BAND GAP REFERENCES

So called "Band Gap" references are transistor/resistor configurations which exhibit zener-like circuit performance at a potential essentially equal to the band-gap voltage of silicon (actual operation of the structure does not depend on any energy gap effects however).

These references have the useful property, through proper component value choices, of essentially zero temperature coefficient.

Refer to the structure shown in Figure 1. Junction potentials can be described as follows (if β is assumed large enough to ignore base currents):

$$\phi_1 = \frac{kt}{q} \ln \frac{I_1}{I_s} \qquad (1)$$

$$\phi_2 = \frac{kt}{q} \ln \frac{I_2}{I_s} \qquad (2)$$

where: T is temperature (°K)
I_s is reverse leakage current
(a process & structure parameter)
k is Boltzmann's constant
q is charge of one electron

note that $\frac{kt}{q}$ = .026 volts at 25°C (298°K).

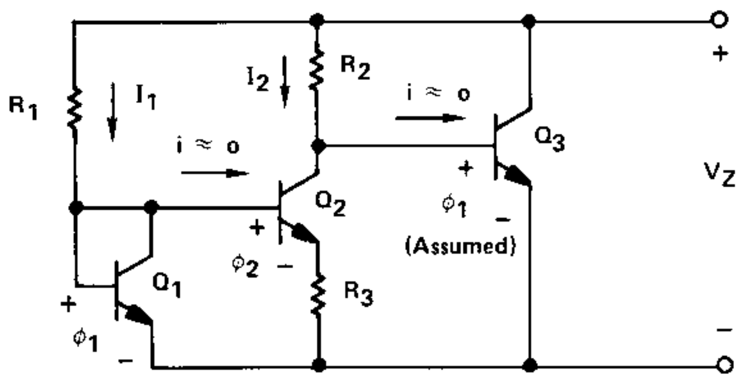

Figure 1.

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From Figure 1 we can see that

$$\phi_1 = \phi_2 + I_2R_3 \tag{3}$$

or

$$\frac{kt}{q}\,\ell n\,\frac{I_1}{I_s} = \frac{kt}{q}\,\ell n\,\frac{I_2}{I_s} + I_2R_3. \tag{4}$$

Rewriting (4) we obtain

$$\frac{kt}{q}\,\ell n\,\frac{I_1}{I_2} = I_2R_3. \tag{5}$$

Viewing the structure of Figure 1 we can conclude the circuit will begin to draw significant current when the potential

$$V_Z = \phi_1 + I_2R_2. \tag{6}$$

(Note the V_{BE} potential of Q_3 has been assumed equal to that of Q_1).

Combining (5) and (6) we obtain:

$$V_Z = \phi_1 + \frac{R_2}{R_3}\,\frac{kt}{q}\,\ell n\,\frac{I_1}{I_2}. \tag{7}$$

Since

$$I_1 = \frac{V_Z - \phi_1}{R_1} \tag{8}$$

and

$$I_2 = \frac{V_Z - \phi_1}{R_2} \tag{9}$$

then

$$\frac{I_1}{I_1} = \frac{R_2}{R_1}. \tag{10}$$

Equation (7) then becomes

$$V_Z = \phi_1 + \frac{R_2}{R_3}\,\frac{kT}{q}\,\ell n\,\frac{R_2}{R_1}. \tag{11}$$

Observe this equation term-by-term. The first term (ϕ_1) has a *negative* temperature coefficient (≈ -2mV/°C) which is constant and essentially independent of current level. The second term has a *positive* temperature coefficient (linear with T). We wish to determine the resistor ratios required to yield a net zero T.C. To accomplish this, differentiate (11) with respect to temperature:

$$\frac{dV_Z}{dT} = \frac{d\phi_1}{dT} + \frac{R_2}{R_3}\,\frac{k}{q}\,\ell n\,\frac{R_2}{R_1} \tag{12}$$

Setting equal to zero and manipulating terms we obtain

$$\frac{R_2}{R_3} = \frac{-\dfrac{d\phi_1}{dT}}{\dfrac{k}{q}\,\ell n\,\dfrac{R_2}{R_1}}. \tag{13}$$

or

$$\frac{R_2}{R_3} = \frac{-T\,\dfrac{d\phi_1}{dT}}{\dfrac{kT}{q}\,\ell n\,\dfrac{R_2}{R_1}}. \tag{14}$$

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Note that R_2/R_1 can be selected; for example choose $R_2/R_1 = e = 2.71828\ldots$

Then

$$\frac{R_2}{R_3} = \frac{-298(-2\times10^{-3})}{.026}$$

$$\frac{R_2}{R_3} = 22.923 \qquad (15)$$

V_Z then becomes (with $\phi_1 = 0.7$)

$$V_Z = 0.7 + 22.923\,(.026)$$
$$V_Z = 1.296 \text{ volts.} \qquad (16)$$

Absolute values may be chosen somewhat arbitrarily; for example choose $R_1 = 2K$, then we derive Figure 2.

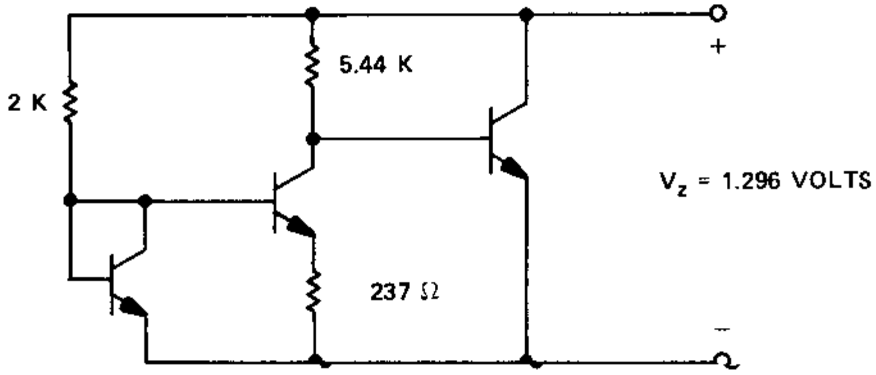

Figure 2.

To this point we have derived a basic band gap reference while making and/or assuming approximations which can have some effect on our performance. Let us now examine the effects of these approximations.

In equation (6) we used ϕ_1 as an absolute initial value without regard to the fact that ϕ_1 will also be a function of current flow (I_1) and thus, for T.C. purposes, the temperature coefficient of R_1. Re-examining equation (2)

$$\phi_1 = \frac{kt}{q} \ln \frac{I_1}{I_s} \qquad (2)$$

Differentiating with respect to all variables and simplifying:

$$\frac{d\phi_1}{dT} = \underbrace{\frac{\partial\phi}{\partial T}}_{\text{Diode Alone}} + \frac{kt}{q}\,\frac{I_s}{I_1}\,\frac{1}{I_s}\,\frac{\partial I_1}{\partial T} \qquad (17)$$

But

$$\frac{\partial I_1}{\partial T} = \frac{\partial}{\partial T}\,\frac{V_Z - \phi}{R_1} \approx -\,\frac{V_Z-\phi}{R_1^2}\,\frac{\partial R_1}{\partial T} \qquad (18)$$

(Holding $V_Z - \phi$ constant)

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or

$$\frac{\partial I_1}{\partial T} = -\frac{V_Z - \phi}{R_1} \cdot \frac{\partial R_1/R_1}{\partial T} \qquad (19)$$

For a typical process:

$$\frac{\partial R_1/R_1}{\partial T} = +2000\text{ppm}/°\text{C} \qquad (20)$$

Thus for our example

$$\frac{\partial I_1}{\partial T} \approx -\frac{1.3 - 0.7}{2 \times 10^3}\, 2 \times 10^{-3}$$

$$\frac{\partial I_1}{\partial T} = -0.6 \times 10^{-6}\ \text{Amps}/°\text{C} \qquad (21)$$

with

$$\frac{kt}{qI_1} \approx 86.67\Omega \qquad (22)$$

$$\frac{d\phi_1}{dT} = -2 \times 10^{-3} - 86.67 \times 0.6 \times 10^{-6}$$

$$\frac{d\phi_1}{dT} = -2.052 \times 10^{-3}\ \text{volts}/°\text{C} \qquad (23)$$

Thus the effective value of $d\phi_1/dT$ differs by 2½% from our assumed value and may be corrected for in our calculations in (15).

Another approximation that we have assumed is perfection in the diode equations (1) and (2), in that we have assumed no offset voltage. We should rewrite (1) and (2) as

$$\phi_1 = \frac{kT}{q} \ln \frac{I_1}{I_s} \qquad (1)$$

$$\phi_2 = \frac{kT}{q} \ln \frac{I_2}{I_s} + V_{OS} \qquad (24)$$

then

$$\phi_1 = \phi_2 + I_2R_3 \qquad (3)$$

or

$$\frac{kT}{q} \ln \frac{I_1}{q} = \frac{kT}{q} \ln \frac{I_2}{I_s} + V_{OS} + I_2R_3 \qquad (25)$$

then

$$\frac{kT}{q} \ln \frac{I_1}{I_2} = I_2R_3 + V_{OS} \qquad (26)$$

or

$$I_2 = \frac{\frac{kT}{q} \ln \frac{I_1}{I_2} - V_{OS}}{R_3} \qquad (27)$$

with

$$V_Z = \phi_1 + I_2R_2 \qquad (6)$$

then

$$V_Z = \phi_1 + \frac{R_2}{R_3}\frac{kT}{q} \ln \frac{I_1}{I_2} - V_{OS}\frac{R_2}{R_3} \qquad (28)$$

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The effect of V_{OS} appears in two ways: an absolute shift in the value of V_Z and a T.C. effect equivalent to $\frac{R_2}{R_3}\frac{\partial V_{OS}}{\partial T}$. Since the sign and value of V_{OS} are essentially unknown, the only recourse is transistor design and processing compatible with minimum V_{OS}, i.e. large, round geometry emitters, cleanly processed.

The most significant approximation that we have made is assuming that β is large enough to ignore. Refer to Figure 3 for currents affected by β. The base current of Q_3 will be ignored in this analysis because, as will be shown later, this effect can be easily removed, as can our concern about the match of Q_1 and Q_3 V_{BE} potentials (ϕ_1).

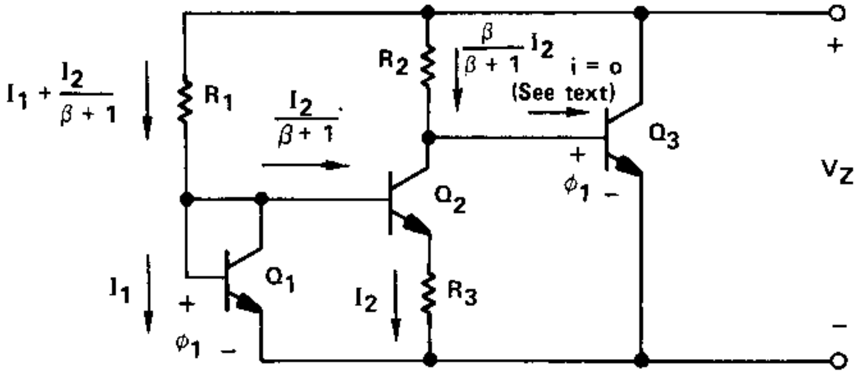

Figure 3.

Recall equation (5):

$$\frac{kT}{q} \ell n \frac{I_1}{I_2} = I_2 R_3 \tag{5}$$

But now

$$V_Z = \phi_1 + \frac{\beta}{\beta+1} I_2 R_2 \tag{29}$$

and

$$\left(I_1 + \frac{I_2}{\beta+1}\right) R_1 = \frac{\beta}{\beta+1} I_2 R_2 . \tag{30}$$

We can now derive the I_1/I_2 ratio as follows:

$$I_1 R_1 = I_2 \left(\frac{\beta}{\beta+1} R_2 - \frac{R_1}{\beta+1}\right) \tag{31}$$

then

$$\frac{I_1}{I_2} = \frac{\beta}{\beta+1} \cdot \frac{R_2}{R_1} - \frac{1}{\beta+1}$$

or

$$\frac{I_1}{I_2} = \frac{\beta \frac{R_2}{R_1} - 1}{\beta+1} . \tag{32}$$

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Our equivalent zener potential is then

$$V_Z = \phi_1 + \frac{\beta}{\beta+1} \bullet \frac{R_2}{R_3} \frac{kT}{q} \ell_n \frac{\beta \frac{R_2}{R_1} - 1}{\beta + 1} . \qquad (33)$$

In the typical situation where $\beta \approx 50$ at 25°C and $\beta \approx 100$ at 125°C, the effect on V_Z is an equivalent temperature coefficient of approximately 68μV/°C.

It is not obvious what steps would be necessary to remove this β sensitivity. Rather than trying to solve a rather messy set of transcendental equations, it may be more informative to examine the addition of corrective networks to eliminate or minimize β from our equations. Consider, for example, the configuration shown in Figure 4.

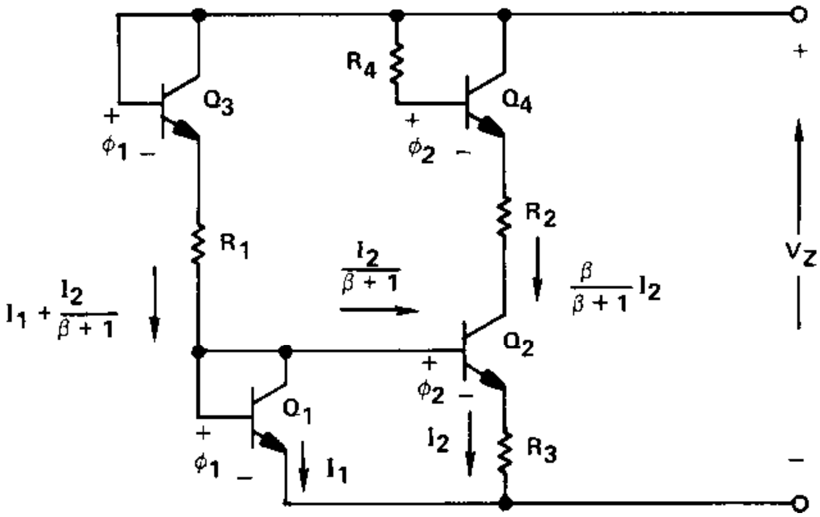

Figure 4.

Our primary aim is to remove β dependence from the ℓ_n term so that linear cancellation methods can be applied.

As before:

$$\phi_1 - \phi_2 = I_2 R_3 = \frac{kT}{q} \ell_n \frac{I_1}{I_2} \qquad (34)$$

and, adding loop drops:

$$V_Z = 2\phi_1 + \left(I_1 + \frac{I_2}{\beta + 1}\right) R_1 \qquad (35)$$

$$V_Z = \phi_1 + \phi_2 + I_2 \left[\frac{\beta}{\beta + 1} R_2 + \frac{\beta}{(\beta + 1)^2} R_4\right] \qquad (36)$$

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or, since $\phi_1 + \phi_2 = 2\phi_1 - I_2R_3$, (36) becomes:

$$V_Z = 2\phi_1 + I_2\left[\frac{\beta}{\beta+1}R_2 + \frac{\beta}{(\beta+1)^2}R_4 - R_3\right]. \quad (37)$$

then

$$I_1 + \frac{I_2}{\beta+1} R_1 = I_2\left[\frac{\beta}{\beta+1}R_2 + \frac{\beta}{(\beta+1)^2}R_4 - R_3\right] \quad (38)$$

or

$$\frac{I_1}{I_2} = \frac{\beta}{\beta+1}\frac{R_2}{R_1} + \frac{\beta}{(\beta+1)^2}\frac{R_4}{R_1} - \frac{R_3}{R_1} - \frac{1}{\beta+1} \quad (39)$$

or, manipulating (and setting $R_4 = R_1 + R_2$):

$$\frac{I_1}{I_2} = \frac{R_2 - R_3}{R_1} + \frac{-\beta R_2 - R_2 + \beta R_1 + \beta R_2 - \beta R_1 - R_1}{(\beta+1)^2 R_1}. \quad (40)$$

then:

$$\frac{I_1}{I_2} = \frac{R_2 - R_3}{R_1} - \frac{R_1 + R_2}{(\beta+1)^2 R_1} \approx \frac{R_2 - R_3}{R_1}. \quad (41)$$

Note, in (41), β dependence has been modified to a second order effect and may be ignored.

Then we can write (again):

$$V_Z = 2\phi_1 + I_2\left[\frac{\beta}{\beta+1}R_2 + \frac{\beta}{(\beta+1)^2}R_4 - R_3\right]. \quad (38)$$

or

$$V_Z = 2\phi_1 + \frac{\frac{kT}{q}\ln\frac{I_1}{I_2}}{R_3}\left[\frac{\beta}{\beta+1}R_2 + \frac{\beta(R_1+R_2)}{(\beta+1)^2} - R_3\right] \quad (39)$$

or

$$V_Z = 2\phi_1 + \frac{\frac{kT}{q}\ln\frac{R_2-R_3}{R_1}}{R_3}\quad\frac{\beta^2+2\beta}{\beta^2+2\beta+1}R_2 + \frac{\beta R_1}{(\beta+1)^2} - R_3 \quad (40)$$

or

$$V_Z \cong 2\phi_1 + \frac{R_2 + \frac{R_1}{\beta} - R_3}{R_3}\frac{kT}{q}\ln\frac{R_2-R_3}{R_1}, \quad (41)$$

which now has small β sensitivity.

The student may now determine that V_Z (at zero T.C.) is $\approx$ 2.6 volts.

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β-STABILIZED BAND GAP REFERENCE

System drops from $2V_{BG}$ rail:

1st Loop

$$2\phi + \rho IR\left(1 + \frac{\rho}{\beta + 1}\right)$$

2nd Loop

$$2\phi + \frac{\beta}{\beta + 1}\rho IR + \frac{1 + \rho}{(\beta + 1)^2}\beta\rho IR$$

Difference

$$\rho IR\left[1 + \frac{\rho}{\beta + 1} - \frac{\beta}{\beta + 1} - \frac{(1 + \rho)\beta}{(\beta + 1)^2}\right]$$

$$= \rho IR\left[\frac{(\beta + 1)^2 + \rho(\beta + 1) - \beta(\beta + 1) - (1 + \rho)\beta}{(\beta + 1)^2}\right]$$

$$= \rho IR\left[\frac{\cancel{\beta^2} + \cancel{2\beta} + 1 + \cancel{\rho\beta} + \rho - \cancel{\beta^2} - \cancel{\beta} - \cancel{\beta} - \cancel{\rho\beta}}{(\beta + 1)^2}\right]$$

$$= \rho IR\,\frac{1 + \rho}{(\beta + 1)^2}$$

Squared term produces substantial improvement in β drift.

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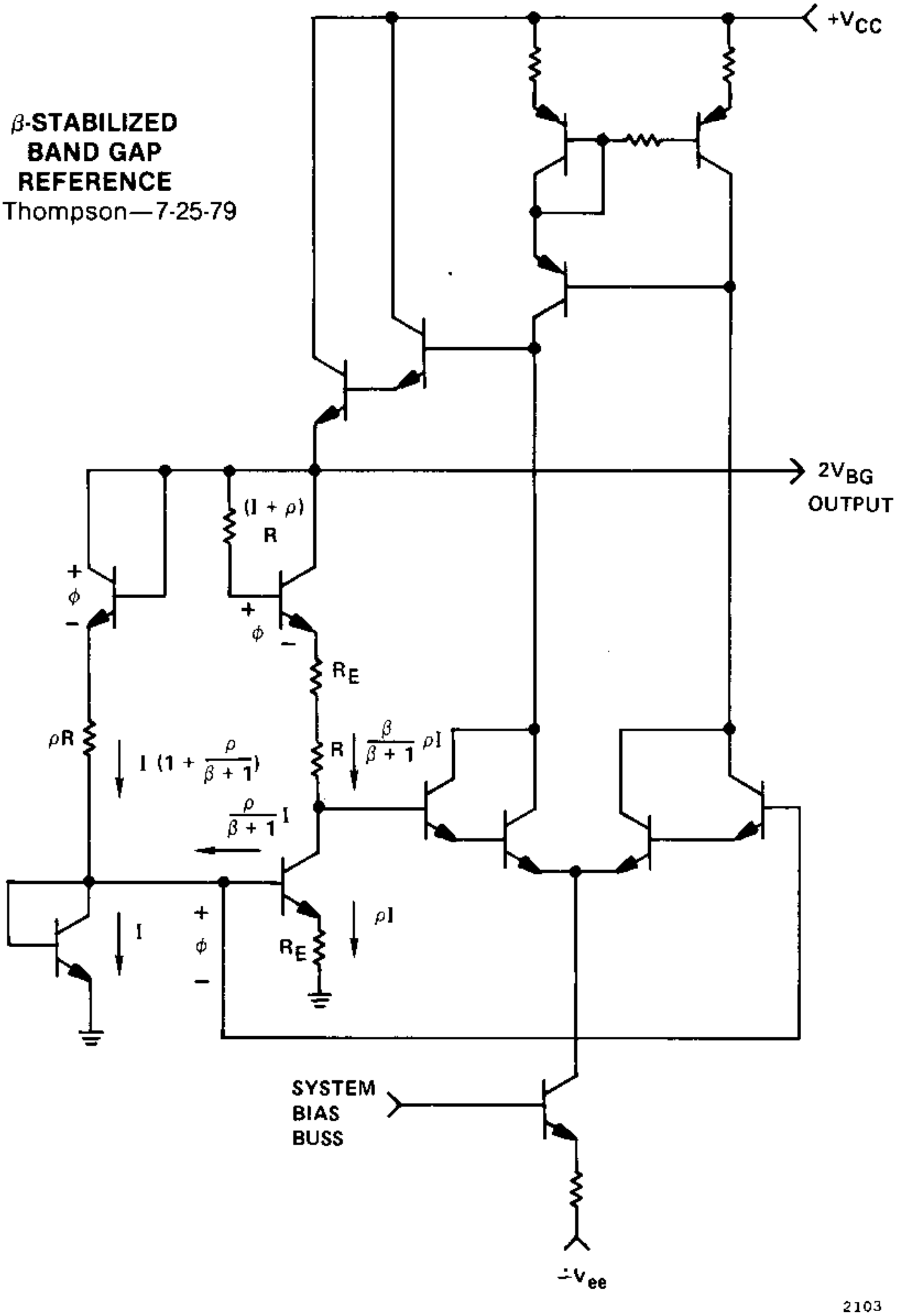
β-STABILIZED BAND GAP REFERENCE

Jim Thompson—7-25-79



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