Semiconductor Technology from A to Z

Analog & Mixed-Signal Design

Bandgap References

Why a Temperature-Stable Reference Voltage?

Many analog and digital circuits require a reference voltage that stays as constant as possible regardless of supply voltage, temperature, and manufacturing spread – for example as a comparison voltage for ADCs and DACs, as the basis for voltage regulators, or to generate reference currents. A single diode voltage or a Zener diode would not be suitable for this, since a diode forward voltage decreases with rising temperature by roughly –2 mV/K; over a typical industrial temperature range of –40 to 125 °C, this would produce an uncompensated drift of more than 300 mV – far too large for precision applications.

The bandgap reference solves this problem by weighting and adding two voltages with opposite temperature behavior so that their temperature dependencies cancel out to first order. The resulting output voltage is about 1.2 V, corresponding to the band gap of silicon extrapolated to absolute zero – hence the name. Good integrated bandgap references achieve temperature coefficients of only 10 to 50 ppm/K, more than two orders of magnitude less drift than an uncompensated diode.

PTAT and CTAT Voltages

The base-emitter voltage of a bipolar transistor decreases with rising temperature and is therefore called a CTAT quantity (Complementary To Absolute Temperature). If instead two bipolar transistors are operated at different emitter areas or current densities, the difference between their base-emitter voltages ΔV_{BE} grows proportionally to the absolute temperature (PTAT, Proportional To Absolute Temperature): $\Delta V_{BE} = (kT/q) \cdot \ln(n)$, where n is the ratio of current densities or emitter areas.

Amplifying the PTAT voltage ΔV_{BE} by a suitable factor and adding it to a CTAT base-emitter voltage cancels the linear temperature coefficients of both terms to first order, leaving the sum nearly constant over a wide temperature range at the extrapolated silicon band gap of about 1.2 V.

Practical Circuits and Residual Error

A common implementation is the Brokaw bandgap cell, in which an operational amplifier forces two bipolar transistors operating at different current densities to the same collector potential and converts the PTAT voltage into a PTAT current through a resistor, which is then added to the CTAT voltage. The choice of the amplification factor determines how precisely the linear temperature terms cancel; typical uncorrected bandgap cells achieve temperature coefficients of about 20 to 50 ppm/K.

Because the base-emitter voltage also contains a weaker, nonlinear temperature term in addition to the linear one, a slight curvature of the output voltage over temperature, on the order of a few millivolts across the full temperature range, remains after the simple compensation. Advanced circuits correct this residual error with additional, deliberately nonlinear compensation currents as well as laser or electrical trimming of individual resistors, achieving temperature coefficients of only 1 to 5 ppm/K, as required in precision ADC references.