

# MORE ABOUT THE AD580 MONOLITHIC IC VOLTAGE REGULATOR OR... LOW-COST CONSTANTS FOR ANALOG CIRCUITS & SYSTEMS

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*Today, voltage-regulator circuits are principally used in power supplies for decreased output impedance and ripple, and improved stability. However, the low cost and excellent performance of the new monolithic regulators, together with their ease of use and small size, bring them face-to-face with the Zener diode for applications that require constant voltage in analog circuits. Here are some of the salient issues and a description of the AD580 precision regulator circuit, introduced in ANALOG DIALOGUE 8-2.*

Block diagrams of analog circuits show 3 classes of voltage — 1) signals: inputs from transducers, results of analog processing, intermediate results at the outputs of op amps, etc., 2) service voltages: excitation power supplies, digital control logic, etc., and 3) constants: converter and system reference voltages, algebraic constants for analog computing, and multiplier-divider scale factors.

The constants used in analog circuitry have diverse accuracy requirements, which are fulfillable by a gamut of devices, ranging from Josephson junctions and electrochemical cells to the highly-popular Zener diodes. Often, one can simply tap off a fraction of the dc supply voltage with a resistive divider and “stiffen” it, if necessary, with the low output impedance of an operational amplifier circuit. This last approach is useful only if the supply has adequate stability and repeatability — which could be costly if the system requires a high-capacity power supply.

## ZENER DIODES AS REFERENCES

Temperature-compensated avalanche breakdown diodes are available to operate from upstream voltages greater than 6V. These diodes have reasonably low dynamic impedance; circuits having quite low temperature sensitivity can be designed using selected devices with constant-current excitation. If the available supply is less than 6V (for example a 5V logic supply used to operate a digital panel meter that requires an internal reference), or if — for any reason — the reference voltage is to be less than 6V, lower-voltage Zener diodes, though available, suffer from both high output impedance and high temperature sensitivity.

Even at reasonable voltage levels, all is not well. Surface breakdown of avalanche diodes is often unstable with time. Certified, tested, time-stable units are available for applications that need stability and repeatability, but at greater expense than for the usual low-cost reference diode.

## SYNTHETIC ZENER DIODES

Low-voltage, low-cost, 2-terminal IC's exist as substitutes for Zener diodes. These “band-gap” devices produce a reference voltage that depends inherently on the properties of transistor junction potentials. Since  $V_{BE}$  depends on bulk properties of the semiconductor material, its long-term stability is essentially

unaffected by the surface phenomena that cause instability in avalanche diodes.

Like Zener diodes, however, these 2-terminal band-gap reference circuits need an auxiliary current supply, which itself needs regulation for best performance. If the load is variable, the no-load supply current has to be greater than the maximum anticipated load current (even if it is required only briefly); this limits their utility in low-power circuits, e.g., with batteries.

Since synthetic Zeners are no more convenient to use than conventional reference diodes, and tend to cost more for equivalent temperature-stability, they tend to be used only where low-voltage operation or long-term repeatability have been essential requirements. Furthermore, the basic 3-transistor cell operates at 1.2 volts, requiring amplification in reference applications; but 1.2V is insufficient common-mode voltage to operate op amps (such as the 741) when used with a single-ended supply (an economical mode of operation for reference amplifiers).

## ENTER THE AD580

The AD580 unites the stable low-voltage operation of the band-gap circuit with the active circuitry needed to make a self-contained Input-Output device on a single monolithic chip in an easy-to-use 3-terminal package. Easily chosen for special-purpose applications where low power drain, excellent long-term stability, and low-voltage operation are essential, its simplicity, low cost, and convenience would also appear to make it a natural choice wherever a stable voltage with substantial low-impedance output capability is desired.

It will operate successfully from voltage as low as 4.5V, and it will easily handle as much as 30V without external current-limiting. Though it supplies an output current of up to 10mA, it idles at about 1mA when lightly loaded, minimizing power dissipation and self-heating. It can operate from batteries or logic supplies, and its 2.5V output is sufficient to bias transistor circuits (including most op amps) into the operating range.

## THE BAND-GAP PRINCIPLE APPLIED TO THE AD580 DESIGN

Most designers are familiar with the  $-2\text{mV}/^\circ\text{C}$  temperature coefficient of the base-emitter voltage of a transistor biased into an active region. The exact value depends on the base-emitter voltage, but it is so reproducible for a given device, that diode-connected transistors are often used as thermometers. If the emitter current is made proportional to temperature, the  $V_{BE}$  tempco is nearly constant over a wide temperature range.

If  $V_{BE}$  for several devices were plotted as a function of temperature and extrapolated towards absolute zero ( $-273^\circ\text{C}$ ), the straight lines would have differing slopes but would intersect at the same value of voltage: 1.205V, the “band-gap voltage of

silicon, extrapolated to zero,” as shown in Figure 1. If it were possible to generate a voltage that increased proportionally with temperature at the same rate at which  $V_{BE}$  of a given transistor decreased, then the sum of the two voltages would be constant, and equal to the bandgap voltage, a physical constant.

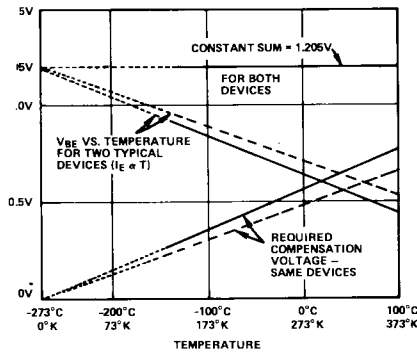


Figure 1. Extrapolated variation of base-emitter voltage with temperature ( $I_E \propto T$ ), and required compensation, shown for two different devices.

We can obtain such a voltage by amplifying the difference between the  $V_{BE}$ 's of similar transistors operating at different values of current density ( $J_1$  and  $J_2$  in  $A/m^2$ ), that is

$$\Delta V_{BE} = \frac{kT}{q} \ln \frac{J_1}{J_2} \quad (1)$$

where  $k/q$  is the ratio of Boltzmann's constant to the unit of electronic charge ( $86.17 \mu V/^\circ K$ ),  $T$  is absolute temperature,  $^\circ K$ , and  $\Delta V_{BE}$  is the difference of the base-emitter voltages. Since  $\Delta V_{BE}$  is proportional to temperature (if  $J_1/J_2$  is constant), it can be scaled up from its normal value of about  $26mV \cdot \ln(J_1/J_2)$  near room temperature to a value that, summed with  $V_{BE}$  at the same temperature, gives a total of 1.205V, which will then be (ideally) independent of temperature.

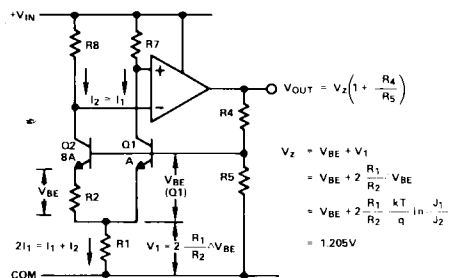


Figure 2. Basic bandgap-reference regulator circuit.

Figure 2 is a simplified version of a scheme that implements this relationship and also provides an amplified output. The two transistors, Q1 & Q2, produce the voltage difference,  $\Delta V_{BE}$ , amplify it, add it to the  $V_{BE}$  of Q1, and scale the output up to a stable 2.5V. Here's how it works:

The amplifier output  $V_{OUT}$  adjusts the base voltage of transistors Q1 & Q2, via the voltage divider R4-R5, in order to establish an equilibrium condition in which the collector currents of Q1 & Q2 are equal (since  $R_7 = R_8$ , and the net input to the amplifier at equilibrium is "zero"). The emitter area of Q2 is 8x that of Q1, so for equal currents at equilibrium,  $J_1 = 8J_2$ .

The base-emitter voltage-difference,  $\Delta V_{BE}$  (across R2) is therefore equal to  $(kT/q) \ln 8$ ; the design value of R2 is determined

by the desired level of current through Q1 & Q2, which must be equal to  $(kT/qR_2) \ln 8$ . The sum of the two currents, equal to  $(2kT/qR_2) \ln 8$ , flows through R1. Since the base voltage,  $V_Z$ , is equal to the sum of the  $V_{BE}$  of Q1 and the voltage across R1,

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

The ratio,  $R_1/R_2$ , is the value necessary for  $V_Z = 1.205V$ . Integrated-circuit process control makes  $V_{BE}$  predictable, so that  $R_1/R_2$  can be predetermined and implemented with stable, low-tracking-TC, thin-film resistors, deposited on the silicon chip.

To establish a given value of base voltage (e.g., 1.205V), the output voltage must be  $(1 + R_4/R_5) V_Z$ . For the AD580, the nominal output voltage is 2.5V; the appropriate resistance ratio,  $R_4/R_5$ , is determined by thin-film resistors deposited on the chip. Figure 3, a complete schematic of the AD580, shows how the op-amp function is implemented. The cell output, at the collectors of Q1 & Q11, drives the output via a level translator and a Darlington current-booster. The amplifier input circuit is bootstrapped to the output to increase the effective open-loop gain and lower the output impedance to less than 1 ohm. R3 compensates for the base-current drop in R4.

Versions of the AD580 are available with output voltage within 2% of nominal and with temperature coefficients as low as 10ppm/ $^\circ C$ . The "rough-and-ready" 3% AD580J provides a complete voltage regulator with  $<0.6\%$  change over a  $70^\circ C$  temperature range and less than  $1\Omega$  output resistance, for only \$2 in 100's.

By the use of a feedback configuration with an op amp, which provides both the output and the AD580's excitation, the nominally better-than  $-0.03\%/V$  ( $7-30V$ ) line regulation can be greatly improved, the output voltage may be adjusted to any value greater than 4.5V, and the output current may be beefed up.

Besides the many applications implied in the first paragraph (and elsewhere), the AD580 can also be used as a series-connected 2-terminal current load. If a fixed resistor is connected between the output terminals, a constant current of approximately  $2.5V/R + 1mA$  will flow between  $V_{IN}$  and the AD580's "common", regardless of the applied voltage (from 4.5V to 40V).

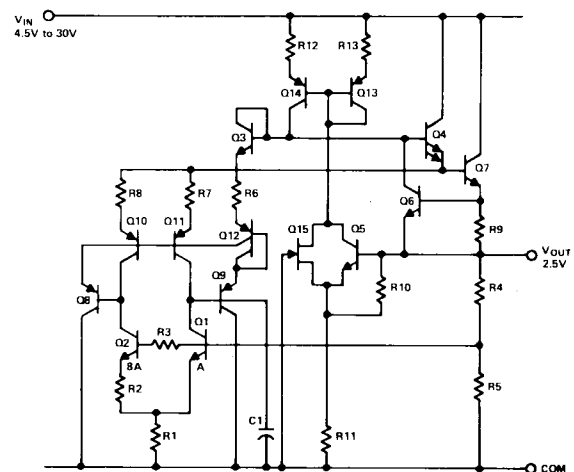


Figure 3. Schematic circuit diagram of the AD580.