1. OBJECTIVE

In this lab you will measure the I-V characteristics of Infrared (IR), Red and Blue light emitting diodes (LEDs). Using a photodetector, the emission intensity as a function of the diode current will be determined for each diode. We will also see (again) how real diode characteristics are both similar to and different from those of the "ideal" diode.

2. OVERVIEW

The first section of the procedure involves identifying the physical structure and orientation of the LEDs based on visual observation. The next two procedural sections will use the LabVIEW program IV_curve.vi to measure the I-V characteristics of test LEDs in forward and reverse bias, respectively. The final procedural section will use the LabVIEW program LED-Output.vi to measure the optical emission intensity of the LED as a function of the LED current. Although it is possible to collect the data for this lab very quickly, it is essential that you understand the different regions found in the I-V characteristics of these diodes and the mechanisms by which current flows through them.

Information essential to your understanding of this lab:

1. Understanding of the operation of biased p-n junction diodes.
2. Understanding of how electrons and holes recombine to produce light.

Materials necessary for this Experiment:

1. Standard testing station.
2. One each: Infrared (IR) LED, Red LED and Blue LED, Photodiode.
3. BACKGROUND INFORMATION

3.1 CHART OF SYMBOLS

Here is a chart of symbols used in this lab. This list is not all-inclusive; however, it does contain the most commonly used symbols.

Table 1. A chart of the symbols used in the Lab IV.

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Symbol Name</th>
<th>Units</th>
</tr>
</thead>
<tbody>
<tr>
<td>$E$</td>
<td>electric field</td>
<td>V / cm</td>
</tr>
<tr>
<td>$A$</td>
<td>junction area</td>
<td>cm²</td>
</tr>
<tr>
<td>$D_p$</td>
<td>diffusivity of holes</td>
<td>cm² / sec</td>
</tr>
<tr>
<td>$D_n$</td>
<td>diffusivity of electrons</td>
<td>cm² / sec</td>
</tr>
<tr>
<td>$\tau_p$</td>
<td>hole life time</td>
<td>sec</td>
</tr>
<tr>
<td>$\tau_n$</td>
<td>electron life time</td>
<td>sec</td>
</tr>
<tr>
<td>$\tau_g$</td>
<td>general carrier lifetime</td>
<td>sec</td>
</tr>
<tr>
<td>$w$</td>
<td>depletion width</td>
<td>cm</td>
</tr>
<tr>
<td>$L_p$</td>
<td>diffusion length of a hole</td>
<td>cm</td>
</tr>
<tr>
<td>$L_n$</td>
<td>diffusion length of an electron</td>
<td>cm</td>
</tr>
<tr>
<td>$V_{bi}$</td>
<td>built in voltage</td>
<td>V</td>
</tr>
</tbody>
</table>
3.2 CHART OF EQUATIONS

All of the equations from the background portion of the manual are listed here.

Table 2. A chart of the equations used in this lab.

<table>
<thead>
<tr>
<th>Equation</th>
<th>Name</th>
<th>Formula</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Total diode current equation</td>
<td>( I = I_d + I_{nr} = I_d e^{q(V-IR)/kT} + I_{nr} e^{q(V-IR)/2kT} )</td>
</tr>
<tr>
<td>2</td>
<td>Peak wavelength equation</td>
<td>( \lambda(nm) = \frac{1240}{E_g(eV)} )</td>
</tr>
</tbody>
</table>

3.3 FORWARD AND REVERSE CHARACTERISTICS OF THE LEDS

LEDs have widespread applications today in displays (including TVs, traffic lights and signs) and as light sources for optical communications, DVD players, remote controls etc. All these LEDs have the same basis of operation, namely that of a PN diode, and one can use the same characterization techniques learned in Lab 4 to characterize LEDs. In the first part of this lab you will capture the forward and reverse bias I-V characteristics of several Light Emitting Diodes (LEDs).

When a PN junction is forward biased, carriers (i.e. electron, holes) diffuse across the depletion region from the side with higher carrier density to the side with lower carrier density. Thus, one can say electrons will diffuse from the n-type side to the p-type side, while holes will diffuse in the opposite direction. Some carriers will make it past the edges of the depletion region; these are now minority carriers and can recombine with the local majority carriers. For semiconducting materials with an indirect bandgap, e.g. silicon, “non-radiative recombination” predominates, resulting in heating of the lattice, i.e. the PN junction gets hot. However, for direct bandgap materials – e.g. GaAs, AlGaAs, GaAsP, InP and GaN - the carriers can recombine by emitting a photon. This process is called “radiative recombination” and the diode produces light when the material is forward biased. This type of light production is called “injection...
electroluminescence”, since we are “injecting” carriers across the junction to undergo radiative recombination.

The recombination process results in lowering of the carrier densities, which allow more diffusion of carriers from the source thus creating a current. The total diode current is the sum of two parts: [1] a “radiative recombination” also known as a “diffusion” current \( I_d \) and [2] a "non-radiative recombination" current \( I_{nr} \). The non-radiative current \( I_{nr} \) results from carriers that recombine at a surface. These carriers recombine without giving off a photon. The surface is usually at the edges of the PN junction. The total diode current equation is:

\[
I = I_d + I_{nr} = I'_d e^{q(V-IR_s)/kT} + I'_{nr} e^{q(V-IR_s)/2kT}
\]

Here \( R_s \) is the device series resistance and \( I_d' \) and \( I_{nr}' \) are the saturation currents for the ‘diffusion’ and ‘non-radiative’ recombination currents, respectively. The light output is proportional to \( I_d' \exp[q(V-IR_s)/(k_BT)] \). At low bias voltage the ‘non-radiative’ current predominates and little light is emitted. With increasing bias voltage the proportion of ‘diffusion’ current becomes larger and when this term dominates over the ‘non-radiative’ current the light output is proportional to the current. At high currents the series resistance term in Eq. (1) has an important effect on the I-V characteristic, however the light versus current curve will remain linear so long as the diffusion current dominates. You will see that this is the case for our Infrared LED but not as well for our red and blue LEDs.

The most studied III-V direct band-gap semiconductors are GaAs and InP, with band gaps at 1.424 eV and 1.351 eV, respectively. The wavelength at which the material emits the most light (the brightest) has approximately the band gap energy. This peak wavelength can be found using the relation between energy and wavelength.

\[
\lambda(nm) = \frac{1240}{E_g(eV)}
\]

The result is emission spectra having the highest intensity at 871 nm (for 1.424 eV) and 918 nm (for 1.351 eV) respectively. These wavelengths are in the near infrared region of the spectrum, and are not visible to the human eye. To be useful as an LED indicator the band gap of the semiconductor must be larger. This can be accomplished by alloying GaAs with higher energy band gap materials, such as AlAs (\( E_g = 2.163 \) eV) and GaP (\( E_g = 2.261 \) eV). This is
exactly what was done for our test devices in this lab. Our Infrared LED is an AlGaAs alloy and results in a peak wavelength of ~875 nm (1.417 eV). Our Red LED is a GaAsP alloy with a peak wavelength of ~635 nm (1.953 eV). The Blue LED is made from GaN and has a peak wavelength of 428 nm (2.897 eV).

There is a large and growing market for LEDs and research is continuing to improve the efficiency of the light emission. You can read further about this in your textbook for the class. Newer III-V semiconductors are being investigated, such as InAlGaP and AlGaInN systems, which have improved emission efficiencies in the visible spectrum. LEDs are now more efficient than incandescent lightbulbs as well as much more rugged, reliable and longer lived. Their response times are 100 to 1000 times faster and LEDs have now become cost effective for a variety of mass-market applications such as automotive indicator lamps, tail lights, dash lights and displays. One of the current goals of optoelectronics engineers is to design red, green, and blue LEDs with higher luminous efficiencies that can be combined to create white light and for practical illumination without excessive heat loss.

Figure 1 shows the emission spectra of the three LEDs we will be testing as a function of wavelength as well as the sensitivity of our detector diode. Figure 2 shows general I-V characteristics expected of the three LEDs. Note that the increase in turn-on voltage is correlated with the increase in the emitted photon’s energy.

The construction of a typical LED device is shown in the cross-sectional view in Figure 3. The LED chip is bonded to the bottom of the shallow reflector cup with conductive epoxy. This cup is on the left hand electrode in Figure 3. A thin gold wire makes the contact between the second lead (on the right) and the top contact pad. For the indicator packages used in this laboratory experiment an epoxy or plastic dome is cast around the lead frame. The rating sheet of the LED usually specifies the forward voltage drop at 20 mA, the luminous intensity at the specified current, and the peak wavelength. These are all listed in Table 3.

<table>
<thead>
<tr>
<th>Color</th>
<th>$V_{fwd}$ @ $I_f=20$ mA</th>
<th>Light Intensity</th>
<th>Peak Wavelength (nm)</th>
<th>Composition</th>
</tr>
</thead>
<tbody>
<tr>
<td>Infrared</td>
<td>1.5 V</td>
<td>20 mW/sr</td>
<td>875</td>
<td>GaAlAs</td>
</tr>
<tr>
<td>Red</td>
<td>2.0 V</td>
<td>10 mcd</td>
<td>635</td>
<td>GaAsP on GaP</td>
</tr>
</tbody>
</table>

Table 3. Specifications of LEDs
Figure 1. The spectra of the Blue (a), Red (b), and Infrared (c) LEDs. The spectral response of the photodetector (d) is also included. Note that it is most sensitive to the infrared LED and least sensitive to the blue LED.
Figure 2. Typical I-V curves for the Infrared, Red and Blue LEDs.

Figure 3. Construction of an indicator type of LED. Picture from [http://smspower.org](http://smspower.org)
3.4 MEASUREMENT OF LED LIGHT OUTPUT USING A PHOTODIODE

Photo detectors can take various forms, but the one we will use in this lab is simply a reverse biased diode. Light shining on a diode produces electron-hole pairs. When the diode is reverse-biased, the electron-hole pairs generated in the junction region are swept out by the electric field within, producing a current. As a result, the current flowing through the reverse-biased diode is directly proportional to the amount of light shining on it. We will use a reverse-biased “pin” diode to detect the light coming from our LEDs. (“pin” in “pin diode” stands for “p-type – intrinsic – n-type” and indicates that the width of the junction region has been made larger by having an intrinsic region placed between the n and p-type regions.) A photo of a typical pin diode in a plastic package is shown in Fig. 4.

![Photo of a typical pin photodiode](http://parts.digikey.com)

**Figure 4.** Construction of a typical pin photodiode. The photodiode is placed on the right hand lead and a thin gold wire connects to it’s top. Picture from [http://parts.digikey.com](http://parts.digikey.com)
4. PREPARATION

1. Read through Sections 8.1 and 8.2 of Streetman and Banerjee. We will use a pin detector in lab and several LEDs (Infrared, Red and Blue.)

2. Describe a quick method for determining whether the substrate of the LED chip is p or n type using the bench equipment.

3. Obtain the values of the turn-on voltage for the diodes shown in Fig. 2. Compare this with the values of the peak emission wavelengths shown in Table 3. (Use Eq. 2 to get energies.) Do you see a correlation?

4. Estimate the series resistance from the I-V curves shown in Fig. 2 for each diode.

5. PROCEDURE

5.1 DIODE INSPECTION

In this experiment you will study the characteristics of three LEDs that emit in the infrared, red and blue parts of the spectrum. As shown in the image, longer lead of the LED is the anode. The photodetector used in this experiment has a square 2.84 x 2.84 mm$^2$ geometry. The longer lead denotes the anode (or positive lead) for forward bias. The photodiode is used in the reverse biased mode, this terminal must be negatively biased to 10 V. Use a current compliance value of 5 mA.

5.2 FORWARD BIAS I-V CHARACTERISTICS

Measure the forward $I$-$V$ characteristics of the three LEDs using the “IV_curve.vi” program.
Figure out the best settings to use. Be sure to limit the current to a maximum value of less than 200 mA (Infrared), 30 mA (Red) and 20 mA (Blue). You may need to adjust the values to obtain an optimum set of curves. Save the I-V measurements for each of the diodes.

A. Display the data on a linear $I$-linear $V$ plot and obtain the usual diode $I$-$V$ curve.

B. To look at the exponential dependence of the current on voltage, switch to the log $I$-linear $V$ scale. This curve should be linear at low currents and saturate at high currents due to the effect of the series resistance. As indicated in Eq. (1) there are two recombination currents, differing only in the prefactor of the $kT$ term in the exponent. Thus (1) can be rewritten in terms of an effective diode current

$$I = I_o \exp\left[\frac{q(V-IR_s)}{(nk_BT)}\right]$$

(3)

where $n$ has a value between 1 and 2, depending on whether the diffusion current or the nonradiative current dominates. The value of $n$ is most easily obtained from a semilog plot of $I$ vs. $V$, selecting a linear region of the curve. Calculate the values of $n$ along the forward bias curves for all three diodes using the equation

$$n = \frac{(q/k_BT)}{(V_2 - V_1) / (\ln(I_2/I_1))}$$

(4)

C. A simple expression for the series resistance is obtained from Eq. 3 by taking the derivative with respect to $I$ of both sides. Rearranging the equation yields

$$R_s = \frac{dV}{dI} - \frac{(k_BT/(qI))}{(dV/dI)}$$

(5)

and for large diode currents the first term on the right hand side dominates the expression. Thus on a linear $I$ - linear $V$ plot the differential slope of the $I$-$V$ curve gives the value of the series resistance. For your report you will determine the $n$ values of the diode equation at different currents from the semilog plot of $I$ vs. $V$. From the linear plot of the $I$ vs. $V$ dependence you will determine the series resistance.
5.3 REVERSE BIAS I-V CHARACTERISTICS

Measure the reverse bias I-V characteristics of the three LEDs up to 10 V reverse bias.

5.4 CURRENT DEPENDENCE OF LIGHT OUTPUT

Measure the current dependence of the light output using the “LED-Output.vi” program. Step the LED current to the maximum values (200 mA (Infrared), 30 mA (Red) and 20 mA (Blue)) in 40 equal steps. That way you will have 41 datapoints for your graphs.
Does the LED light output increase linearly with current? What differences are there between the three different devices? What similarities?

6. LAB REPORT

Type a lab report with a cover sheet containing your name, title, your lab partner’s name, class (including section number), date the lab was performed and the date the report is due. Use the following outline to draft your lab report:

ABSTRACT: Briefly describe the purpose of the lab, the analyses you performed, and your key findings.

INTRODUCTION: not required.

PROCEDURE: not required.

DATA PRESENTATION: not required; no data set to be reported.

ANALYSIS:

Diode Inspection:
1. Draw (not in pen or pencil; use a software tool) a detailed sketch of the basic LED geometry of the IR diode (look closely through the plastic dome.)
2. Determine the semiconductor type of the substrate and the top cladding material for the Red and Blue LED. In your conclusion, mention how you determined these features.

Forward Bias I-V Characteristics:
(Note for all graphs make sure to have proper titles, labeled axes, legends, along with plots that can be distinguished either in gray-scale or color.)
3. Attach a linear current vs. linear voltage graph with the plots of all three LEDs together (3 plots on 1 graph).
4. Attach a semi-log plot (Log current vs. linear voltage) with the plots of all three LEDs together (3 plots on 1 graph).
5. Attach a graph of the ideality factor \( n \) for all three LEDs. Inspect your plots carefully, and, in your conclusion, discuss any regions that have transitions from \( n=1 \) to \( 2 \) (or vice versa), and their implications (read Section 3).
6. Attach plots of the series resistance (3 plots on 1 graph). In your conclusion, note any significant differences in the series resistance among the three LEDs.

Reverse Bias I-V Characteristics:
7. Attach plots of the I-V characteristics (3 plots on 1 graph) of the three LEDs. Are there any significant differences among the three LEDs?
Current Dependence of the Light Output:
8. Attach a plot of the light output as measured by the photodiode current as a function of current of the LEDs.
9. Calculate the slope of the curves. In your conclusion, discuss whether the dependence is linear over the complete current range. Explain the origin of the current dependence of the LED’s brightness.

Conclusions: Answer the questions asked in the analysis section in a coherent and logical manner. Refer to yours plots, calculated values, etc. as needed. The goal in writing your conclusion is to organize and communicate your ideas concisely for quick reading (and better grading!)

Attach: Signed instructor verification form.