P-N Junctions–A Tool for Temperature Measurement

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Abstract. Silicon semiconductors were investigated for use as temperature transducers ($-25°C \rightarrow +75°C$), and were found to have good stability, linearity, and high sensitivity. When one ma of forward current was applied to a diode, a sensitivity of approximately 1.9 mv/°C was obtained with a forward voltage drop of approximately 600 mv.

Temperature measurements are an integral part of many research investigations. Air and soil temperature profiles are commonly recorded to help us understand the transport phenomena in heat flow. Temperature measurements also help us determine the movement characteristics of ground water. Accuracy, sensitivity, and response time are significant parameters in the detection and recording of temperature. By using inherent temperature drift, which is characteristic of P-N silicon junctions, we developed a stable, highly sensitive, linear transducer for point temperature measurements.

The temperature transducer consists of a GE IN4154 silicon diode encapsulated in Hysol R9-2039 epoxy (Figure 1). The epoxy gives mechanical strength and protection to the transducer assembly, eliminates external current paths, and increases the response time of the transducer. Two conductor shielded cables carry the signal from the transducer to the temperature readout circuit. At present more than 50 such transducers are used in energy balance studies at the Southwest Watershed Research Center. (Further details may be obtained from C. G. Enfield, Earth Sciences Section, PSB, 3000 Area, Battelle Memorial Institute, P. O. Box 999, Richland, Washington, 99352.)

We tested several transducers to determine linearity, sensitivity, response time, forward voltage drop at 0°C, dependence of forward voltage drop on forward current, and dependence of thermal sensitivity on forward current. To obtain the transducer parameters, we meas-

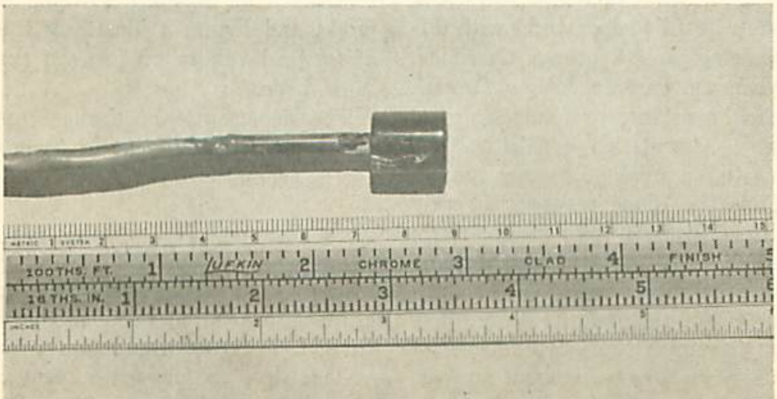

Fig. 1. Temperature transducer consisting of a silicon diode encapsulated in epoxy.

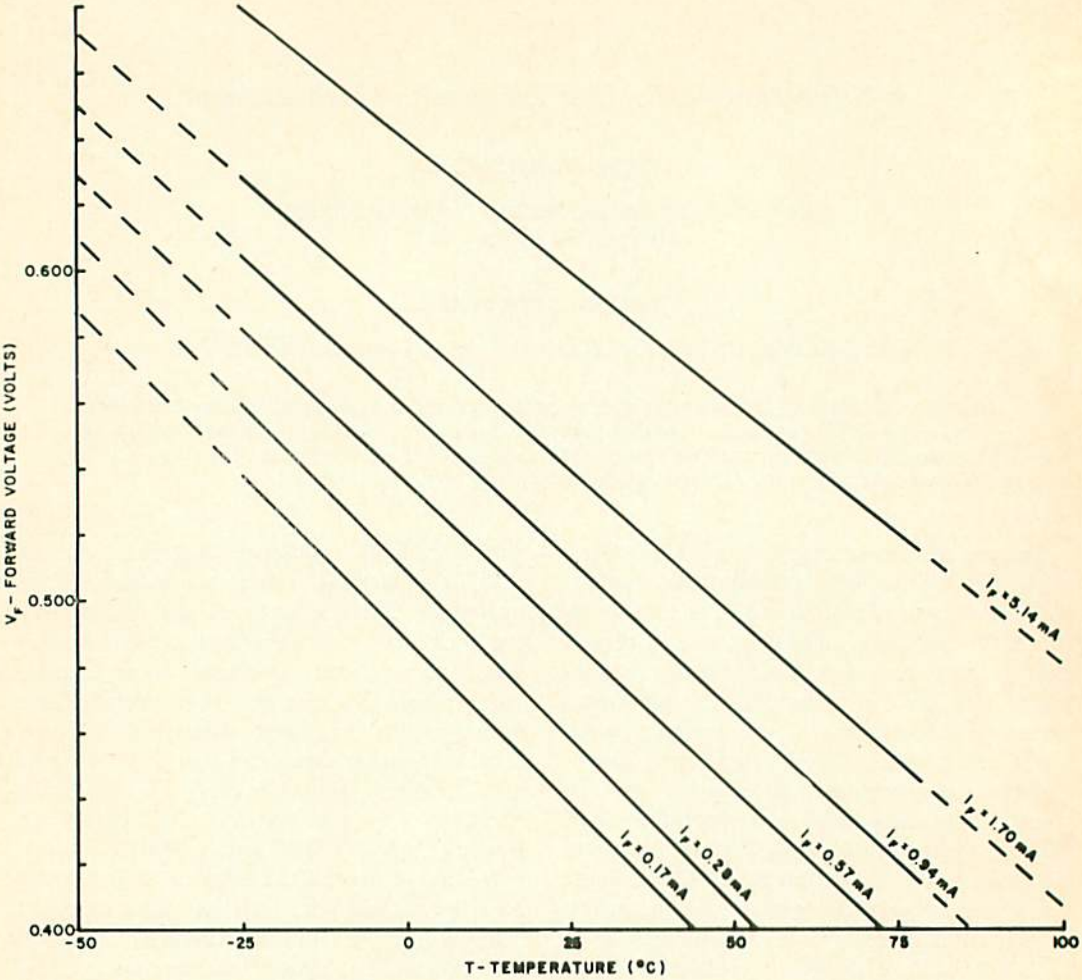

Fig. 2. Family of curves relating forward current, forward voltage drop, and temperature for one diode.

ured the forward voltage drop across the silicon diode at various selected temperatures with different currents being passed through the diode. In all cases when the current flowing through the diode was held constant, we obtained a good thermal linearity. Correlation coefficients for least-squares fit to a straight line were greater than 0.999. Thus the diode responds linearly with temperatures over the temperature range considered ($-25°C \rightarrow +75°C$). Figure 2 shows a family of curves relating forward current, forward voltage drop, and temperature. From these data we can determine the dependence of thermal sensitivity on forward current and the dependence of forward voltage on forward current. Figure 3 shows the dependence of thermal sensitivity on forward current for a selected diode, and Figure 4 illustrates the dependence of forward voltage on forward current for the same diode.

The dependence of thermal sensitivity and forward voltage drop at 0°C can be expressed by the general equation

$$V_F = m(I_F)T + b(I_F)$$

where V_F is the forward voltage drop, $m(I_F)$ is a function relating the sensitivity to forward current, $b(I_F)$ is a function relating forward voltage drop to forward current, and T is the temperature in degrees centigrade.

For the specific data shown in Figures 3 and 4

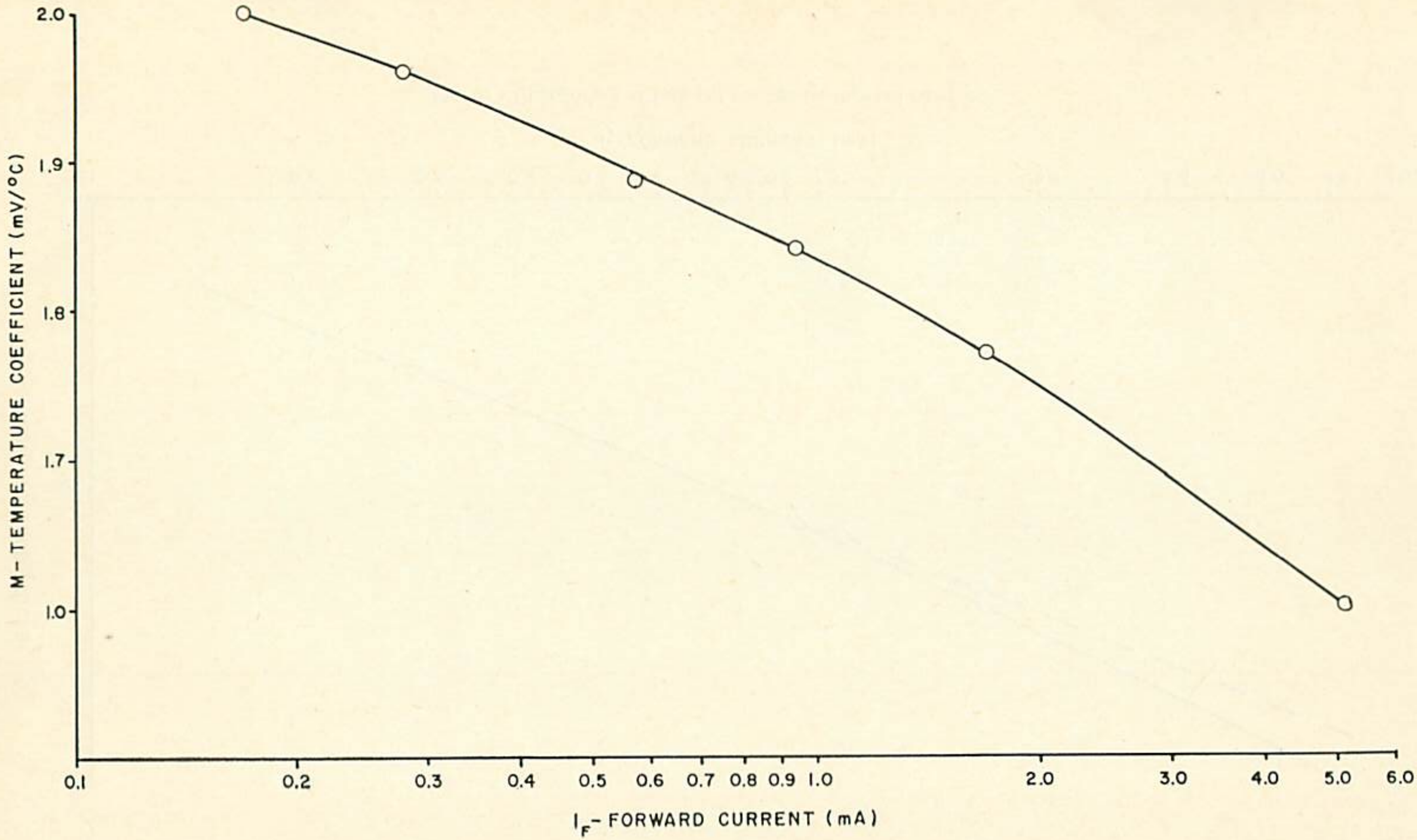

Fig. 3. Dependence of thermal sensitivity on forward current for a selected diode.

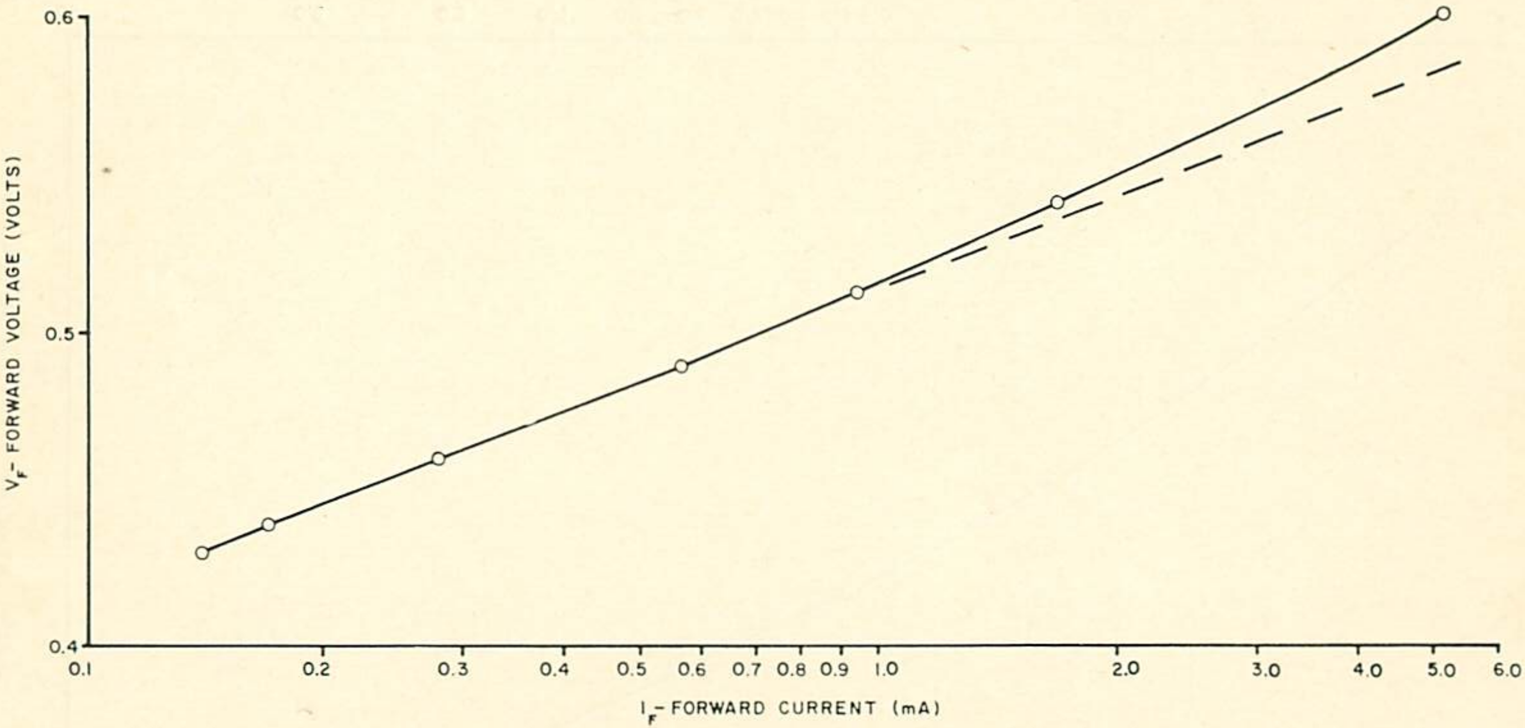

Fig. 4. Dependence of forward voltage on forward current.

TABLE 1. Calibration Data for Least Squares Fit to a Straight Line
($V_F = mT + b$ where V_F is the forward voltage drop at 1 ma of forward current, m is the slope of line, T is the temperature, and b is the voltage at 0°C)

Diode No.	Millivolts/°C Thermal Sensitivity, m	Millivolts at 0°C, b	Linear Regression Correlation Coefficient
1	−1.84	604.85	−0.999984
2	−1.91	635.20	−0.999987
3	−1.88	620.50	−0.999995
4	−1.90	623.28	−0.999986
5	−1.90	624.11	−0.999978
6	−1.91	612.58	−0.999974
7	−1.76	610.42	−0.999987
8	−1.80	613.86	−0.999579
9	−1.90	626.12	−0.999983
10	−2.28	650.00	−0.999966
11	−2.06	591.20	−0.999971
12	−1.93	629.62	−0.999975
13	−1.82	596.54	−0.999985
14	−1.77	605.53	−0.999999
15	−1.88	619.77	−0.999975
Standard deviation	0.12	14.62	
Mean (arithmetic)	1.90	617.57	
Variance	0.015	213.76	

$$m(I_F) = 2.0484 - 0.1868(I_F) - 0.7827(I_F^2) + 1.3228(I_F^3) - 0.6388(I_F^4) + 0.080120(I_F^5)$$

where I_F is current in milliamperes and $m(I_F)$ has units mv/°C

$$b(I_F) = 0.3913 + 0.3466(I_F) - 0.4836(I_F^2) + 0.3814(I_F^3) - 0.1353(I_F^4) + 0.0150(I_F^5)$$

where $m(I_F)$ is current in milliamperes and $b(I_F)$ has units of millivolts.

Table 1 summarizes calibration data from randomly selected diodes for least-squares fit to a straight line and may be expressed as

$$V_F = mT + b$$

where V_F is the forward voltage drop in millivolts with 1 ma forward current, m is the slope (sensitivity) in millivolts per degree centigrade, T is the temperature in degrees centigrade, and b is the forward voltage drop in millivolts at zero degrees centigrade.

If absolute temperatures are desirable, it is necessary either to determine calibration curves for each individual diode or to select diodes with similar forward voltage drop at some preselected temperature. However, if only temperature changes are desired, the calibration curve of one diode may be used to determine relative changes in temperature.

The circuit in Figure 5 is constructed in two parts and supplies a constant current to the diode. Operational amplifier A1, together with the reference zener diode D1, provides a reference dc voltage for operation amplifier A2 that provides a constant dc current through the transducer D2. The output voltage E_o can be read on a voltmeter, a digital instrument, or be used to supply a temperature dependent voltage to a data acquisition system.

(Manuscript received October 14, 1969; revised February 16, 1970.)

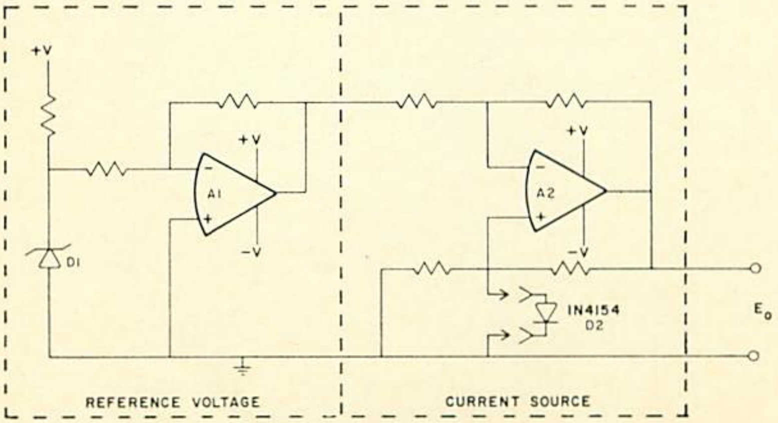

Fig. 5. Grounded constant current source.