EXPERIMENT 4

Diodes and Transistors

Introduction

The experiments in this laboratory exercise will provide an introduction to electronic circuits involving diodes and transistors. Three devices will be studied: p-n junction diodes, light-emitting diodes (LED's), and bipolar junction transistors (BJT's).

Experiment Objectives:

- Learn how diodes work
- Learn how transistors work
- Develop proficiency at breadboarding circuits and taking data.

Bring to Lab:

Your completed Pre-Lab. Turn this in when you get to lab.
Several sheets of Engineering Paper.

Theory: Solid State Electronics

Most electronic devices today are made from silicon which has been made either *p-type* or *n-type* by adding "dopants" such as boron, phosphorus, or antimony. In p-type material, electrical current is carried primarily by *holes*. In n-type material, current is carried primarily by electrons. A hole is a quantum particle which has a positive charge equal in magnitude to that of an electron. The unique characteristics of the interface between p-type and n-type doped silicon yield the useful behavior of diodes and transistors. In addition, the interaction of solid-state materials with light is important in devices such as solar cells, light sensors, LED's, and solid-state lasers.

Theory: Diodes

There are several types of diodes. We will study two of the most common: a silicon p-n junction switching diode (also called a rectifier) and a light-emitting diode (LED).

A diode is a two-terminal device. The circuit symbol and nomenclature are shown below.

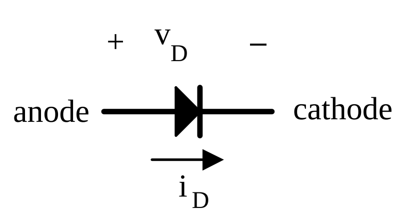

Figure 1. p-n junction diode circuit symbol.

The two terminals are called the <u>anode</u> and <u>cathode</u>. The diode acts like a one-way valve for electrical current. When the anode voltage is higher than the cathode voltage (V_D is positive), the diode is said to be <u>forward-biased</u> and can conduct current. Otherwise, the diode is said to be reverse-biased and cannot conduct current. The behavior of a diode is modeled by the diode equation given below. The parameters in the equation are given in Table 1.

$$\text{Diode Equation:} \quad i_D = I_S\left[-1 + e^{\left(v_D/nV_T\right)}\right] \qquad \text{Eqn. 1}$$

Table 1. Diode Equation Parameters

Parameter	Name / Description	Typical Values or Range	Units
I_S	diode saturation current	1×10^{-9} to 1×10^{-16}	A
V_T	thermal voltage $V_T = kT/q$	25 mV at "room temperature"	V
k	Boltzmann constant	1.381×10^{-23}	J/K
T	absolute temperature	"room temp" is approx. 300 K	K (degrees Kelvin)
q	magnitude of electronic charge	1.602×10^{-19}	C (Coulomb)
n	ideality factor	$1 \le n \le 2$ (default = 1)	dimensionless

Some important facts about the diode equation:

- When $v_D = 0$, $i_D = 0$ (the plot of Eqn. 1 goes through the origin).
- When v_D is positive, the current increases exponentially (the –1 term has little effect).
- When v_D is negative, the current is almost exactly equal to $-I_S$ (the exponential term is negligible).

How Real Diodes Behave

Real diodes obey the Diode Equation (Eqn. 1) fairly well, but they have several additional features worth noting. The forward-bias region for a typical diode is shown in Figure 2. The current remains small until the voltage v_D exceeds approximately 0.5 V. At this point, the diode current increases rapidly, and small changes in voltage cause large changes in current. The voltage required to bring the diode into significant conduction is often called either the turn-on or cut-in voltage, and is notated V_{ON}.

The reverse bias region is shown in Figure 3. The current is equal to the extremely small value of $-I_S$ until the magnitude of the voltage exceeds a value called the zener voltage, V_Z. If the reverse-bias voltage is increased beyond V_Z, the diode goes into the breakdown region. In breakdown, the diode current increases so rapidly with applied voltage that the voltage is effectively clamped at V_Z. Diode breakdown is routinely used in voltage regulation circuits. Breakdown is not destructive to the diode as long as the external circuit limits the current (and thus the power dissipated) in the diode, and it is completely reversible, i.e., a diode can be cycled in and out of breakdown indefinitely. Breakdown is not modeled by the diode equation, but it is shown in Figure 3.

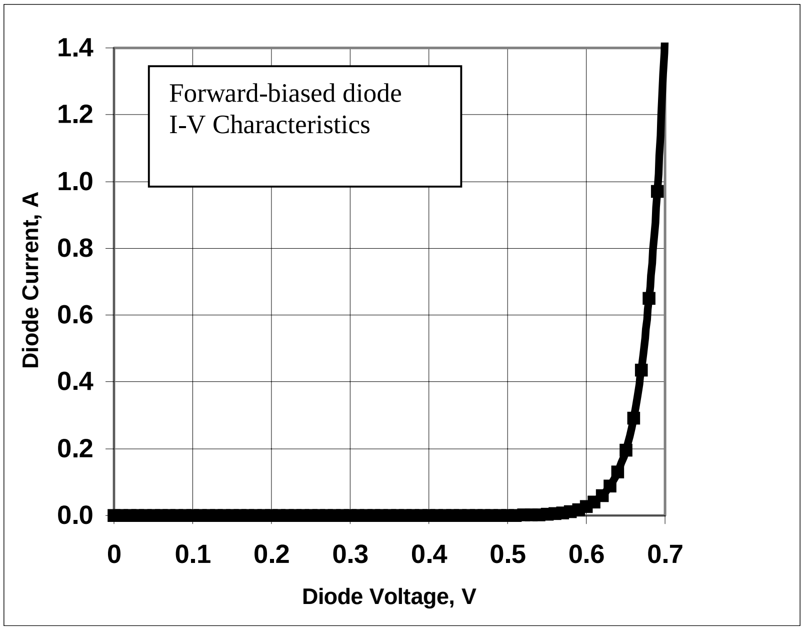

Figure 2. P-n junction diode forward-bias characteristic calculated from the Diode Equation with $I_S = 1 \times 10^{-12}$ A, n = 1, and $V_T = 25$ mV.

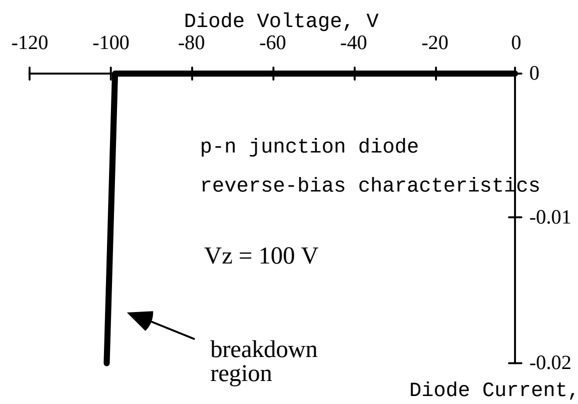

Figure 3. P-n junction reverse-bias characteristic calculated from the Diode Equation with $I_S = 1 \times 10^{-12}$ A, n = 1, and $V_T = 25$ mV. Also shown is the breakdown region for $v_D < -V_Z$ where $V_Z = -100$ V.

Rectifier Diode Ratings

Rectifier diodes are typically rated and sold by the following specifications:

- Peak reverse voltage
- Maximum reverse current at rated voltage, measured in microamperes (μA)
- Maximum forward voltage at rated current
- Capacitance, measured in picofarads (pF)
- Reverse recovery time, measured in nanoseconds (ns)
- Power Dissipation, measured in milliwatts (mW)
- Package type

An example catalog page listing some diodes can be found at the DigiKey web site:

http://www.diodes.com/datasheets/ds12019.pdf

Theory: Light-Emitting Diodes (LED's)

P-n junction diodes can be manufactured using materials other than silicon. With appropriate choices of semiconductor materials, diodes can be made which emit light at various wavelengths (colors) when current passes through them. The most familiar LED's emit red light, but LED's can be manufactured to emit at any wavelength in the visible spectrum, and into the infrared region as well. The circuit symbol for an LED is the same as for a conventional diode, with the addition of arrows indicating the luminescence:

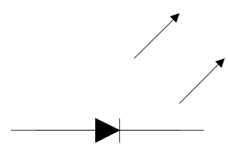

Figure 4. LED circuit symbol

LED Ratings

LED's are typically rated and sold by the following specifications:

- Color
- Brightness, measured in milli-candles (mcd)
- Maximum current, measured in milliamperes (mA)
- Viewing angle, measured in degrees
- Lens size (in millimeters) and type (clear, diffused, round, square, etc.)

Other important characteristics not always clearly specified include reverse breakdown voltage V_Z, and forward turn-on voltage, V_{ON}. The web link below provides an example(may be different now) of some LED's with specifications and pricing.

http://rocky.digikey.com/WebLib/Fairchild/Web%20Data/MV5337,5433,5437,5438,5439.pdf
http://rocky.digikey.com/WebLib/Fairchild/Web%20Data/HLMP-K400,401,402,600,640.pdf

The red LED's we use are designed to emit maximum light intensity at about 20 mA of forward current. Higher current levels should be avoided, since the life of the LED will be shortened.

Theory: Transistors

Transistors can be thought of as electrically-operated valves. These valves permit a "working current" to flow under the control of a (usually small) voltage or current signal. Transistors are most commonly used as electronically-operated switches, and as amplifiers. There are several types of transistors. We will study the bipolar junction transistor (BJT).

Bipolar Junction Transistor

The BJT is a 3-terminal device made by sandwiching one type of silicon (say p-type) between two layers of the opposite type of silicon (n-type). There are two possible types of BJT's, called *npn* and *pnp*. The structure of the npn-BJT is drawn below in Figure 5. The pnp-BJT is similar, but the locations of n- an p-type silicon are exchanged.

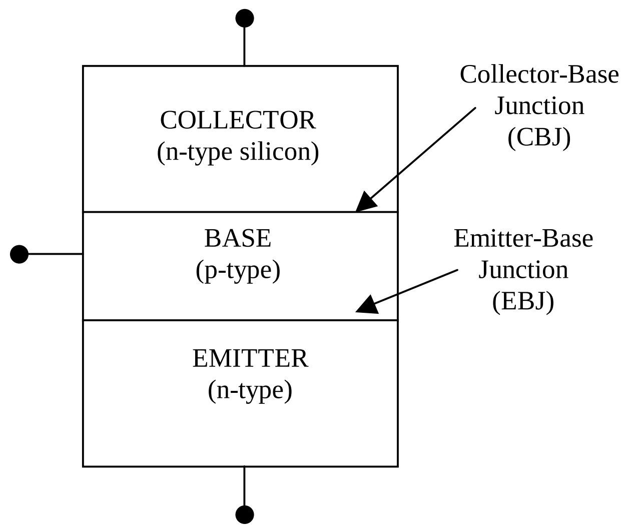

Figure 5. Illustration of the physical construction of an npn-BJT.

The junction between the base and emitter (the EBJ) behaves like a diode. If the EBJ is forward-biased, some current will flow into the base terminal. We will call this the "control" current. Due to the transistor physics, this will cause a much larger "working" current to flow between the collector and emitter. This is illustrated in Figure 6.

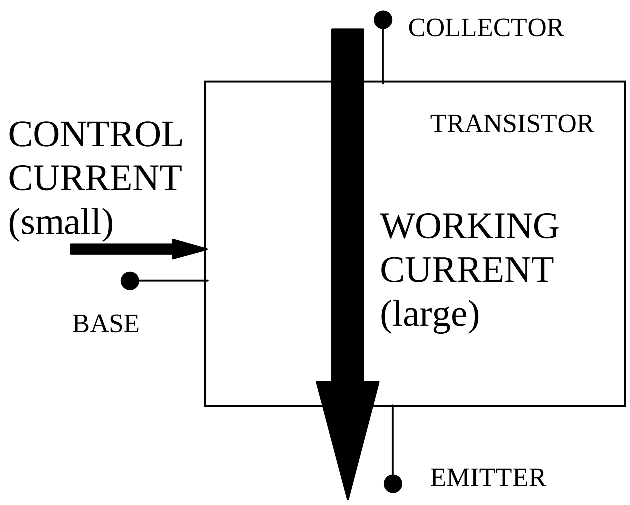

Figure 6. Illustration of the operation of a bipolar junction transistor (BJT).

Operating Regions of the BJT

The BJT can operate in various modes depending on the control current. Three of the most common modes are discussed below.

1. CUTOFF (Control Current and Working Current equal to zero)

If the control current is zero, the BJT is said to be in CUTOFF. In this mode, there is no connection between the collector and emitter, and the working current is zero.

In CUTOFF mode the BJT is like an OPEN SWITCH.

2. FORWARD-ACTIVE (Working Current proportional to Control Current)

If the control current is within a certain range, the working current will be linearly proportional to the control current. This behavior provides the important function of amplification. The constant of proportionality is called the transistor current gain, designated β (Greek letter "beta") or h_{FE}. Also in this mode, the voltage across the base-emitter junction is nearly constant with a value of approximately 0.7 V.

In the FOWARD-ACTIVE mode the BJT acts as an amplifier. The current gain β is constant, and V_{BE} is approximately 0.7 V.

3. SATURATION (Working Current reaches maximum value)

When the control current reaches a certain limit, the working current reaches a saturation value and no longer increases any further. Also, in this case, the voltage drop between collector and emitter is very small. In this mode, the BJT acts like a closed switch (the collector is connected to the emitter).

In SATURATION mode the BJT is like a CLOSED SWITCH.

The two types of BJT's have the circuit symbols and nomenclature shown below. The three terminals are the emitter (E), base (B), and collector (C). The emitter terminal is labeled with an arrow. This arrow is part of the circuit symbol. The arrow direction (relative to the vertical bar) indicates whether the BJT is an npn or pnp type.

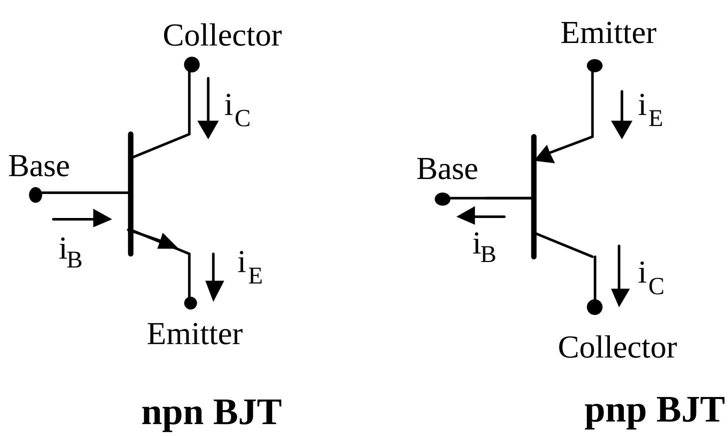

Figure 7. Bipolar junction transistor (BJT) circuit symbols

BJT Circuit Examples

A BJT circuit is drawn below in Figure 8. For our examples, we will use the following values: V_{BB} = 5 V, V_{CC} = 12 V, and R_C = 1 kΩ.

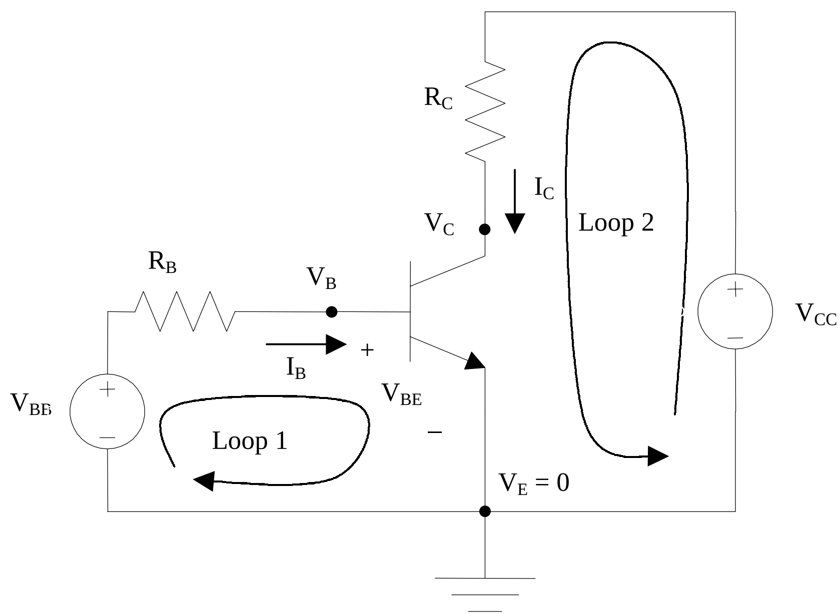

Figure 8. A circuit containing an npn BJT.

Example 1: Assume the BJT is in the <u>forward-active</u> mode with β = 100 and V_{BE} = 0.7 V. Also, let R_B = 100 kΩ.

Problem: Find values for I_B, I_C, V_B, and V_C.
Solution: Start by writing a loop equation for Loop 1 to find I_B:

$$V_{BB} = I_B R_B + V_{BE}$$

so

$$I_B = \frac{V_{BB} - V_{BE}}{R_B} = \frac{5 - 0.7}{100 \times 10^3} = 43 \times 10^{-6} = 43 \mu A$$

Use the transistor β to calculate I_C:

$$I_C = \beta I_B = 100\left(43 \times 10^{-6}\right) = 4.3 \times 10^{-3} = 4.3 mA$$

Now write the equation for Loop 2 :

$$V_{CC} = I_C R_C + V_C$$

and solve for V_C (note that V_C = V_{CE} since V_E is zero):

$$V_C = V_{CC} - I_C R_C = 12 - (4.3 mA)(1 k\Omega) = 7.7 V$$

Example 2: Assume the BJT is in the <u>saturation</u> mode and let $R_B = 10\ k\Omega$.

Problem: Find values for I_B, I_C, V_B, and V_C.
Solution: Start by writing a loop equation for Loop 1 to find I_B:

$$V_{BB} = I_B R_B + V_{BE}$$

so

$$I_B = \frac{V_{BB} - V_{BE}}{R_B} = \frac{5 - 0.7}{10 \times 10^3} = 4.3 \times 10^{-6} = 4.3\,\mu A$$

Because the transistor is in saturation, we know that the collector and emitter are almost directly connected, so we can assume $V_C = V_E = 0$.

Then we can use Ohm's law to calculate the collector current:

$$I_C = \frac{V_{CC} - V_C}{R_C} = \frac{12 - 0}{1000} = 12 \times 10^{-3} = 12\,mA$$

Parts List: (1) LED - preferred red color, (2) BJT (NPN)-2N3904, (3) Data sheet of this BJT , (4) Resistors (1 k, 100 k)

Your Name____

Prelab Questions (10 points)

Answer these questions before coming to lab and turn them in when you arrive. You may do your work on separate paper (for example you might want to do your work on a computer), but please attach your work to this sheet for submission.

1. Use the diode equation (repeated here for convenience) to calculate the voltage drop across a p-n junction diode if the diode current is 10 mA, the saturation current is 1.0 x 10^{-15} A, the thermal voltage is 25 mV, and the ideality factor is 1.0. (Ans.: V_D = 0.748 V.)

   Diode Equation: $$I_D = I_S\left(e^{\frac{V_D}{nV_T}} - 1\right)$$

2. Using the diode parameters from Prob. 1, fill in the table below and then make a careful plot of the diode current versus diode voltage. When you fill in the table, enter your results in mA with exactly two (2) significant digits. Two values are already entered in the table for you. (Recall that 1 mA = 0.001 A.). You may make the plot by hand on graph paper, or you may use a computer tool such as Excel and print the result.

V_D (V)	-1.0	-0.5	0	0.2	0.4	0.6	0.7	0.72	0.74	0.76	0.78	0.8
I_D (mA)							1.4					79

3. Go to the web site given in the Prelab for LED's and answer the following questions:

(a) What is the price per piece for a red, clear LED if you buy 10 pieces?

(b) What is the price per piece if you buy 5000 pieces?

(c) What is the price per piece for a blue LED?

(d) What special handling precautions are necessary for blue LED's?

4. Use the transistor circuit in Figure 8, but let R_B = 47 kΩ. Calculate I_C if the transistor is in the forward active mode. Use the same assumptions as in Example 1. (*Ans.: 9.15 mA*)