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Richard Ocaya
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An experiment to profile the voltage, current and temperature behaviour of a P–N diode

R O Ocaya

Department of Physics, North West University, P Bag X2046, Mmabatho, South Africa

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Abstract
This paper describes an experiment that studies the effect of diode temperature and excitation current on forward diode voltage for a common silicon diode, the 1N4148. Experimental data are used to obtain a plausible model relating coefficient of voltage drift with temperature and its validity is then tested. The paper provides a reasonable temperature and current profile of the diode in forward bias. A practical design for a direct reading thermometer is also presented.

1. Introduction

The conventional characterization of a diode involves varying the voltage across it and measuring the current flowing through it under the generally incorrect assumption that the temperature remains constant throughout. The motivation for this experiment was to characterize a common diode, the 1N4148, by the current and voltage response in a manner that also establishes its *temperature* behaviour. This experiment is important if the diode is to be used in an accurate temperature sensing application. While the idea of driving a diode with a constant current is not new, it was clear from the literature that there is a prevalent assumption that the coefficient of drift of voltage with temperature is constant. This experiment aims to show that this is in fact not the case, but that it is directly dependent on the logarithm of the diode current. A plausible, if simplistic model is presented for the purposes of designing an accurate temperature sensor around a given type of diode. Finally, a typical design procedure for a direct reading thermometer application is presented.

2. The diode equation and ideality

In forward bias the Shockley equation for p–n junction diodes can be written as

$$I \approx I_o \exp\left(\frac{V_D}{nV_T}\right), \tag{1}$$

where I_o is the reverse saturation current, V_D is the applied diode voltage, $V_T = kT/q$ is the thermal voltage, k is Boltzmann's constant, and q is electron charge [1]. The term $n = 1, \ldots, 2$, is a property of the real diode that is referred to as the *ideality factor* [2]. It is a number which depends on the diode chosen and characterizes the slope of the plot of logarithmic current versus voltage for the diode. It arises from the fact that the forward characteristics of real p–n diodes are affected by high injection and current dependent series resistance [3]. It is easy to show from equation (1) that

$$V \approx \alpha \ln I + \beta, \tag{2}$$

where $\alpha = \frac{nkT}{q}$ and $\beta = -\frac{nkT}{q} \ln I_o$.

Also,

$$n = \alpha \frac{q}{kT}, \tag{3}$$

where $q = 1.60 \times 10^{-19}$ C and $k = 1.38 \times 10^{-38}$ J K^{-1}. Thus if the gradient of the plot of V against $\ln I$ is known at a specific temperature, then n can be determined experimentally. Generally, under high diode currents the I–V curve is more linear than exponential and equation (1) breaks down. The 1N4148 data sheet [4] shows exponential behaviour for currents below 10 mA.

2.1. Generating a constant current

An adjustable constant current source is an essential apparatus in this experiment. A diode requires electrical excitation before it can generate a response. An effective current–mirror current source with good output voltage compliance is shown in figure 1. A single variable resistor sets the output current. A digital microammeter in series with the output lead monitors the output current [5].

2.1.1. Operation of the current mirror. The current mirror uses two transistors of similar characteristic connected in such a way that they share the base-emitter voltage, V_{BE}. Thus under load, the second collector current, I_2, will 'mirror' the preset first collector current, I_1. In practice, it is difficult to accurately match two transistors even of the same part number. Differences in doping and ambient conditions can cause mismatch in the two collector currents. The mismatch can be further minimized by physically bonding the two cases together with a thermal compound to allow similar ambient influences, which tend to cancel out. The output current may also fluctuate with varying load since the diode under test (DUT) is a nonlinear device. However, because the current is monitored on the microammeter, fluctuations in output current can quickly be corrected.

In figure 1 it can be seen that

$$V_B = V_{CC} - V_{BE} \tag{4}$$

and

$$I_1 = \frac{V_B}{R} = \frac{V_{CC} - V_{BE}}{R}. \tag{5}$$

Then

$$I_1 = I_2, \quad \text{since for each transistor } V_{BE} \approx 0.7 \text{ V}. \tag{6}$$

If R is made variable from 2.2 kΩ to 47 kΩ then the output current can be adjusted from 95 μA to 1955 μA for $V_{CC} = +5.0$V. In figure 1, R is the series combination of the fixed 2 k and the variable 47 k resistor.

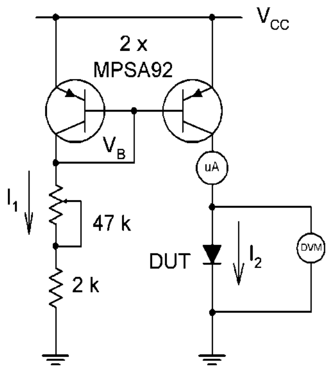

Figure 1. A simple but effective constant current source.

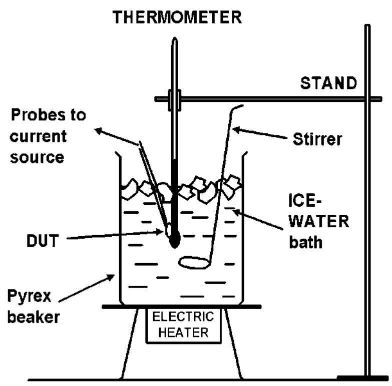

Figure 2. Experimental setup for the diode constant-current experiment.

2.2. The procedure

The following procedure was followed.

(1) Set up the experiment as shown in figure 2. Make sure that before the DUT is inserted into the ice-water bath, it is properly insulated from the water.
(2) Connect the current source to the DUT and mount it close to the thermometer in the bath.
(3) Set the constant current to 100 μA. The ice-water bath is at a temperature of approximately 3 °C. Record the temperature and the diode voltage.
(4) Gradually heat up the ice-water bath while stirring frequently to ensure even temperature. Record the diode voltage and temperature at suitable intervals while making sure that the preset current has not changed. Repeat this step until the water has come up to boiling point (around 95 °C, but depends on altitude).
(5) Repeat the experiment with constant currents of 400 μA, 800 μA and 1500 μA.
(6) Tabulate the results in a suitable table.

3. Results and analysis

3.1. The results

The experiment was carried out for four diode currents that were chosen for two reasons. Firstly, to provide a good spread of results while keeping within the limits of self-heating

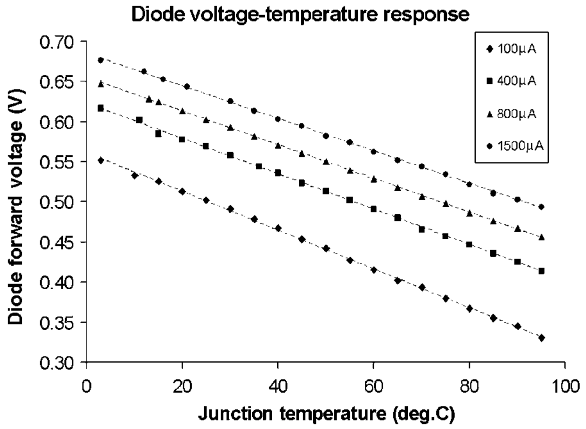

Figure 3. Plot of voltage versus temperature at constant diode current.

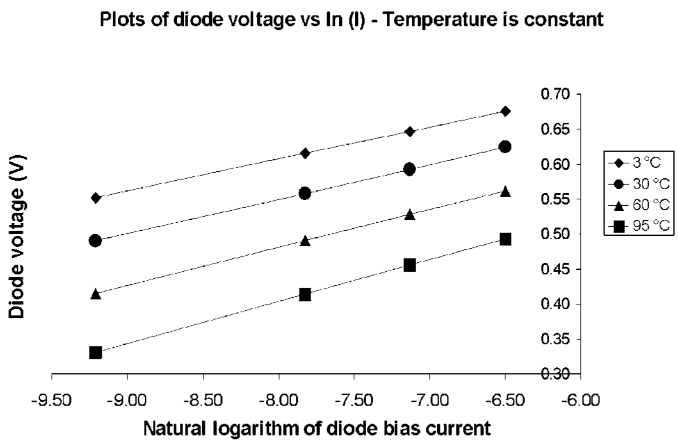

Figure 4. Plot of diode voltage versus natural logarithm of applied current under constant temperature.

effects; secondly, to operate the DUT within the exponential portion of the diode response where equation (1) is valid. For the 1N4148, above 10 mA the rise is more linear than exponential and equation (1) no longer holds. The data sheet specifies the thermal resistance of the diode as 300 °C W^{-1}. Even with a worst case current of 1.5 mA at 0.8 V the expected self-heating is less than 0.4 °C.

3.2. The analysis

3.2.1. V–T response, I constant. Figure 3 is a plot that shows the voltage versus temperature response of the 1N4148 diode at different constant currents.

3.2.2. V–T response, T constant. The constant temperature behaviour of the diode can be evaluated by constructing a new table from the results table by picking off the voltages at points of the same temperature for different currents. The temperatures used are 3 °C, 30 °C, 60 °C and 95 °C. Figure 4 shows the resulting linearly fitted plot of V versus $\ln I$ under

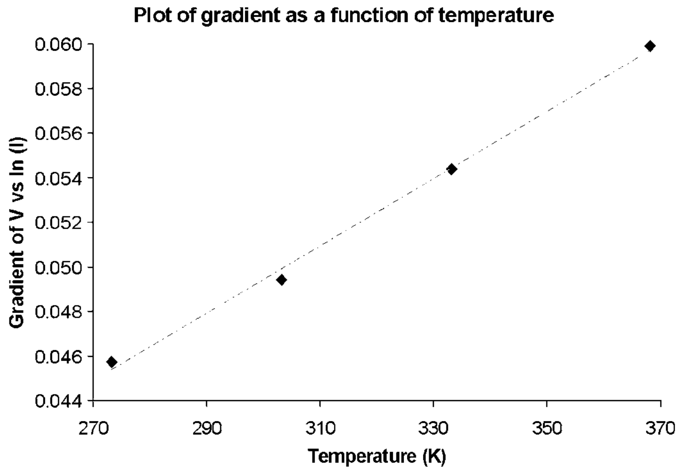

Figure 5. Plot of gradient versus temperature.

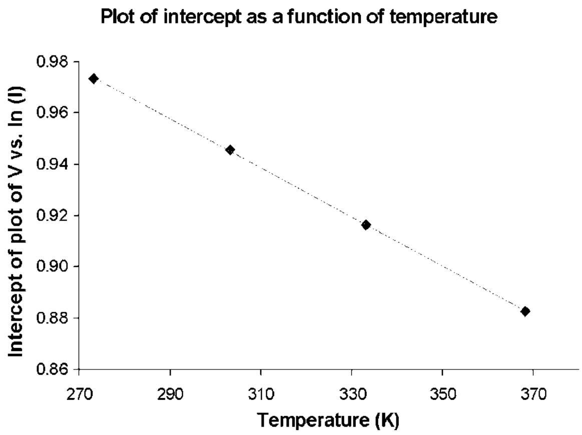

Figure 6. Plot of intercept versus temperature.

constant temperature for the four temperatures. Each line has a high R^2 correlation better than 0.990.

3.2.3. The ideality factor, n. The voltage, current and temperature measurement accuracies were 1 mV, 1 μA and 1 K respectively. The biggest uncertainty in α (gradient) was graphically determined from the data of figure 3 to be ± 0.02 so that $n = 1.90 \pm 0.01$. This value agrees with the literature value [6] for the 1N4148 diode.

3.3. An approximate model

The plots of gradient (α in logamps) and intercept (β in volts) of equation (2) as functions of absolute temperature are shown in figures 5 and 6, respectively.

An inspection of these plots shows that both gradient and intercept *appear* to be linearly dependent on absolute temperature over the range of the experiment. This can be modelled

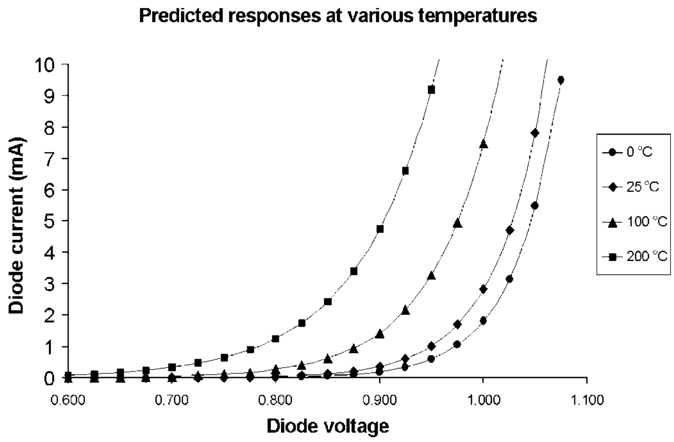

Figure 7. Application of the model reveals the familiar diode characteristic.

by writing

$$\alpha(T) = \eta T + \epsilon \tag{7}$$

$$\beta(T) = \rho T + \zeta, \tag{8}$$

where η, ϵ, ρ and ζ are constants. Using the data above:

$$\eta = 1.55 \times 10^{-4}\ \mathrm{VK^{-1}\ logamps^{-1}}$$
$$\epsilon = 2.65 \times 10^{-3}\ \mathrm{logamps}$$
$$\rho = -9.84 \times 10^{-4}\ \mathrm{VK^{-1}}$$
$$\zeta = 1.25\ \mathrm{V}.$$

Then substitution of equations (7) and (8) into (2) gives an expression of the temperature and current dependence of the voltage response of a diode in forward bias:

$$V(I, T) = \alpha(T)\ln(I) + \beta(T) \tag{9}$$

$$= (\eta T + \epsilon)\ln I + (\rho T + \zeta). \tag{10}$$

Solving equation (10) for $I(V, T)$ gives

$$I = I(V, T) = \exp\left(\frac{V - \rho T - \zeta}{\eta T + \epsilon}\right). \tag{11}$$

4. Testing the model

4.1. By I–V characteristic plot

The model was tested for the 1N4148 diode at four arbitrary temperatures as shown in figure 7.

4.2. Forward voltage temperature coefficient

It is well known that for the 1N4148 silicon diode

$$\left.\frac{\partial V}{\partial T}\right|_{I=100\,\mu\mathrm{A}} \approx -2.41\,\mathrm{mV\,K^{-1}}. \tag{12}$$

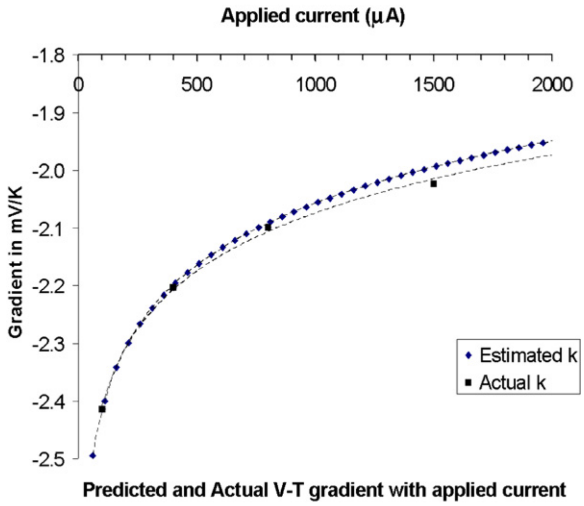

Figure 8. Plot of κ with applied constant current.
(This figure is in colour only in the electronic version)

Equation (10) established an experimental model. By differentiating both sides of equation (10) while keeping the current constant,

$$\kappa = \left.\frac{\partial V}{\partial T}\right|_{I=\mathrm{const}} = \rho + \eta \ln(I). \tag{13}$$

For currents that are not expected to cause significant self-heating in the diode (10 μA to 4 mA diode current) the literature [8] reports κ in the vicinity of $-2\,\mathrm{mV}\,{}^{\circ}\mathrm{C}^{-1}$, which agrees well with the experiment, plotted in figure 8.

5. Deductions

The forward voltage characteristics of the diode are modelled using coefficients of the function $\ln I$ versus V as linear functions of temperature. The prediction that this simple model makes for voltage–temperature gradient at constant current is in remarkable agreement with the actual observed gradient, although the model begins to show disagreement as the constant current increases. Furthermore, the model reproduces the familiar diode I–V characteristic at different temperatures as expected.

6. A practical application

Thermometers based on silicon diodes have been slow to gain acceptance for two main reasons. Firstly, suitable signal conditioning circuits tend to be rather complex circuits. Secondly, the knowledge of their suitability is generally not widespread [9]. However, there have been a number of application circuits of varying complexity and accuracy [10]. In this section, we describe a typical design procedure for a thermometer based on the 1N4148 diode.

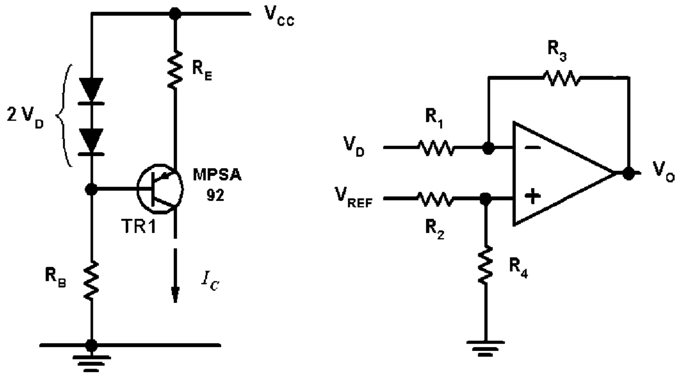

Figure 9. Conditioning circuits for a direct reading thermometer.

6.1. A direct reading thermometer, DRT

It is required to implement a circuit with a voltage output in the range of 0–1.00 V that corresponds to the temperature range 0–100 °C. With a fixed diode current of 800 μA equations (10) and (13) can be solved to give the diode voltage

$$V_D = -0.002\,09T + 0.668. \tag{14}$$

For direct temperature read-out the diode needs a conditioning circuit with a transfer function of the form $V_o = aV_D + V_B$, where a and V_B are constants. Then

$$V_o = -0.002\,09aT + 0.668a + V_B. \tag{15}$$

Application of the conditions $V_o = 0$ V $\equiv 0$ °C and $V_o = 1.00$V $\equiv 100$ °C gives $V_o = -4.76V_D + 3.18$.

A suitable transfer function can be implemented using an operational amplifier subtractor circuit [5], shown in the right-hand part of figure 9. If $R_1 = R_4$ and $R_2 = R_3$ then

$$V_o = -\frac{R_3}{R_1}V_D + V_{REF}. \tag{16}$$

Therefore, $R_3 = 4.76R_1$ and $V_{REF} = +3.18$V. The complete circuit of a practical DRT is shown in figure 10. Although not tested below 0 °C, the circuit should continue to work down to cryogenic temperatures.

6.1.1. The current source. The current source in figure 1 has good output compliance under different loads [5] but is not strictly needed in a DRT since only a single current value is required. The circuit in the left part of figure 9 is a suitable alternative. It is not difficult to show that the output current is $I_C \approx V_D/R_E$. Normally R_B is chosen to bias the two diodes beyond the knee of their I–V characteristic, and the current through it set to a least ten times the emitter current to lessen the effect power supply fluctuations on I_C. Temperature stability of I_C can be improved by bonding the two diodes to the case of TR1 and enclosing the complete circuit in a plastic box.

6.2. Calibration

Adjust the 1 k multi-turn variable resistor until the voltage on its wiper is 3.18 V. Then dip the insulated sensor into a water-ice bath and adjust the 68 k variable resistor until V_o is at 0 V.

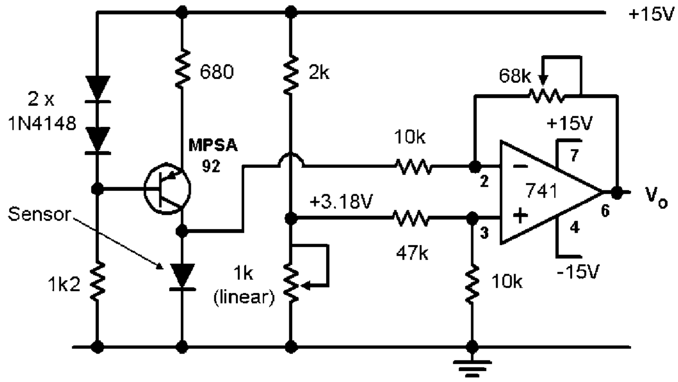

Figure 10. Complete circuit of the DRT.

The DRT is then ready for use. A test of the DRT set-up as in figure 2 shows a measurement accuracy of 1 °C.

7. Conclusions

This paper has presented a very simple experiment intended for an undergraduate laboratory. It highlights some interesting facts about the p–n diode that are normally assumed. The paper is valuable for the undergraduate experimenter because it provides a temperature behaviour alongside the normal *I*–*V* characteristic that ordinarily assumes constant temperature during the experiment. For the same reason, it is useful for the low-cost thermometer builder because it shows just how a temperature gradient can be manipulated by simply adjusting the constant current flowing through it. The idea of modelling and model testing based on real observations is also introduced. Finally, a simple but accurate direct reading thermometer was implemented.

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