SESSION IV: Design Applications

Chairman: C. A. Franklin

Defense Research Board, Ottawa, Canada

WPM 4.1: A New Semiconductor Voltage Standard

D. F. Hilbiber

Fairchild Semiconductor, Div. Fairchild Camera-Instr. Corp.

Palo Alto, Calif.

THE USE of the avalanche diode as a reference voltage source is well known in the art. If suitable precautions are taken, it has been found possible to obtain short-term stabilities of 10-50 ppm over moderate ranges of temperature. It is difficult, however, to select devices that provide similar long-term behavior for periods up to 1,000 hours or more.

This paper will describe the evolution of a new reference voltage source. The magnitude and stability of this voltage is comparable to the Weston standard cell. A prototype system that has a nominal output of 1.25670 v was built; it has maintained this value with a 10 μv envelope for over 12,000 hours. Although this particular network employs silicon planar structures, other semiconductor devices have been used with considerably degraded long-term behavior.

For the ideal pn junction, forward voltage, V_F, and its temperature dependence, $d/dT(V_F)$, are a function of current density and the junction impurity profile. This is given by Shockley's equation:

$$p_n \simeq \frac{n_i^2}{N_D} \text{ and } n_p \simeq \frac{n_i^2}{N_A},$$

$$I = I_s \left[\exp\left(\frac{qV}{kT}\right) - 1 \right] \tag{1}$$

where I_s is the junction saturation current given by

$$I_s = q\left(\frac{D_p}{L_p} p_n + \frac{D_n}{L_n} n_p\right) \tag{2}$$

and the parameters have their usual meanings. The temperature dependence of I_s is more readily shown by using the approximations

where $n_i^2 = C_o T^3 \exp\left(\frac{-E_G}{kT}\right)$. Thus,

$$I_s = qn_i^2 \left(\frac{D_p}{L_p N_D} + \frac{D_n}{L_n N_A}\right)$$

which becomes

$$I_s \simeq C_1 T^{\beta_p} \exp\left(\frac{-E_G}{kT}\right) \tag{3}$$

for a p^+n junction, and

$$I_s \simeq C_2 T^{\beta_n} \exp\left(\frac{-E_G}{kT}\right) \tag{4}$$

for an n^+p junction. β is a constant that takes into consideration the approximate temperature dependence of the diffusion coefficients, and diffusion lengths.

Unfortunately, the ideal behavior is not observed for single Ge or Si junctions at normal temperatures due to surface effects and/or the generation and recombination of carriers in the depletion layer[1]. It has been observed by Sah[2], however, that equation (1) accurately describes the base-emitter voltage of a transistor as a function of collector current.

Then from equations (1) and (2), it is possible to express V_{BE} in a Taylor's series expansion, as shown in in Figure 1. This equation provides a considerable insight into the low-frequency, low-level behavior of V_{BE}. It is seen that as junction doping density is increased, V_{BE} increases and $d/dT(V_{BE})$ becomes less negative. An increase of current density also has the same effect. The curves of Figure 2 and Figure 3 demonstrate this behavior for the 2N917 and 2N1893 transistors*. The emitter junction impurity gradients of these two devices differ by about an order of magnitude. Although V_{BE} and $d/dT(V_{BE})$ are shown as a function of emitter current, if the current gain is sufficiently high, $I_B << I_C$, and the series expansion can be used with I_E substituted for I_C.

The circuit of the reference voltage source is shown in Figure 4. If m *quasi-diodes* of type I and r of type II are used, and r-m = 1, the output voltage is given by the equation of Figure 5. The third and higher order terms are not included, since for $|T - T_o| < 50°$, their contribution to the output voltage is less than 20 μv.

It is possible to eliminate the main source of temperature dependence by choosing θ such that,

$$\theta = \phi + \frac{E_{Go}}{kT_o} \tag{7}$$

Then, from equations (6) and (7), an expression is obtained for V_{out} such that for $|T - T_o| < 5°$C, V_{out} will remain constant within 10 μv.

It is to be noted that E_{Go}, the energy gap voltage at zero degrees K, is much greater than $\phi \frac{kT_o}{q}$, and thus V_{out} is primarily a function of the semiconductor material. Further, variations of ϕ are sufficiently small that V_{out} is quite predictable.

The long-term stability of the voltage source using the 2N917 and the 2N1893 is of the order of 3 to 5 ppm. This figure arises primarily from variations of the zener diode in the current source network, which has a stability of about 150 to 200 ppm.

Many variations of the basic circuit are possible, including the use of diodes fabricated from other semiconductors such as germanium or gallium arsenide. However, it has not been possible to demonstrate long-term stability with devices other than npn silicon planar transistors.

---

* Fairchild.

[1] Sah, C. T., Noyce, R. N., and Shockley, W., "Carrier Generation and Recombination in p-n Junction Characteristics," *Proc. IRE*, p. 1228-1243; Sept., 1957.

[2] Sah, C. T., "Effect of Surface Recombination and Channel on p-n Junction and Transistor Characteristics," *IRE Trans. PGED*, p. 94-108; Jan., 1962.

$$V_{BE} = \frac{kT_0}{q}\left\{ \ln \frac{I_C}{I_S(T_0)} + \left[\ln \frac{I_C}{I_S(T_0)} - \left(\beta + \frac{E_{GO}}{kT_0}\right)\right]\left(\frac{T}{T_0} - 1\right) - \frac{\beta}{2}\left(\frac{T}{T_0} - 1\right)^2 + \cdots + \frac{\beta(-1)^{n-1}}{n(n-1)}\left(\frac{T}{T_0} - 1\right)^n + \cdots \right\} \qquad (5)$$

$$V_{BE} > \frac{4kT}{q} \qquad T < 2T_0$$

FIGURE 1 — **A Taylor's series expansion of V_{BE} demonstrating the temperature and current dependence.**

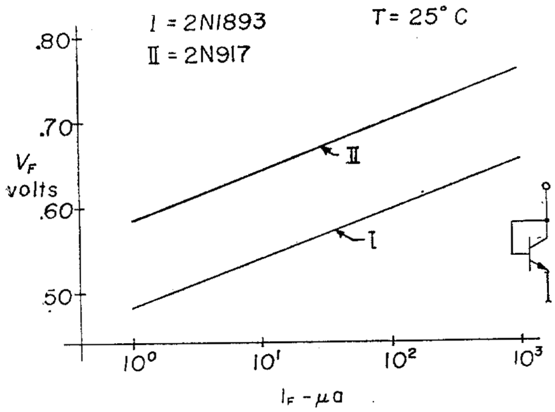

FIGURE 2—**Forward voltage versus current for the transistor *quasi-diode*.**

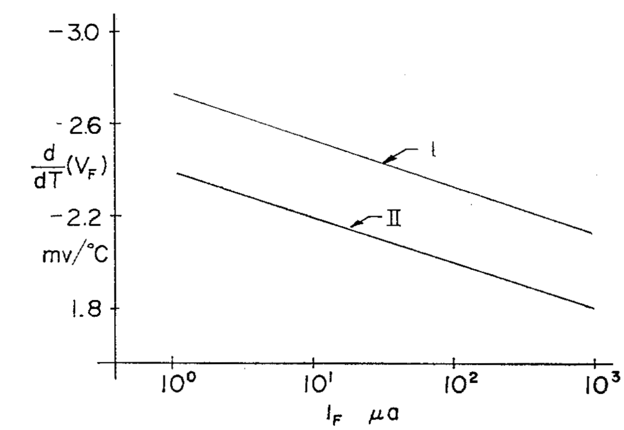

FIGURE 3—**The temperature dependence of forward voltage versus current for the *quasi-diode*.**

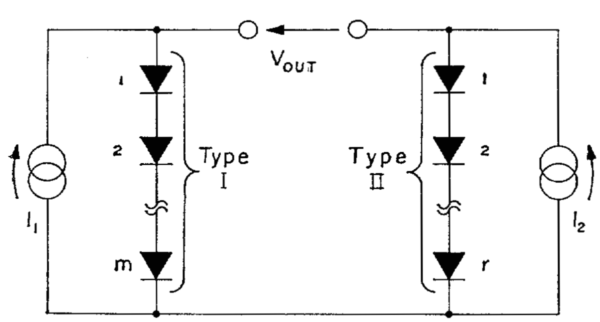

FIGURE 4—**The basic circuit of the reference voltage source.**

$$V_{OUT} = \frac{kT_0}{q}\left[\theta + \left(\theta - \phi - \frac{E_{GO}}{kT_0}\right)\left(\frac{T}{T_0} - 1\right) - \frac{\phi}{2}\left(\frac{T}{T_0} - 1\right)^2\right] \qquad (6)$$

$$\theta = r \ln \frac{I_{C2}}{I_{S2}(T_0)} - m \ln \frac{I_{C1}}{I_{S1}(T_0)}$$

$$\phi = r\beta_{II} - m\beta_I$$

$$V_{OUT} = E_{GO} + \phi \frac{kT_0}{q}\left[1 - \frac{1}{2}\left(\frac{T}{T_0} - 1\right)^2\right] \qquad (8)$$

FIGURE 5—**The general output voltage equation (6), and the output voltage with the first order temperature dependence eliminated (8).**