4.5 (A4.3) - TEMPERATURE INDEPENDENT BIASING (BANDGAP)

INTRODUCTION

Objective
The objective of this presentation is:
1.) Introduce the concept of a bandgap reference
2.) Show circuits that implement the bandgap reference
3.) Show how to improve the performance of the bandgap reference

Outline
• Introduction
• Development of the bandgap circuit
• Bandgap reference circuits
• Improved bandgap reference circuits
• Summary
Temperature Stable References

• The previous reference circuits failed to provide small values of temperature coefficient although sufficient power supply independence was achieved.

• This section introduces the bandgap voltage concept combined with power supply independence to create a very stable voltage reference in regard to both temperature and power supply variations.

Bandgap Voltage Reference Principle

The principle of the bandgap voltage reference is to balance the negative temperature coefficient of a pn junction with the positive temperature coefficient of the thermal voltage, \( V_t = kT/q \).

Concept:

\[ V_{REF} = V_{BE} + KV_t \]

![Fig. 4.6-1](image)

Result: References with \( TC_P \)'s approaching 10 ppm/°C.
DEVELOPMENT OF THE BANDGAP REFERENCE CIRCUIT

Derivation of the Temperature Coefficient of the Base-Emitter Voltage

To achieve small TCF's we must know the TCF of $V_{BE}$ more precisely than approximately $-2 \text{mV/°C}$.

1.) Start with the collector current density, $J_C$:

$$J_C = \frac{q D_n n_{po}}{W_B} \exp\left(\frac{V_{BE}}{V_t}\right)$$

where,

- $J_C = I_C/\text{Area} = \text{collector current density}$
- $D_n = \text{average diffusion constant for electrons}$
- $W_B = \text{base width}, V_{BE} = \text{base-emitter voltage}$
- $V_t = \frac{kT}{q}$

$k = \text{Boltzmann's constant} \ (1.38 \times 10^{-23} \text{J/°K}), T = \text{Absolute temperature}$

$n_{po} = n_i^2/NA = \text{equilibrium concentration of electrons in the base}$

$$n_i^2 = DT^3 \exp\left(-\frac{V_{GO}}{V_t}\right) = \text{intrinsic concentration of carriers}$$

$D = \text{temperature independent constant}$

$V_{GO} = \text{bandgap voltage of silicon} \ (1.205 \text{V})$

$N_A = \text{acceptor impurity concentration}$
Derivation of the Temperature Coefficient of the Base-Emitter Voltage - Continued

2.) Combine the above relationships into one:

\[ J_C = \frac{q D_n}{N_A W_B} DT^3 \exp \left( \frac{V_{BE} - V_{GO}}{V_t} \right) = AT^\gamma \exp \left( \frac{V_{BE} - V_{GO}}{V_t} \right) \]

where, \( \gamma = 3 \)

3.) The value of \( J_C \) at a reference temperature of \( T = T_0 \) is

\[ J_{C0} = AT_0^\gamma \exp \left[ \frac{q}{kT_0} (V_{BE} - V_{GO}) \right] \]

while the value of \( J_C \) at a general temperature, \( T \), is

\[ J_C = AT^\gamma \exp \left[ \frac{q}{kT} (V_{BE} - V_{GO}) \right] \]

4.) The ratio of \( J_C/J_{C0} \) can be expressed as,

\[ \frac{J_C}{J_{C0}} = \left( \frac{T}{T_0} \right)^\gamma \exp \left[ \frac{q}{k} \left( \frac{V_{BE} - V_{GO}}{T} - \frac{V_{BE0} - V_{GO}}{T_0} \right) \right] \]

or

\[ \ln \left( \frac{J_C}{J_{C0}} \right) = \gamma \ln \left( \frac{T}{T_0} \right) + \frac{q}{kT} \left( V_{BE} - V_{GO} - \frac{T}{T_0} (V_{BE0} - V_{GO}) \right) \]

where \( V_{BE0} \) is the value of \( V_{BE} \) at \( T = T_0 \).

5.) Solving for \( V_{BE} \) from the above results gives,

\[ V_{BE}(T) = V_{GO} \left( 1 - \frac{T}{T_0} \right) + V_{BE0} \left( \frac{T}{T_0} \right) + \frac{\gamma kT}{q} \ln \left( \frac{T_0}{T} \right) + \frac{kT}{q} \ln \left( \frac{J_C}{J_{C0}} \right) \]
Derivation of the Temperature Coefficient of the Base-Emitter Voltage - Continued

6.) Next, assume \( J_C \propto T^\alpha \) and find \( \partial V_{BE}/\partial T \).

\[
\frac{V_{BE}}{T} = \frac{V_{GO}}{T} \left( 1 - \frac{T}{T_0} \right) - \frac{V_{GO}}{T_0} + \frac{V_{BE0}}{T_0} + \frac{\gamma kT}{q} \cdot \frac{\ln(T_0/T)}{T} + \ln \left( \frac{T_0}{T} \right) \left( \frac{\gamma kT/q}{T} \right) + \frac{kT}{q} \left( \frac{\ln(JC/JC_0)}{T_0} \right) + \frac{\alpha \ln(JC/JC_0)}{T_0}
\]

7.) Assume that \( T = T_0 \) which means \( J_C = J_{C0} \). Since, \( \partial V_{GO}/\partial T = 0 \),

\[
\frac{V_{BE}}{T} \bigg|_{T=T_0} = -\frac{V_{GO}}{T_0} + \frac{V_{BE0}}{T_0} + \frac{\gamma kT}{q} \cdot \frac{\ln(T_0/T)}{T} + \frac{kT}{q} \left( \frac{\ln(JC/JC_0)}{T} \right)
\]

8.) Note that,

\[
\frac{\ln(T_0/T)}{T} = \frac{T}{T_0} \left( \frac{T_0}{T} - 1 \right) = -\frac{1}{T} \quad \text{and} \quad \frac{\ln(JC/JC_0)}{T} = \frac{J_{C0}}{J_C} \left( \frac{J_C}{J_{C0}} \right) = \frac{\alpha}{T}
\]

Therefore,

\[
\frac{V_{BE}}{T} \bigg|_{T=T_0} = -\frac{V_{GO}}{T_0} + \frac{V_{BE0}}{T_0} - \frac{\gamma k}{q} + \frac{\alpha k}{q} \quad \text{or} \quad \frac{V_{BE}}{T} \bigg|_{T=T_0} = \frac{V_{BE0} - V_{GO}}{T_0} + (\alpha - \gamma) \left( \frac{k}{q} \right)
\]

Typical values of \( \alpha \) and \( \gamma \) are 1 and 3.2. Therefore, if \( V_{BE0} = 0.6 \text{V} \), then at room temperature:

\[
\frac{V_{BE}}{T} \bigg|_{T=T_0} = \frac{0.6 - 1.205}{300} + (1 - 3.2) \left( \frac{0.026}{300} \right) = \frac{0.6 - 1.205 - 0.1092}{300} = -1.826 \text{mV}/^\circ\text{C}
\]

Derivation of the Temperature Coefficient of the Thermal Voltage \((kT/q)\)

1.) Consider two identical pn junctions having different current densities,
\[ \Delta V_{BE} = V_{BE1} - V_{BE2} = \frac{kT}{q} \ln \left( \frac{J_{C1}}{J_{C2}} \right) \]

2.) Find \( \frac{\partial (\Delta V_{BE})}{\partial T} \),

\[
\frac{(\Delta V_{BE})}{T} = \frac{V_t}{T} \ln \left( \frac{J_{C1}}{J_{C2}} \right) = \frac{k}{q} \ln \left( \frac{J_{C1}}{J_{C2}} \right)
\]
**Derivation of the Gain, K, for the Bandgap Voltage Reference**

1.) In order to achieve a zero temperature coefficient at \( T = T_0 \), the following equation must be satisfied:

\[
0 = \frac{V_{BE}}{T} \bigg|_{T=T_0} + K'' \frac{(\Delta V_{BE})}{T}
\]

where \( K'' \) is a constant that satisfies the equation.

2.) Therefore, we get

\[
0 = K'' \left( \frac{V_{t0}}{T_0} \right) \ln \left( \frac{J_{C1}}{J_{C2}} \right) + \frac{V_{BE0} - V_{GO}}{T_0} + \frac{(\alpha - \gamma)V_{t0}}{T_0}
\]

3.) Define \( K = K'' \ln \left( \frac{J_{C1}}{J_{C2}} \right) \), therefore

\[
0 = K \left( \frac{V_{t0}}{T_0} \right) + \frac{V_{BE0} - V_{GO}}{T_0} + \frac{(\alpha - \gamma)V_{t0}}{T_0}
\]

4.) Solving for \( K \) gives

\[
K = \frac{V_{GO} - V_{BE0} - V_{t0}(\alpha-\gamma)}{V_{t0}}
\]

Assuming that \( J_{C1}/J_{C2} = A_{E1}/A_{E2} = 10 \) and \( V_{BE0} = 0.6V \) gives,

\[
K = \frac{1.205 - 0.6 + (2.2)(0.026)}{0.026} = 25.469
\]

5.) The output voltage of the bandgap voltage reference is found as,

\[
V_{REF} \bigg|_{T=T_0} = V_{BE0} + KV_{t0} = V_{BE0} + V_{GO} - V_{BE0} + (\gamma-\alpha)V_{t0} \quad \text{or} \quad V_{REF} = V_{GO} + (\gamma-\alpha)V_{t0}
\]

For the previous values, \( V_{REF} = 1.205 + 0.026(2.2) = 1.262V \).
Variation of the Bandgap Reference Voltage with respect to Temperature

The previous derivation is only valid at a given temperature, $T_0$. As the temperature changes away from $T_0$, the value of $\frac{\partial V_{REF}}{\partial T}$ is no longer zero.

Illustration:

Bandgap Curvature Correction will be necessary for low ppm/C bandgap references.
BANDGAP REFERENCE CIRCUITS

Classical Widlar Bandgap Voltage Reference

Operation:

\[ V_{BE1} = V_{BE2} + I_2R_3 \]

gives

\[ \Delta V_{BE} = V_{BE1} - V_{BE2} = I_2R_3 \]

But,

\[ \Delta V_{BE} = V_t \ln \left( \frac{I_1}{I_{S1}} \right) - V_t \ln \left( \frac{I_2}{I_{S2}} \right) = V_t \ln \left( \frac{I_1I_{S2}}{I_2I_{S1}} \right) \]

Assume \( V_{BE1} = V_{BE3} \), we get \( I_1R_1 = I_2R_2 \)

Therefore,

\[ I_2 = \frac{\Delta V_{BE}}{R_3} = \frac{V_t}{R_3} \ln \left( \frac{I_1I_{S2}}{I_2I_{S1}} \right) = \frac{V_t}{R_3} \ln \left( \frac{R_2I_{S2}}{R_1I_{S1}} \right) \]

Now we can express \( V_{REF} \) as

\[ V_{REF} = I_2R_2 + V_{BE3} = \frac{R_2}{R_3} V_t \ln \left( \frac{R_2I_{S2}}{R_1I_{S1}} \right) + V_{BE3} = KV_t + VBE \]

Design \( R_1, R_2, I_{S1}, \) and \( I_{S2} \) to get the desired \( K \).

Example:

Let \( K = 25 \) and \( I_{S2} = 10I_{S1} \) and design \( R_1, R_2, \) and \( R_3 \). Choose \( R_2 = 10R_1 = 10k\Omega \). \( \ln(100) = 4.602 \).

Therefore \( R_2/R_3 = 25/4.602 \) or \( R_3 = R_2/5.4287 = 1.842k\Omega \).

A CMOS Bandgap Reference using PNP Lateral BJTs

Bootstrapped Voltage Reference using PNP Laterals-

\[ I_2 = \frac{V_{BE1} - V_{BE2}}{R_2} = \frac{V_t}{R_2} \left[ \ln \left( \frac{I_1}{I_{s1}} \right) - \ln \left( \frac{I_2}{I_{s2}} \right) \right] = \frac{V_t}{R_2} \ln \left( \frac{I_{s2}}{I_{s1}} \right) = \frac{V_t}{R_2} \ln \left( \frac{A_{E2}}{A_{E1}} \right) \]

if \( I_1 = I_2 \) which is forced by the current mirror consisting of M1 and M2.

\[ V_{REF} = V_{BE1} + I_1 R_1 = V_{BE1} + \left( \frac{R_1}{R_2} \ln \left( \frac{A_{E2}}{A_{E1}} \right) \right) V_t = V_{BE1} + KV_t \]

While an op amp could be used to make \( I_1 = I_2 \) it suffers from offset and noise and leads to deterioration of the bandgap temperature performance.

\( V_{REF} \) is with respect to \( V_{DD} \) and therefore is susceptible to changes on \( V_{DD} \).
A CMOS Bandgap Reference using Substrate PNP BJTs

Operation:

The cascode mirror (M5-M8) keeps the currents in Q1, Q2, and Q3 identical. Thus,

\[ V_{BE1} = I_2R + V_{BE2} \]

or

\[ I_2 = \frac{V_t}{R} \ln(n) \]

Therefore,

\[ V_{REF} = V_{BE3} + I_2(kR) = V_{BE3} + kV_t \ln(n) \]

Use k and n to design the desired value of K (n is an integer greater than 1).
Weak Inversion Bandgap Voltage Reference

Circuit:

![Diagram of a Weak Inversion Bandgap Voltage Reference Circuit]

Analysis:

For the p-channel transistors:

\[ I_D = I_{DO}(W/L) \exp\left(\frac{V_{BG}}{nV_t} - \frac{V_{BS}}{V_t} + \exp\left(-\frac{V_{BD}}{V_t}\right)\right) \]

where \( V_t = kT/q \).

If \( V_{BD} >> V_t \), then

\[ I_D = I_{DO}(W/L) \exp\left(\frac{V_{BG} - V_{BS}}{nV_t} - \frac{V_{BD}}{V_t}\right) \]

The various transistor currents can be expressed as:

\[ I_{D1} = I_{D2} = I_{DO}(W_2/L_2) \exp\left(\frac{V_{BG2}}{nV_t}\right) \quad \text{and} \quad I_{D3} = I_{D4} = I_{DO}(W_4/L_4) \exp\left(\frac{V_{BG4}}{nV_t} - \frac{V_{BS4}}{V_t}\right) \]

Note that \( V_{BG2} = V_{BG4} \) and \( V_{BS4} = V_{R1} \).

Therefore,

\[ \frac{I_{D1}}{I_{D3}} = \frac{W_2/L_2}{W_4/L_4} \exp\left(\frac{V_{R1}}{V_t}\right) \]

where

\[ V_{R1} = V_t \ln\left(\frac{W_1W_4L_2L_3}{L_1L_4W_2W_3}\right) \quad \text{and} \quad I_{R1} = \frac{V_{R1}}{R_1} \]
Weak Inversion Bandgap Voltage Reference - Continued

The reference voltage can be expressed as,

\[ V_{REF} = R_2I_6 + V_{BE5} \]

However,

\[ I_6 = \frac{W_6L_3}{L_6W_3} \quad I_R1 = \frac{W_6L_3}{L_6W_3} \frac{V_t}{R_1} \ln\left(\frac{W_1W_4L_2L_3}{L_1L_4W_2W_3}\right). \]

Substituting \( I_6 \) and the previously derived expression for \( V_{BE}(T) \) in \( V_{REF} \) gives,

\[ V_{REF} = \frac{W_6L_3}{L_6W_3} \frac{R_2}{R_1} V_t \ln\left(\frac{W_1W_4L_2L_3}{L_1L_4W_2W_3}\right) + V_{GO}\left(1 - \frac{T}{T_0}\right) + V_{BE0}\left(\frac{T}{T_0}\right) + 3V_t \ln\left(\frac{T_0}{T}\right) \]

To achieve \( \frac{\partial V_{REF}}{\partial T} = 0 \) at \( T = T_0 \), we get

\[ \frac{V_{REF}}{T} = \left(\frac{k}{q}\right) \frac{R_2}{R_1} \frac{W_6L_3}{L_6W_3} \ln\left(\frac{W_1W_4L_2L_3}{L_1L_4W_2W_3}\right) - \frac{V_{GO}}{T_0} + \frac{V_{BE0}}{T_0} + \frac{3k}{q} \]

Therefore,

\[ \frac{R_2W_6L_3}{R_1L_6W_3} \ln\left(\frac{W_1W_4L_2L_3}{L_1L_4W_2W_3}\right) = q \frac{kT_0}{T} (V_{GO} - V_{BE0}) - 3 \]

Under the above constraint, \( V_{REF} \) has an approximate zero value of temperature coefficient at \( T = T_0 \) and has a value of

\[ V_{REF} = V_{GO} + \frac{3kT}{q} \left[ 1 + \ln\left(\frac{T_0}{T}\right) \right] = V_{GO} + \frac{3kT}{q} \]

Practical values of \( \frac{\partial V_{REF}}{\partial T} \) for the weak inversion bandgap are less than 100 ppm/°C.
IMPROVEMENT OF THE BANDGAP REFERENCE CIRCUIT

Curvature Correction Techniques:

- Squared PTAT Correction:

\[
V_{\text{Ref}} = V_{\text{BE}} + V_{\text{PTAT}} + V_{\text{PTAT}}^2
\]

Temperature coefficient ≈ 1-20 ppm/°C

- \(V_{\text{BE}}\) loop


- \(\beta\) compensation


- Nonlinear cancellation

**$V_{BE}$ Loop Curvature Correction Technique**

**Circuit:**

![3-Output Current Mirror ($I_{BE}+I_{NL}$)](image)

**Operation:**

$$I_{NL} = \frac{V_{BE1} - V_{BE2}}{R_3} = \frac{V_t}{R_3} \ln \left( \frac{I_{c1}A_2}{I_{c2}} \right)$$

$$= \frac{V_t}{R_3} \ln \left( \frac{2I_{PTAT}}{I_{NL} + I_{Constant}} \right)$$

where

$$I_{Constant} = I_{NL} + I_{PTAT} + I_{VBE}$$

(a quasi-temperature independent current subject to the temperature coefficient of the resistors)

$$V_{REF} = \left[ \frac{V_{BE}}{R_2} + \frac{V_t}{R_3} \ln \left( \frac{2I_{PTAT}}{I_{NL} + I_{Constant}} \right) + I_{PTAT} \right] R_1$$

Temperature coefficient ≈ 3 ppm/°C with a total quiescent current of 95µA.
**β Compensation Curvature Correction Technique**

Circuit:

```
  V_{in}  |
  -----  
  \    |
  \  I=AT |
  R   |
  I=BT  |
  V_{REF}  |
```

Operation:

\[
V_{REF} = V_{BE} + \left( AT + \frac{BT}{1 + \beta} \right) R \star V_{BE} + \left( AT + \frac{BT}{\beta} \right) R
\]

where

- \( A \) and \( B \) are constant
- \( T \) = temperature

The temperature dependence of \( \beta \) is

\[
\beta(T) \propto e^{-1/T} \Rightarrow \beta(T) = Ce^{-1/T}
\]

\[
V_{REF} = V_{BE}(T) + \left( AT + \frac{BT e^{1/T}}{C} \right)
\]

Not good for small values of \( V_{in} \):

\[
V_{in} \geq V_{REF} + V_{sat.} = V_{GO} + V_{sat.} = 1.4V
\]
Nonlinear Cancellation Curvature Correction Technique

Objective: Eliminate nonlinear term from the base-emitter.

Result: 0.5 ppm/°C from -25°C to 85°C.

Operation: From above,

\[ V_{REF} = V_{PTAT} + 4V_{BE}(I_{PTAT}) - 3V_{BE}(I_{Constant}) \]

Note that, \( I_{PTAT} \Rightarrow I_c \propto T^1 \Rightarrow \alpha = 1 \)
and \( I_{constant} \Rightarrow I_c \propto T^0 \Rightarrow \alpha = 0, \)

Previously we found,

\[ V_{BE}(T) = V_{GO} - \frac{T}{T_0} \left[ V_{GO} - V_{BE}(T_0) \right] - (\gamma - \alpha) V_t \ln \left( \frac{T}{T_0} \right) \]

so that

\[ V_{BE}(I_{PTAT}) = V_{GO} - \frac{T}{T_0} \left[ V_{GO} - V_{BE}(T_0) \right] - (\gamma - 1) V_t \ln \left( \frac{T}{T_0} \right) \]

and

\[ V_{BE}(I_{Constant}) = V_{GO} - \frac{T}{T_0} \left[ V_{GO} - V_{BE}(T_0) \right] - \gamma V_t \ln \left( \frac{T}{T_0} \right) \]

Combining the above relationships gives,

\[ V_{REF}(T) = V_{PTAT} + V_{GO} - \frac{T}{T_0} \left[ V_{GO} - V_{BE}(T_0) \right] - [\gamma - 4] V_t \ln \left( \frac{T}{T_0} \right) \]

If \( \gamma \approx 4, \) then

\[ V_{REF}(T) \approx V_{PTAT} + V_{GO} \left( 1 - \frac{T}{T_0} \right) + V_{BE}(T_0) \frac{T}{T_0} \]
Other Characteristics of Bandgap Voltage References

Noise
Voltage references for high-resolution A/D converters are particularly sensitive to noise.
Noise sources: Op amp, resistors, switches, etc.

PSRR
Maximize the PSRR of the op amp.

Offset Voltages
Becomes a problem when op amps are used.

\[ V_{BE2} = V_{BE1} + V_{R1} + V_{OS} \]
\[ \Delta V_{BE} = V_{BE2} - V_{BE1} = V_{R1} + V_{OS} = V_t \ln \left( \frac{i_{C2} A_{E1}}{iC1 A_{E2}} \right) \]
\[ i_{C2} R_3 = i_{C1} R_2 - V_{OS} \]
or
\[ \frac{i_{C2}}{i_{C1}} = \frac{R_2}{R_3} - \frac{V_{OS}}{i_{C1} R_3} = \frac{R_2}{R_3} \left( 1 + \frac{V_{OS}}{i_{C1} R_2} \right) \]

Therefore,
\[ V_{R1} = -V_{OS} + V_t \ln \left[ \frac{R_2 A_{E1}}{R_3 A_{E2}} \left( 1 + \frac{V_{OS}}{i_{C1} R_2} \right) \right] \]
\[ V_{REF} = V_{BE2} - V_{OS} + i_{C1} R_2 = V_{BE2} - V_{OS} + \left( \frac{V_{R1}}{R_1} \right) R_2 = V_{BE2} - V_{OS} + \left( \frac{R_2}{R_1} \right) V_{R1} \]

\[ V_{REF} = V_{BE2} - V_{OS} \left( 1 + \frac{R_2}{R_1} \right) + \frac{R_2}{R_1} V_t \ln \left[ \frac{R_2 A_{E1}}{R_3 A_{E2}} \left( 1 - \frac{V_{OS}}{i_{C1} R_2} \right) \right] \]
**How do you get a Stable Reference Current from the Bandgap?**

Assume that a temperature stable reference voltage is available (i.e. bandgap reference) and use the zero TC NMOS current sink.

The problem is that $V_{REF}$ may not be equal to the value of $V_{GS}$ that gives zero TC.

$$V_{GS} = I_{R2}R_2 = R_2\left(\frac{V_{REF}}{R_1}\right) = \left(\frac{R_2}{R_1}\right)V_{REF}$$

$$\therefore \quad \frac{dV_{GS}}{dT} = \left(\frac{R_2}{R_1}\right)\frac{dV_{REF}}{dT} + \frac{V_{REF}dR_2}{R_1} - \frac{R_2}{R_1}\frac{dR_1}{dT} = \frac{R_2}{R_1}\left[\frac{dV_{REF}}{dT} + \frac{dR_2}{dT} - \frac{dR_1}{dT}\right]$$

If the temperature coefficients of $R_1$ and $R_2$ are equal $\left(\frac{dR_1}{dT} = \frac{dR_2}{dT}\right)$ then

$$\frac{dV_{GS}}{dT} = \frac{R_2}{R_1}\frac{dV_{REF}}{dT} \quad \text{and } V_{GS} \text{ is proportional to the temperature dependence of } V_{REF}.$$
Practical Aspects of Temperature-Independent and Supply-Independent Biasing

A temperature-independent and supply-independent current source and its distribution:

\[ I_{REF} = \frac{V_{BG}}{R_{ext}} \]

where

\[ V_{BG} = V_{BE3} + I_{PTAT} R_2 = V_{BE3} + \frac{V_T}{R_1} \ln(n) \cdot R_2 \]
Practical Aspects of Bias Distribution Circuits - Continued

Distribution of the current avoids change in bias voltage due to $IR$ drop in bias lines.

Slave bias circuit:

![Slave Bias Circuit Diagram](image-url)
SUMMARY OF BANDGAP REFERENCES

**Summary**

- Bandgap voltage references can achieve temperature dependence less than 50 ppm/°C
- Bandgap voltage references are also independent of power supply
- Correction of second-order effects in the bandgap voltage reference can achieve very stable (1 ppm/°C) voltage references.
- Watch out for second-order effects such as noise when using the bandgap voltage reference in sensitive applications.