The Semiconductor Diode

Physics Topics

If necessary, review the following topics and relevant textbook sections from Neamen "Semiconductor Physics and Devices", 4th Ed.

- Section 8.1.5, especially equation 8.27

Introduction

A diode is a device which allows a large current to flow in one direction, but not the other; think of a diode as a "one way valve" for current. If we connect the diode to a voltage source, we may get a current or not depending on the polarity of the applied voltage. If we have the voltage source connected to the diode in such a way that a large current flows, we say that the diode is *forward biased*. If we attempt to pass current through the diode in the opposite direction (by switching the voltage leads), almost no current will flow and we say that the diode is *reverse biased*.

The semiconductor diode is usually created by attaching a n-doped semiconductor to a p-doped semiconductor forming a pn junction.

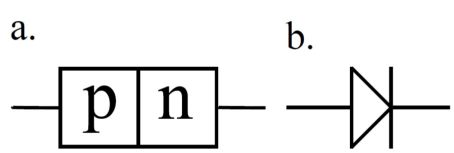

Figure 1: a.) A pn junction b.) The associated circuit schematic for a diode

A pn semiconductor junction has a current-voltage relationship described by

$$I = I_0 \left[\exp\left(\frac{V}{V_t}\right) - 1 \right]. \tag{1}$$

Here I is the current flowing through the device and V is the applied voltage across the junction. The quantity I_0 is called the reverse saturation current; it is the maximum current which can flow if the diode is reverse biased. Note that I_0 is typically **very** small, on the order of μA or nA.

The quantity V_t is sometimes called the "thermal voltage" and is defined as

$$V_t = \frac{k_B T}{|q|} \tag{2}$$

where k_B is Boltzmann's constant, T is the temperature, and $|q|$ is the (absolute value of the) charge on the charge carriers.

Equation (1) applies to either forward, or reverse bias condition as follows: if the diode is forward biased, the applied voltage V is positive, and the current is positive. If the diode is reverse biased, the applied voltage V is negative and the current is negative (meaning it flows in the opposite direction).

Diodes can be used to create AND and OR gates in logic circuits. Other computer circuits may be constructed with the addition of the transistor which can be thought of as two diodes placed back-to-back, sharing a base region[1] as shown in Fig. 2.

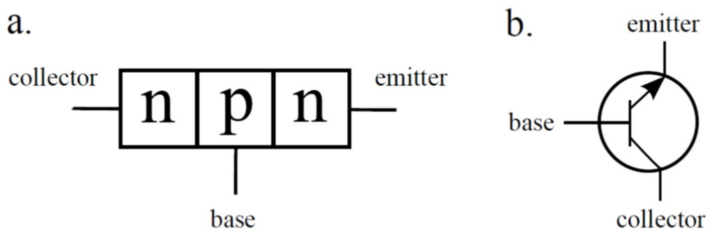

Figure 2: a.) An n-p-n bipolar junction transistor b.) The associated circuit schematic

In this experiment an n-p-n transistor will be used to observe some characteristics of a diode. In a silicon transistor (Fig. 2) the emitter current diffuses almost entirely across the base region to the collector with only a small portion flowing out the base connection. Hence, the collector current represents the emitter-base junction current. In this experiment, we will measure the collector current and the base emitter voltage to obtain an approximation of the "ideal" pn junction current/voltage relationship. By taking appropriate measurements, it is possible to experimentally determine Boltzmann's constant k_B.

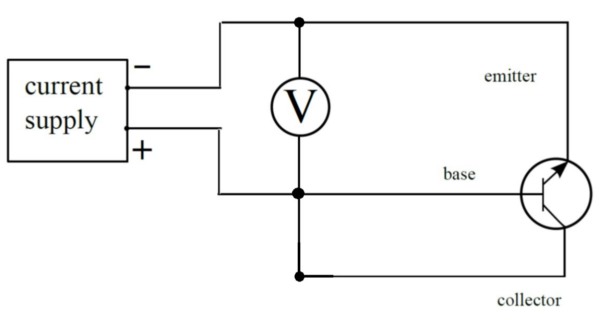

Figure 3: The experimental setup to measure the I-V characteristic of an ideal diode.

[1]It should be noted that the base region is made very thin in a transistor to obtain effects not obtained by simply connecting two separate diodes together.

Pre-Lab Questions

Please complete the following questions prior to coming to lab. They will help you prepare for both the lab and the pre-lab quiz (Found on D2L).

1.) Read through the entire lab writeup before beginning

2.) What is the **specific** goal of this lab? Exactly what question(s) are you trying to answer? Be as specific as possible. ("To learn about topic X..." is **not** specific!)

3.) What **specific** measurements or observations will you make in order to answer this question?

4.) The ideal diode current/voltage relationship is given by equation (1). At room temperature, what is the value of the thermal voltage V_t? (Your answer should have units of volts).

5.) The ideal diode current/voltage relationship is given by equation (1). This equation has two terms inside the parenthesis: the exponential term and the "-1". If the applied voltage is much larger than the thermal voltage (for example, say $V = 1$ volt when the device is at room temperature), one of these two terms can be neglected. Which term can be neglected (the exponential term, or the "-1")? Why?

6.) The ideal diode current/voltage relationship is given by equation (1). This equation has two terms inside the parenthesis: the exponential term and the "-1". If the applied voltage is *negative* and $|V| \gg V_t$ (for example, say $V = -1$ volt when the device is at room temperature), one of these two terms can be neglected. Which term can be neglected (the exponential term, or the "-1")? Why?

7.) Use your results from the previous two questions to draw a careful sketch of I, the diode current vs. V the applied voltage. Put I on the y-axis and V on the x-axis. You'll want to clearly show what's going on if V is large and positive, at $V = 0$ and if V is large and negative.

Apparatus

- Silicon bipolar junction transistor (*n*-*p*-*n*, TIP41A)
- Dual multimeter box
- 200mA current supply
- Temperature Probe
- Vernier LabQuest Mini or LabPro
- Insulated cup
- Ice cubes
- Hot water ($\sim 50°C$)

Procedure

1.) Connect the temperature sensor to the LabQuest/Pro and open Graphical analysis. You should see a live temperature readout in the bottom right corner of the screen.

2.) Connect the emitter and the base of the *n*-*p*-*n* transistor to the multimeter, turn on the multimeter and set it to the "diode" setting (the symbol is the same as the schematic shown in Fig. 1. The diode setting applies a voltage of 1.5V to the diode being tested, which should cause a forward bias current for most diodes. Note the reading on the meter.

3.) Reverse the leads on the meter and again note the reading.

4.) Repeat the previous two steps for the collector and base leads. This procedure should convince you that the transistor does in fact consist of diodes and that diodes conduct current in one direction only.

5.) Connect the transistor, meter(s), and power supply according to the circuit diagram shown (Fig. 3). On the device, you should be able to see letters for "B" (Base), "E" (emitter), and "C" (collector). As shown in the diagram make sure that the base (yellow wire) is connected directly to the collector (red wire).

6.) Take measurements of the collector current and base voltage starting at a small current value and going up to 200mA. Take successive values of current and voltage doubling the current each time until 200 mA is reached. **Do not exceed 200mA as this is the limit for the power supplies**.

7.) Record room temperature, which will be the approximate temperature of the transistor.

   (a) Press the collect button in Graphical Analysis and let the probe collect data for at least 60s before pressing stop

   (b) Click and drag to highlight all the data you collected

   (c) Click the 'Graph Options' button in the bottom left corner and select 'View Statistics'

   (d) Record the mean temperature value and an associated uncertainty

8.) Repeat step (6) with the transistor immersed in a mixture of ice and water. Record the temperature of the ice-water mixture (submerge the end of the probe in the water).

9.) Repeat step (6) with the transistor immersed in hot tap water. Record the temperature of the hot water (submerge the end of the probe in the water).

10.) Dismantle the circuit and return any water to the kettles/cooler.

Analysis

1.) Assuming that $V \gg V_t$, the diode equation becomes approximately

$$I \approx I_0 \exp\left[\frac{|q|V}{k_B T}\right] \tag{3}$$

Using this equation as a guide, plot your three data sets in such a way that each one is a straight line.

2.) Fit your data with straight lines. Use the slope and intercept of each line to determine Boltzmann's constant and the reverse saturation current I_0.

3.) You should now have three measurements of k_B and I_0. Use these measurements to quote a final result for k_B and for I_0 including uncertainty. (Remember that if you have several measurements of the same quantity, a good estimate for the uncertainty in this quantity is the *standard deviation* of the measurements).

4.) Compare your results for k_B with the accepted value, including uncertainty. Are the results consistent? If there is a disagreement with the accepted value, discuss why this may be the case.

Wrap Up

The following questions are designed to make sure that you understand the physics implications of the experiment and also to extend your knowledge of the physical concepts covered. Your report should answer these questions in the noted section in a seamless manner.

1.) [Theory] You now know that a reverse saturation current I_0 flows through the circuit when the diode is reverse biased. Why is it that when people are speaking informally they say a diode does not allow any current to flow when it is reverse biased?

2.) [Discussion] The equation (3) which used in the analysis makes the assumption $V \gg V_t$. Is this actually the case for your data points? Calculate the thermal voltage for the three temperatures which you measured, and compare with the voltages in your data set.

3.) [Discussion] Suppose you keep the applied forward bias voltage to a diode fixed, but you then raise its temperature. Will the current passing through the diode increase/decrease/stay the same? Explain in words.

Report

Labs will be completed in groups, you will enroll in a group with your lab partner at the beginning of each lab session. Each group will submit a single report through the assignment section on D2L.

- **Introduction**
  - What is the experiment's objective?
- **Theory**
  - You may be able to show a derivation of the physics you're investigating, or you may want to reference a source that provides a description/equation representing the physics you're investigating.
  - You may want to provide graphs that illustrate or predict how you expect the system under study to behave.
- **Procedure**
  - Explain the systematic steps required to take any measurements.
- **Results and Calculations**
  - Tabulate your measurements in an organized manner.
  - Based on your procedure, you should know what your tables show
  - Provide examples of any calculations.
- **Discussion and Conclusions**
  - Discuss the main observations and outcomes of your experiment.
  - Summarize any significant conclusions.
- **References**
- **(Appendices)**