LAB IV. SILICON DIODE CHARACTERISTICS

1. OBJECTIVE

In this lab you will measure the $I-V$ characteristics of the rectifier and Zener diodes, in both forward and reverse-bias mode, as well as learn 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 inspection. 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 the operation of biased p-n junction rectifier diodes
2. Understanding the operation of the Zener diodes

Materials necessary for this Experiment

1. Standard testing station
2. One pair of banana-alligator clip cables
3. One rectifier diode (1N4002)
4. One zener diode (1N4740)
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>cm$^2$</td>
</tr>
<tr>
<td>$D_p$</td>
<td>diffusivity of holes</td>
<td>cm$^2$/sec</td>
</tr>
<tr>
<td>$D_n$</td>
<td>diffusivity of electrons</td>
<td>cm$^2$/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>Ideal Diode Equation</td>
<td>( I_f = I_0 \left( e^{(qV_{appl}/nk_bT)} - 1 \right) )</td>
</tr>
<tr>
<td>2</td>
<td>Reverse Saturation</td>
<td>( I_0 = n_i^2 qA \left( \frac{D_p}{N_A} \sqrt{\frac{1}{\tau_p}} + \frac{1}{N_D} \sqrt{\frac{D_n}{\tau_n}} \right) )</td>
</tr>
<tr>
<td></td>
<td>Current Equation</td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>Ideality Factor</td>
<td>( n = \left( \frac{q}{k_bT} \right) \left( \frac{V_2 - V_1}{\ln(I_2/I_1)} \right) )</td>
</tr>
<tr>
<td></td>
<td>Equation</td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>Piecewise Diode</td>
<td>( I_f = I_{piecewise} \left( e^{(qV_{appl}/n_{piecewise}k_bT)} - 1 \right) )</td>
</tr>
<tr>
<td></td>
<td>Equation</td>
<td></td>
</tr>
<tr>
<td>5</td>
<td>Forward Recombination</td>
<td>( I_{fr} = \frac{qn_i wA}{\tau_g} )</td>
</tr>
<tr>
<td></td>
<td>Current Equation</td>
<td></td>
</tr>
<tr>
<td>6</td>
<td>High Level Injection</td>
<td>( V_{appl} = V_A - I_f R_S )</td>
</tr>
<tr>
<td></td>
<td>Applied Voltage Equation</td>
<td></td>
</tr>
<tr>
<td>7</td>
<td>Reverse Bias</td>
<td>( I_{avalanche} = I_0 \left[ 1 - \left( \frac{V_{appl}}{V_{br}} \right)^m \right] )</td>
</tr>
<tr>
<td></td>
<td>Avalanche Breakdown</td>
<td></td>
</tr>
</tbody>
</table>

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. (a) P-N junction (b) schematic symbol (c) diode packaging.[1]

Understanding how a diode works from an ‘atomistic’ and a ‘circuit elements’ point-of-view is a necessary first step towards understanding more complex semiconductor devices such as BJTs, JFETS, MOSFETs, etc. In fact, many complex devices can be reduced to a representation of PN junctions, resistors and capacitors, allowing simple analysis using circuit theory. The specifications of the two diodes studied in this lab are found in Table 3.

Table 3. Materials and specifications of diodes.

<table>
<thead>
<tr>
<th>Diode Type</th>
<th>Rectifier Diode</th>
<th>Zener Diode</th>
</tr>
</thead>
<tbody>
<tr>
<td>Material</td>
<td>Silicon</td>
<td>Silicon</td>
</tr>
<tr>
<td>Voltage Range</td>
<td>$V_{br}$ to 1.2 V</td>
<td>-$V_z$ to 1.2 V</td>
</tr>
<tr>
<td>Current Range</td>
<td>-5 µA to 1.0 A</td>
<td>-20 mA to 100 mA</td>
</tr>
<tr>
<td>Typical Operation</td>
<td>Forward and Reverse bias</td>
<td>Reverse bias</td>
</tr>
<tr>
<td>Application</td>
<td>Rectification and switching</td>
<td>Voltage reference</td>
</tr>
</tbody>
</table>

### 3.4 FORWARD BIASED SILICON DIODES

#### 3.4.1 THE IDEAL DIODE EQUATION

Characterizing a diode involves finding the I-V behavior of the diode for both the forward and the reverse bias modes of operation. A typical representation of a diode’s IV-characteristics for both modes of operation, plotted on a linear scale, is shown in Figure 2.

![Diagram of diode IV characteristics](image)

**Figure 2. An ideal diode I-V characteristics.**

The “ideal diode” equation, (1), is a good approximation of the diode current over a particular range of voltages. It works reasonably well for the voltage ranges: \( V_{br}/2 < V_{appl} < 0 \) V and \( \sim 5kT/q < V_{appl} < 2/3*(E_G/q) V \). 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

\[
I_f = I_0 \left( e^{(qV_{appl} / n k_b T)} - 1 \right)
\]

(1)
where the variable $I_0$ is called the “Reverse Saturation Current” and is calculated for abrupt junctions as

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

(2)

$D_p$ and $D_n$ are the diffusion constants, $\tau_p$ and $\tau_n$ 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,

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

(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.

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

(4)
$I_{\text{piecewise}}$ 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, $n_{\text{piecewise}}$ has one of three characteristic values depending on the mechanism causing current flow in the diode. $V_{\text{appl}}$ is the voltage applied to the depletion width, which can be approximated to $V_A$, the voltage applied to the diode.

A significant part of the analysis of this lab is evaluating the ideality factors ($n_{\text{piecewise}}$) to determine the regions in which certain current mechanisms dominate the current flow. 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 $q/(n_{\text{piecewise}} k_B T)$ if $qV$ in the exponent of (4) is greater than a few $k_B T$. 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 $n_{\text{piecewise}}$.

**Forward Recombination Region**

In the first region, denoted by the lowest solid line (green) 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 *forward recombination region*. In this region the ideality factor, $n_{\text{piecewise}}$, is approximately equal to 1.5 to 2.0. In addition $I_{\text{piecewise}}$ is equal to $I_{fr}$ where $I_{fr}$ is

$$I_{fr} = \frac{q n_i A}{\tau_g}$$

(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.
**Diffusion Region**

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 $I_{\text{piecewise}}$ is the same as $I_0$ (equation 2) and $n_{\text{piecewise}}$ is equal to 1. Diffusion is the dominant current mechanism in this region. Therefore, 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**

The upper most solid line (blue) in Figure 3 is the **high level injection region**. Most of the effects in this region are due to a change in the majority carrier concentrations on both sides of the depletion region. **In the high level injection region, $I_{\text{piecewise}}$ is equal to $I_{h0}$ and $n_{\text{piecewise}}$ 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 is the mechanism that usually dominates for large current values (10’s of mA range for our discrete silicon diodes at typical room temperatures).

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 high level injection region and will be accounted for, 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,

$$V_{appl} = V_A - I_f R_S$$

(6)

where $R_S$ can be found by taking the reciprocal of the slope of the tangent to the I-V curve in the high level injection 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 power dissipated in the diode due to Joule (i.e. resistive or Ohmic) heating is $I^*V$. Since $V_{br}$ is generally quite large ($\sim 10V$ for our 1N4740 diode) even a relatively small amount of current can mean an excessive amount of power is being dissipated in the diode. This may cause the diode to burn up! Check the data sheets for the maximum current rating, and be sure to stay below it.

3.5.2 REVERSE BIAS ZENER DIODES

There are actually two types of “Zener” diodes. [1] Diodes with reverse breakdown voltages smaller than $\sim 6E_G/q$ 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 $\sim 6E_G/q$ 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).

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

(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 $m \sim 2$ 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 $\sim 4$ 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 draw 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, e.g. voltage regulators or voltage comparators.
4. PREPARATION

1. Study the Figure 5-37 in Streetman. Describe, in your own words, what is happening at the microscopic scale for each region of the realistic I-V characteristics of a typical diode.

2. Outline sections 3.4 and 3.5 of the lab manual. Take note of the main concepts contained in each section. Describe each main concept; use equations if necessary.

5. PROCEDURE

5.1 VISUAL INSPECTION AND DIODE POLARITY

Inspect each diode carefully; Compare both to Figure 1. Determine each diodes polarity mark and which end is the anode. Determine how to set it up for either forward or reverse biased operation.

5.2 FORWARD BIAS I-V CHARACTERISTICS

1. Open IV Curve.vi in the “LabVIEW IVs>3110” folder. (You will use this vi-file to take the I-V characteristics of both the rectifier and Zener diodes.)

2. 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.

3. Enter the proper voltage range and voltage steps for the diode you are currently testing into the program from Table 4.

4. Enter the proper current limit (i.e. compliance value for the SMU) into the program for the diode. See Table 4.

Table 4. IV Curve.vi forward bias settings.

<table>
<thead>
<tr>
<th>Part</th>
<th>Voltage Range (V)</th>
<th>Step Size (V)</th>
<th>Current Limit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rectifier Diode</td>
<td>0.0 V to 1.2 V</td>
<td>0.02 V</td>
<td>1.0 A</td>
</tr>
<tr>
<td>Zener Diode</td>
<td>0.0 V to 1.2 V</td>
<td>0.02 V</td>
<td>0.50 A</td>
</tr>
</tbody>
</table>
5. Run the program and save the data into a spreadsheet. **Do not interrupt the Keithley Source Measure Unit during measurement.** 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.

6. 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.

7. 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 Table 5 below with the voltage range for each region. Next, plot the ideality factor versus voltage using equation (3) to aid in the interpretation of the data.

8. 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 high level injection region. Plot the resistance of the diode versus the voltage in order to estimate the resistance of the diode.

**Table 5. Voltage Range of each region and Series Resistance of each diode.**

<table>
<thead>
<tr>
<th>Region:</th>
<th>Recombination</th>
<th>Diffusion</th>
<th>High Level Injection</th>
<th>Series Resistance (High Level Injection Region)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rectifier Diode</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Zener Diode</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
5.3 REVERSE BIAS I-V CHARACTERISTICS

You will measure the reverse bias I-V characteristics using the **IV Curve.vi** for each diode according to the instructions, and settings given in Table 6, below:

1. Place your diode in reverse bias connect the positive lead from the SMU (bottom Keithley, GPIB 25) to the cathode and the negative lead to the anode.

2. Enter the voltage range, step size, and current limit denoted in Table 6 in to the program. Run the program, save the data to a file.

3. From the plot, estimate the break down voltage ($V_{br}$) for each set of parameters and record your estimate in the Table 6.

**NOTE:** Some diodes may not break down for the given voltage range. If they do not, record NB for “no breakdown”. **MAKE SURE YOU HAVE CONFIGURED THE DIODE CORRECTLY. IF YOU OPERATE THESE DIODES IN FORWARD BIAS WITH THE RANGES INDICATED IN THE TABLE BELOW IT MAY DESTROY THE DIODE!**

<table>
<thead>
<tr>
<th>Part</th>
<th>Voltage Range (V)</th>
<th>Step Size (V)</th>
<th>Current Limit</th>
<th>$V_{br}$ (estimate)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rectifier Diode</td>
<td>0.0 V to 50.0 V</td>
<td>0.25 V</td>
<td>0.100 A</td>
<td></td>
</tr>
<tr>
<td>Zener Diode</td>
<td>0.0 V to 11.0 V</td>
<td>0.1 V</td>
<td>0.200 A</td>
<td></td>
</tr>
<tr>
<td>Zener Vbr (Close Up)</td>
<td>$V_{br} + 0.25V$ to $V_{br} - 0.25V$</td>
<td>0.005 V</td>
<td>0.200 A</td>
<td></td>
</tr>
</tbody>
</table>
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:

**Introduction:** Describe the purpose of the lab.

**Analysis:**

**A. Forward bias I-V characteristics**

1. Create a **Linear (I) vs. Linear (V) plot** and a **Log (I) vs. Linear (V) plot** for each diode. Make sure both axes are labeled and the graph is appropriately titled.
2. Identify and suitably color-code each of the regions.
3. Derive $R_S$ from the Linear (I) vs. Linear (V) plot for each diode. Clearly report the value.
4. Use Equation (3) to find $n_{piecewise}$ for each region. Note your $n_{piecewise}$ values may vary significantly from the expected values. Show work, i.e. equations AND values used. Clearly report your values. Do this for both diodes.
5. Using these $n_{piecewise}$ values, along with the measured $I_f$ values, calculate $I_{piecewise}$ for each region. Show work i.e. equations AND values used. Clearly report your values. Do this for both diodes.

**B. Reverse bias I-V characteristics**

1. Create a **Linear(I) – Linear(V) plot** from reverse bias data set for each diode. Make sure both axes are labeled and the graph is appropriately titled.
2. Mark the breakdown voltage, if applicable, on the plot. Keep in mind one of your diodes may not clearly show the breakdown voltage. Report this value clearly.
3. Create a **Linear(I) – Linear(V) plot** of “Zener Vbr (Close Up)” reverse bias data set (see Table 6).

Add plots of equation (7) for m=2 and m=4 to the plot. Use voltage from your dataset as $V_{appl}$. Find $I_o$ (hint: check your data for current when $V_{appl} = 0$.) You should now have a total of three plots on one graph.

Adjust the current axis ("zoom in") so you can see all three curves. Which curve does your data follow the most? The m=2
curve? Or the m=4 curve? What does this imply about your zener diode’s doping (section 3.5.2)?

4. Determine which mechanism - the Zener Effect or the Avalanche breakdown process – dominates for your Zener diode. Assume 25°C. Show work i.e. equations AND values used. Clearly report your values.

**Conclusions:** Type your conclusions for this lab. Discuss the findings of your analysis and their significance with respect to the theory:

- What does your data indicate about your diodes’ behavior according to the realistic diode model? What regions did your particular diode have or didn’t have?
- How did you use \( R_s \) in your analysis?
- Are the current values of the expected order of magnitude (section 3.4.2)? What mechanism does your Zener use?
- What did your analysis say about your zener diode’s doping (section 3.5.2)?
- Be coherent and terse; organize your paragraphs for better reading (and grading!)

**Attach:** Signed instructor verification form.