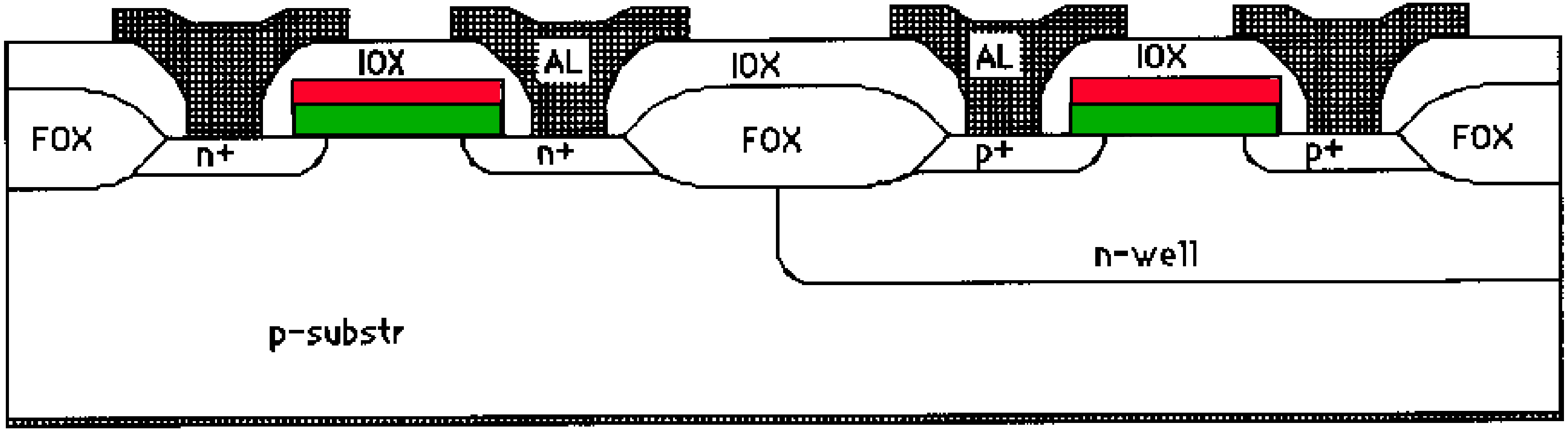
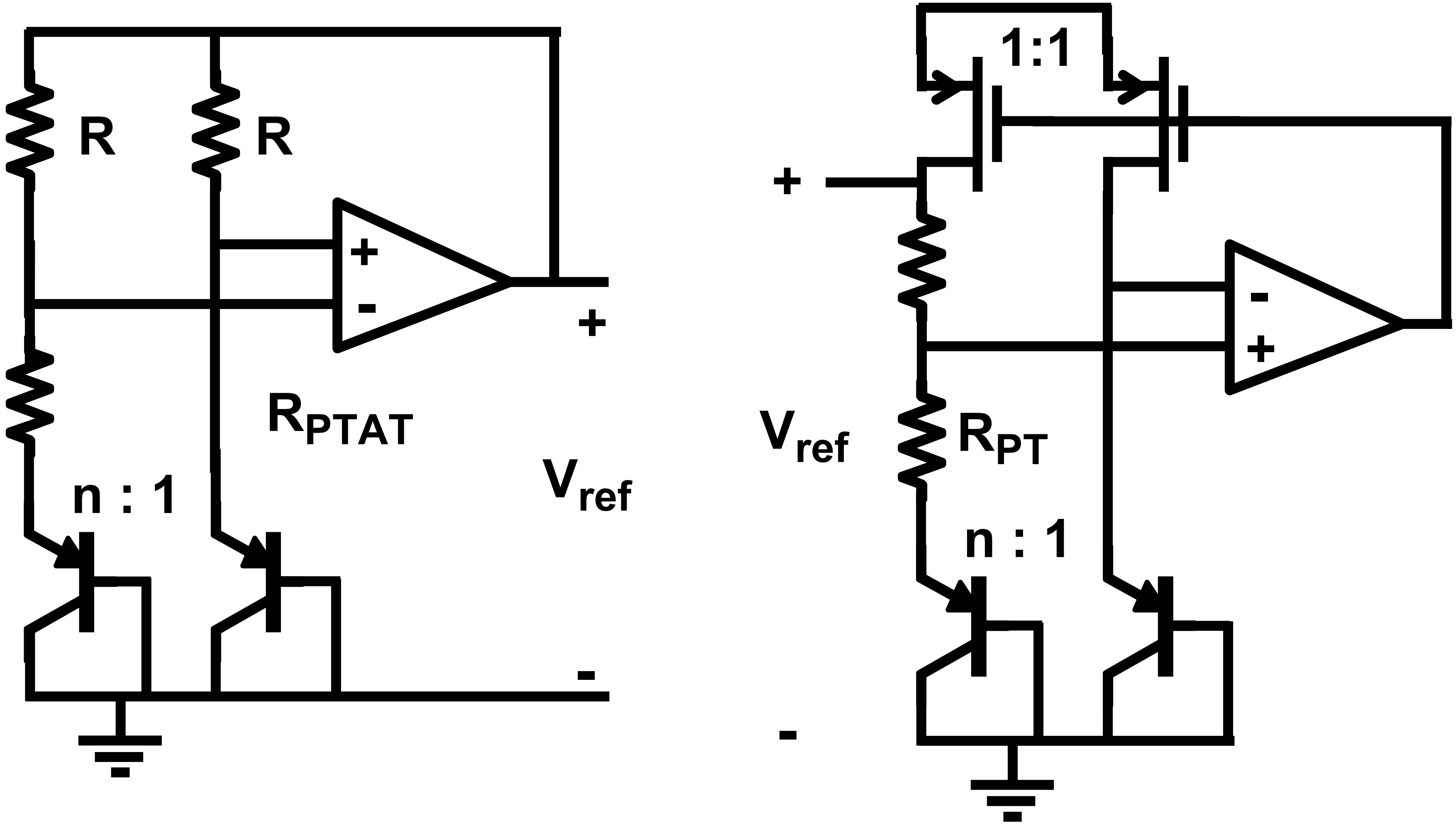
N-well CMOS technology



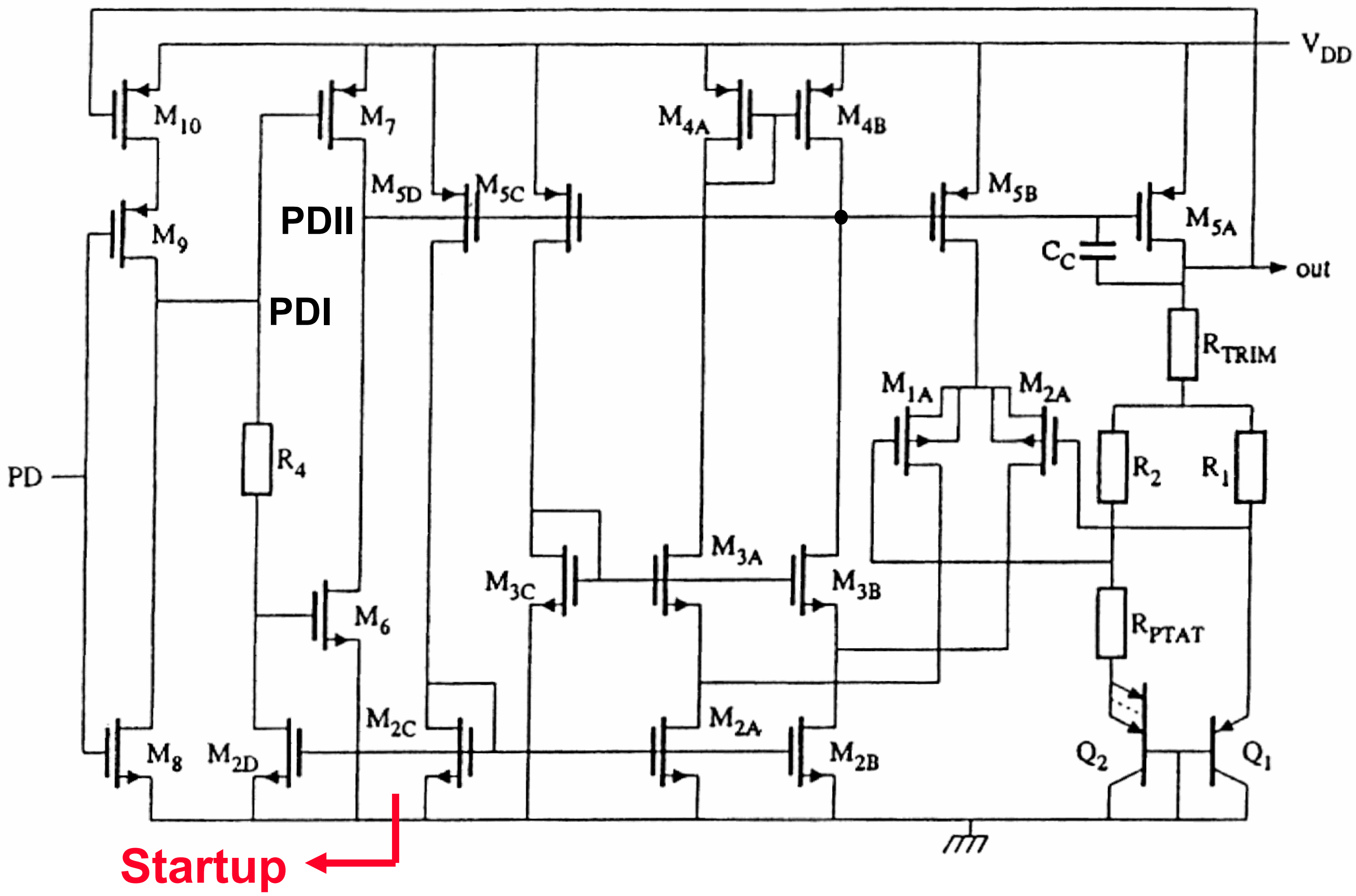
Gate oxyde

Polysilicon gate

CMOS Bandgap reference with opamp



Full CMOS bandgap reference circuit



2.7 ... 5.5 V

17 μA

1.2 ± 0.02 V

10 μA max.

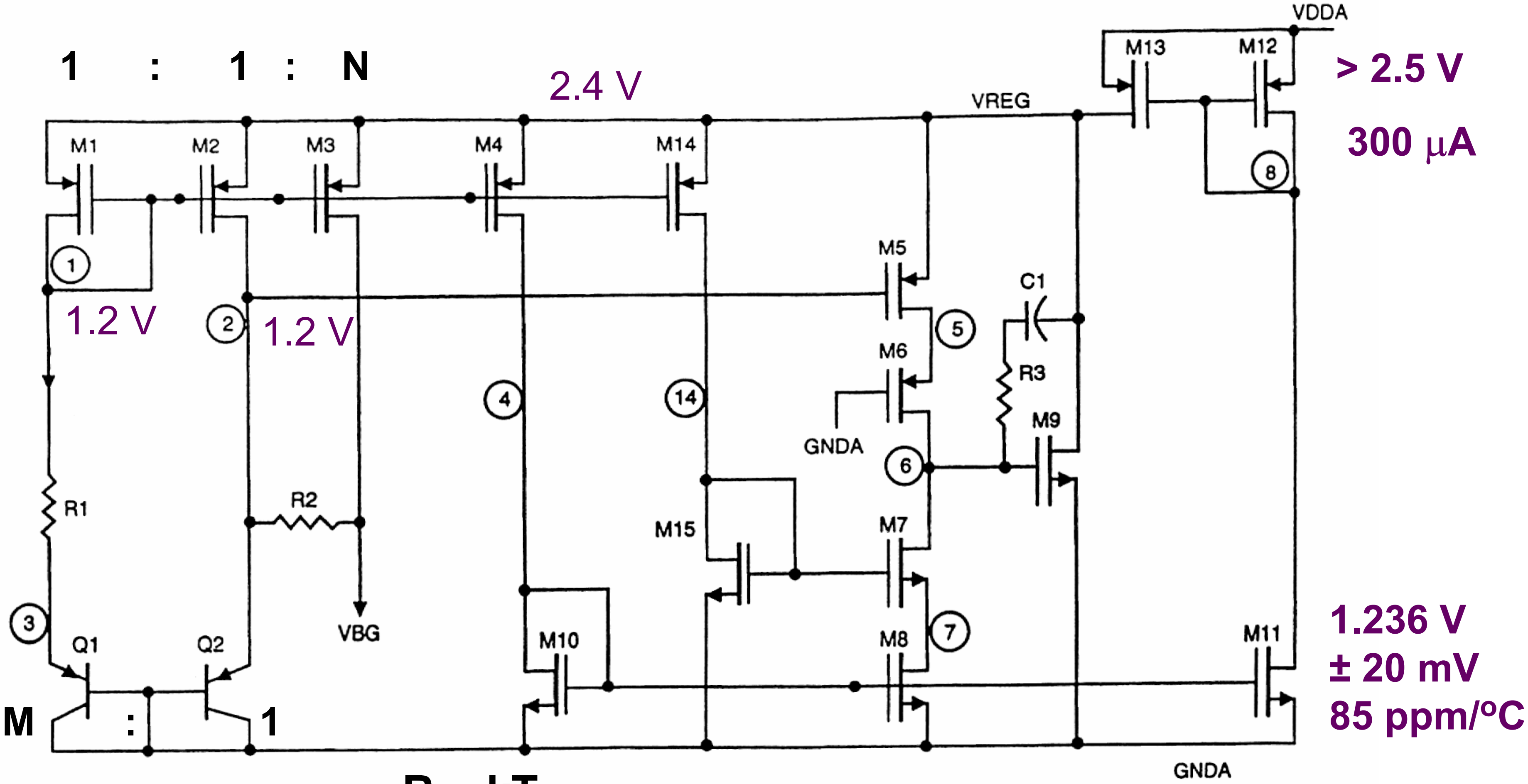
4000 ppm

-50 °C

+150 °C

Ref. MIETEC; Meijer, ACD, Kluwer 1995

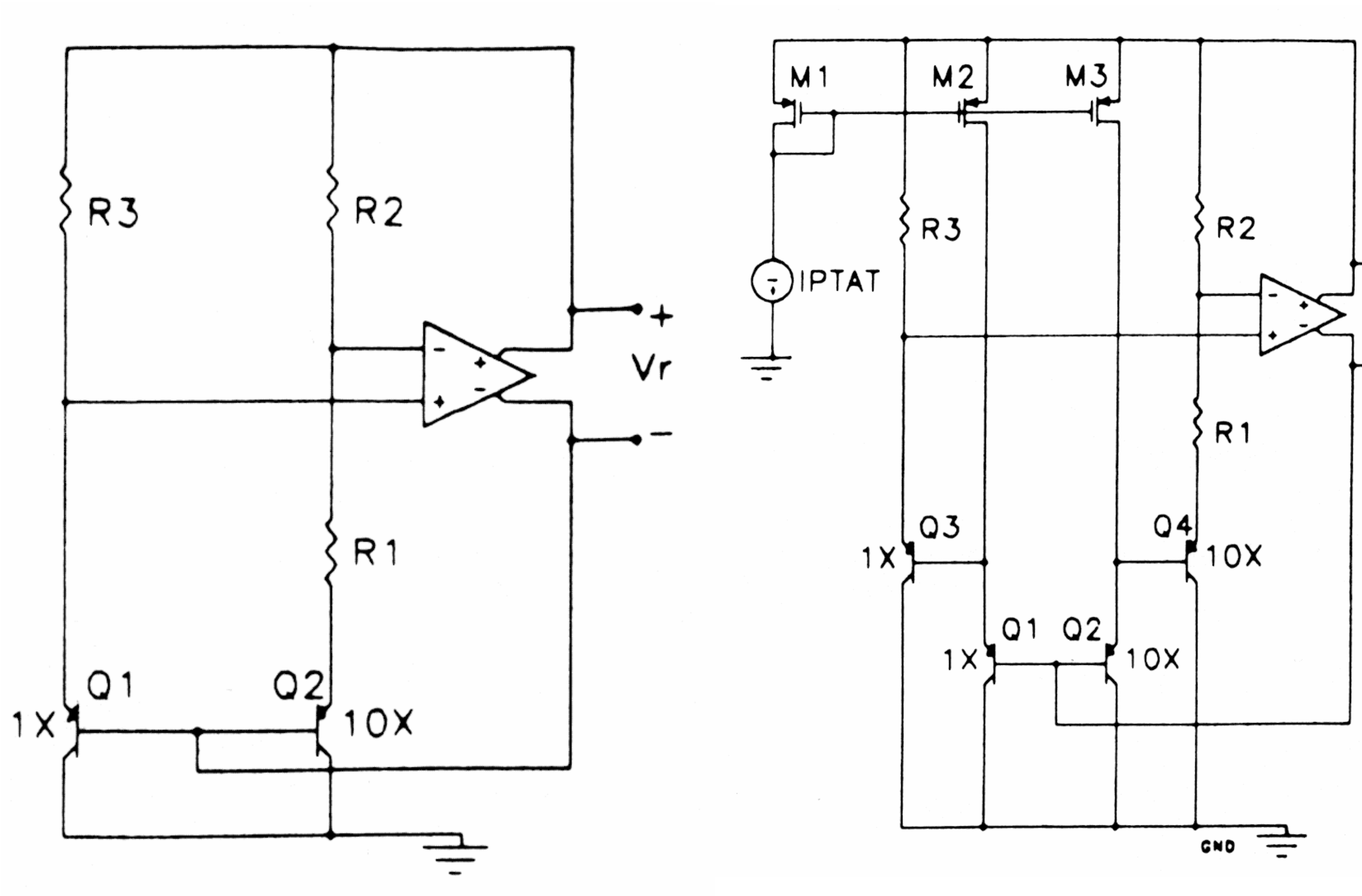
Bandgap reference with high PSRR



$$V_{BG} = V_{BE2} + N \frac{R_2}{R_1} \frac{kT}{q} \ln [M (N+1)]$$

Ref.Tham, JSSC, May 95, pp.586-590

Floating CMOS bandgap reference

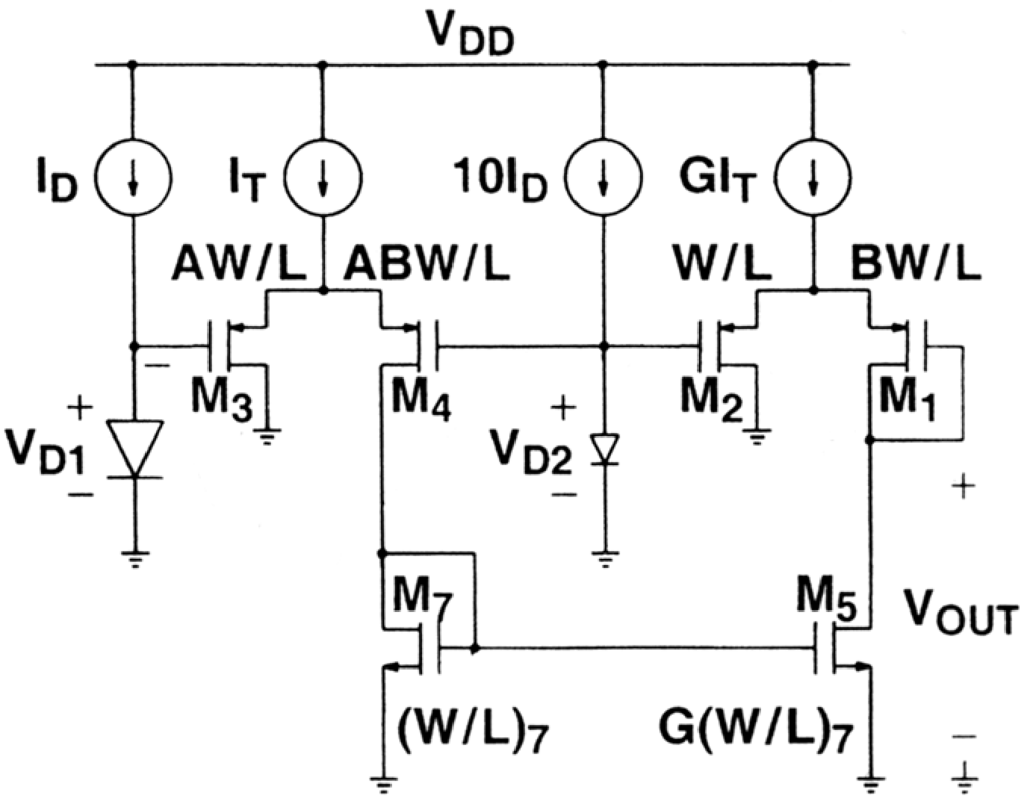


2.48 V
± 24 mV
21 ppm/^{o}C

5 V 1.2 mA

Ref.Ferro, JSSC, June 89, pp.690-697

CMOS Bandgap without resistors



$\Delta V_D = V_{D2} - V_{D1}$

$V_{OUT} = V_{D2} + AG\,\Delta V_D$

$V_{OUT} \approx 1.12$ V

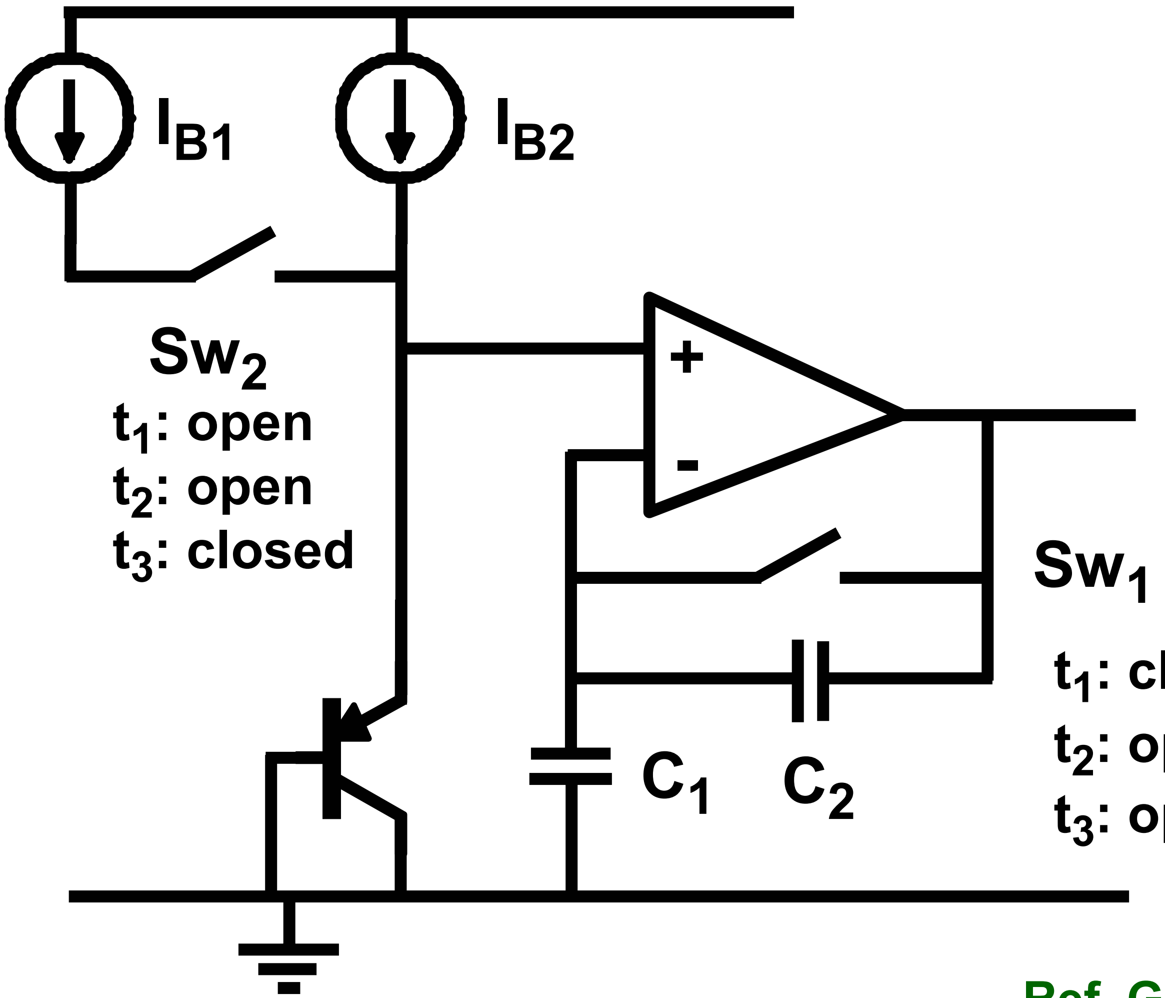
9 mV 0 …70 ^{o}C

3.7 V; 0.4 mA

A = 1.5
B = 4
G = 6
$A_{D1}/A_{D2} = 8$

Ref.: Buck, JSSC Jan. 2002, 81-83

Single-junction CMOS Bandgap reference



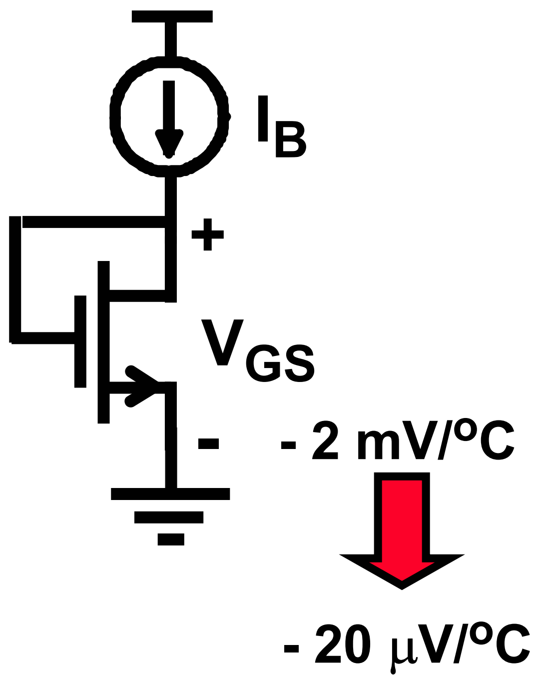
t_1: closed : $V_{out} = V_{BE1}$

t_2: open

t_3: open $\quad + \dfrac{C_1+C_2}{C_2} \Delta V_{BE21}$

Ref. Gilbert, ACD, Kluwer 1995

MOST in weak inversion ?



$$I_{DS} = I_{DS0} \exp\left(\frac{V_{GS}}{nkT/q}\right)$$

$$n = 1 + \frac{C_D}{C_{ox}}$$

$C_D\ (V_{CB})$

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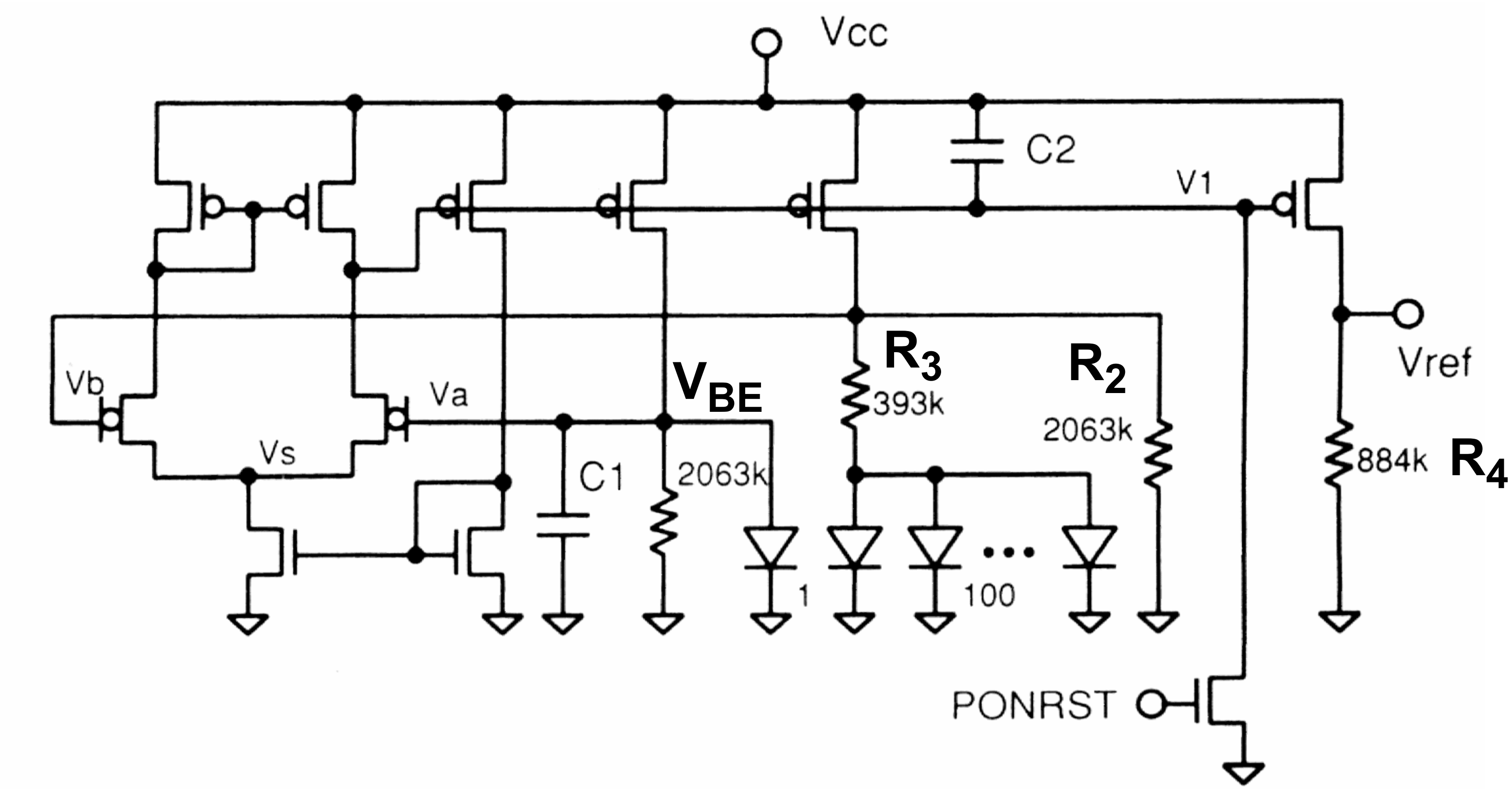
Ref.: B. Gilbert, G.Meijer, ACD , Kluwer 1995

Sub-1 V CMOS bandgap reference



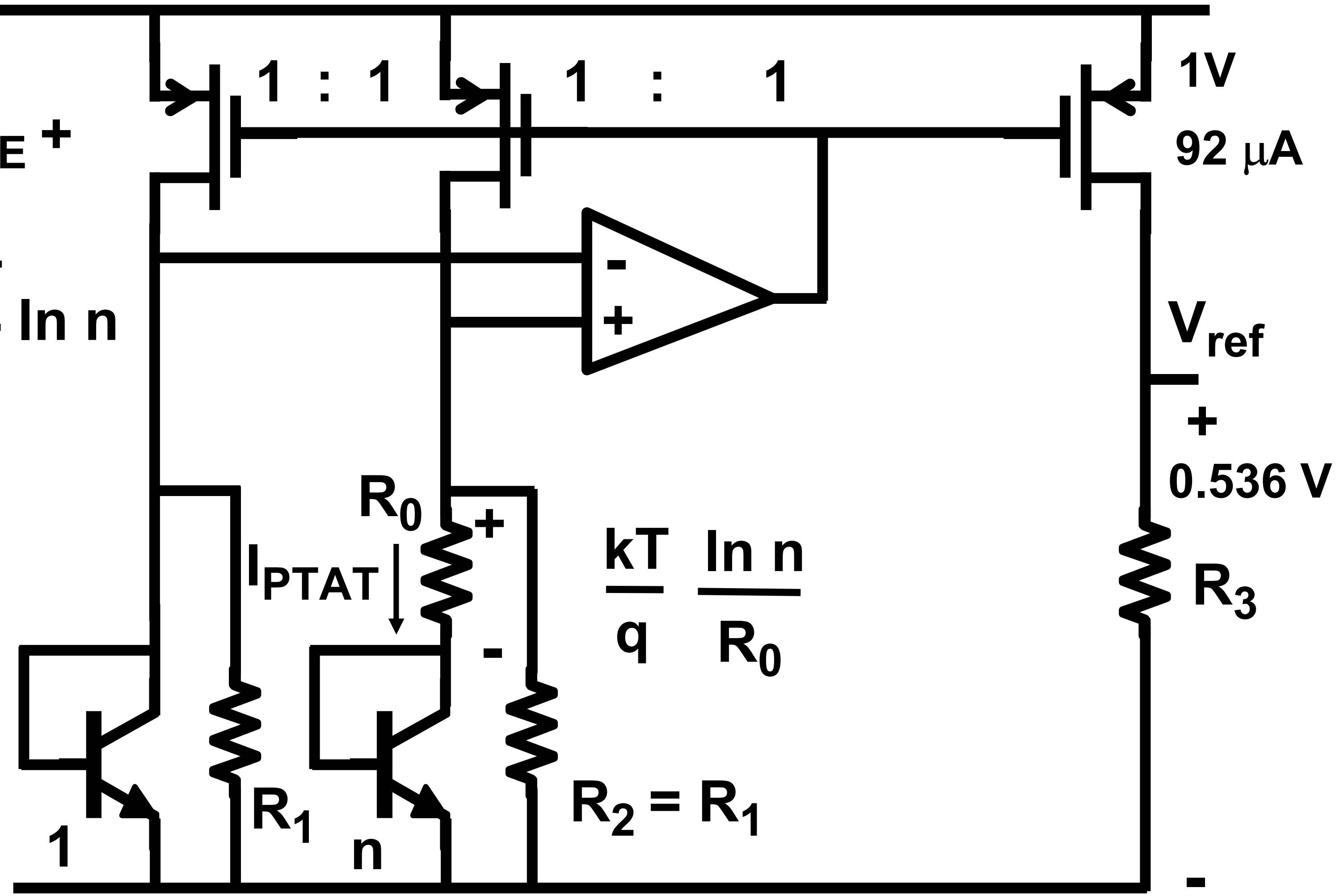
518 mV
± 15 mV

$$V_{ref} = \frac{R_4}{R_2} V_{BE} + \frac{R_4}{R_3} \frac{kT}{q} \ln n \qquad n = 100$$

Banba, .., JSSC May 99, 670-673

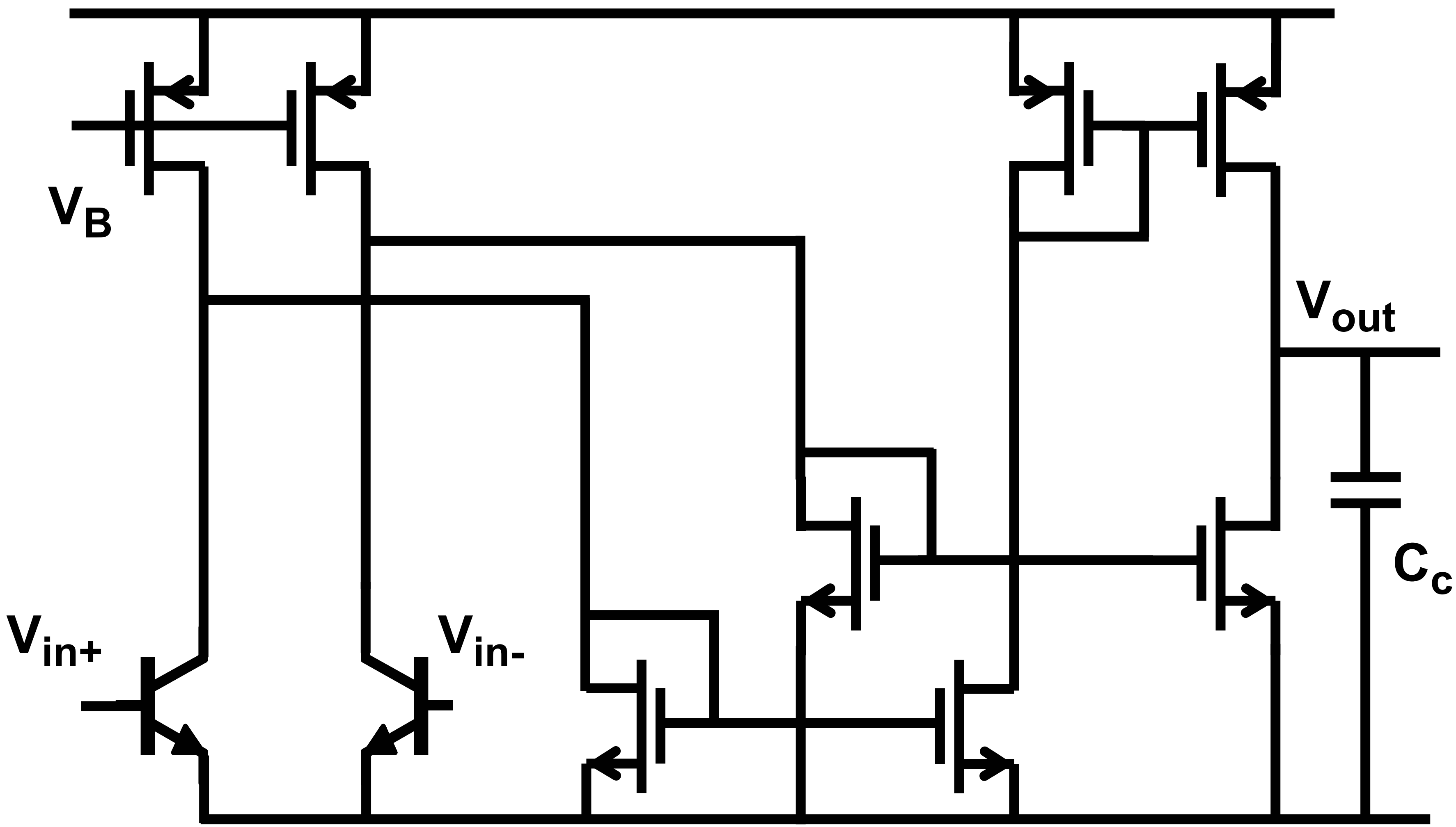
CMOS Bandgap with supply < 1 V

$$V_{ref} = \frac{R_3}{R_2} V_{BE} + \frac{R_3}{R_0} \frac{kT}{q} \ln n$$

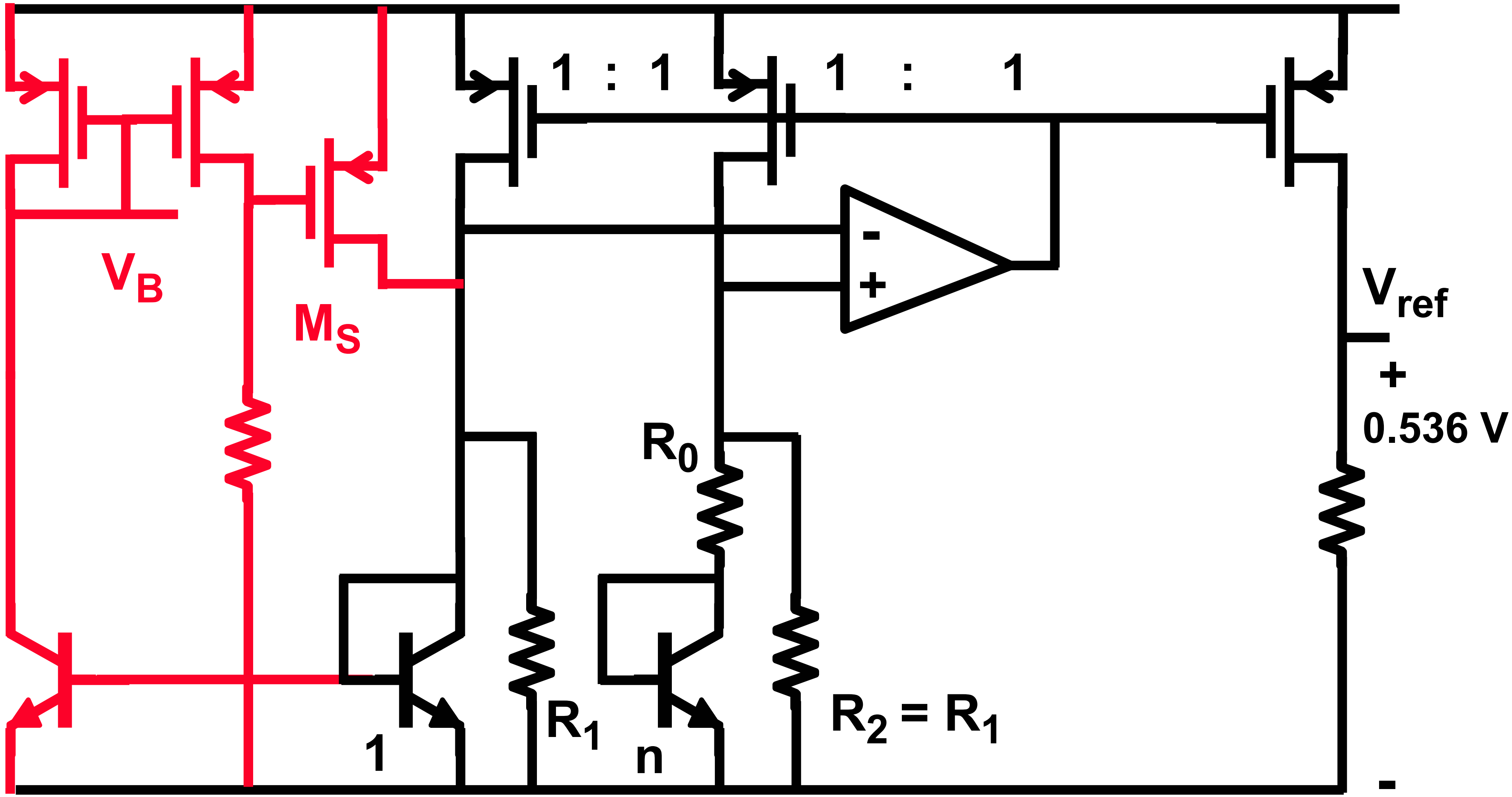


Ref.:
Malcovati, JSSC
July 01, 1076-1081

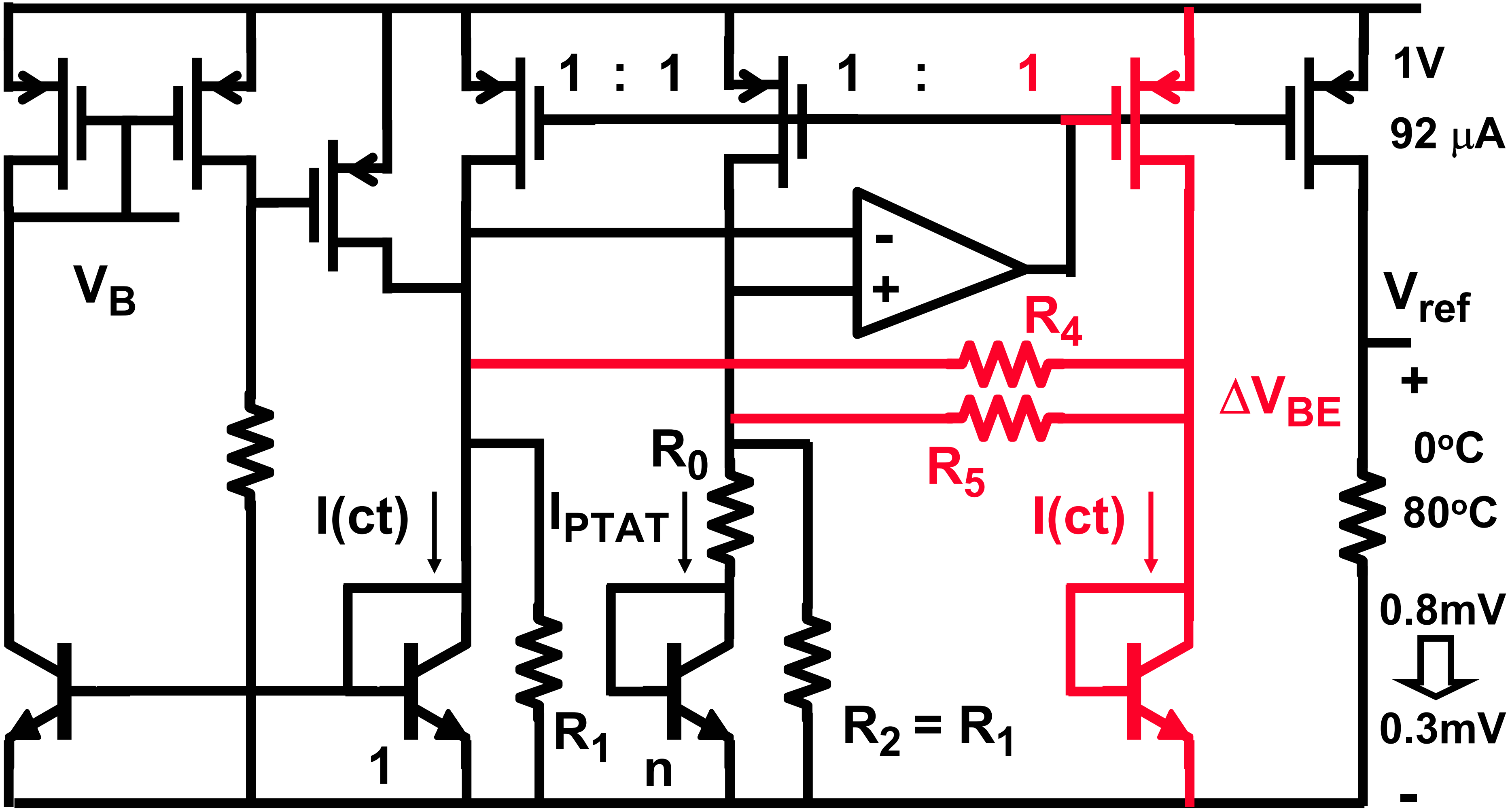
1 V opamp (1.2 MHz 25 pF 35 μA)



Start-up circuit



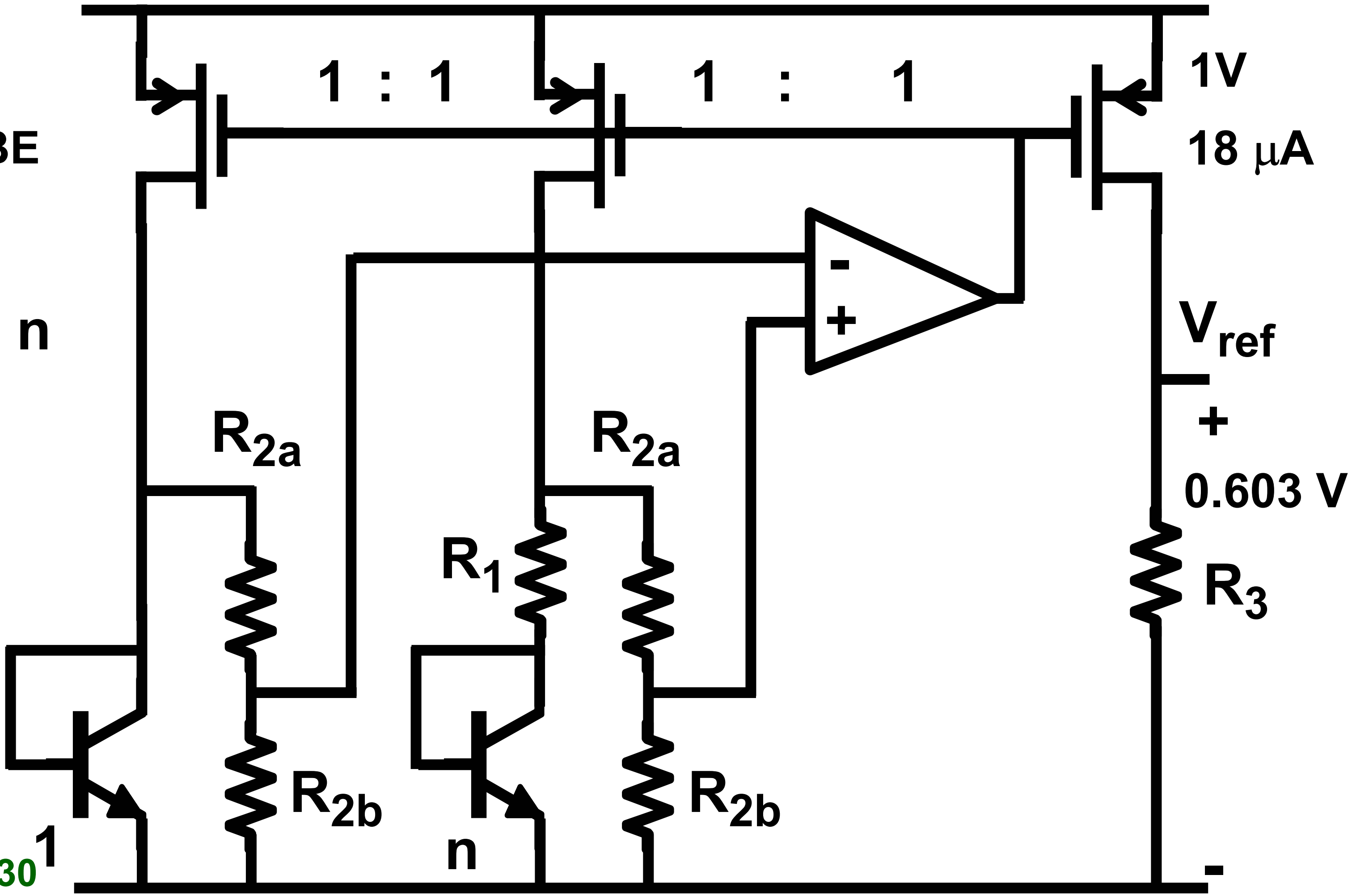
Curvature correction



CMOS Bandgap with supply < 1 V

$$V_{ref} = \frac{R_3}{R_2} V_{BE}$$

$$+ \frac{R_3}{R_1} \frac{kT}{q} \ln n$$



Ref.:
Leung, JSSC
April 2002, 526-530

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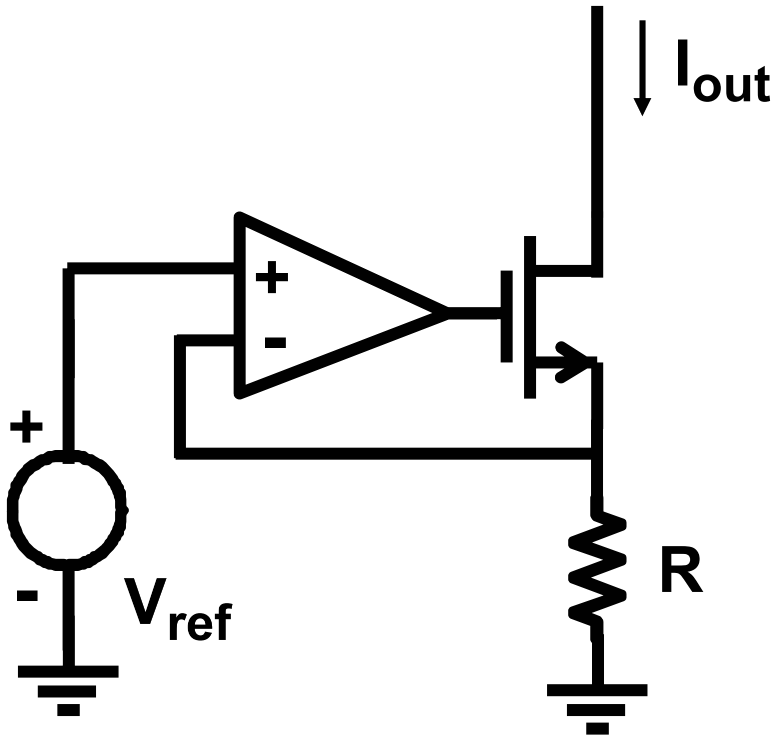
Voltage-current converter



$$I_{out} = \frac{V_{ref}}{R}$$

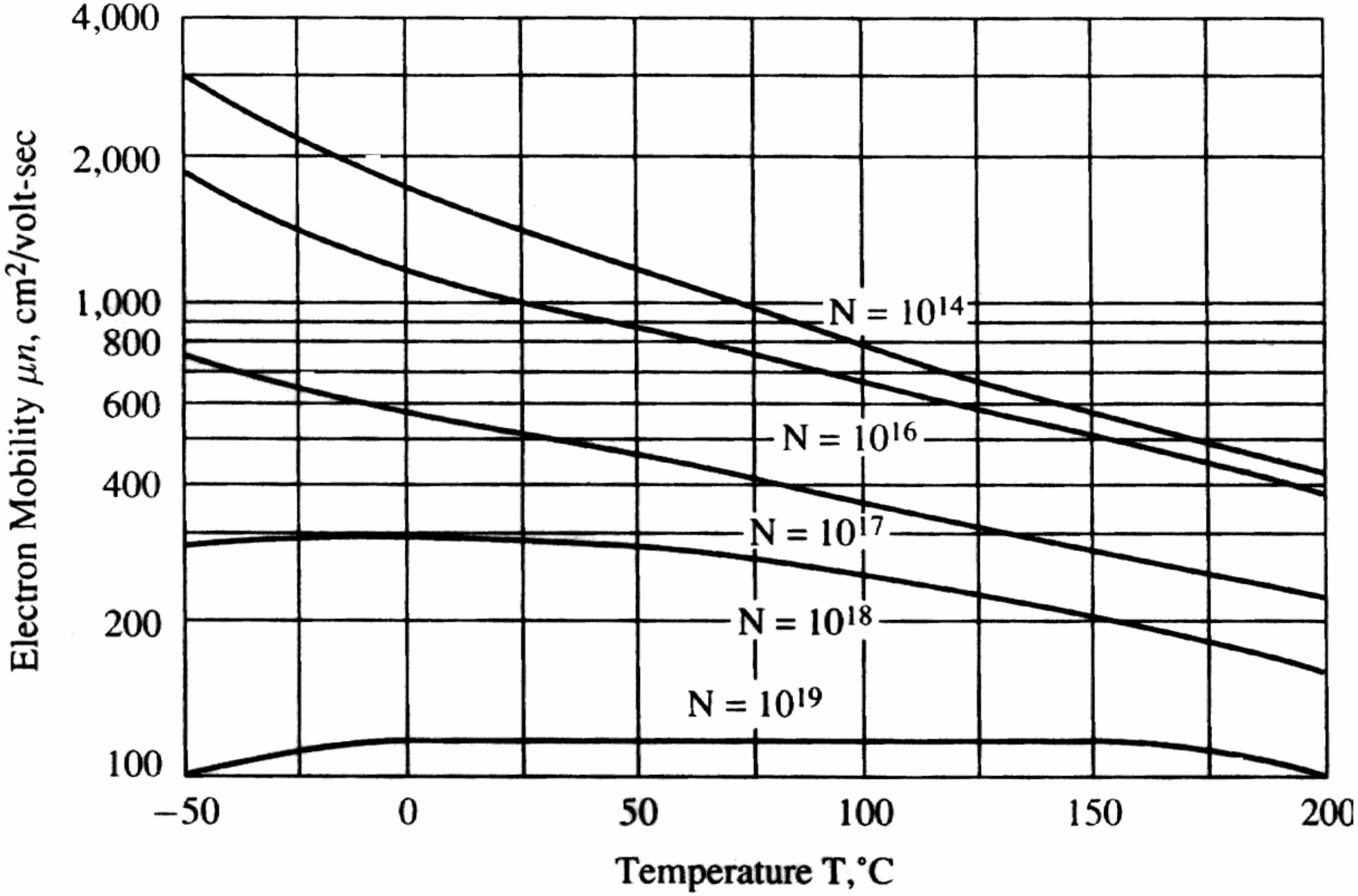
Temperature coefficient :

depends on

V_{ref}

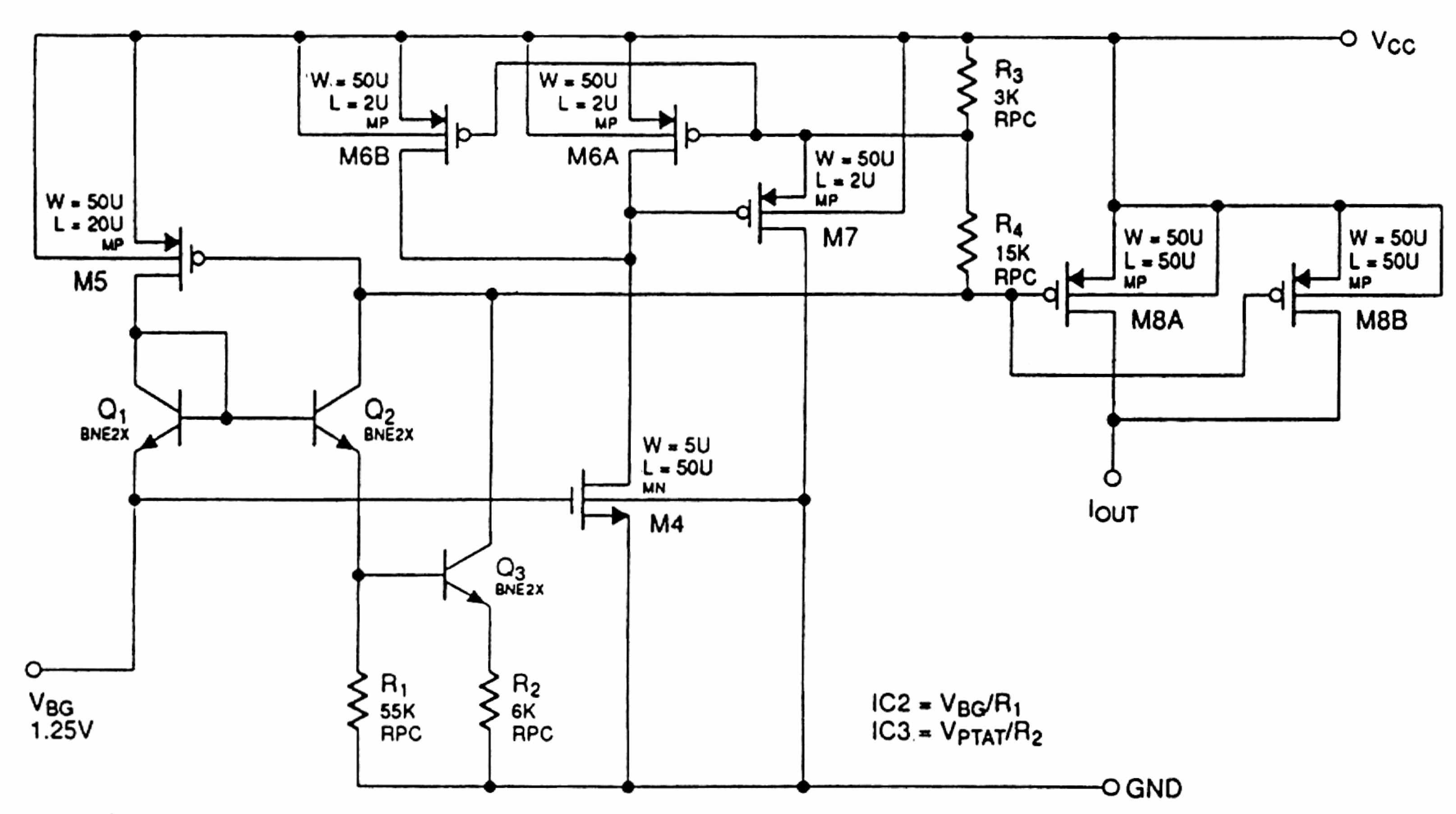
R !

Temperature coefficient of resistors



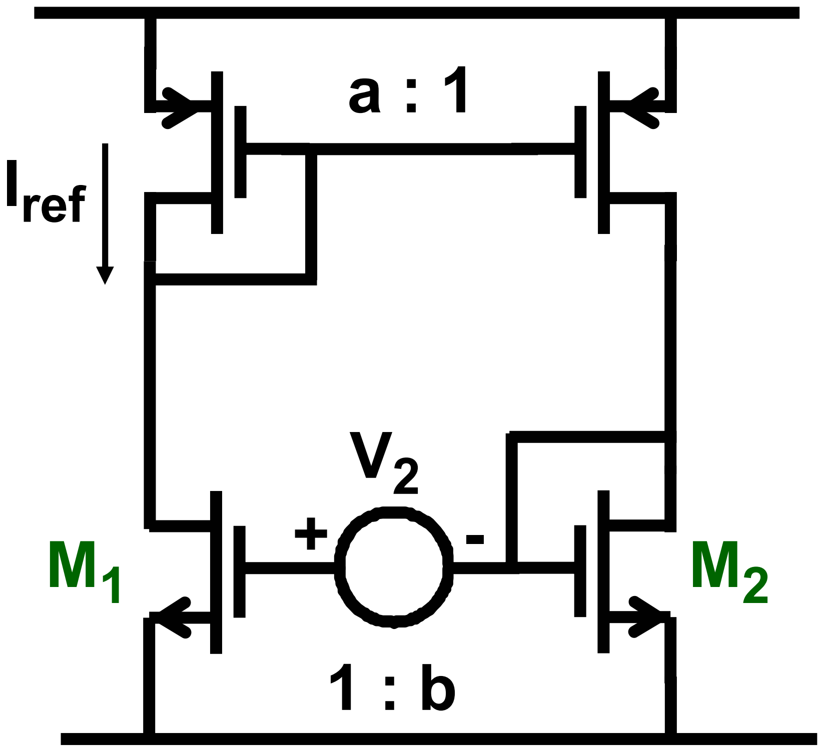
cm^{-3}

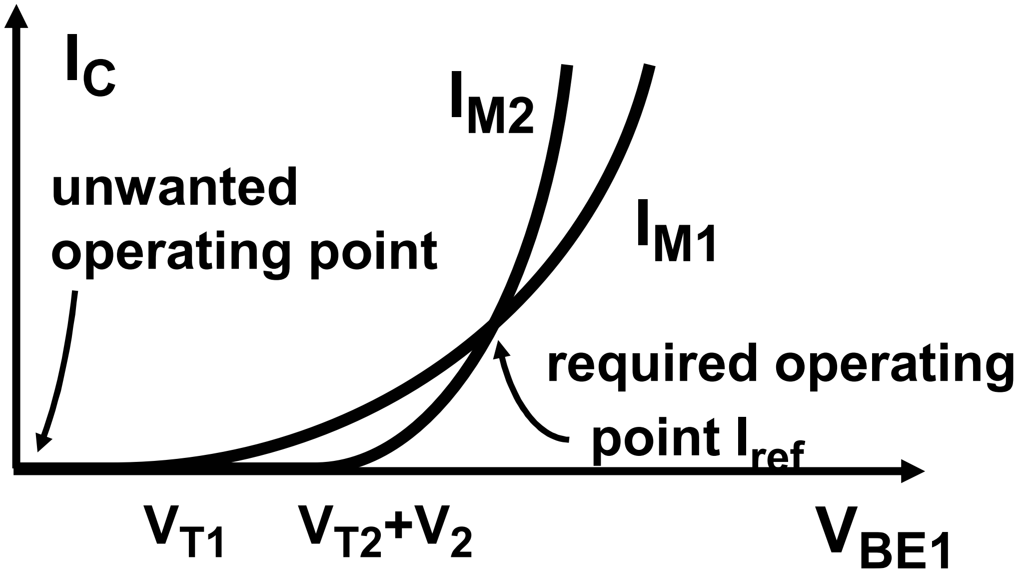
Voltage to current converter



Blauschild, ACD Kluwer 1995

Current reference without resistors





$$I_{ref} = K'_n \frac{W_1}{L_1} \frac{V_2^{\,2}}{(1 - \sqrt{m})^2} \qquad m = \frac{1}{ab}$$

Vcc > 3.5 V 2 μA

0.774 ± 0.02 μA

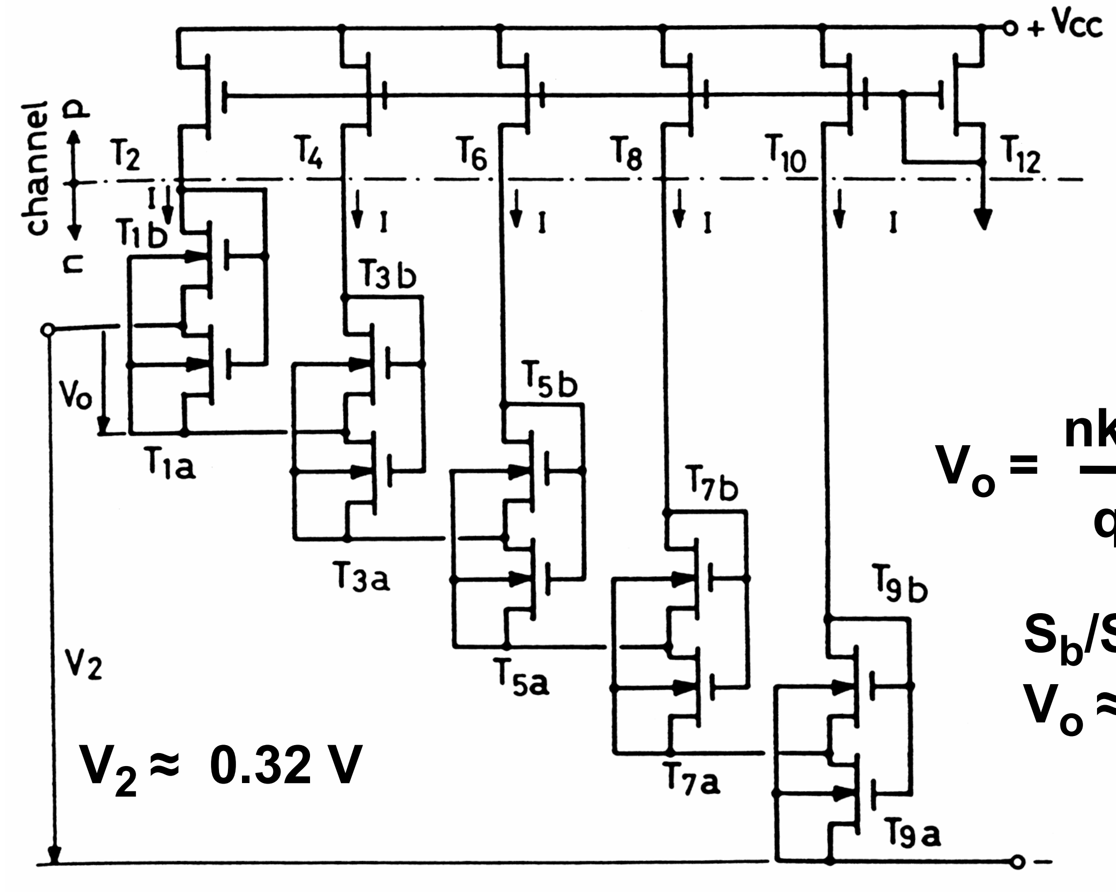
3 %   0° ... 80°C

$K'_n \sim T^{-1.5}$ $\quad V_2 \sim T$ $\quad I_{ref} \sim T^{-0.5}$

$V_2 \approx 0.32$ V

Ref. Op 't Eynde, JSSC June 88, pp. 821-824

Current reference

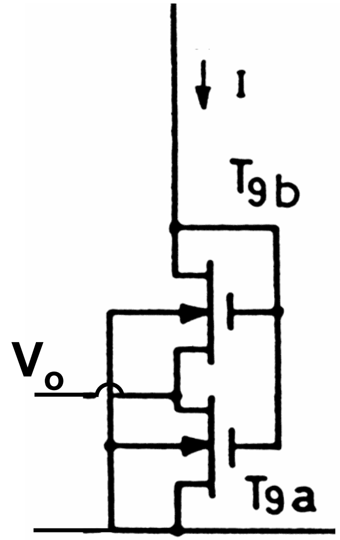


$V_2 \approx\ 0.32$ V

$$V_o = \frac{nkT}{q} \ln\left(1 + \frac{S_b}{S_a}\right)$$

$S_b/S_a = 5$

$V_o \approx 64$ mV



Both in wi.

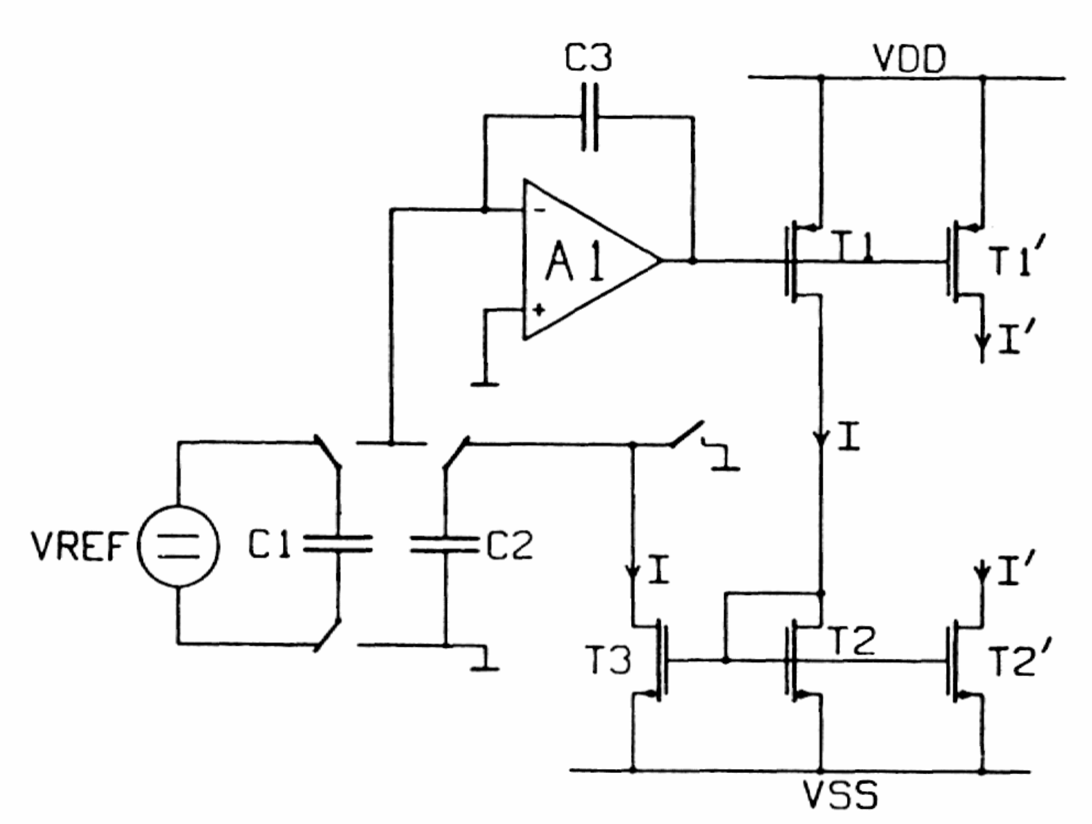
Vcc > 3.5 V 2 μA

0.774 ± 0.02 μA

3 % 0° ... 80°C

Ref. Vittoz, JSSC June 79, pp. 573-577   Ref. Op 't Eynde, JSSC June 88, pp. 821-824

SC Voltage-current converter



$$V_{ref}\, C_1 = I_{ref}\, T_c/2$$

$$R_{eff} = \frac{1}{2 f_c C_1}$$

$$I_{ref} = \frac{V_{ref}}{R_{eff}}$$

$C_1 = C_2 = 3$ pF $f_c = 270$ kHz ±5 V 4 μA

Ref. H.Klein, W. Engl, ESSCIRC 83, pp. 119-122

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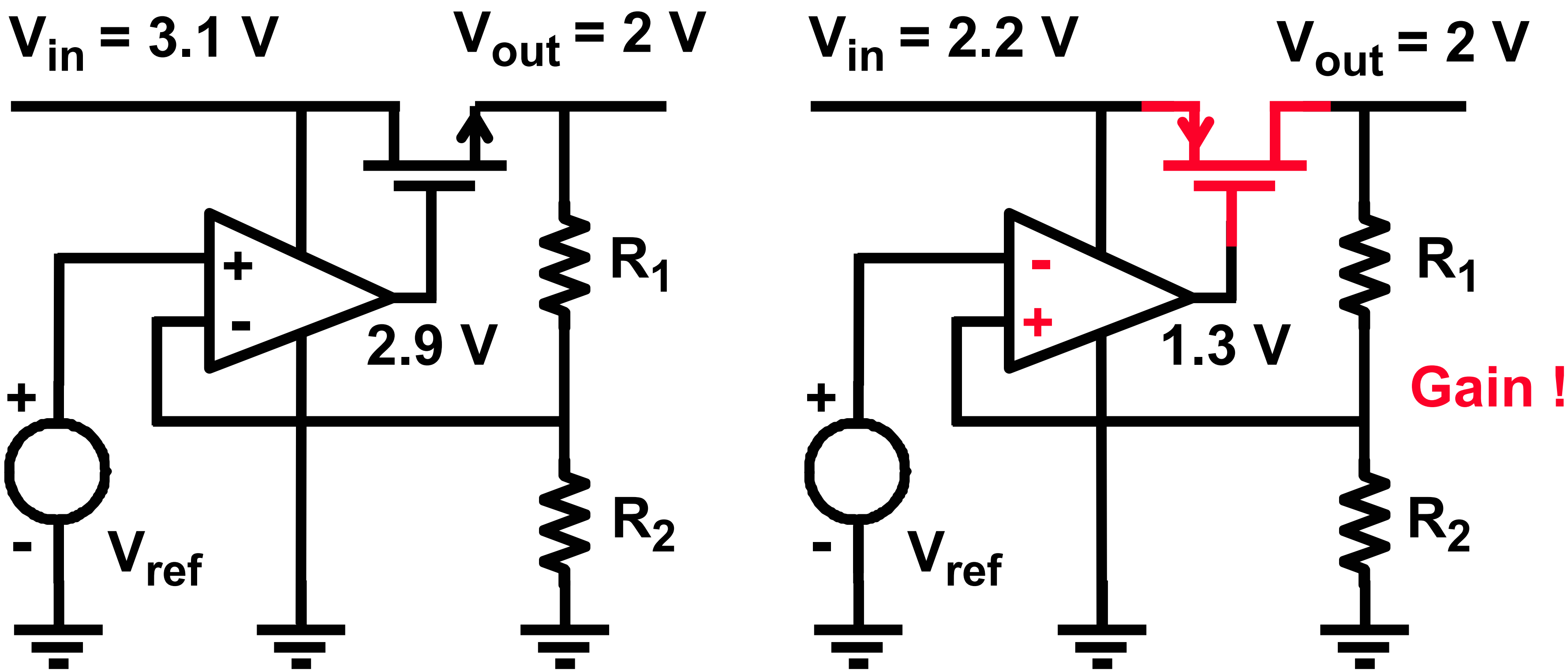
Ref.: B. Gilbert, G.Meijer, ACD , Kluwer 1995

Low drop-out regulator : principle



$V_{GS} \approx 0.9$ V

$$V_{out} = V_{ref} \frac{R_1 + R_2}{R_2}$$

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Ref.: B. Gilbert, G.Meijer, ACD , Kluwer 1995

References

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