Diode as a Temperature Sensor

Introduction

A p-n junction diode obeys the Shockley equation,

$$I_D = I_s \left(e^{V_a/V_T} - 1 \right) \approx I_s \, e^{V_a/V_T} \quad \text{for} \quad V_a \gg V_T, \tag{1}$$

where V_a is the applied voltage, $V_T = kT/q$ is the thermal voltage, and I_s is the reverse saturation current of the diode. As the temperature (T) increases, the exponential factor decreases. However, an increase in T causes I_s to increase since $I_s \propto n_i^2$, where

$$n_i = \sqrt{N_C(T) N_V(T)} \, \exp\left(-\frac{E_g(T)}{2kT} \right) \tag{2}$$

is the intrinsic carrier concentration of the material. As T is increased, the exponential factor in Eq. 2 increases, and so do the effective densities of states N_C and N_V. As a result, n_i increases significantly[1] with T and so does I_s. The increase in I_s more than compensates the decrease in the exponential term in Eq. 1, and the net result is that, for the same applied voltge, the diode current is higher at a higher temperature. In other words, the diode I-V curve shifts left with temperature, as shown in Fig. 1.

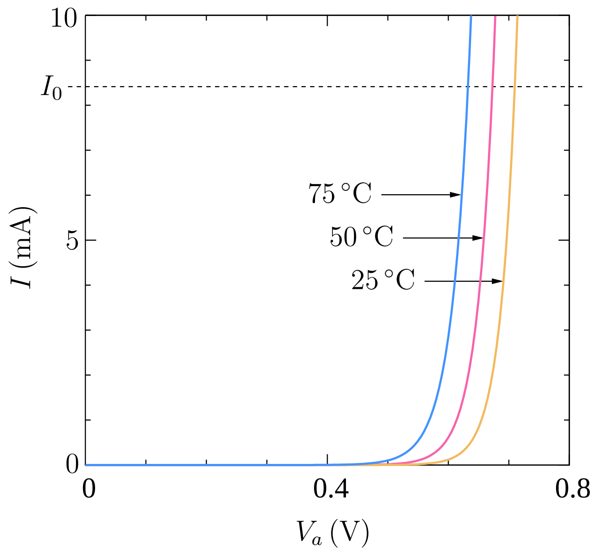

Figure 1: I-V curve of a silicon diode under forward bias at different temperatures (representative plot)

If the diode current is held constant (I_0 in the figure), we can see that the diode voltage decreases as the temperature is increased. For a silicon diode, this change is about $-2\,\text{mV}/°\text{C}$.

[1]For silicon, n_i roughly doubles as the temperature is increased by $10\,°\text{C}$.

The diode voltage under a constant current condition is therefore an indicator of its operating temperature.

Constant current source

A key requirement in using the above principle for making a diode-based temperature sensor is a current source. Various circuits are available for this purpose. We will use the circuit shown in Fig. 2 in our experiment. The desired current $I_L = I_C \approx I_E$ can be obtained simply by

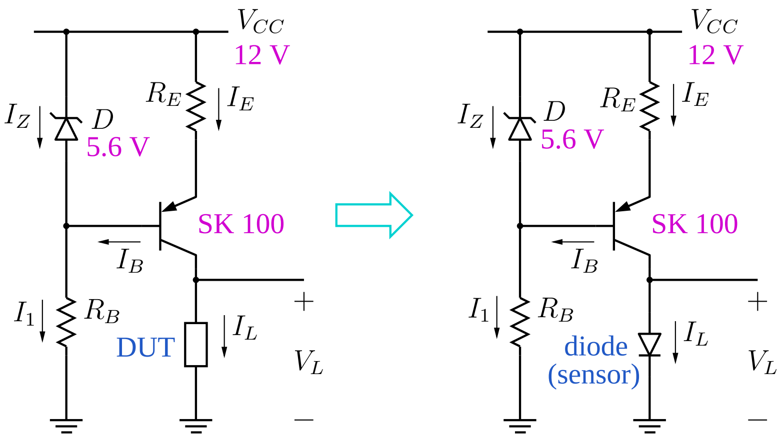

Figure 2: Implementation of a constant current source. DUT stands for "device under test" which is a diode-connected transistor in our experiment.

choosing R_E suitably, as shown below. Using KVL, we get

$$V_Z = I_E R_E + V_{EB} \approx I_L R_E + 0.7 \;\rightarrow\; R_E = \frac{V_Z - 0.7}{I_L}\,. \tag{3}$$

The resistance R_B should be selected to ensure that the Zener diode is biased at the desired current I_Z (typically, a few mA). If I_B is assumed to be small, $I_Z \approx I_1$, i.e., $I_Z \approx \dfrac{V_{CC} - V_Z}{R_B}$.

The circuit works as a constant current source as long as the transistor is in the active regoin, i.e., $V_E - V_C > 0.3\,\text{V}$ or $(V_{CC} - V_Z + 0.7) - V_L > 0.3$, i.e., $V_L < (V_{CC} - V_Z + 0.4)$. In our experiment, V_L is the diode forward voltage (about 0.7 V), and the above condition is satisfied.

Experimental set-up

Fig. 3 shows the experimental set-up. A 5 W resistor is used as a heat source, and the voltage V_R across the resistor is varied in order to obtain different temperature values. The diode, which serves as the sensing element in our scheme, is in thermal contact with this resistor, i.e., the diode and the 5 W resistor can be assumed to be at the same temperature in steady state[2]. In order to calibrate our diode-based sensor, we will use a commercially available sensor (LM-35) which is also kept in thermal contact with the 5 W resistor. The overall calibration procedure is as follows (see Fig. 3).

[2]When V_R is changed, it will generally take 3 to 4 minutes for the temperature to settle to its new value.

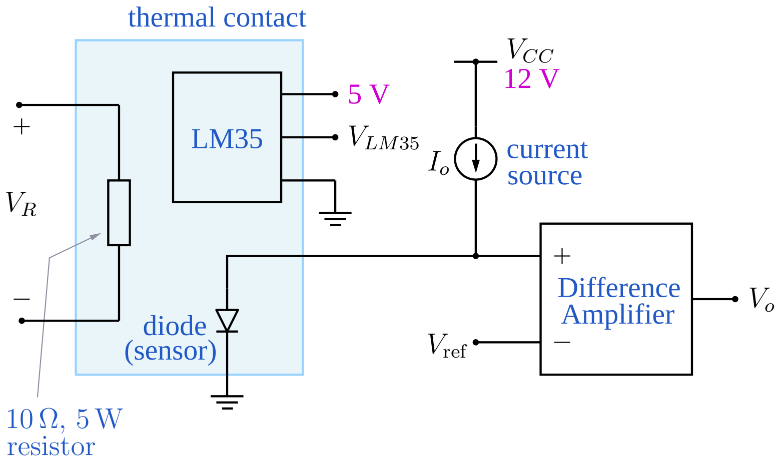

Figure 3: Schematic diagram of the experimental set-up.

(a) Set V_R. Wait for for five minutes for the temperature to settle to its steady-state value.

(b) Measure V_{LM35}. The temperature T (in °C) is given by $T = V_{LM35} \times 100$. For example, $V_{LM35} = 0.3$ V implies $T = 30$ °C.

(c) Measure V_o, the output of the diode-based sensor circuit.

(d) Repeat the above steps for several values of V_R.

Using the above measurements, we can obtain the response of the diode sensor with respect to temperature, i.e., $V_o(T)$.

The complete diode sensor circuit (see Fig. 4) consists of (a) the diode (i.e., diode-connected transistor 2N2222) driven by a constant current source, (b) a voltage divider circuit to generate a reference voltage V_{ref}, and (c) a difference amplifier to amplify the difference between the diode voltage and the reference voltage.

Let us look at the difference amplifier circuit now. The purpose of a difference amplifier – as the name suggests – is to amplify the difference between the input voltages (see Fig. 5), i.e., to produce an output voltage of the form $V_o = K\,(V_1 - V_2)$.

Assuming linear operation of the op amp in Fig. 5, we can apply superposition to obtain V_o. With $V_2 = 0$ V, the circuit behaves like an inverting amplifier, and we get

$$V_o^{(1)} = -\frac{R_2}{R_1}\,V_1. \tag{4}$$

With $V_1 = 0$ V, the circuit operates as a non-inverting amplifier, with $V_{\mathrm{in}} = \dfrac{R_4}{R_3 + R_4}\,V_2$ (by voltage division). The output is now

$$V_o^{(2)} = \left(1 + \frac{R_2}{R_1}\right) V_{\mathrm{in}} = \left(1 + \frac{R_2}{R_1}\right) \frac{R_4}{R_3 + R_4}\,V_2\,. \tag{5}$$

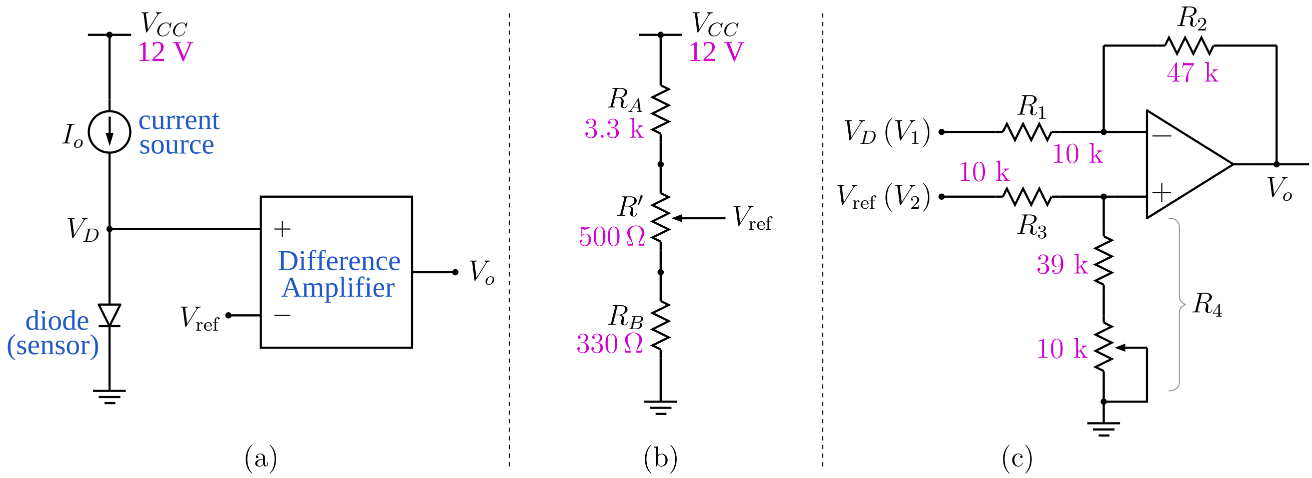

Figure 4: (a) Overall sensor circuit, (b) potential divider to obtain V_{ref}, (c) difference amplifier.

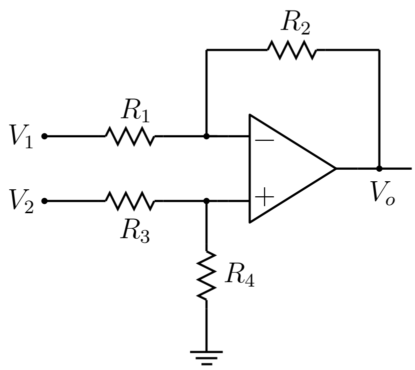

Figure 5: Difference amplifier.

The net output voltage is

$$V_o = V_o^{(1)} + V_o^{(2)} = -\frac{R_2}{R_1} V_1 + \left(1 + \frac{R_2}{R_1}\right) \frac{R_4}{R_3 + R_4} V_2 = \frac{R_2}{R_1} (V_2 - V_1), \tag{6}$$

if we make $\dfrac{R_4}{R_3} = \dfrac{R_2}{R_1}$.

In practice, the output voltage of the difference amplifier can have a small non-zero component proportional to the common-mode input $\dfrac{V_1 + V_2}{2}$ because of finite resistance tolerances. In designing a commercial sensor circuit, these "second-order" effects (including op amp offset voltage, bias currents) must be taken care of. Since our goal is to demonstrate the basic operation of the diode sensor, we will ignore the second-order effects.

One of the inputs to the difference amplifier is V_D, the diode voltage, and the other input comes from a voltage divider circuit (see Fig. 4). The voltage divider serves two purposes:

(a) It provides a reference voltage in order to satisfy the calibration condition (for example, to make the output V_o in Fig. 4 (c) equal to that of the commercial LM-35 sensor at room temperature).

(b) It enables amplification of $V_D(T) - V_D(T_{\text{ref}})$ rather than $V_D(T)$ itself (where T_{ref} could be the room temperature). Amplification of this difference is advantageous from the resolution perspective. As an example, suppose $V_D(T_{\text{ref}}) = 0.765\,\text{V}$ and $V_D(T) = 0.755\,\text{V}$. If we directly amplify V_D, the difference between the two readings appears in the second significant digit. On the other hand, if we amplify $\Delta V_D = V_D(T_{\text{ref}}) - V_D(T)$, the difference would appear in the first significant digit. Clearly, the second approach would give better resolution.

As seen from the difference amplifier (Fig. 4), the voltage divider should appear as a constant voltage, i.e., a voltage source with a small series resistance. The resistances R_A and R' should therefore be selected to be much smaller than R_3 of the difference amplifier.

Acknowledgment: This experiment was designed by Prof. Joseph John, Department of Electrical Engineering, IIT Bombay.