Voltage reference and bandgap circuits
Basic blocks for voltage reference circuits

What characteristic can be used to generate a reference voltage?

**Bipolar**

- Base-emitter-voltage $V_{be}$: depends on temperature, but is not sensitive to process variation.

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

**MOS**

- Gate-source-voltage $V_{gs}$: depends strongly on process variation

  - MOS device-based voltage reference circuits will not achieve high accuracy
Characteristics of bipolar transistors

\[ I_C = I_S \cdot \left( \frac{V_{BE}}{e^{V_{t} - 1}} \right) \]

\[ V_t = \frac{k \cdot T}{q} \approx 26mV \ [25^\circ C] \]
Temperature dependence of BJT characteristics

Bipolar Transistor: $V_{BE} = f(T)$

Temperature behaviour approx. -2 mV/K

-1.8 mV/K

-2 mV/K

IC=100µA

IC=10µA

Normal operating range for integrated circuits in automotive applications

Extended temp. range

-40°C 27°C 150°C 175°C
Temperature dependence of $\Delta V_{BE}$

\[ V_{BE} = \ln \left( \frac{I_C}{I_S} \right) \cdot V_t \]

\[ \Delta V_{BE} = \ln \left( \frac{I_{C1}}{I_{C2}} \right) \cdot V_t \]

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

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

\[ q = 1,602 \cdot 10^{-19} \text{As} \]

<table>
<thead>
<tr>
<th>T [°C]</th>
<th>T [K]</th>
<th>VT [mV]</th>
</tr>
</thead>
<tbody>
<tr>
<td>-40</td>
<td>233</td>
<td>20,1</td>
</tr>
<tr>
<td>25</td>
<td>298</td>
<td>25,7</td>
</tr>
<tr>
<td>100</td>
<td>373</td>
<td>32,1</td>
</tr>
<tr>
<td>150</td>
<td>423</td>
<td>36,4</td>
</tr>
<tr>
<td>200</td>
<td>473</td>
<td>40,7</td>
</tr>
</tbody>
</table>

absolute value of Vbe depends on transistor parameter Is, delta Vbe is independent of individual transistor parameter.
Temperature-compensation of $V_{BE}$ voltage

The negative temperature dependence of $V_{be}$ can be compensated by the positive temperature dependence of delta-$V_{be}$
Temperature-constant Reference Voltage: “Bandgap-Reference”
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 chosen as integer.
If collector-currents are equal, the base-emitter-voltages (V_{BE}) of Q1, Q2 are different.

\[ \Delta V_{BE} = V_t \cdot \ln(n) \]
\[ n = \frac{AE(Q1)}{AE(Q2)} \]
\[ V_t = \frac{k}{q} \cdot T \]

\[ V_{R1} = \Delta V_{BE} = I_1 \cdot R_1 \]
\[ V_{R2} = (I_1 + I_2) \cdot R_2 = 2 \cdot I_1 \cdot R_2 = 2 \cdot \frac{R_2}{R_1} \cdot \Delta V_{BE} \]

\[ V_{REF} = V_{BE2} + V_{R2} = 1.20...1.25V \text{ for optimal temp. comp.} \]

Example:
\[ n=10 \]
\[ \Delta V_{BE} = 60 \text{ mV [25°C]} \]
\[ R_2/R_1 = 5 \]
\[ VR2 = 600 \text{ mV} \]
\[ V_{BE2} = 600 \text{ mV} \]
\[ V_{REF} = 1.2 \text{ V} \]

Voltage drop at R1 equals delta-V_{be} and has the same positive tc (temp. coefficient) as V_t. So also the voltage VR2 has the same tc, the absolute value of VR2 is chosen to a value similar to V_{BE}.
This leads to a compensation of the negative tc of V_{BE} 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 V_{ref} 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

Max. useable current for bandgap-reference as long as current follows the exponential law

\[ \beta = \frac{I_C}{I_B} \]
Startup-Problem of Bandgap-Reference Circuit

Current Mirror Q3/Q4 forces $I_1=I_1$, this defines the operating point.

But there exists a second stable operating point: $I_1=I_2=0$

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 dependence (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 feedback 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.
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

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

\[ V_{ref} = V_{R1} \cdot m \cdot \frac{R2}{R1} + V_{BE} \]
„Widlar“ Bandgap – Reference

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

Here the current difference in the transistors is set by resistors $R_1$, $R_2$ to the ratio 10, not by the size of the transistors.

If you would additional set $Q_2$, $Q_1$ to different size this result to:

$$V_{REF} = V_{BE} + \frac{R_2}{R_3} \cdot V_t \cdot \ln\left(\frac{\text{area}(Q_2)}{\text{area}(Q_1)} \cdot \frac{R_2}{R_1}\right)$$

Current - Reference based on $\Delta V_{BE}$

If $M1 = M2 \rightarrow I_1 = I_2$

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

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 $\Delta V_{BE}$

\[ U_{BE1} + U_{BE4} + U_{R2} = U_{BE2} + U_{BE3} \]
\[ V_T \ln \frac{I_1}{mI_s} + V_T \ln \frac{I_2}{nI_s} + I_2R = V_T \ln \frac{I_2}{I_s} + V_T \ln \frac{I_1}{I_s} \]
\[ I_2R = V_T \left( \ln \frac{I_2}{I_s} - \ln \frac{I_2}{nI_s} + \ln \frac{I_1}{I_s} - \ln \frac{I_1}{mI_s} \right) \]
\[ I_2R = V_T \left( \ln \frac{I_2}{I_s} \cdot \frac{nI_s}{I_2} + \ln \frac{I_1}{I_s} \cdot \frac{mI_s}{I_1} \right) = V_T \ln(n + m) \]

\[ I_2 = \frac{V_T \cdot \ln(n \cdot m)}{R_2} = I_{REF} \]

The effect of cross-coupling is that the current $I_1$ (defined by resistor $R_1$ and $V_s$) has no influence to the resulting current $I_2$.

$R_1$ could be an inaccurate devices e.g. p-well resistor or junction-fet

$R_2$ defines the accurate reference-current (Iref always depends on a resistor accuracy)

Easy temp.compensation, if $R_2$ is a diffusion resistor (with pos. tc)
Adjustable Z-diode

If the temperature-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).

\[
V_{OUT} = \frac{R_1 + R_2}{R_2} \cdot (V_{BE} + V_z)
\]