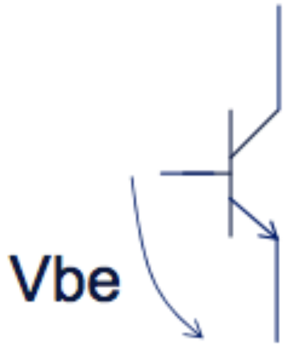
Voltage reference and bandgap circuits

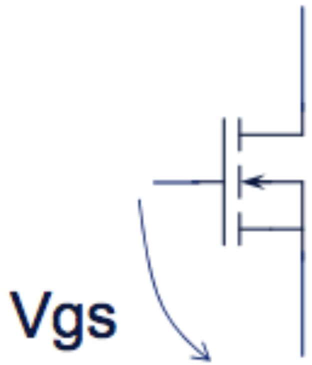
Basic blocks for voltage reference circuits

What characteristic can be used to generate a reference voltage?

Bipolar



MOS



Base-emitter-voltage Vbe:
depends on temperature, but is not sensitive to process variation.

⇨ Bipolar device is the key component for accurate voltage reference circuits

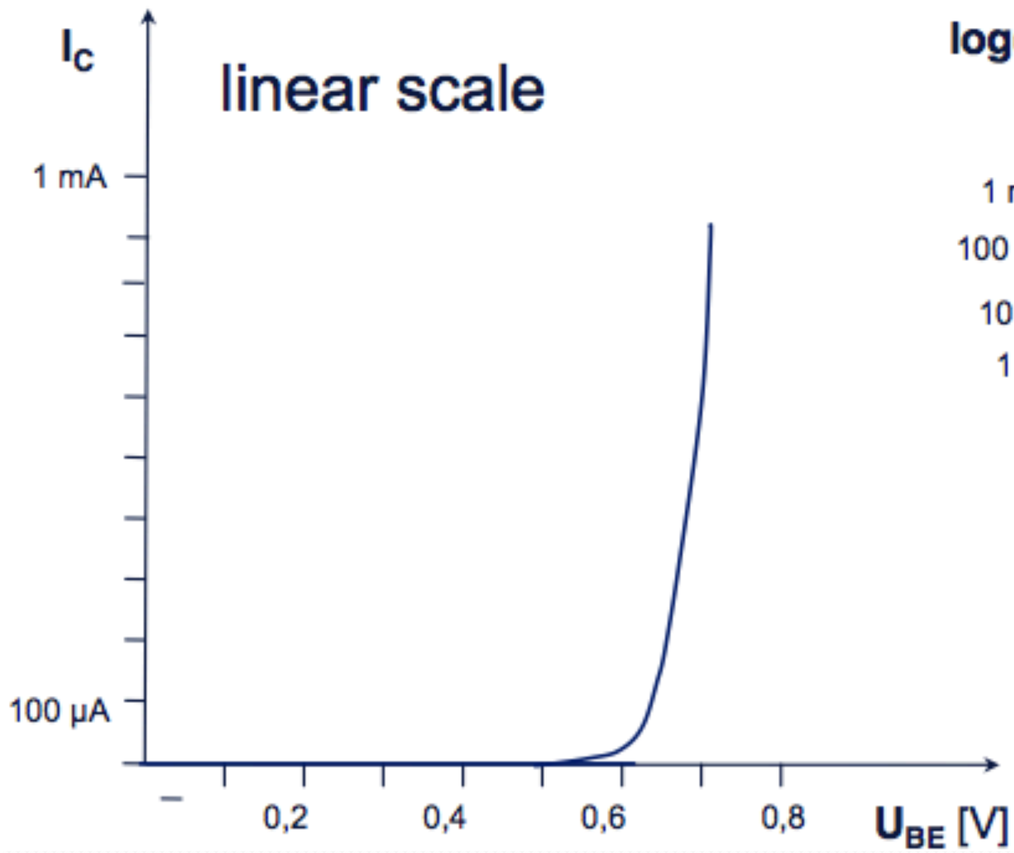
Gate-source-voltage Vgs:
Depends strong on process variation

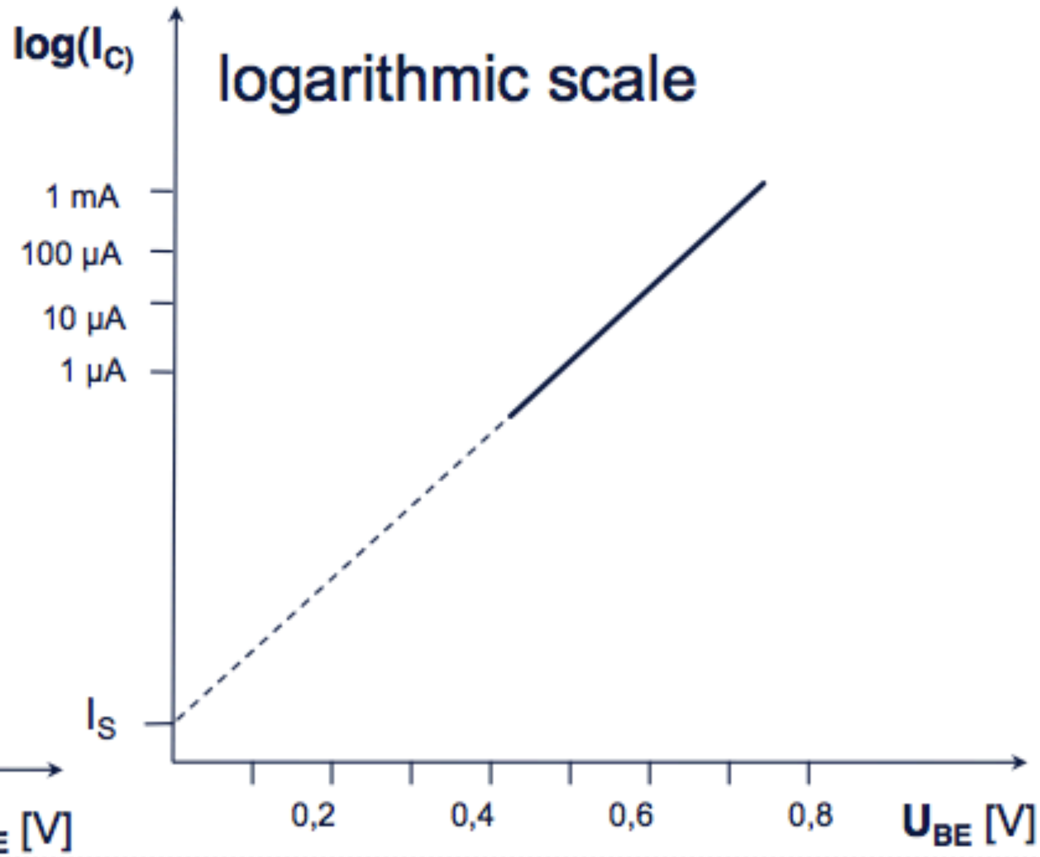
⇨ MOS device based voltage reference circuits will not achieve high accuracy

Characteristics of bipolar transistors

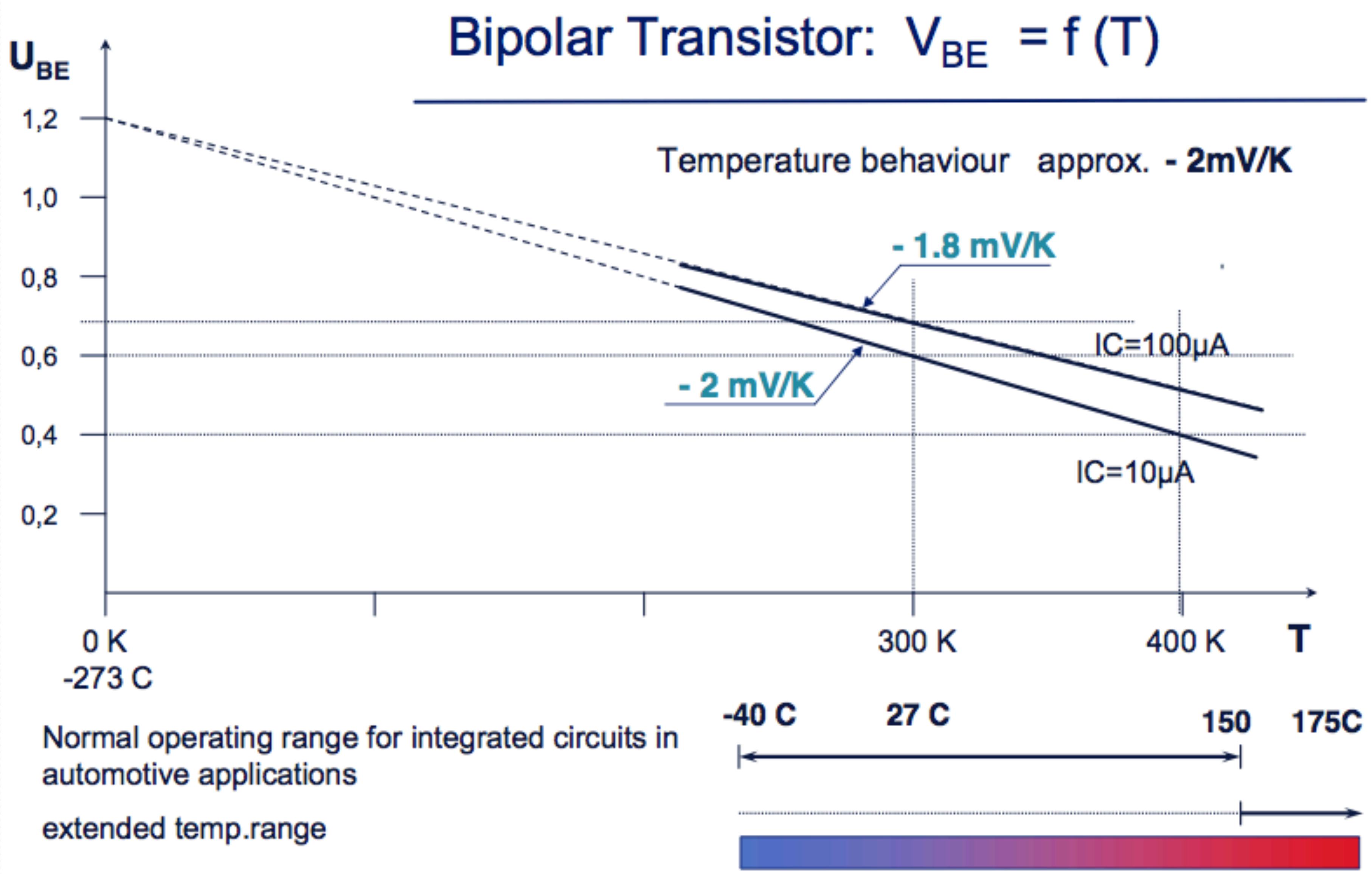
$$I_C = I_S \cdot \left(e^{\frac{V_{BE}}{Vt}} - 1 \right)$$

$$Vt = \frac{k \cdot T}{q} \approx 26mV \;\; [25^\circ C]$$

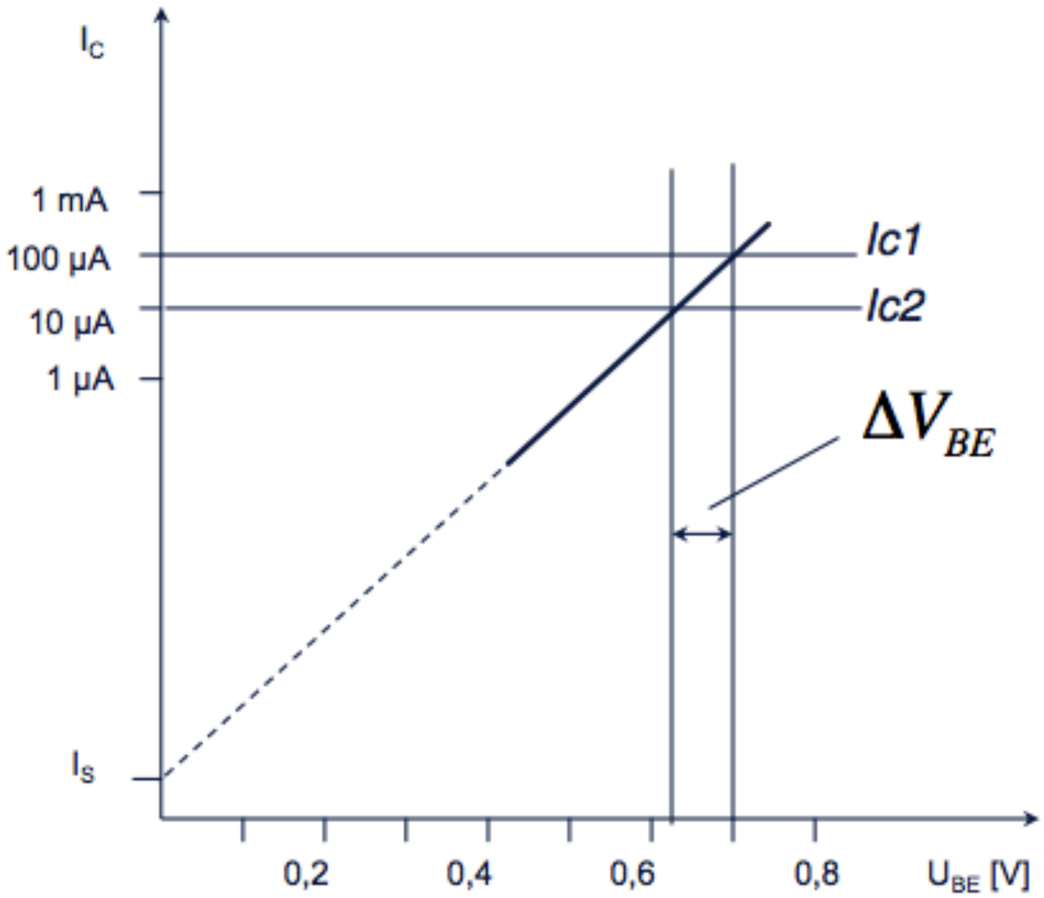




Temperature dependence of BJT characteristics



Temperature dependence of ΔV_{BE}



absolute value of Vbe depends on transistor parameter Is,
delta Vbe is independent of individual transistor parameter

$$V_{BE} = \ln\left(\frac{I_C}{I_S}\right)\cdot Vt$$

$$\Delta V_{BE} = \ln\left(\frac{I_{C1}}{I_{C2}}\right)\cdot Vt$$

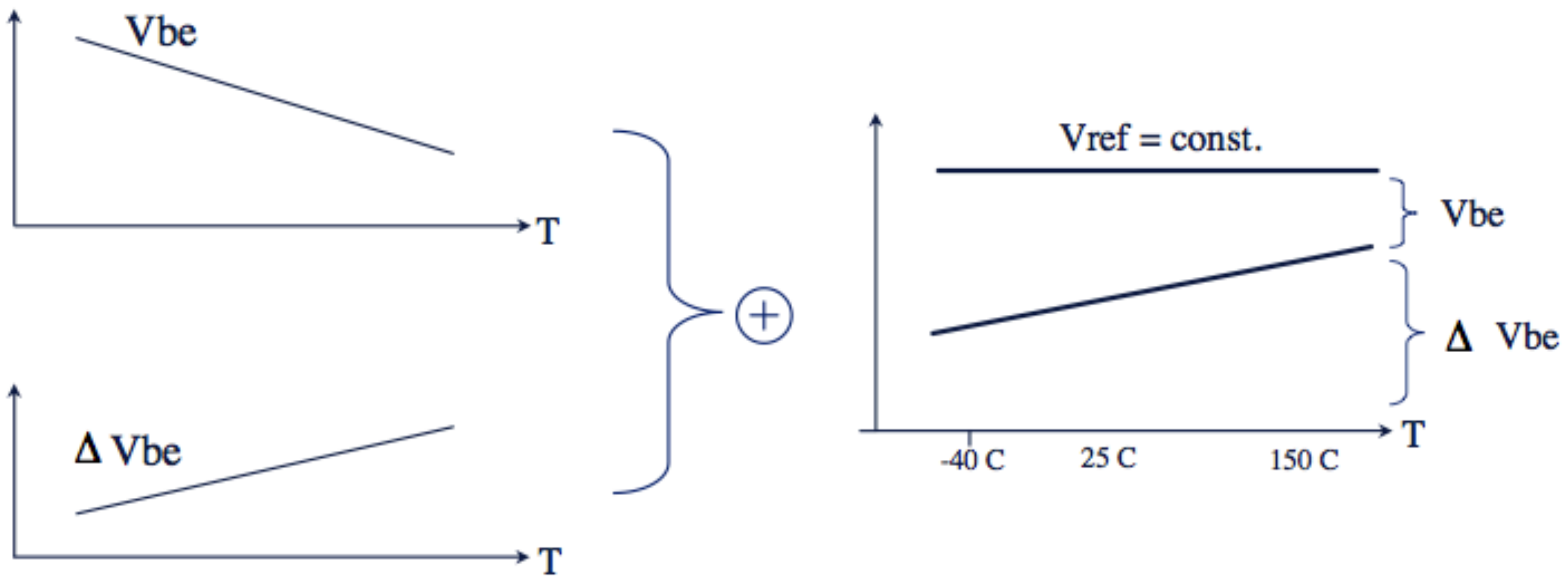
$$Vt = \frac{k\cdot T}{q} \approx 26mV\ [25^\circ C]$$

$$k = 1{,}38\cdot 10^{-23}\ J/K$$

$$q = 1{,}602\cdot 10^{-19}\ As$$

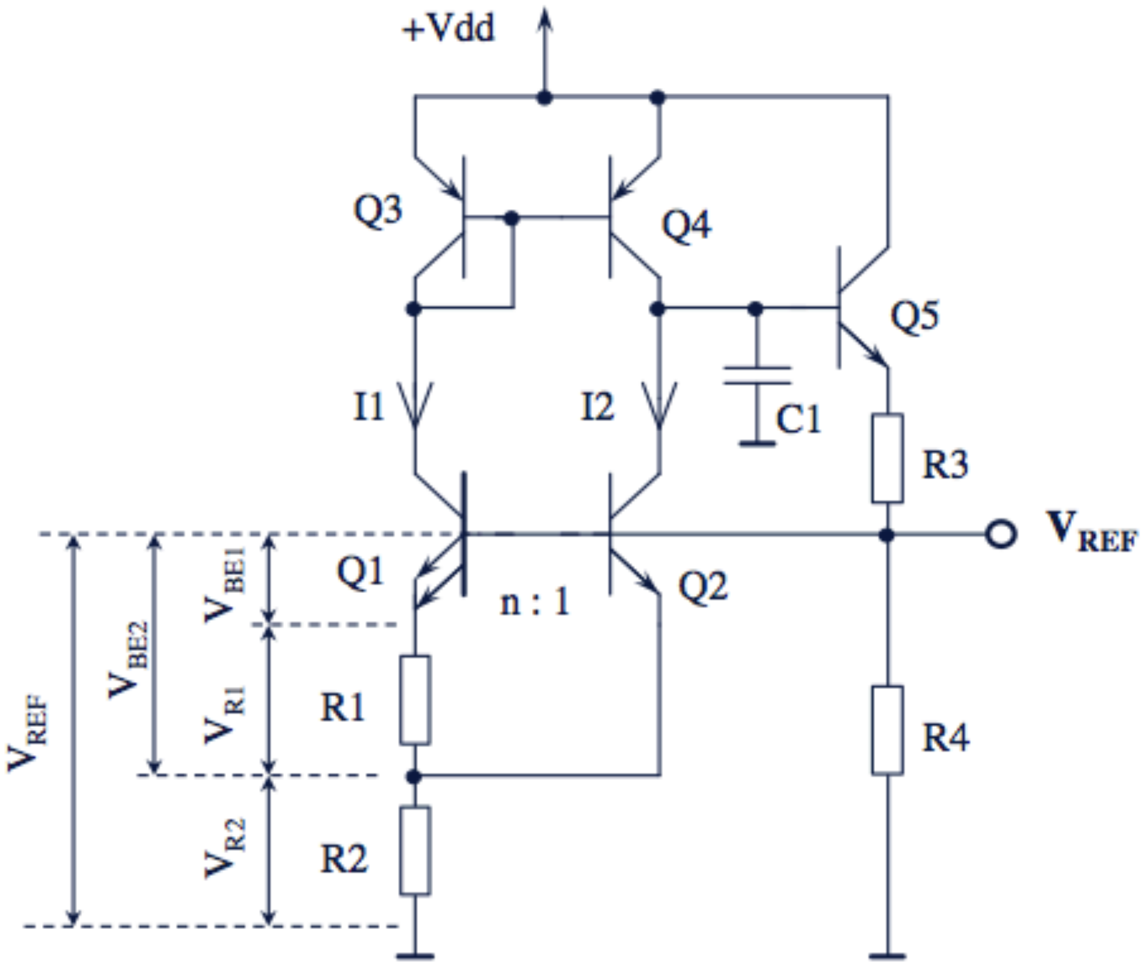
T [°C]	T [K]	VT [mV]
-40	233	20,1
25	298	25,7
100	373	32,1
150	423	36,4
200	473	40,7

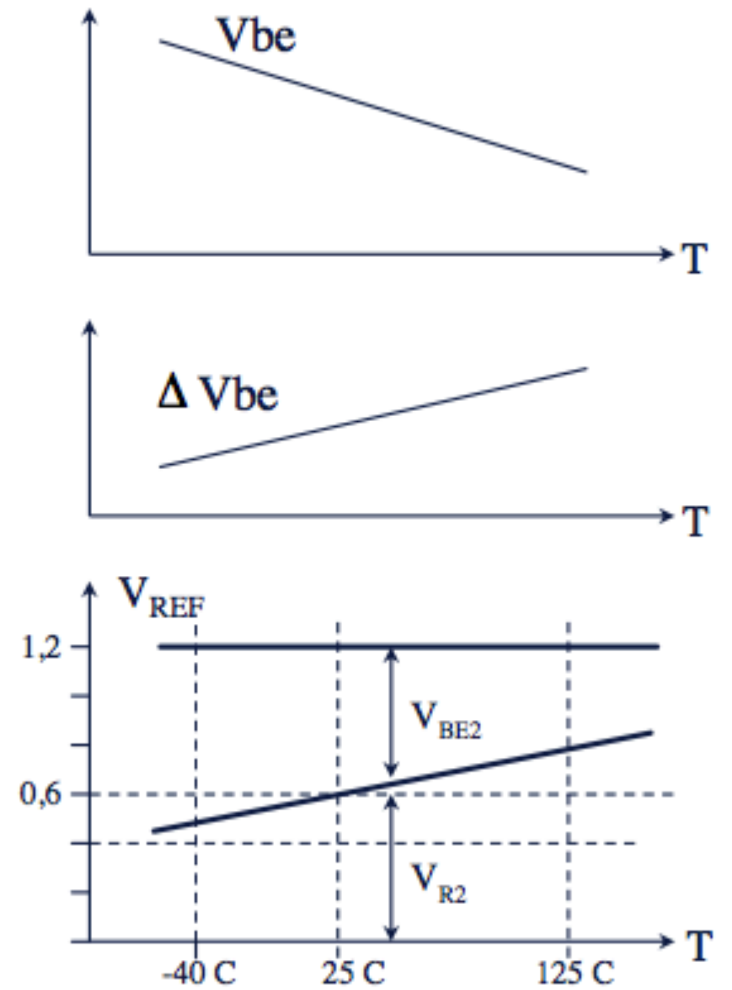
Temperature-compensation of V_{BE} voltage



The negative temperature dependence of Vbe can be compensated by the positive temperature dependence of delta-Vbe

Temperature-constant Reference Voltage: “Bandgap-Reference”





This topology was first published by P.Brokaw, IEEE Journal of solid-state circuits, Dec. 1974

Operation of Bandgap-Reference Circuit

Assumption: I1 =I2, this is done by current mirror Q3,Q4.
Q1, Q2 have different emitter areas (AE) with AE(Q1) > AE(Q2) .
Ratio n is choosen as integer.
If collector-currents are equal, the base-emitter-voltages (V_{BE}) of Q1, Q2 are different.

$$\Delta V_{BE} = Vt \cdot \ln(n) \qquad n = \frac{AE(Q1)}{AE(Q2)} \qquad Vt = \frac{k}{q} \cdot T$$

$$V_{R1} = \Delta V_{BE} = I_1 \cdot R_1$$

$$V_{R2} = (I_1 + I_2) \cdot R_2 = 2 \cdot I_1 \cdot R_2 = 2 \cdot \frac{R_2}{R_1} \cdot \Delta V_{BE}$$

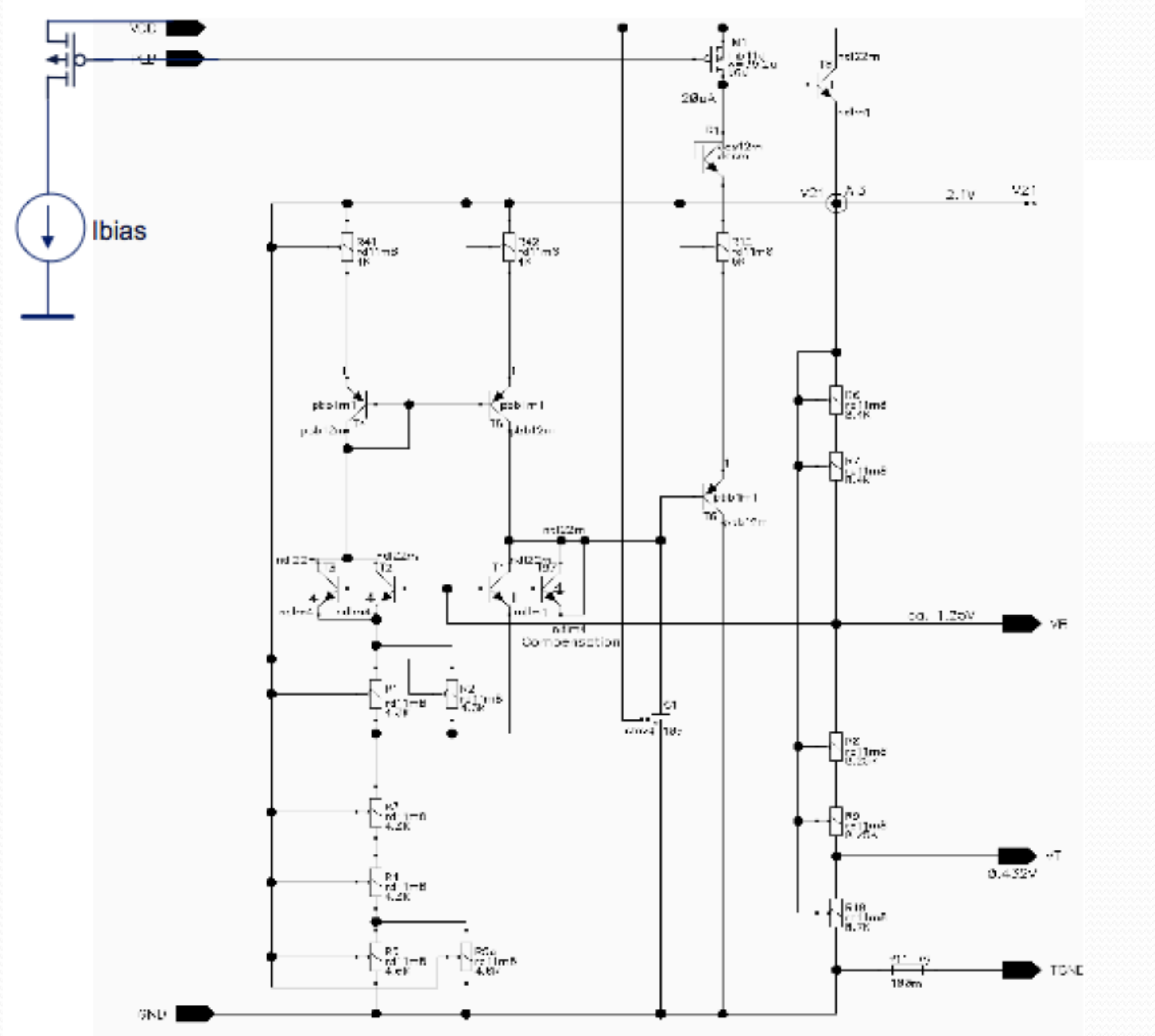
$$V_{REF} = V_{BE2} + V_{R2} = 1{,}20 \ldots 1{,}25V \quad \textit{for optimal temp.comp.}$$

Example:

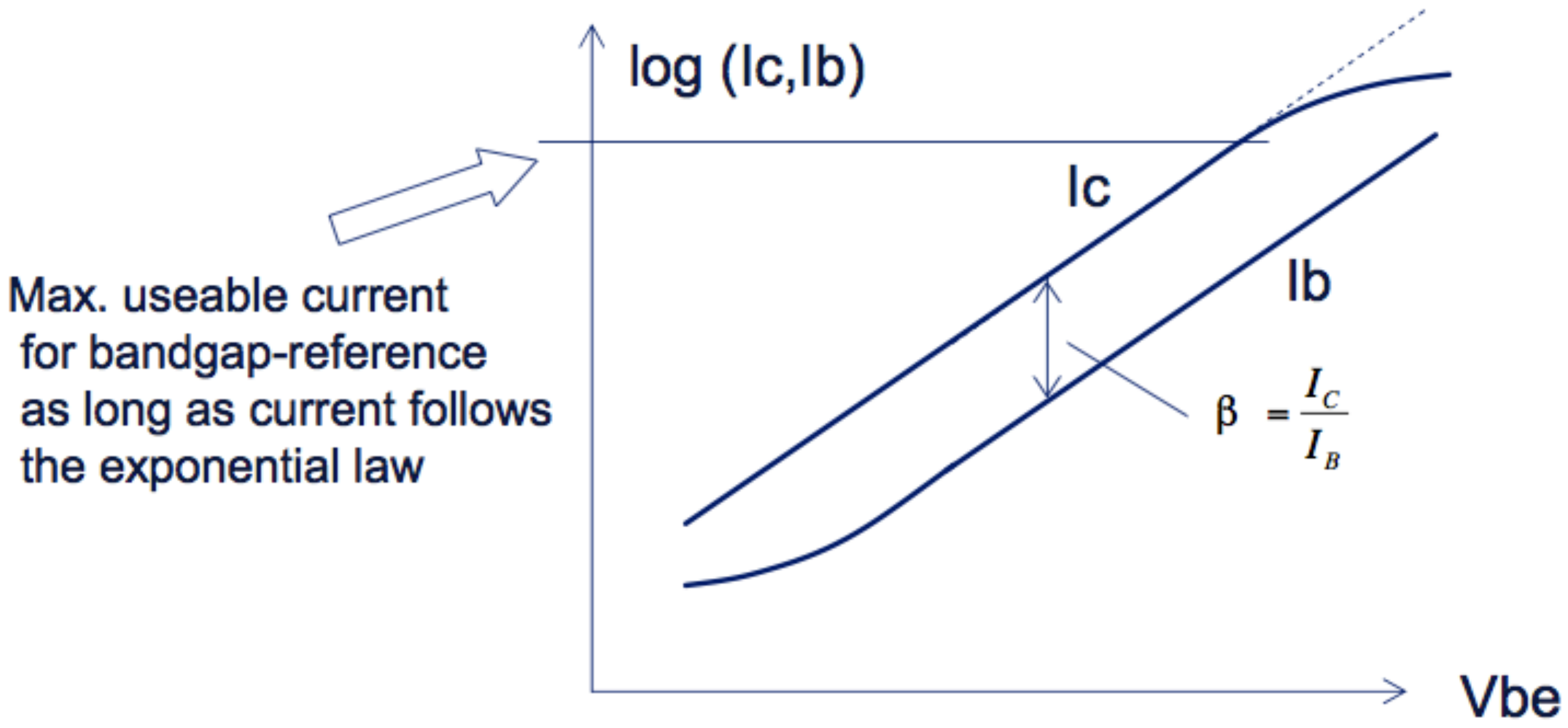
n=10
$\Delta V_{BE} = 60\ mV\ [25\ C]$
R2/R1 = 5
VR2 = 600 mV
VBE2=600 mV
VREF = 1,2 V

Voltage drop at R1 equals delta-Vbe and has the same positiv tc (temp.coefficient) as Vt. So also the voltage VR2 has the same tc, the absolute value of VR2 is choosen to a value similar to VBE . This leads to a compensation of the negative tc of VBE over full temperature range. The resulting temperature error is of 2nd order and is in practice lower than 1%. The best temperature compensation will be achieved if the voltage Vref is adjusted to 1.2 - 1.25 V. The absolute value of this reference voltage is better than +/- 5% assuming all practical manufacturing tolerances

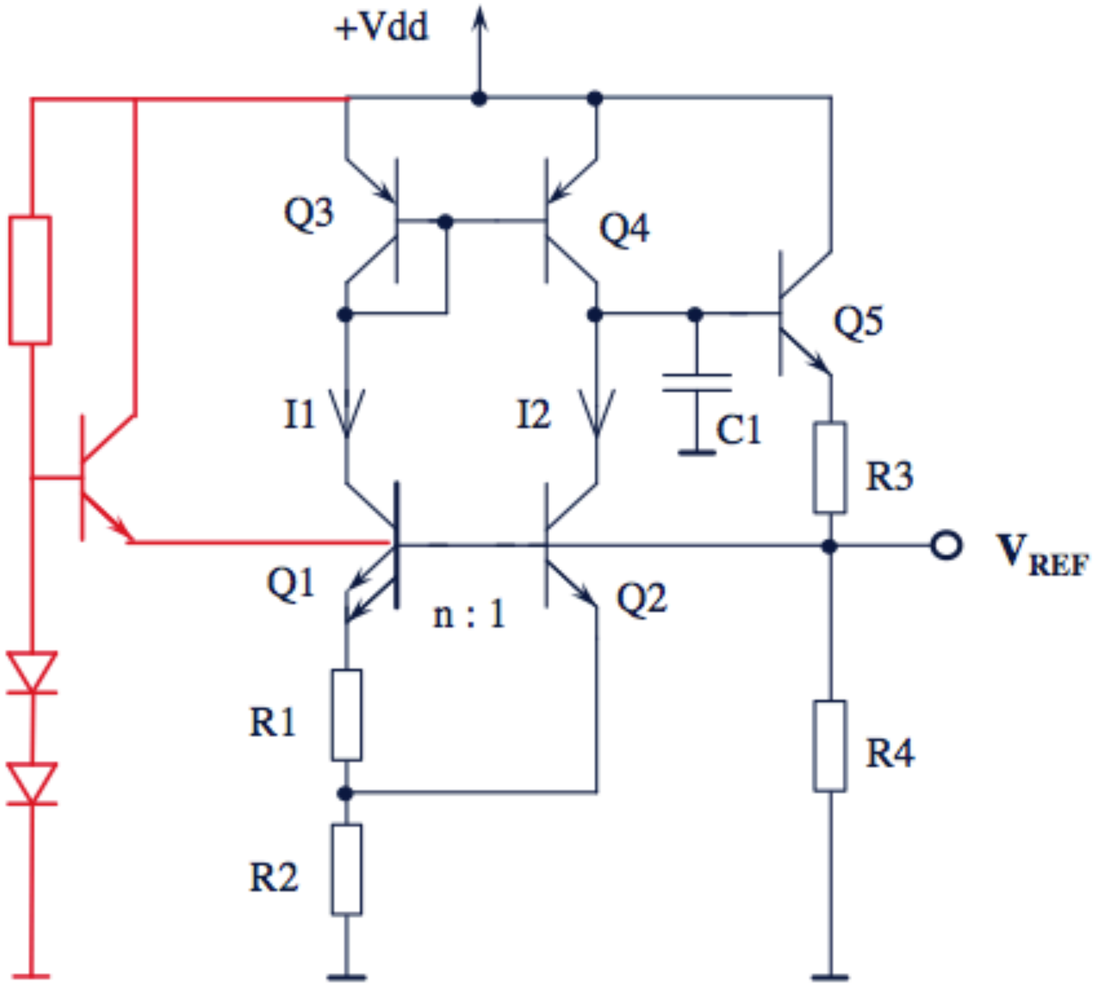
Bandgap-Reference Circuit

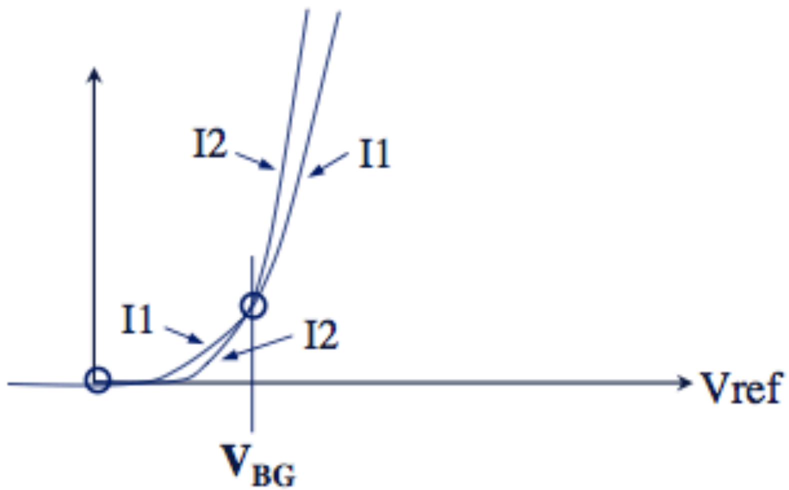


Gummel plot of BJT



Startup-Problem of Bandgap-Reference Circuit



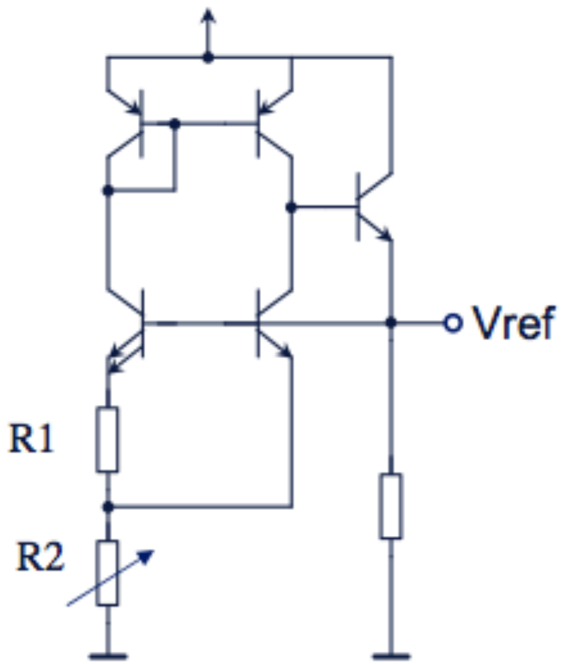


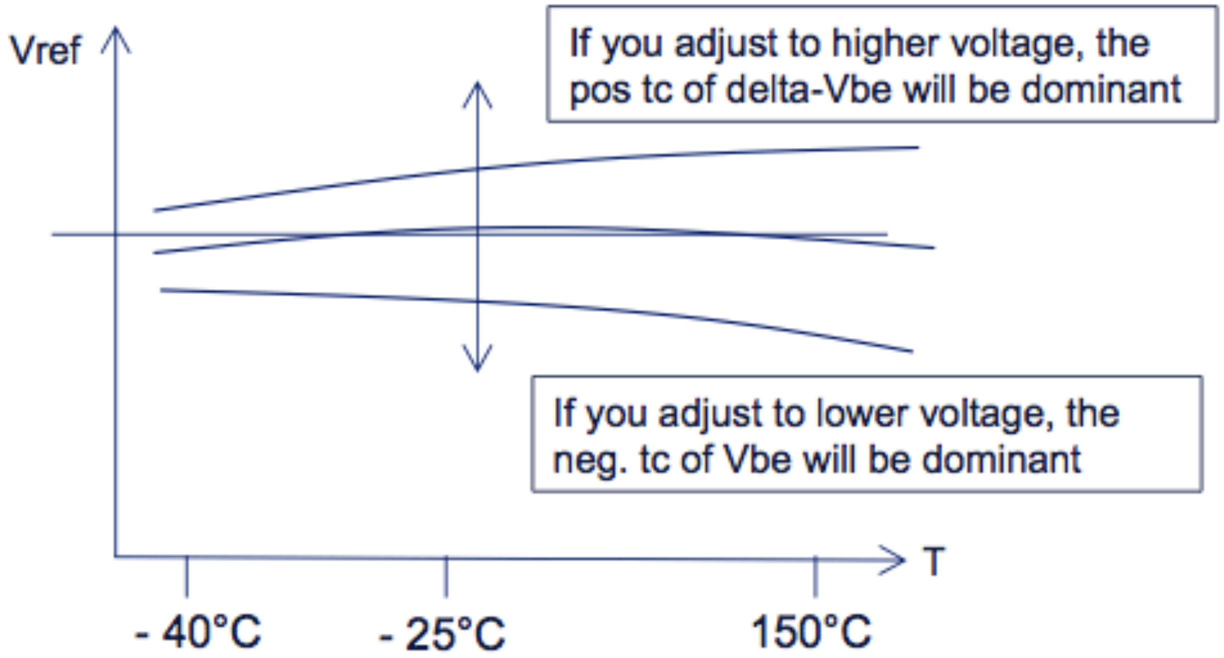
Current Mirror Q3/Q4 forces I1=I1, this defines the operating point.

But there exists a second stable operating point: I1=I2=0

A startup-circuit is required

Adjustment of bandgap reference voltage

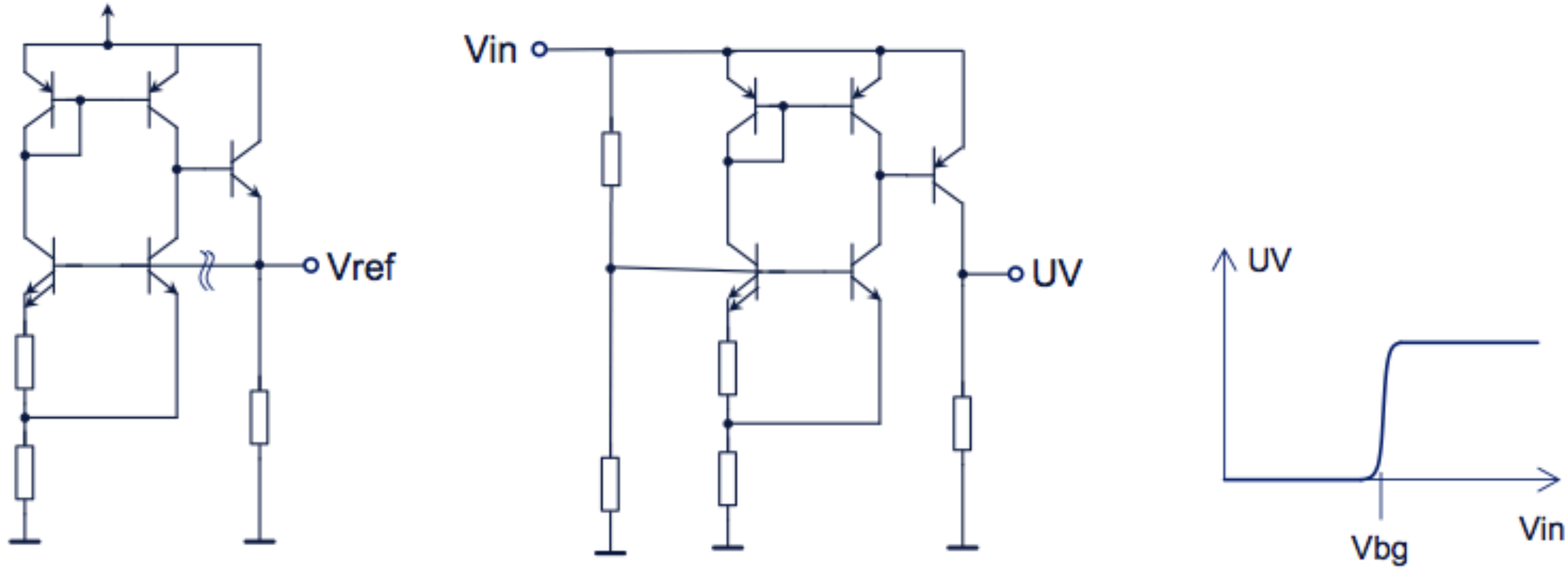




Adjusting the Vref by changing the value of the resistor ratio R1/R2 changes not only the output voltage but also the temperature behaviour.
There exists one point with minimal temperature depedence (in practice < 1%)
For bipolar technologies this optimal voltage is around 1,25V

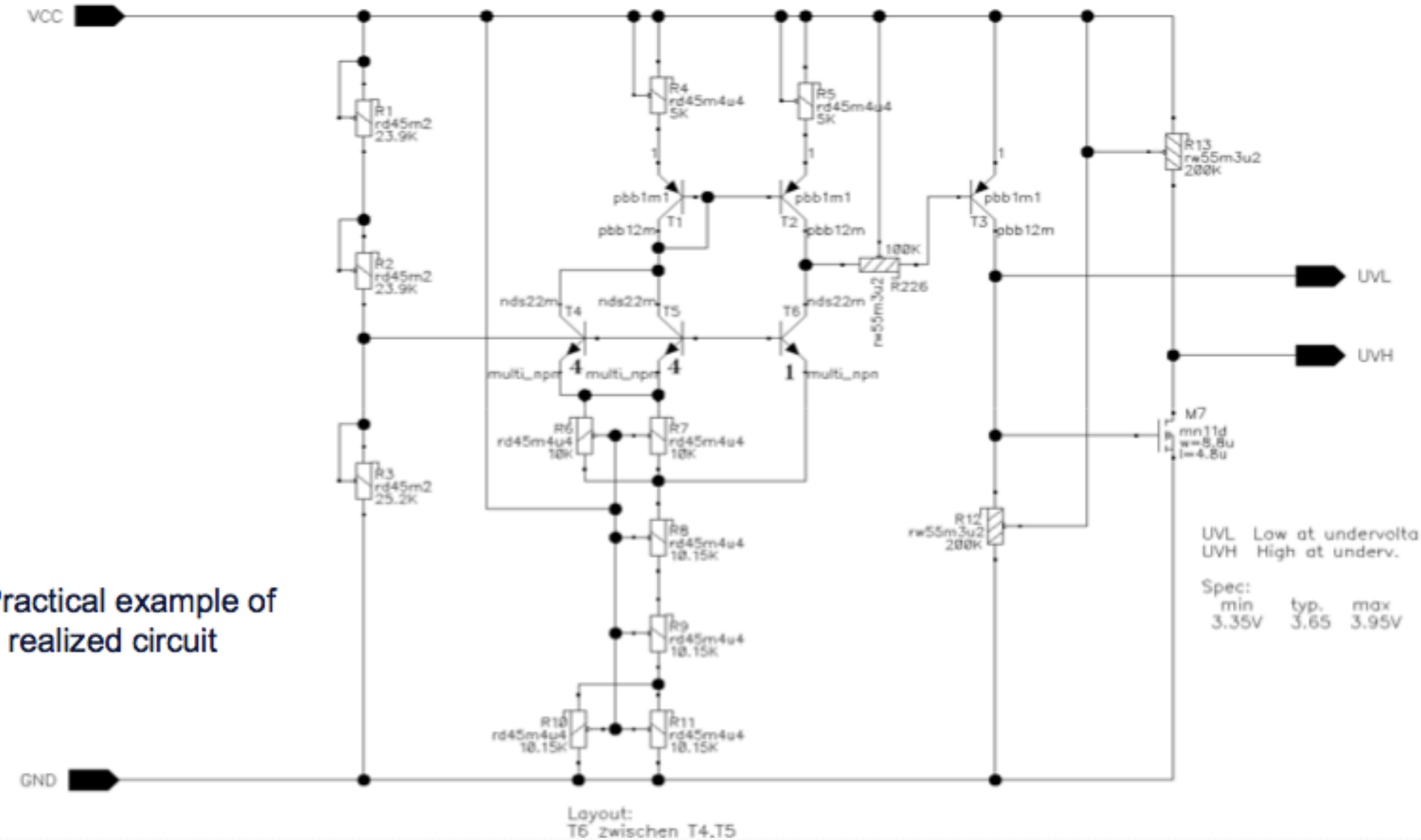
Adjustment can be done during wafer measurement, using „zener-zapping“ or laser trimming.

Undervoltage detection circuit based on the bandgap reference principle



By opening the feeback of the bandgap reference circuit, similar circuit can be used for accurate switching at a given voltage threshold, e.g. for undervoltage detection

Undervoltage detection circuit



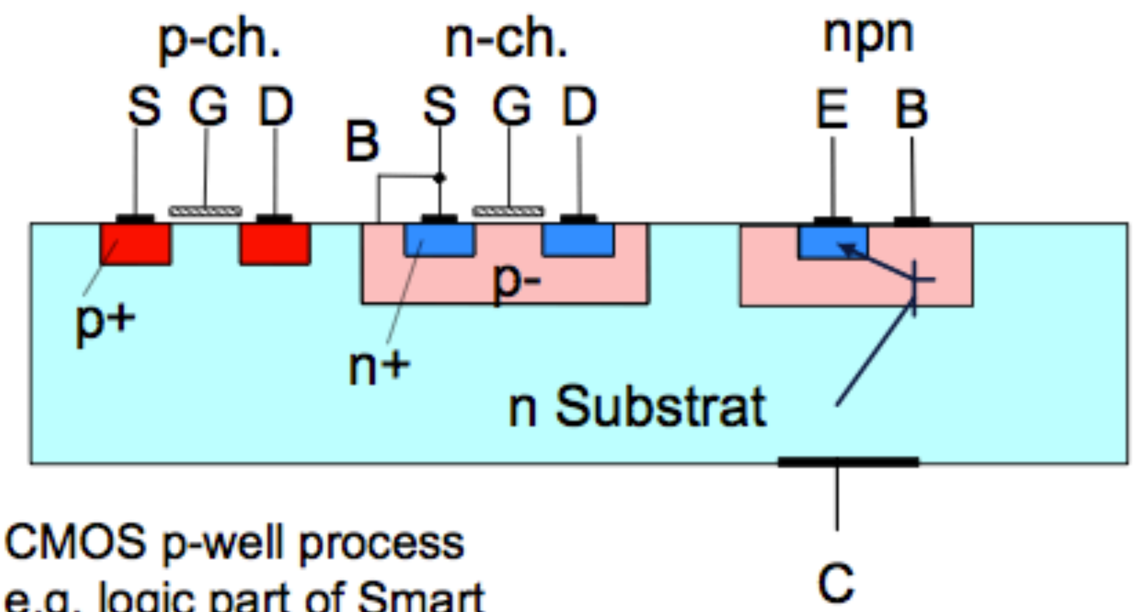
Practical example of a realized circuit

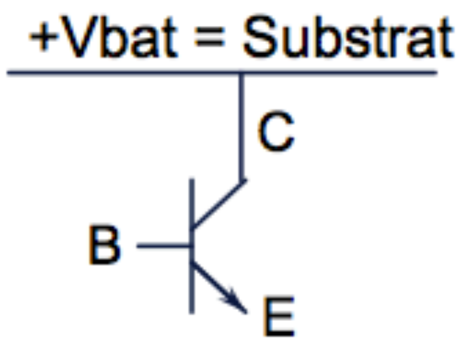
CMOS Compatible Bandgap Reference

If in a CMOS process no real npn is available, use the „substrat-npn“, which always is available in a p-well CMOS technology, as bipolar reference.
e.g. in the Smart technology this substrat-npn exists.

The collector is fixed to + Vbat (=substrat in that technologies), so you cannot use the npn as amplifier. You have only free access to base and emitter, which is enough to use the emitter-scaling for the Delta-Vbe principle.

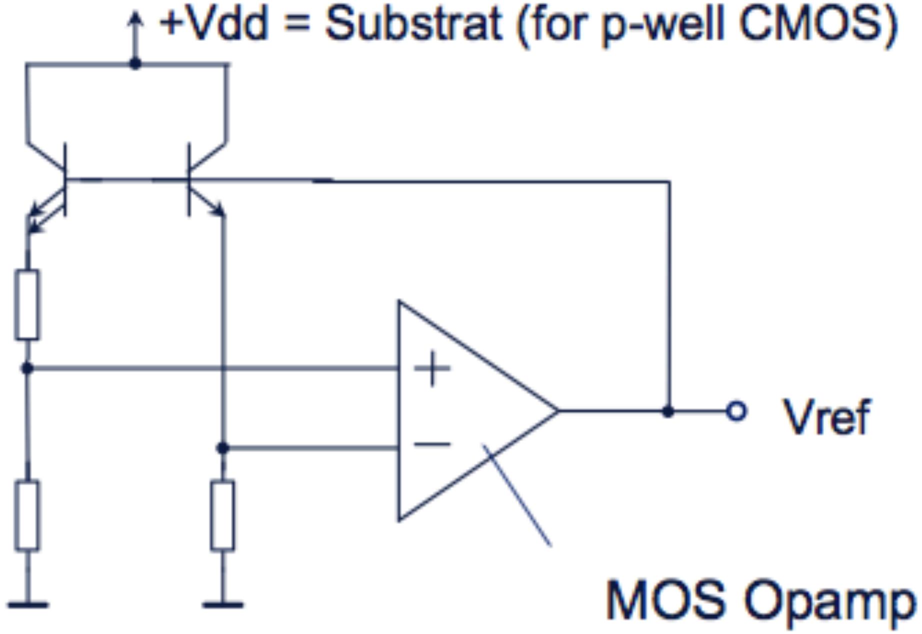
Amplifier has to be done in MOS which will cause more offset as a pure bipolar solution.





CMOS p-well process
e.g. logic part of Smart

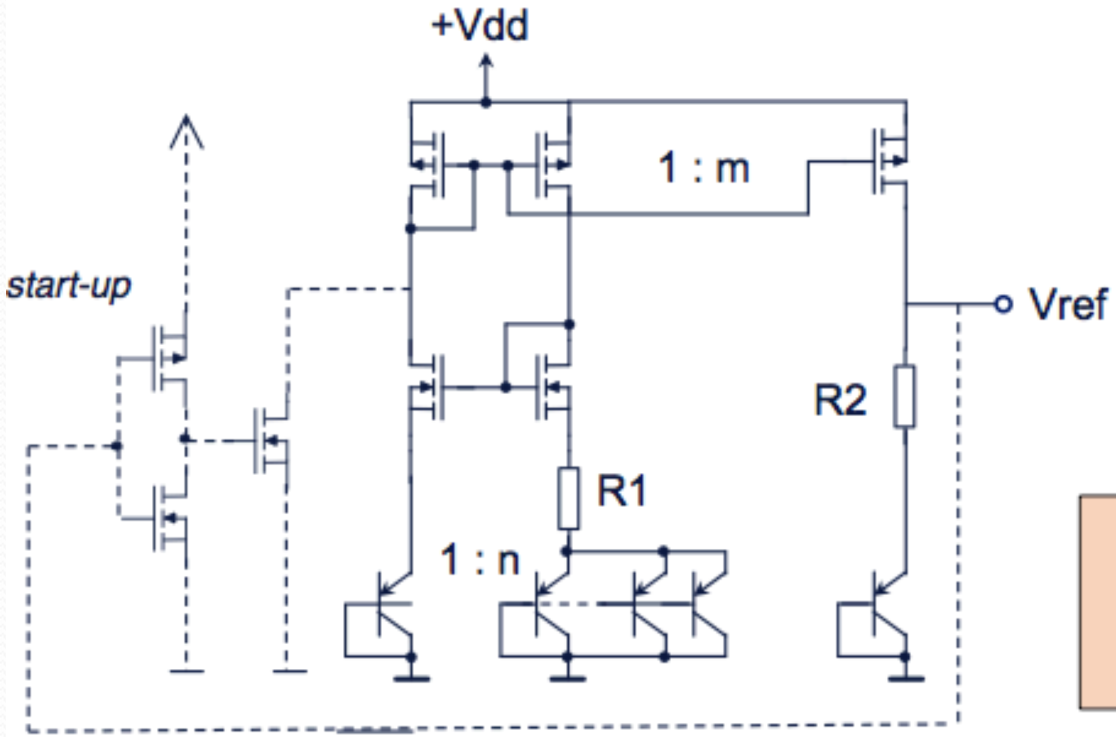
Bandgap reference with all npn-collectors connected to V_{DD}



1) This is a possible solution to realise a bandgap reference in a CMOS technology. Take care of opamp offset

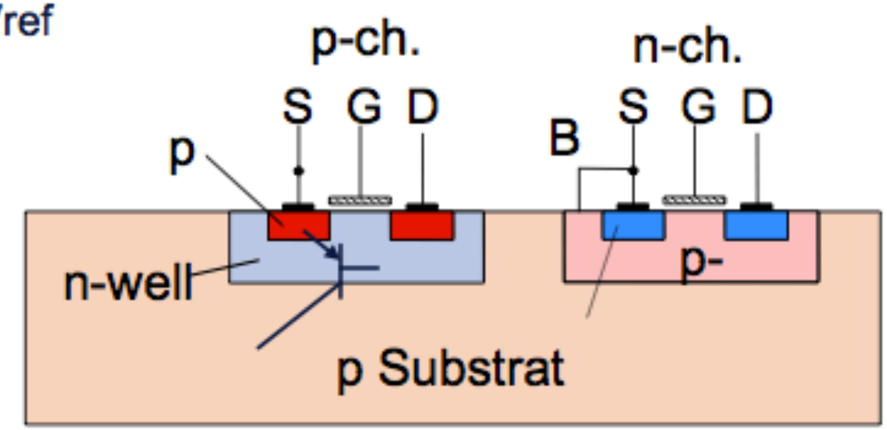
2) This circuit is robust against leakage currents and other parasitic currents at the bipolar collectors. So it can also be used with bipolars in the BCD process to improve robustness.

Bandgap reference in a n-well CMOS technology



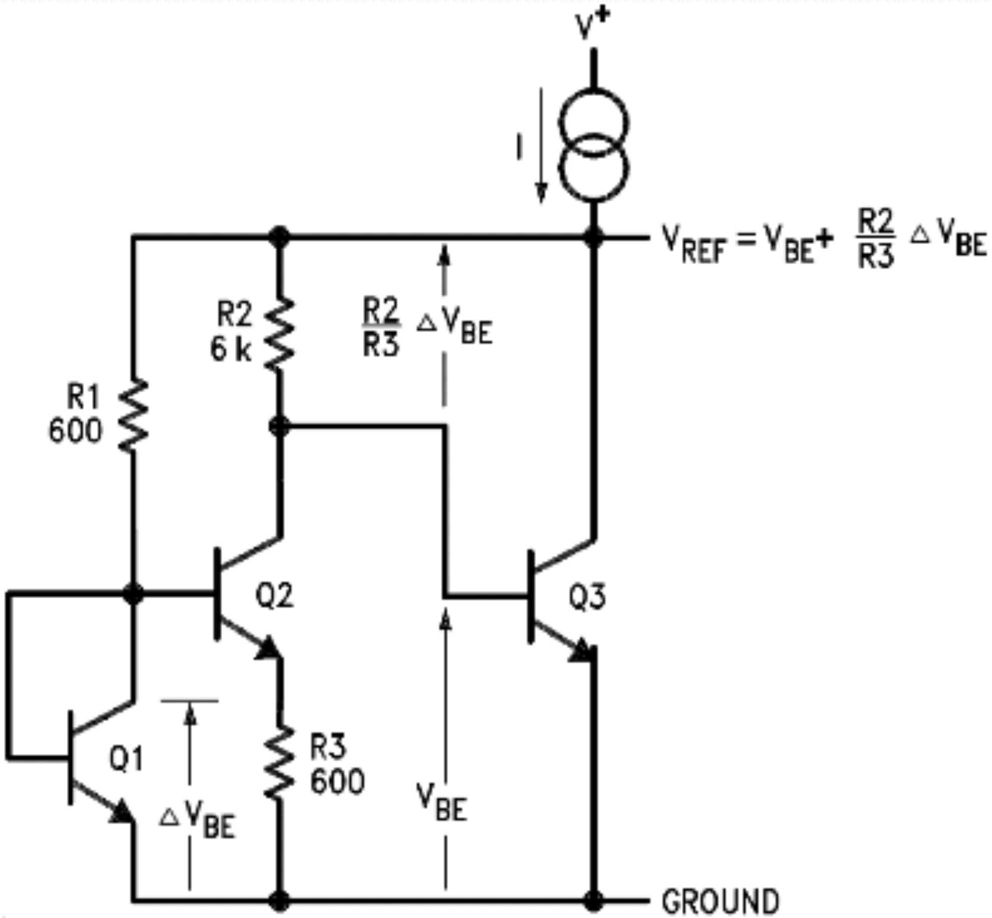
$$V_{R1} = \Delta V_{BE} = Vt \cdot \ln(n)$$

$$V_{ref} = V_{R1} \cdot m \cdot \frac{R2}{R1} + V_{BE}$$



parasitic pnp can be used as bipolar diode

„Widlar“ Bandgap – Reference



Source: Widlar, IEEE Journal of solid-state circuits, Feb. 1971

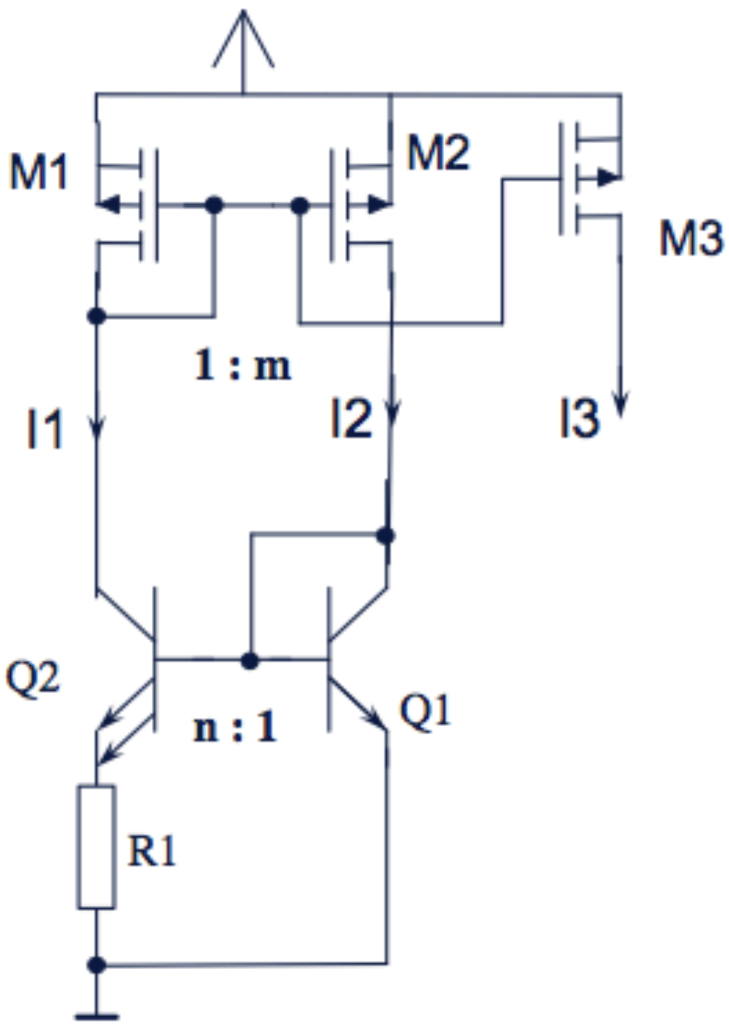
One of the first published bandgap circuits, using this idea to sum up a Vbe (neg.temp-coeff) with a delta-Vbe (pos.Temp-coeff.)

Here the current difference in the transistors is set by resistors R1, R2 to the ratio 10, not by the size of the transistors.

If you would additional set Q2, Q1 to different size this result to:

$$V_{REF} = V_{BE} + \frac{R_2}{R_3} \cdot Vt \cdot \ln\left(\frac{area\,(Q2)}{area\,(Q1)} \cdot \frac{R_2}{R_1}\right)$$

Current - Reference based on ΔV_{BE}



If M1 =M2 -> I1 = I2

:

$$I_1 = \frac{\Delta V_{BE}}{R_1} = \frac{Vt \cdot \ln(n)}{R1}$$

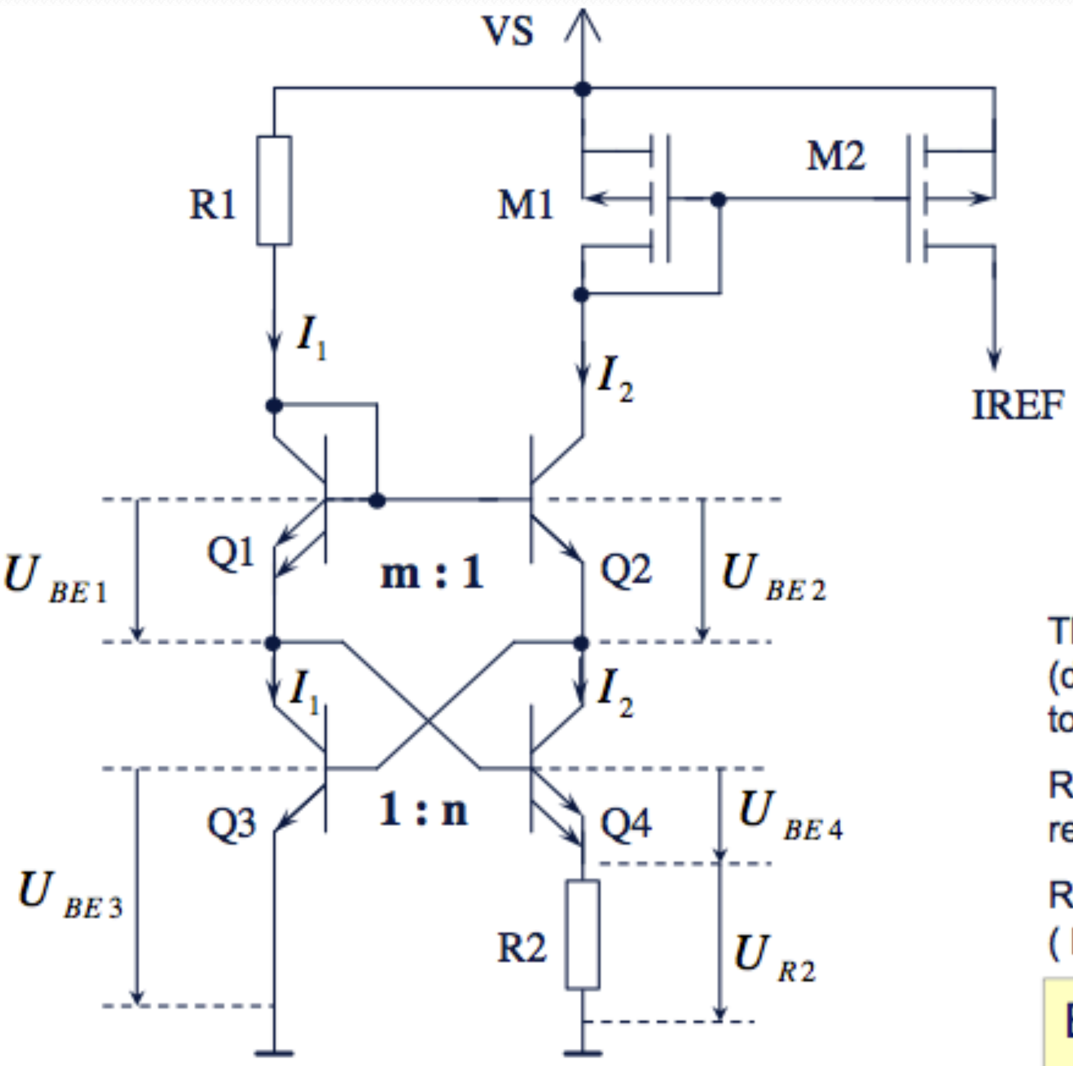
If M1, M2 not equal: M2/M1 = m

Ratio m acts as multiplication-factor:

$$I_1 = \frac{\Delta V_{BE}}{R_1} = \frac{Vt \cdot \ln(n \cdot m)}{R1}$$

Similar to bandgap reference, this circuit could need a startup-circuit

Cross-coupled current source based on ΔV_{BE}



$$U_{BE1} + U_{BE4} + U_{R2} = U_{BE2} + U_{BE3}$$

$$V_T \ln \frac{I1}{mI_S} + V_T \ln \frac{I_2}{nI_S} + I_2 R = V_T \ln \frac{I_2}{I_S} + V_T \ln \frac{I_1}{I_S}$$

$$I_2 R = V_T \left(\ln \frac{I_2}{I_S} - \ln \frac{I_2}{nI_S} + \ln \frac{I_1}{I_S} - \ln \frac{I_1}{mI_S} \right)$$

$$I_2 R = V_T \left(\ln \frac{I_2}{I_S} \cdot \frac{nI_S}{I_2} + \ln \frac{I_1}{I_S} \cdot \frac{mI_S}{I_1} \right) = V_T \ln(n + m)$$

$$I_2 = \frac{Vt \cdot \ln(n \cdot m)}{R_2} = I_{REF}$$

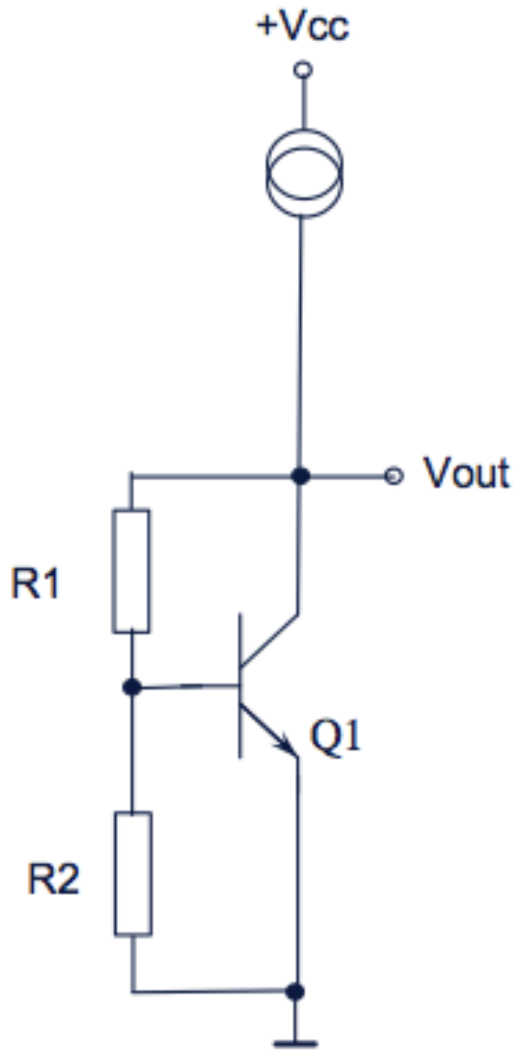
The effect of cross-coupling is that the current I1 (defined by resistor R1 and Vs) has no influence to the resulting current I2.

R1 could be an inaccurate devices e.g. p-well resistor or junction-fet

R2 defines the accurate reference-current (Iref always depends on a resistor accuracy)

Easy temp.compensation, if R2 is a diffusion resistor (with pos. tc)

Adjustable Z-diode

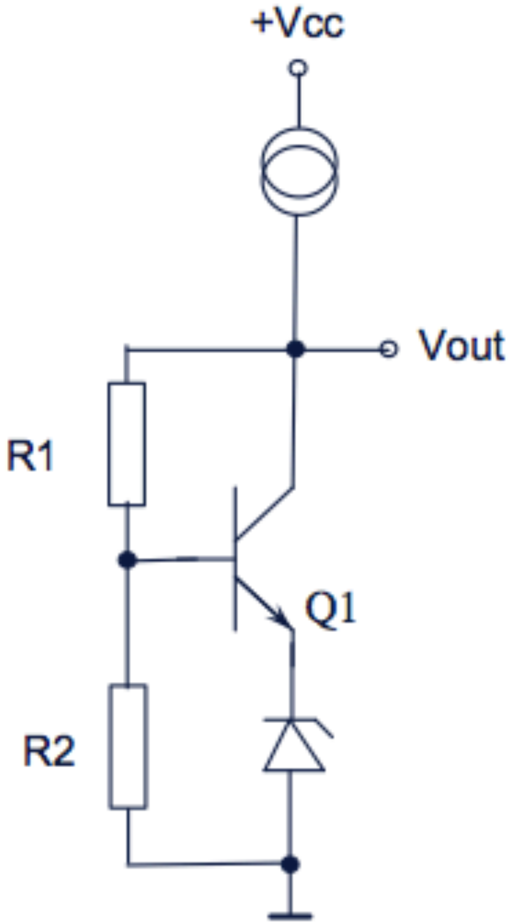


If the temperatur-dependence of Vbe can be accepted, this is an easy solution to simulate a z-diode with a bipolar transistor.

Inside integrated circuits z-diodes are not available in each wanted voltage range, so this could be a solution.

$$V_{OUT} = \frac{R_1 + R_2}{R_2} \cdot V_{BE}$$

Z-diode voltage multiplier



:

This circuit replaces a high-voltage Z-diode

Combination of bipolar-Vbe and Z-diode could lead to a first order temp.-compensation (depend on temp-dependence of Z-diode)

$$V_{OUT} = \frac{R_1 + R_2}{R_2} \cdot (V_{BE} + Vz)$$