WEEK 2--ECE 230L LABORATORY

Electrical Characterization and Parameter Extraction of Silicon PN-Junction Diodes

1. Objectives of this Laboratory

The objectives of this laboratory session are as follows:

- to measure the $I_D(V_{PN})$ current-voltage characteristics of a PN-junction diode using standard test and measurement equipment,
- to measure the $I_D(V_{PN})$ current-voltage characteristics of a PN-junction diode using LabVIEW,
- to evaluate the limitations of the electrical measurements as compared to theory, and
- to explore one technological applications of PN – junction diodes in the form of either power electronics (half-wave and bridge rectifiers) or LED lighting

Note: *A detailed introduction of the use of LabVIEW can be found on the Sakai site.*

2. Electrical Characterization of a Silicon PN-Junction Diode

In this laboratory, you will measure the static current-voltage $I_D(V_{PN})$ characteristics of silicon PN-junction diode 1N4148 manually with standard test and measurement equipment and using LabVIEW. The measurement set-up includes the following:

- JAMECO JE25 Solderless Breadboard
- JAMECO Wire box with wires (various sizes and colors)
- HP E3631A Triple Output power supply
- Agilent 34410A multimeter

A schematic cross-section and circuit symbol of the PN-junction diode is shown in Figure 1.

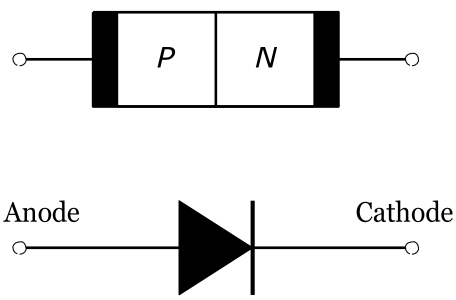

Figure 1 Schematic cross-section (top) and circuit symbol (bottom) of a PN-junction diode.

The arrow indicates the direction of current.

Using the LabVIEW software installed on your laboratory workstation, obtain the I_D (V_{PN}) static current-voltage characteristics of the silicon PN-junction diode 1N4148 by carrying out the following steps:

1. Obtain a 1N4148 diode from the parts bins.
2. Build the circuit shown in Figure 2 using the E3631A Power Supply's +6 V source and the 34410A Digital Multimeter as an Ammeter with the diode connected in series. The maximum continuous current that the 1N4148 diode can conduct is 200 mA (see datasheet). An alternative way to protect the diode from excessive currents is to use a series resistor. Because the diode current depends exponentially on its bias voltage, if the power-supply voltage were inadvertently set to its highest voltage level (6 V for the 6 V supply used in this experiment), an excessive current could flow through the diode which would damage it permanently. The resistor prevents this condition from taking place. **What is the value of the series resistor that you must choose for the 1N4148 diode (with a 200 mA maximum current) attached to this 6 V power supply?**

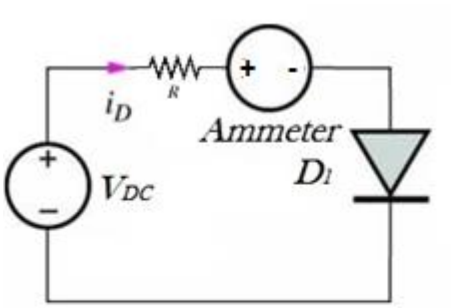

Figure 2 PN-Junction diode test circuit

3. Apply a small voltage, 0.01V to the test circuit; record the current through the diode.
4. Increase the voltage to the circuit slowly and determine approximately the voltage at which the diode begins to conduct current.
5. Sketch a plot of measured V_{DC} vs. I for this circuit.
6. Now, LabVIEW will be used to more accurately measure the above diode characteristics. The LabVIEW program will automatically limit the maximum value of the current that can pass through the diode. Note that no additional settings of power supply and multimeter are required. LabVIEW will be used to control these digital instruments remotely using the GPIB (general-purpose interface bus) cable connecting the computer with the measurement equipment.
7. Run the LabVIEW Virtual Instrument (VI) called: singleloop.vi You will have to select the voltage start and stop points carefully, as well as the step size to obtain an accurate $I_D(V_{PN})$ curve for the diode. **You will want to have enough data so that you can see the graph curving at the end.** The

1N4148 diode data sheet should be consulted before setting the measurement. LabVIEW data can be saved by right clicking on the graph and selecting "export data".

8. To account for the accuracy of your voltage source in producing its values as set by LabVIEW, it is important to measure the voltage V_{PN} directly across the diode. Measuring the voltage V_{PN} directly across the diode will give you the actual voltage across the diode for each input voltage step used in LabVIEW; this voltage, V_{PN}, will be plotted versus I_D to obtain the diode I-V curve. To measure the diode voltage V_{PN}, you will have to run singleloop.vi, while measuring voltage in LabVIEW. These programs will allow you to set the start and stop voltages of the power supply at your bench and measure corresponding output voltages. Measure the voltage across the diode using the same power supply start and stop values as step sizes that you used to measure the current, I_D of the 1N1418 diode. Save this file. This V_{PN} file together with the I_D file you saved will allow you to plot the diode current I_D vs. the diode voltage V_{PN}. Re-save the file using the naming convention above. You need only save ONE file. You should measure several 1N4148 diodes if you are interested in learning about the diode-to-diode variation in the $I_D(V_{PN})$ characteristics. These variations will be reflected as variations in the extracted parameters.
9. Keep your diode in case you need to re-characterize it later. Repeat the above experiment to measure the reverse-bias current-voltage characteristics of your diode. One way to do this is to reverse the polarity of the power supply in the above circuit. Run singleloop.vi in LabVIEW a few times using different start and stop values and step sizes until you are satisfied with the resulting $I_D(V_{PN})$ reverse-bias diode characteristics. Once again, be sure to measure the diode current I_D and the diode voltage V_{PN} using singleloop.vi. When you are satisfied with your results, save one file for later analysis. Make sure to save the data as a .xls file.

3. Theoretical curve of the Current-Voltage Characteristics of a PN-Junction Diode

There are a large number of parameters used in the representation of a PN- junction diode, but only the most commonly used parameters will be considered here. The first two parameters are related to the representation of the diode current-voltage behavior assumed to be in the following form:

$$I_D(V_{PN}) = I_S e^{(\frac{qV_{PN}}{\nu k_B T}-1)}$$

This relationship is written to obtain an empirical fit to experimental data and was not derived from physics-based principles. For $V_{PN} > 3k_BT/q$, which is approximately 75 mV at room temperature, Eq. (1) reduces to the following:

$$I_D(V_{PN}) \cong I_S \exp\left(\frac{qV_{PN}}{\nu k_B T}\right)$$

The values most commonly specified include the following: the saturation current, IS, the emission coefficient, N, the series resistance, RS, and the junction capacitance, CJO, the transit time, TT (default=0 sec), the reverse-bias breakdown voltage, BV, and the reverse-bias breakdown current, IBV.

The ideality factor ν in the above equation may be found from the following formula:

$$\nu = \frac{V_{PN2} - V_{PN1}}{\frac{k_B T}{q} \ln\left(\frac{I_D(V_{PN2})}{I_D(V_{PN1})}\right)}$$

Note that the experimentally measured ideality factor ν often ranges from 1 and 2.

The third parameter is the series resistance RS. The fourth parameter in the table is the energy gap EG which will depend on the semiconductor being used and the temperature. The fifth parameter in the table is the reverse breakdown voltage BV. The current at the breakdown voltage is IBV, which is the sixth parameter. These first six parameters in Table 1 describe the static behavior of the PN-junction diode. Both BV and IBV are specified as positive numbers.

The next two parameters are the transit time TT and the zero-bias depletion capacitance CJO. They describe the $C_{pn}(V_{PN})$ characteristics of the PN-junction diode. The total capacitance C_{pn} of the PN-junction diode is the sum of its depletion capacitance $C_{pn\text{-}dep}(V_{PN})$ and diffusion (or storage) capacitance $C_{pn\text{-}diff}(V_{PN})$. If a PN-junction diode is reverse-biased, the depletion capacitance then dominates. If the PN-junction diode is forward-biased, both the depletion and diffusion capacitances are important.

4. Explorations (choose one):

(Option 1)

The PN-Junction-Diode Half-Wave and Bridge Rectifiers

One application of a PN-junction diode is to allow only the positive-going voltages of a time-varying input-voltage signal to pass to the output. Because a PN-junction diode allows current to flow through a circuit only in the forward direction, it can be used to allow the positive-going portions of an input signal to pass to the output while blocking the negative-going portions of the waveform. This kind of circuit is called a rectifier.

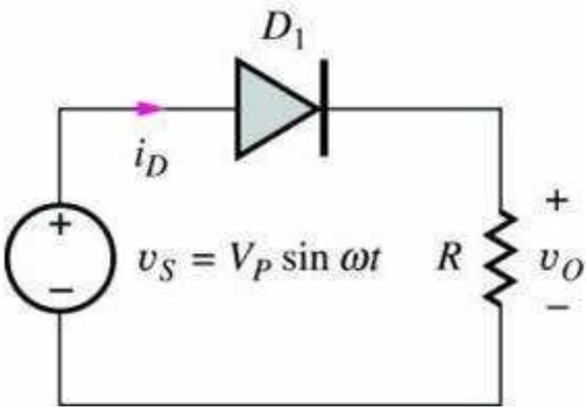

Figure 3 Diode Half-Wave Rectifier Circuit

1. Build a half-wave diode rectifier circuit using a Si 1N4148 diode, as shown in Fig. 3. Use a 5 V_{pp} sinusoidal input waveform from the function generator. Use a resistor value of 1 kΩ at the output.

- Observe the output voltage of the circuit as measured across the resistor on the oscilloscope. You should see that the positive-going portions of the input-voltage waveform are allowed to pass to the output node, while the negative-going portions of the waveform are not.
- Measure the peak voltage from the ground reference (GND or 0V) on the oscilloscope screen to V_{peak} of the rectified waveform. What do you notice about the maximum voltage of the rectified waveform? Is it greater than or smaller than the maximum peak voltage of the input waveform? What is the difference in Volts? Is this difference value a characteristic of the diode behavior?
- Last, add a large capacitor (1 uF) to the output of this circuit; the capacitor should be connected from Vo+ to GND (i.e. in parallel with the output resistor, R). Now observe the output waveform. What has happened? How could this circuit be useful?

2. Repeat the above experiment using a Ge diode in the lab.

It is possible to improve upon the above circuit by using both halves of the sinusoidal input voltage. To do so, more than one diode is required. An intermediate improvement would be to add a second (2nd) diode: this circuit is referred to generally as Full Wave

Rectifier. A common and even better implementation of the Full Wave Rectifier utilizes four (4) diodes: it is referred to as a Bridge Rectifier. (The reason it is even better than a common Full Wave Rectifier is because it does not require a centrally tapped DC reference point.) Figure 4 shows a Bridge Rectifier circuit. To provide a new ground for the full-wave rectified circuit, **a transformer between the power source and the diodes is required.** This allows both the positive- and negative- going portions of the input-voltage waveform to pass to the output node. (This circuit does not need to be built in lab.)

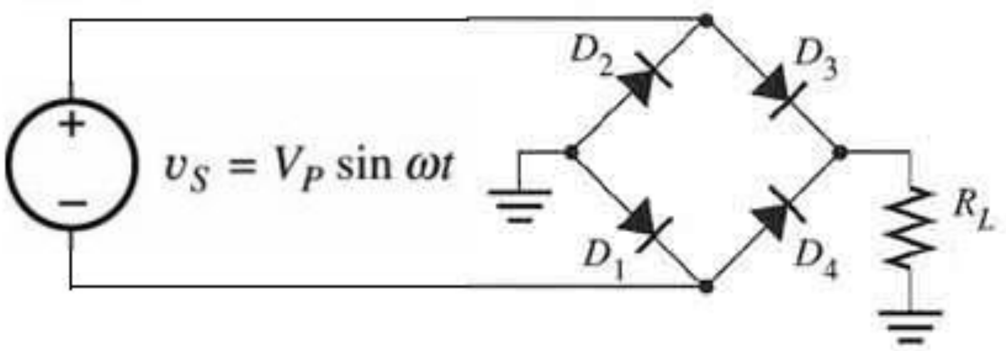

Figure 4 Bridge Rectifier schematic

(Option 2)

LED Lighting

A recent technological application of LEDs can be seen in area of new, efficient lighting. In this Exploration, you will look at exactly how much more efficient consumer LED lights really are as compared to standard incandescent light bulbs. You will need to design a phototransistor circuit and build it on a standard breadboard of testing purposes. You will also measure the I-V characteristics of an LED from the light bulb after taking apart the bulb. The I-V curve of the LED from the bulb will be compared to the Silicon 1N4148 diode you tested in the laboratory exercises.

1. First, plug the power measurement device into a standard socket in the power-strip at your lab bench. This unit will indicate how much power a device in drawing when plugged in.
2. Obtain a standard incandescent light bulb. Screw it in to the desk lamp provided in lab. Now, plug in the lamp into the outlet with power measurement installed. Turn on the light bulb. Record how much power is being drawn.
3. It is important to measure the luminous output of the light bulb. To do so, build a circuit using a photodiode available in lab to measure current flow when the light bulb is on. Be sure to accurately record the distance of the light source from the phototransistor.
4. Repeat the above steps for the LED light bulb making sure to record power drawn from the LED light bulb when plugged in and the current flow through the photodiode circuit you designed. To make a fair comparison of luminous intensity of the LED lamp, the LED light and phototransistor should be placed at the same source distance as the incandescent light bulb was above.
5. Be sure to take a look at the LED light bulb that has been disassembled for you. Note that the bulb consists of several LED pads arranged on a central metal shaft. This metal shaft serves the dual purpose of positioning the LEDs around the glass bulb and provides a heat-sinking mechanism. The electrical circuit that powers these LEDs produces a 220VDC voltage. The LEDs pads when observed closely consist of many individual LEDs. Several of these LED pads have been carefully removed for testing.

(Option 3)
Colored LEDs

LEDs are available in a variety of colors and wavelengths to suit the needed application. For instance, different colors may provide better feature visibility depending upon lighting conditions. Colored LEDs have been used extensively in the automotive industry, aviation, for traffic signals, and in multi-color displays. In optical applications, a precisely known spectrum allows tightly matched filters to be used to separate informative bandwidth or to reduce disturbing effects of ambient light. LEDs usually operate at comparatively low working temperatures, simplifying heat management and dissipation. This allows the use of plastic lenses, filters, and diffusers. LEDs are durable and robust lighting sources that last much longer the incandescent light sources and can operate in harsh environment. Even weather and waterproof units have been designed for use in the food, beverage, and oil industries. In this Exploration, you will look at the I-V characteristics of several colored LEDs and compare them to the Silicon diode characterized in lab: you will compare the I-V characteristics of Red, Yellow, and Green LEDs available in the laboratory to the Silicon 1N4148 diode you tested in the laboratory.

1. Create forward-biased I-V curves only for the Red, Yellow, and Green LEDs available in lab. Use the circuit set-up described in the laboratory exercise as well as the automated test and measurement scripts provided in LabVIEW to take measurements of the LEDs. Measure Red, Yellow, and Green LED I-V curves and plot them on the same graph as the Silicon 1N4148 diode measured in the laboratory exercise above. For each of the LEDs, determine 1.) the 'knee' voltage where the diode turns on, 2.) the saturation current, I_S, 3.) the ideality factor, γ, and 4.) the series resistance, R_S. Also determine 5.) the current at which the LED begins to become damaged, and 6.) the voltage and current when the LED completely stops functioning (i.e. blow it up—this may require as much as 10V). Be sure to dispose of any damaged LEDs so that they do not get mixed in with good LEDs in the lab. After you have destroyed an LED, throw it away to prevent it from getting mixed back in with good LEDs in the lab.

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5. Questions

1. Referring to the PN-junction diode current-voltage relationship $I_D(V_{PN})$ above, define all parameters and variables in the relationship.

2. Plot the $I_D(V_{PN})$ characteristics obtained using LabVIEW on a log-linear plot. The y-axis label should be '1N4148 Diode Current, I_D (A)' and the y-axis labels reading for example 10^{-9}, 10^{-8}, 10^{-7}, 10^{-6}, 10^{-5}, 10^{-4}, 10^{-3}, etc. The x-axis should read 'Diode Voltage, V_{PN} (V)' and the x-axis labels should read 0, 0.1, 0.2, 0.3, 0.4, 0.5, etc. Make sure to have enough data points to generate a smooth curve. Use the measured value of V_{PN} (from your V_{PN} vs V plot) across the diode in this plot, i.e., do not assume that the voltages supplied by the power supply are those across the diode.

3. From the above log-linear plot of the I-V characteristics of the 1N4148, determine the saturation current, I_S, the ideality factor, γ, and the series resistance, R_S. (refer to the slides on Sakai)

4. To the above plot, add the theoretical PN-junction diode $I_D(V_{PN})$ characteristic curve. Use the parameters calculated in question 3. Vary the parameters, if necessary, to match the **log-linear** portion of the experimentally measured data.

5. Comment on the values of I_S and v that yield the best fit to the data. How do your experimental and varied values compare with those given in the diode-manufacturer data sheets? (For R_s use Figure 2, curve 2, on the Vishay datasheet. I_s can be found under reverse current, and ν should be about 2.3.)

ECE 230L PN Junction Diode Grading Rubric

	Points Possible
Circuit Diagram (all components labelled)	2 points
Sketch and knee voltage	4 points
Plots of $I_D(V_{DC})$	7 points
Series resistor value to prevent diode damage	2 points
Question 1	10 points
Question 2	10 points
Question 3	10 points
Question 4	10 points
Question 5	10 points
- include percent error	
Exploration	30 points
Quality of thought/analysis	5 points