LAB IV. SILICON DIODE CHARACTERISTICS

1. OBJECTIVE

In this lab you are to measure *I-V* characteristics of rectifier and Zener diodes in both forward and reverse-bias mode, as well as learn to recognize what mechanisms cause current flow in each region of diode operation. We will also see more clearly 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 diodes based on visual observation. The two remaining procedural sections will use the LabView program **IV Curve.vi** to measure the *I-V* characteristics of test diodes in forward and reverse bias. 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 rectifier diodes
2. Understanding of the operation of the Zener diodes

Materials necessary for this Experiment

1. Standard testing stations
2. One rectifier diode (1N4002)
3. One zener diode (1N4740)

3. BACKROUND 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.

Symbol	Symbol Name	Units
E	electric field	V / cm
A	junction area	cm^2
D_p	diffusivity of holes	cm^2 / sec
D_n	diffusivity of electrons	cm^2 / sec
τ_p	hole life time	sec
τ_n	electron life time	sec
τ_g	general carrier lifetime	sec
w	depletion width	cm
L_p	diffusion length of a hole	cm
L_n	diffusion length of an electron	cm
V_{bi}	built in voltage	V

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.

Equation	Name	Formula
1	Ideal Diode Equation	$I_f = I_0\left(e^{(qV_{appl}/nk_bT)} - 1\right)$
2	Reverse Saturation Current Equation	$I_0 = n_i^{\,2} qA\left(\frac{1}{N_A}\sqrt{\frac{D_p}{\tau_p}} + \frac{1}{N_D}\sqrt{\frac{D_n}{\tau_n}}\right)$
3	Ideality Factor Equation	$n = \left(\frac{q}{k_bT}\right)\frac{(V_2 - V_1)}{\ln(I_2/I_1)}$
4	Piecewise Diode Equation	$I_f = I_{piecewise}\left(e^{(qV_{appl}/n_{piecewise}k_bT)} - 1\right)$
5	Forward Recombination Current Equation	$I_{fr} = \frac{qn_iwA}{\tau_g}$
6	Ohmic Resistance Applied Voltage Equation	$V_{appl} = V_A - I_fR_S$
7	Reverse Bias Avalanche Current Breakdown Equation	$I_{avalanche} = I_0 \Big/ \left[1 - \left(\frac{V_{appl}}{V_{br}}\right)^m\right]$

3.3 GENERAL INFORMATION ON DIODES

3.3.1 DIODE NOMENCLATURE AND IDENTIFICATION

From examining Figure 1, you should note that the anode corresponds to the p-type side while the cathode corresponds to the n-type side of the diode. On the rectifier and Zener diodes you will be able to identify the n-type side, or the cathode, by the band, circling the package, as seen below.

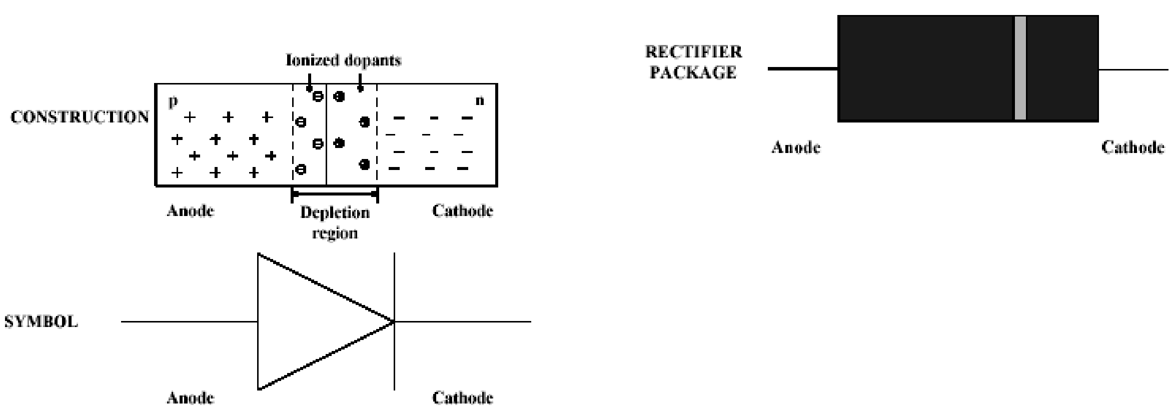

Figure 1. Diode nomenclature and identification of polarity.

Understanding a diode cracks the floodgate of understanding for complex semiconductor devices. In fact, many complex devices may be reduced to pn junctions, resistors and capacitors.

The materials and applications of the two major types of diodes studied in this lab are found in Table 3 below.

Table 3. Materials and specifications of diodes.

Diode Type	**Rectifier Diode**	**Zener Diode**
Material	Silicon	Silicon
Voltage Range	V_{br} to 1.2 V	$-V_Z$ to 1.2 V
Current Range	-5 uA to 1.0 A	-20 mA to 100 mA
Typical Operation	Forward and Reverse bias	Reverse bias
Application	Rectification and switching	Voltage reference

3.4 FORWARD BIASED SILICON DIODES

3.4.1 THE IDEAL DIODE EQUATION

When you take your measurements for this experiment, you will find the response of your diode for both the forward and the reverse bias modes of operation. If you took your data from both modes of operation and plotted it on a linear scale it would look similar to Figure 2.

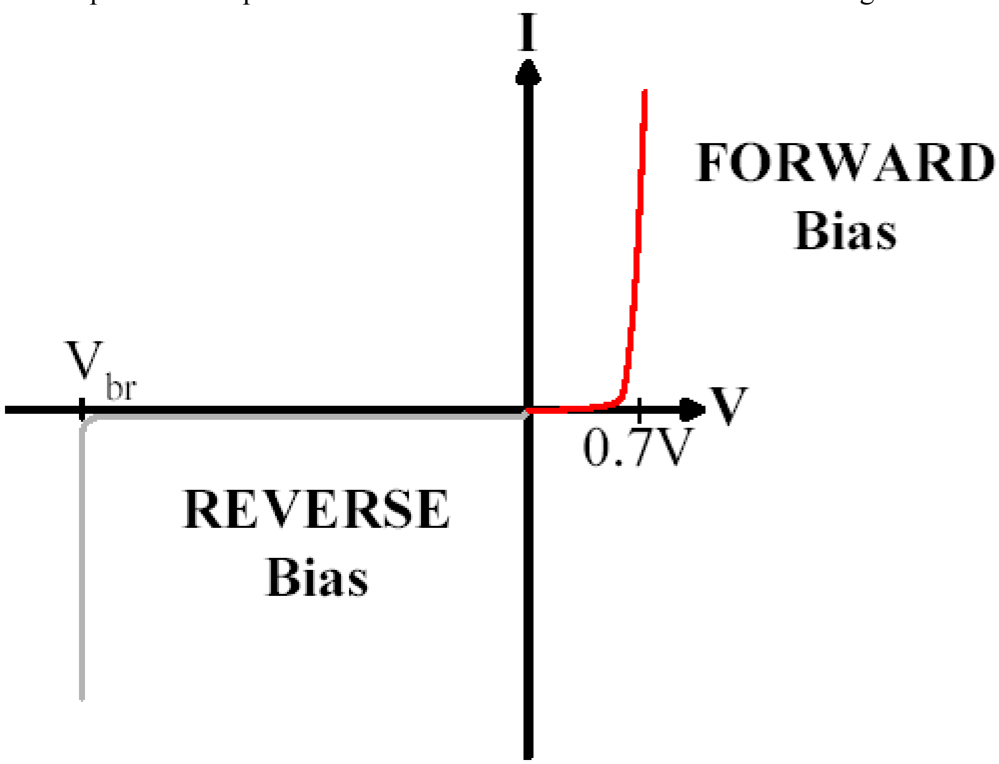

Figure 2. An ideal diode I-V characteristics.

The “ideal diode” equation is a good approximation of the diode current over selected ranges of voltage, but not for all possible voltages. In particular, it works reasonably well for the voltage ranges: $V_{br}/2 < V_{appl} < 0$ V and a $\sim 5kT/q < V_{appl} < 2/3 * E_G$ V. Note that V_{appl} is the voltage “applied” across the depletion region of the diode, E_G is the band-gap and V_{br} is the reverse bias break down voltage. This equation does not describe the current flowing through the diode well from 0 V to $\sim 5kT/q$ V and voltages more negative than $V_{br}/2$. The Ideal Diode Equation is

$$I_f = I_0\left(e^{(qV_{appl}/nk_bT)} - 1\right) \tag{1}$$

where the variable I_0 is called the "Reverse Saturation Current" and is calculated for abrupt junctions as

$$I_0 = n_i^{\,2} qA\left(\frac{1}{N_A}\sqrt{\frac{D_p}{\tau_p}} + \frac{1}{N_D}\sqrt{\frac{D_n}{\tau_n}}\right) \tag{2}$$

D_p and D_n are the diffusion constants, τ_p and τ_n are the minority carrier lifetimes, and A is the cross sectional area of the junction. The variable n is called the "ideality factor." The ideality factor changes depending on the mechanism causing current flow in your semiconductor. One way of determining n is the following equation,

$$n = \left(\frac{q}{k_b T}\right)\frac{(V_2 - V_1)}{\ln(I_2/I_1)} \tag{3}$$

Where both (I_1,V_1) and (I_2,V_2) are points taken within the region where a particular current mechanism dominates. The chosen points should be taken a considerable distance away from each other on the voltage scale. (I_1,V_1) is identified as the lower voltage point and (I_2,V_2) is identified as the higher voltage point. We will address more about the ideality factor later as we modify the ideal diode equation.

3.4.2 A REALISTIC FORWARD BIAS DIODE MODEL

In order to more accurately model a real diode, a number of non-idealities that are commonly found must be taken into account. The Ideal Diode equation makes a number of assumptions. The first is that it assumes **low level injection** of carriers across the junction. Second, it is assumed that the **resistance of the n-type and p-type regions is negligible**. There are points in the I-V characteristics of a real diode where these assumptions do not hold accurately enough to model a real diode. To help you better see the regions where these assumptions do not hold in a real diode, the ideal diode equation can be renamed as the piecewise diode equation (4) to emphasize that certain mechanisms dominate certain regions of a diode's I-V characteristic.

$$I_f = I_{piecewise}\left(e^{(qV_{appl}/n_{piecewise}k_bT)} - 1\right) \tag{4}$$

$I_{piecewise}$ is one of **three** different constant values depending on the mechanism dominating the current flow in the current regions of the I-V characteristic. Likewise, $n_{piecewise}$ has one of three characteristic values depending on the mechanism causing current flow in the diode. V_{appl} is the voltage applied to the depletion width, which can be approximated to V_A, the voltage applied to the diode.

<u>A significant part of the analysis of this lab is evaluating the ideality factors ($n_{piecewise}$) to determine the regions in which certain current mechanisms dominate the current flow.</u> What would happen if you plotted (4) on a semi-log graph (current (log) and voltage (linear))? According to (4), the characteristic should look like three approximately straight lines each with a slope of $q/(n_{piecewise}k_bT)$ if qV in the exponent of (4) is greater than a few k_bT. This tells us that we will be able to recognize what is the dominant current mechanism in our experimental diode by finding changes in the slope corresponding to $n_{piecewise}$.

<u>Forward Recombination Region</u>

In the first region, denoted by the lowest solid line (<u>green</u>) in Figure 3, recombination in the depletion region is the dominant mechanism causing current to flow. At low forward voltages, the depletion width hardly shrinks while allowing some majority carriers to start diffusing across the junction. These carriers end up recombining inside the depletion width instead of making it across the depletion region. We call this the **<u>forward recombination</u>** region. In this region the ideality factor, $\boldsymbol{n_{piecewise}}$**, is approximately equal to 1.5 to 2.0**. In addition $\boldsymbol{I_{piecewise}}$ **is equal to** $\boldsymbol{I_{fr}}$ where I_{fr} is

$$I_{fr} = \frac{q n_i w A}{\tau_g} \quad (5)$$

In general, forward recombination current dominates only for very small current values (nA range for discrete silicon diodes at typical room temperatures).

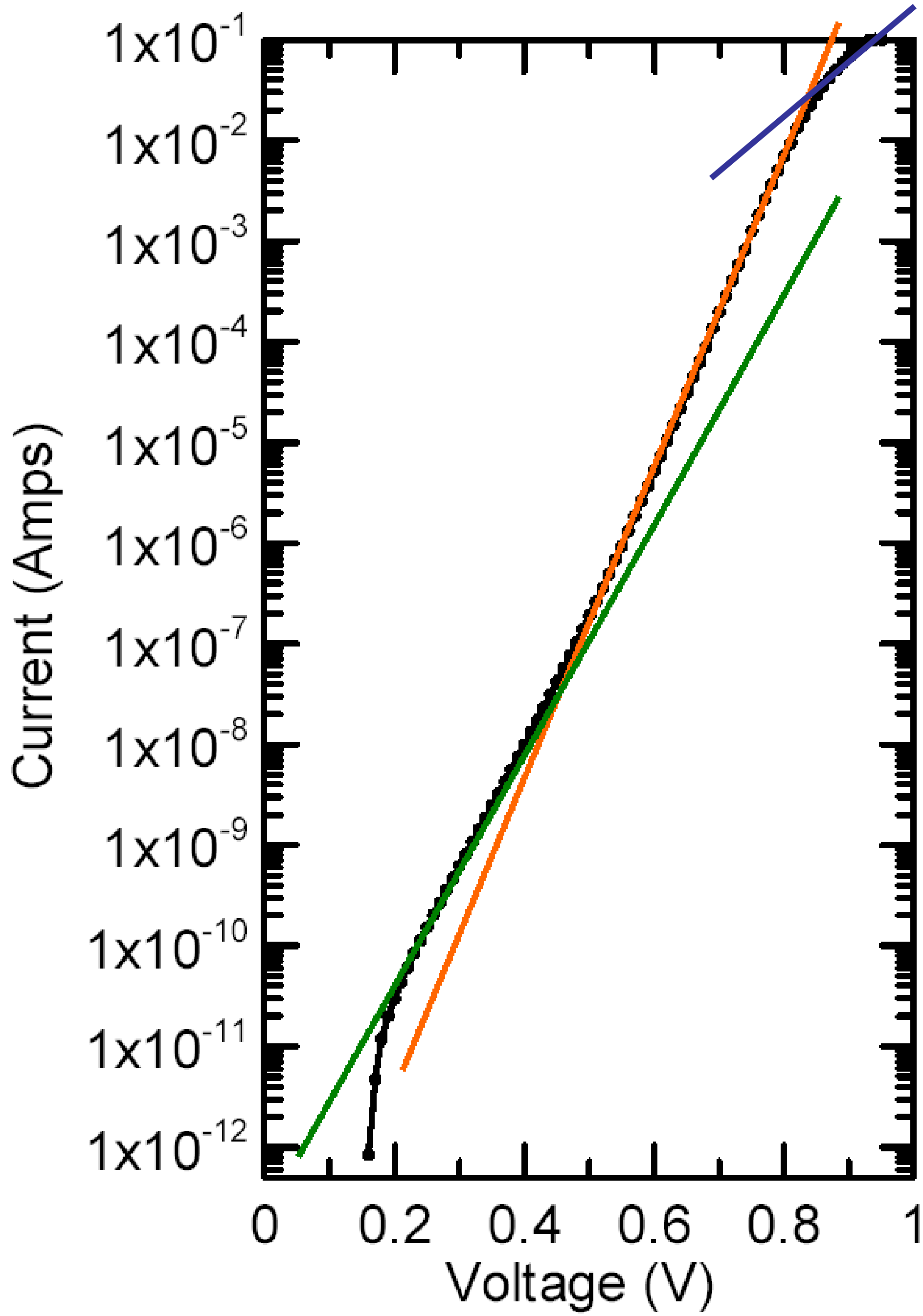

Figure 3. I-V characteristic for a forward biased realistic diode.

<u>**Diffusion Region**</u>

The second region of the characteristic is called the **diffusion region** of operation and is approximated by the middle solid line (orange) in Figure 3. In this region $I_{piecewise}$ **is the same as** I_0

(equation 2) and $n_{piecewise}$ is equal to 1. Diffusion is the dominant current mechanism in this region. In summary, the intermediate current values in the I-V characteristic of a diode can be approximated by diffusion current effects alone. Currents in this region are in the μA range in common discrete silicon diodes operating at room temperature.

High Level Injection Region and Ohmic Effects

The upper most solid line (blue) in Figure 3 is the region in which we begin to see **high level injection** and **ohmic effects**. The **high level injection region** has a substantially steeper slope than the **ohmic region** which becomes much flatter at higher currents. Note that the **high level injection region** is oftentimes obscured by the slope-over associated with the series resistance.

Most of the effects in the **high level injection region** are due to a change in the majority carrier concentrations on both sides of the depletion region. In the **high level injection region**, **$I_{piecewise}$ is equal to I_{h0} and $n_{piecewise}$ is approximately equal to 2.0**. Deriving I_{h0} is something that we will be doing analytically from the graph and not by using an equation. High level injection would typically occur at larger current values (10's of mA range for our discrete silicon diodes at typical room temperatures) if it is observed at all.

Recall that up to this point we have assumed that the resistance in the n-type and the p-type regions of the diode are negligible. The series resistance of the n-type and p-type regions becomes measurable in the **ohmic region** and must be accounted for in order to make our approximation more accurate. A voltage drop occurs across the series resistance, R_S, as I_f flows through the diode affecting V_{appl}, the voltage across the depletion width. Through Ohm's Law we find that,

$$V_{appl} = V_A - I_f R_S \tag{6}$$

where R_S can be found by taking the reciprocal of the slope of the tangent to the I-V curve in the **ohmic region**.

Using the theory of this section you should be able to develop a piecewise approximation of your experimental I-V characteristic when your diode is forward biased. **Developing a piecewise approximation of the characteristic is a major portion of this lab. If you do not understand the theory above, read it again before going on.**

3.5 REVERSE BIAS SILICON DIODES

3.5.1 REVERSE BIAS DIODE MODEL

All diodes can start conducting large currents in the reverse direction for reverse bias voltages bigger than the breakdown voltage, V_{br}. This large reverse current is non-destructive as long as it is limited to a small enough value (a current limiting resistor can do this). Note that the Joule power dissipated in the diode is I*V. Since V_{br} is generally quite large (~10V for our 1N4740 diode) even a relatively small amount of current can cause the amount of Joule power dissipated in the diode to be large! As result, it can be surprisingly easy to cause the diode to literally burn up!

3.5.2 REVERSE BIAS ZENER DIODES

There are actually two types of "Zener" diodes. [1] Diodes with reverse breakdown voltages smaller than $\sim 6E_G/(k_BT)$ have their operation dominated by the Zener effect and therefore are true Zener diodes. You can read about the theory of operation of these diodes in the textbook you are using for the class. Diodes with reverse breakdown voltages greater than $\sim 6E_G/(k_BT)$ have their operation dominated by an avalanche multiplication effect. These diodes are still called "Zener" diodes, but they are actually "avalanche breakdown" diodes. Their reverse bias current at voltages just below breakdown, V_{br}, is modeled in Eqn. (7).

$$I_{diode(avalanche)} = I_0 / (1 - (V_{appl} / V_{br})^m) \qquad (7)$$

The variable **m** in Eqn. (7) is a fitting parameter that depends on the doping of the pn junction. Empirically, it has been found that m ~ 2 for a n^+p silicon diode. (This is a diode with a very heavily doped n-type region connected to a comparatively lightly doped p-type region.) m is ~ 4 for a p^+n silicon diode. Look at Eqn. (7) carefully and note that the current becomes infinite when $V_{appl} = V_{br}$. Of course, infinite current is impossible, so this equation only applies for $|V_{appl}| < |V_{br}|$. When V_{appl} becomes $\geq V_{br}$, the current is limited by factors other than the diode's avalanche multiplication and as a consequence this equation no longer describes the current.

All "Zener" diodes are designed to operate in reverse bias and have a very steep current-voltage characteristic at the reverse breakdown voltage. Once a Zener diode breaks down, an increase in applied voltage may source more current to the circuit, but the voltage across the diode will stay almost exactly at V_{br}. Thus, a Zener diode operating in reverse bias breakdown can provide a reference voltage for systems that need one like voltage regulators or voltage comparators.

4. PREPARATION

1. Study the Figure 5-37 in Streetman and Banerjee and describe the I-V characteristics of typical realistic diode in your own words.
2. Outline sections 3.4 and 3.5 of the lab manual. Take note of main concepts contained in each section.

5. PROCEDURE

5.1 FORWARD BIAS I-V CHARACTERISTICS

We are using incremental steps in voltage to plot the current response of the rectifier and Zener diodes and practice recognizing the regions where certain mechanisms dominate the current flow. Open **IV Curve.vi** in the 3110 folder. You will take the forward I-V characteristics of the rectifier and Zener diodes.

Do not interrupt the Keithley Source Measure Unit during testing. If you do, it may register an error in its memory and **will not work properly**. If this happens, turn off the SMU and then turn it on again. This will manually clear the memory.

Part	Voltage Range (V)	Step Size (V)	Current Limit
Rectifier Diode	0.0 V to 1.2 V	0.02 V	1.0 A
Zener Diode	0.0 V to 1.5 V	0.02 V	1.0 A

A. Connect the positive lead from the SMU (bottom Keithley, GPIB 25) to the anode and the negative lead to the cathode. This will place your diode in a forward bias configuration.
B. Enter the proper voltage range and voltage steps for the diode you are currently testing into the program from the table above.
C. Enter the proper current limit (compliance value for the SMU) into the program for the diode you are on.
D. Run the program and save the data into a spreadsheet.
E. View the data using a log(Y) – linear(X) plot with Y ranging from 100 pA to the current limit as found in the table above.
    - To change the Y-scale to logarithmic, right click anywhere on the graph, then select Y-scale, then Mapping, then Logarithmic.

- To change the Y-scale range, first deselect the auto scale option in the Y-scale menu. Next, simply double click on the upper or lower limit and set the value to the desired range after the auto-scale has been deselected.

F. After you have data in the log (I) vs. linear (V) form, take a piece of paper and use its straight edge to approximate each region. Not all regions may be present in the data you have, so look carefully and compare the regions to those shown in Figure 3. Fill out the table below by recording the voltage range for each region. Also plot up the ideality factor versus voltage using equation (3) to aid in the interpretation of the data.

G. In order to find the series resistance (R_S) of the diode, change the X-Y scales of the I-V curve to linear-linear scale. Estimate the series resistance of the forward biased diode R_S. It can be found by taking the reciprocal of the slope of the tangent to the I-V curve in the ohmic region. Plot up the resistance of the diode versus the voltage in order to estimate the resistance of the diode.

Part	Recombination	Diffusion	High Level Injection Effects	Ohmic Region
Rectifier Diode				
Zener Diode				

5.2 REVERSE BIAS I-V CHARACTERISTICS

You will measure the reverse bias I-V characteristics using the **IV Curve.vi** for each diode with its respective settings, shown in the table below. To place your device in reverse bias using the settings in the table below, connect the positive lead from the SMU (bottom Keithley, GPIB 25) to the cathode and the negative lead to the anode. To the best of your ability, estimate the break down voltage (V_{br}) for each set of parameters and record your estimate in the table below. Some diodes may not break down in this voltage range. If they do not, record NB for no breakdown. MAKE SURE YOU HAVE CONFIGURED THE DIODE CORRECTLY. IF YOU OPPERATE THESE DIODES IN FORWARD BIAS WITH THE RANGES INDICATED IN THE TABLE BELOW **<u>IT MAY DESTROY THE DIODE!</u>**

Part	Voltage Range (V)	Step Size (V)	Current Limit	V_{br} *(estimate)*
Rectifier Diode	0.0 V to 50.0 V	0.25 V	0.100 A	
Zener Diode	0.0 V to 10.0 V	0.1 V	0.200 A	
	V_{br} + 0.25V to V_{br} – 0.25V	0.005 V	0.200 A	

6. LAB REPORT

Type a lab report with a cover sheet containing your name, your 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.

- **Introduction**: Type a summary of the summary of the experiment.
- **Forward bias I-V characteristics**
  - Create a <u>Linear (I) vs. Linear (V) plot</u> and a <u>Log (I) vs. Linear (V) plot</u> for each set of data. Make sure both axes are labeled and the graph is appropriately titled.
  - Identify and suitably color-code each of the regions.
  - Derive R_S from the Linear (I) vs. Linear (V) plot for each diode.
  - Use Equation (3) to find $n_{piecewise}$ for each region. Using this value and with the measured I_f values, calculate $I_{piecewise}$ for each region

- **Reverse bias I-V characteristics**
  - Create a Linear(I) – Linear(V) plot for each set of data in the reverse bias**. Mark the breakdown voltage if applicable on the plot. Keep in mind your diodes may not clearly show the breakdown voltage.**
- **Conclusions**: Type your conclusions for this lab.