Lab 3. Measurement of Diode Characteristics

In this lab, you will learn about a diode and its characteristics. The diode is a two-terminal electronic component that conducts current primarily in one direction. It has low resistance in one direction, and high resistance in the other.

Using simulation and the NI ELVIS III, you will learn about the fundamental behavior of diodes by simulating a circuit in Multisim. Then, you will confirm that behavior by building a circuit and measuring the current through diode.

Learning Objectives

After completing this lab, you will be able to:

1. Capture and analyze the relationship between voltage and current in a semiconductor device.
2. Select semiconductor devices based on circuit requirements
3. Identify the device parameters in semiconductor applications which drive design decisions
4. Describe the relationship between the terminal characteristics of a transistor and the internal operation of that device.
5. Design and construct an oscilloscope test set to plot I-V characteristics of a two terminal device for a specified voltage and/or current range.

Required Tools and Technology

Platform: NI ELVIS II/II+ Instruments used in this lab: ● Instrument 1: Function Generator ● Instrument 2: Oscilloscope ● Instrument 3: Variable Power Supply **Note:** The NI ELVIS Cables and Accessories Kit (purchased separately) is required for using the instruments.	View User Manual: https://bit.ly/36DFFrv https://bit.ly/36CnQZH (Credit to Clemson University) View Tutorials: https://bit.ly/35Ae9Kc (Credit to Colorado State University) Install Soft Front Panel support: https://bit.ly/2NbhTv6
Hardware: NI ELVIS II/II+ Default Prototyping Board	View Breadboard Tutorial: http://www.ni.com/tutorial/54749/en
Hardware: Electronics Kit	Components used in this lab: • Various value of resistors • Diode, 1N4148 or similar
Software: NI Multisim Live	Access online http://multisim.com View Help http://multisim.com/help/

1. Background Information

A semiconductor generally means any material which is neither strictly conductive nor insulating. However, this only scratches the surface of what semiconductors are capable of. Modern computing is built almost entirely upon transistors and other semiconductor components, often integrated into a silicon substrate. All digital computation is, at its most basic, a process of generating, storing, and comparing analog values. These tasks, as well as a host of purely analog processes are accomplished by the application of transistors and diodes.

Whether a passive component such as a diode, or an active component like a transistor, understanding how semiconductors function both in static and dynamic states is essential to be an effective electrical designer.

1.1. The Ideal Diode

You can think of an ideal diode as a one-way valve for current. If the voltage at the anode exceeds the voltage at the cathode, then the diode is "forward biased" and ideally will conduct current with no resistance. Conversely, if the cathode voltage is higher, then the diode is "reverse biased" and should ideally have infinite resistance, allowing zero current flow. The terminal characteristic of the ideal diode is shown in Figure 1.

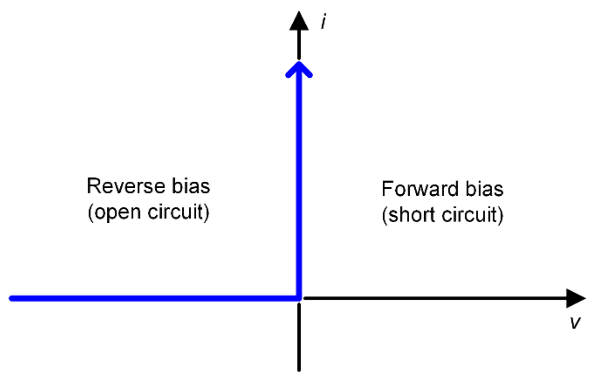


Figure 1. Ideal diode I-V characteristics

Obviously, since one state requires infinite current throughput, and the other infinite resistance, it is not going to be possible to implement an ideal diode in hardware.

PASSIVE PHASE SHIFTS:

- The loop is valid if the component (or circuit) contains inductors or capacitors.
- The loop is due to oscilloscope input capacitance or stray circuit capacitance.
  - For effects due to oscilloscope input capacitance, set the input coupling to DC.
  - For effects due to stray circuit capacitance: reduce the signal frequency.

ACTIVE PHASE SHIFTS:

- The component heats up as increased voltage is applied and cools down as the voltage is reduced. The loop is valid.

The characteristics of an ideal diode and the implemented 1N4148 general diode (pn junction) are listed below.

Specifications for the 1N4148 Fast Switching Diode (as given in a datasheet):

$V_{(BR)}$	Reverse Breakdown	75V for IR = 5µA
I_R	Static Reverse Current	25 nA @ V_R=20V
V_F	Static Forward Voltage (worst case)	1 V for I_F = 10 mA
	(typical)	0.8 V for I_F = 10 mA
P_d^{Max}	Maximum Steady State Power Dissipation (Operation with less than 100 mA is recommended -- it gets HOT!)	500 mW for 25 °C

The characteristics in table 1-1 are the principal values which define the functionality of a diode. The physical design of diode will alter the operation and characteristics of the diodes. Some diodes are designed specifically to be close to an "ideal" pn junction diode for a specific characteristic, alternately others are intentionally designed to operate and behave differently. This second option is key to some of the special types of diodes we will discuss in this section.

1.2. Real-world response of a diode

The typical shape of the I-V curve of any diode will look something like that shown in Figure 2.

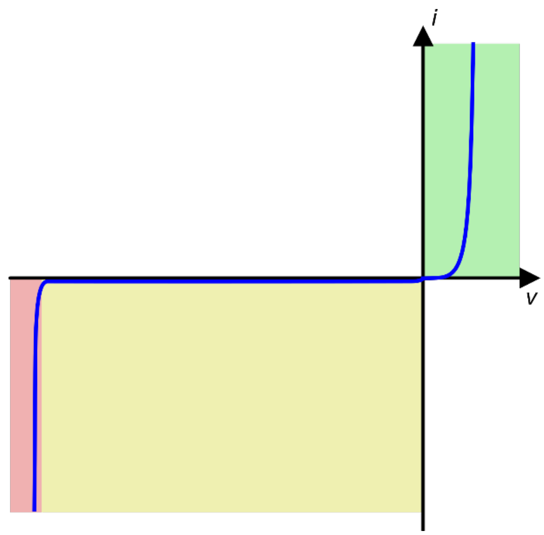


Figure 2: Typical diode terminal characteristic

There are three areas of interest, which have been color-coded in the figure. The green area is the forward biased region, in which the current rapidly approaches infinity (damage to the diode due to overcurrent notwithstanding). Notice that the forward current does not begin to increase until the voltage is well above zero. The voltage at which this occurs is the *forward* voltage of the diode. The yellow region is the reverse biased region in which the diode completely (or very nearly completely) blocks reverse current flow. This region is between zero and $-V_{ZK}$ which is the voltage of the "knee" of the I-V curve, or the voltage at which the curve transitions from being generally constant-current to constant-voltage. Finally, when the voltage is below $-V_{ZK}$, the diode enters the breakdown region, in which the current rapidly approaches negative infinity.

Plotting the same curve with a greatly expanded scale for the current gives a better view of the actual behavior in the reverse region. There is a small negative current flow referred to as the reverse leakage current.

1.3. Modelling a diode

As you can see in Figure 2, the behavior of a diode is non-linear and cannot be easily fit using a single curve, so we will treat the forward and reverse regions separately. In the forward region, the I-V curve is approximated by equation 1.

$$i = I_s(e^{v/V_T} - 1) \qquad \text{(Equation 1)}$$

where I_s is the saturation current of the diode, which is extremely small, but also very susceptible to changes in temperature. V_T is the thermal voltage of the diode which is given by equation 2:

$$V_T = 0.0862T \qquad \text{(Equation 2)}$$

where T is the temperature in degrees Kelvin. For the purposes of this lab, we will assume room temperature of 25 degrees Celsius, or 298 degrees Kelvin, giving a rough value of 25 mV for V_T. The effect of temperature on the forward operation of a diode is examined in more detail in the Temperature Sensing application lab.

The behavior of the diode in the reverse and breakdown regions is actually quite complicated but is modelled as two linear regions. For voltages between zero and $-V_{ZK}$ the current is roughly constant and is given by the reverse leakage specification for the diode. For voltages below the breakdown voltage, the relationship between voltage and current is roughly linear with an extreme slope. For most applications, we can assume the slope of the I-V curve below V_{ZK} to be essentially infinite, however in special cases such as the Zener diode this slope may be given in the device specifications.

1.4. Types of diodes

Besides the general (pn junction) diode, there are three variants of the diode which we will examine in this lab: Schottky, Zener, and light-emitting diodes. Each of these diode variants function in the same manner as the general diode, however they have key differences which are specific to their physical properties.

The **Schottky barrier diode** differs from a general pn junction diode in that, it uses a metal-semiconductor junction, rather than a silicon-silicon junction to rectify the current flow. The difference being that this type of junction has a lower forward voltage and faster switching time than a general diode.

The **Zener diode** is usually structurally identical to a general pn-junction diode, however it is designed to operate in the breakdown region. These are usually used to provide a predictable current flow at a desired breakdown or “Zener” voltage.

Light-emitting diodes as the name implies, emit light when sufficient forward current is present. These diodes are generally designed to maximize light output efficiency, rather than functionality as a diode, however they *are* still diodes, and can be used as such in addition to their light emissive properties.

1.5. A Quick Method for Testing Diodes

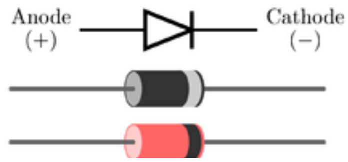


Figure 3. Diode circuit symbol with anode/cathode labeled

Figure 3 defines the device current and voltage polarity convention for diodes. Conventional current flows from the anode (P) to the cathode (N). The terms, anode and cathode, appear in technical literature regarding semiconductor diodes.

If the device voltage (v_d) and current (i_d) are positive, the diode is forward biased. In this case, the voltage and current are the forward voltage (v_F) and forward current (i_F). Capital letters (V_F, I_R, etc.) are used for DC voltages.

If the device voltage (v_d) and current (i_d) are negative, the diode is reverse biased. In this case, the voltage and current are the reverse voltage (v_R) and reverse current (i_R).

Quick Diode Test:

1. Determine voltage polarity of ohmmeter leads. (Use scope or other meter).
2. Measure resistance of diode in both directions.
    - HIGH resistance indicates REVERSE bias. NP direction.
    - LOW resistance indicates FORWARD bias. PN direction.
3. If both directions measure the same, diode is dead or ohmmeter range is ineffective.

Almost any DMM will measure the reverse resistance of a diode. Many will not measure the forward resistance. To effectively test a diode, the equivalent source voltage of the ohmmeter must be large enough to “turn the diode on” and the equivalent source resistance of the ohmmeter must be small enough to allow enough current to flow.

1.6. I-V Plots of Two-Terminal Devices

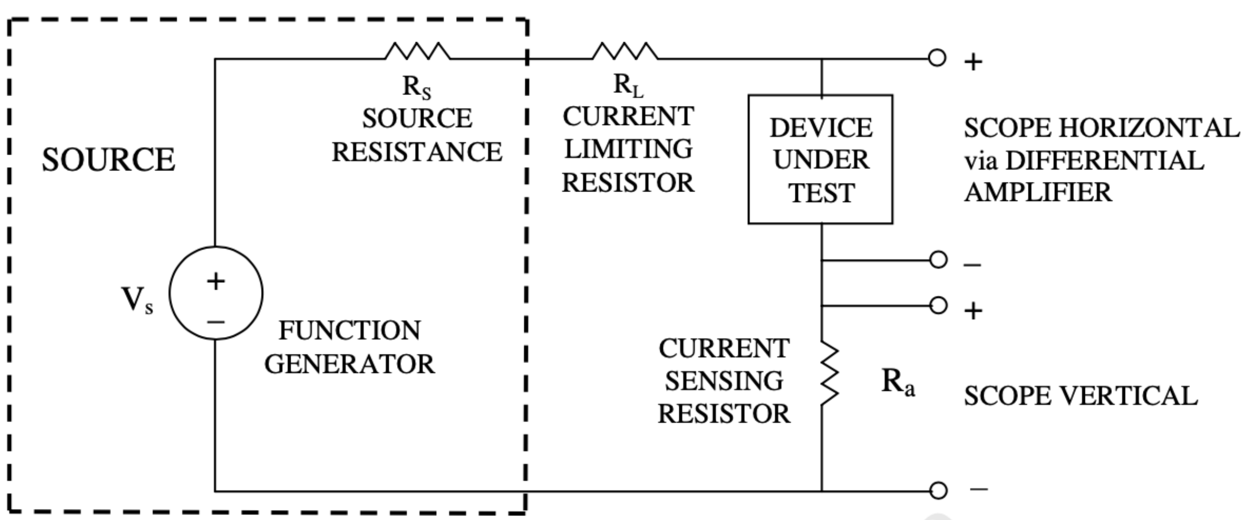


Figure 4. Test set to display the I-V characteristics of a two-terminal device

The circuit shown in Figure 3 is used to display the I-V characteristics of two-terminal devices. Circuit components are chosen so that the desired test can be performed without exceeding the ratings of the Device-Under-Test (DUT). Examples 1 and 2 illustrate test set design. The following is a quick reference summary of the components.

- **Function Generator.** The test waveform is created with the function generator. Its waveform, amplitude, offset, and frequency controls are adjusted to cause the desired voltage at the device under test. Care is taken to avoid exceeding the positive and negative voltage limits (maximum voltage ratings) of the device. If the maximum ratings are known, it is easy to avoid exceeding them. Otherwise, common sense and gradual increases are used. The output impedance, R_S, of the function generator must be considered in all test set designs.
- **Current Sensing Resistor, R_a.** The voltage across a current sensing resistor is called a burden. Two factors control the choice of the current sensing resistor: reasonable burden and convenience in reading the display.
  Example: Current to be sensed is 0 to 10 mA. The maximum source voltage is 5 volts. A 1 KΩ sensing resistor won't work! 100 Ω or 10 Ω would be a better choice.
- **Current Limiting Resistor, R_L.** This resistor is added to the circuit when necessary. Its purpose is to ensure that the DUT operates up to the desired test current maximum. To select the current limiting resistor:
  $$(V_{S,max} - V_{D,\ test}) / I_{D,test} < R_S + R_a + R_L$$
  where V_S is the maximum source voltage, V_D is the voltage across a typical device at the maximum test current, and I_D is the maximum test current. If V_D is unknown, then begin by assuming it to be 0.
- **Differential Amplifier.** Differential amplifiers measure potential difference. Either input may be connected to any point in a circuit. To ensure that both input voltages are within the operating range of the amplifier, circuit and amplifier commons are connected. The output of your *diff-amp* is connected to an oscilloscope input using a (x1) probe.

1.7. Example 1. Determine the I-V characteristic of a 4.7 KΩ resistor from –4 to 8V.

This type of test if performed thousands of times each day. Resistors are tested to see if they really are linear (obey Ohm's Law) over a specified voltage range. The following procedure is not as detailed nor as accurate as the typical test. However, it is the same test.

Step 1. Answer the question: Will the maximum device ratings be exceeded?

Resistors from the CK-1 Kit have a rated power dissipation of 0.25 Watt. It is good practice to limit the dissipation to 0.125 Watt.

The maximum voltage across the resistor is to be 8 volts. In this case, the power dissipation will be (8V x 8V) / 4700Ω = 0.014 Watt. **The test is safe!**

Step 2. Choose the voltage source.

The NI ELVIS II/II+ function generator has R_S = 50Ω. Its maximum range is ± 10V. So, it can deliver a –5 to +10 V triangle wave to an open circuit.

Step 3. Choose the current-sensing resistor.

The maximum test voltage is 8 V. The function generator can create 10 V. Therefore, 2 volts is available for current sensing. At 8 volts, the device current will be (8V / 4700Ω) = ± 1.7 mA.

If a 1 KΩ sensing resistor is chosen, the device current is limited to 1.74 mA because 10 V / (4700 + 1000 + 50) = 1.74 mA. Then, the voltage across the 4700 Ω resistor is 1.74 mA x 4700 Ω = 8.18 V. That is close enough.

Step 4. Choose the current limiting resistor. (This step can't be omitted.)
No current limiting resistor is needed. Why?

2. Exercise

2.1. Simulation

Before experimenting on actual diodes on your TI Analog Electronics board, we will use NI Multisim to run a SPICE simulation of a diode and look at the effects of changing various parameters on its characteristics and performance.

1. Open a new Multisim circuit. Add a generic virtual diode to the schematic and connect the anode to the positive output of an AC source. Ground the remaining terminals as shown in Figure 3:

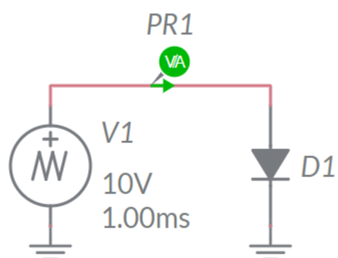


Figure 5: Diode simulation circuit

2. Add a voltage/current measurement on the connecting trace as shown.
3. Adjust the voltage source to a ±10 V triangle wave with a period of 10 ms, and a fall time of 10 μS.
4. Run the transient simulation and adjust the graphing window so you can see a single rising slope of the voltage signal. Record the resulting current waveform. Make note of the relationship between this waveform and the diode terminal characteristic.
5. Experiment with the four primary model parameters (IS, RS, N, and BV) found under edit model in the value tab. Record the effect they have on the current waveform. Note that you will have to stop the simulation to change the RS parameter.
6. Open the datasheet for the BAS16 diode. Update the model parameters for the general diode to align with the datasheet.
7. Capture the terminal characteristic waveform for your BAS16 model.

2.2. Experiments

In this activity, you will investigate the I-V characteristic of a 1N4148 diode.

1. Use the Multisim to set up the following circuit:

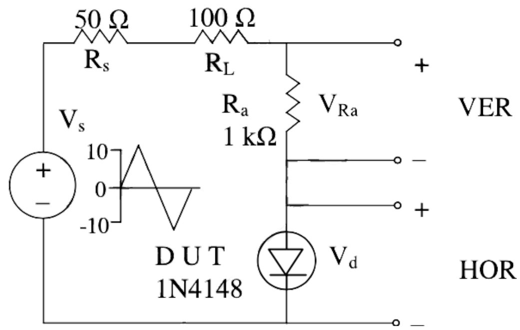


Figure 6. Circuit diagram for the experiment

2. Implement Example 1 (Section 1.7) to measure a diode using a source that ranges from –10 V to +10 V. Limit the typical device forward current to approximately 8 mA. It is expected that the forward voltage of the diode will be less than 1.0 V at 8 mA. However, this test is designed to gather statistics for a faulty batch of diodes. A test range of ± 10V is required

Step 1. Answer the question: Will the maximum device ratings be exceeded?
$V_{R,max}$ = 75 V, Pd, max = 500 mW
$V_{R,max}$ will not be exceeded.
The expected worst case power is 8 mA at 1.0 volts, 8 mW. Absolute worst case is about 8 mA at 10V, ~80 mW. Therefore, the test is safe.
Step 2. Choose the voltage source.
The NI ELVIS II/II+ function generator has R_S = 50Ω. It can deliver a 20 Vpp triangle wave to an open circuit. Therefore, it can apply a 60 Hz triangle wave with up to ±10V amplitude. (±10.0V yields a convenient R_L. See Step 4.)
Step 3. Choose the current-sensing resistor.
Try 1000 Ω.
Step 4. Choose the current limiting resistor. (This step can't be omitted.)
Using Figure 1a, at 8 mA the typical diode voltage is estimated to be 0.75 volts. The current limiting resistor is computed using Equation 2.1:

$$(10.0V - 0.75V) / 8mA \leq 50\Omega + 1000\Omega + R_L$$

Therefore, R ≥ (1156 – 1050) = 106 Ω. Choose R = 100. I_F = 8.04 mA.
Note: $R_S + R_a + R_L$ = 1150Ω. The worst-case current is 10V/1150Ω = 8.7 mA.

3. Plot XY using the measured $V_{R,a}$ (vertical) and V_d (horizontal) as shown in Figure 7.

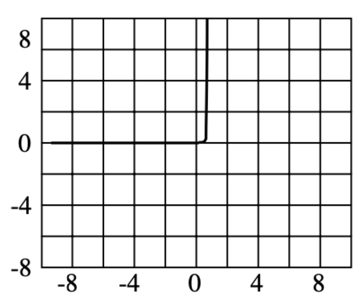
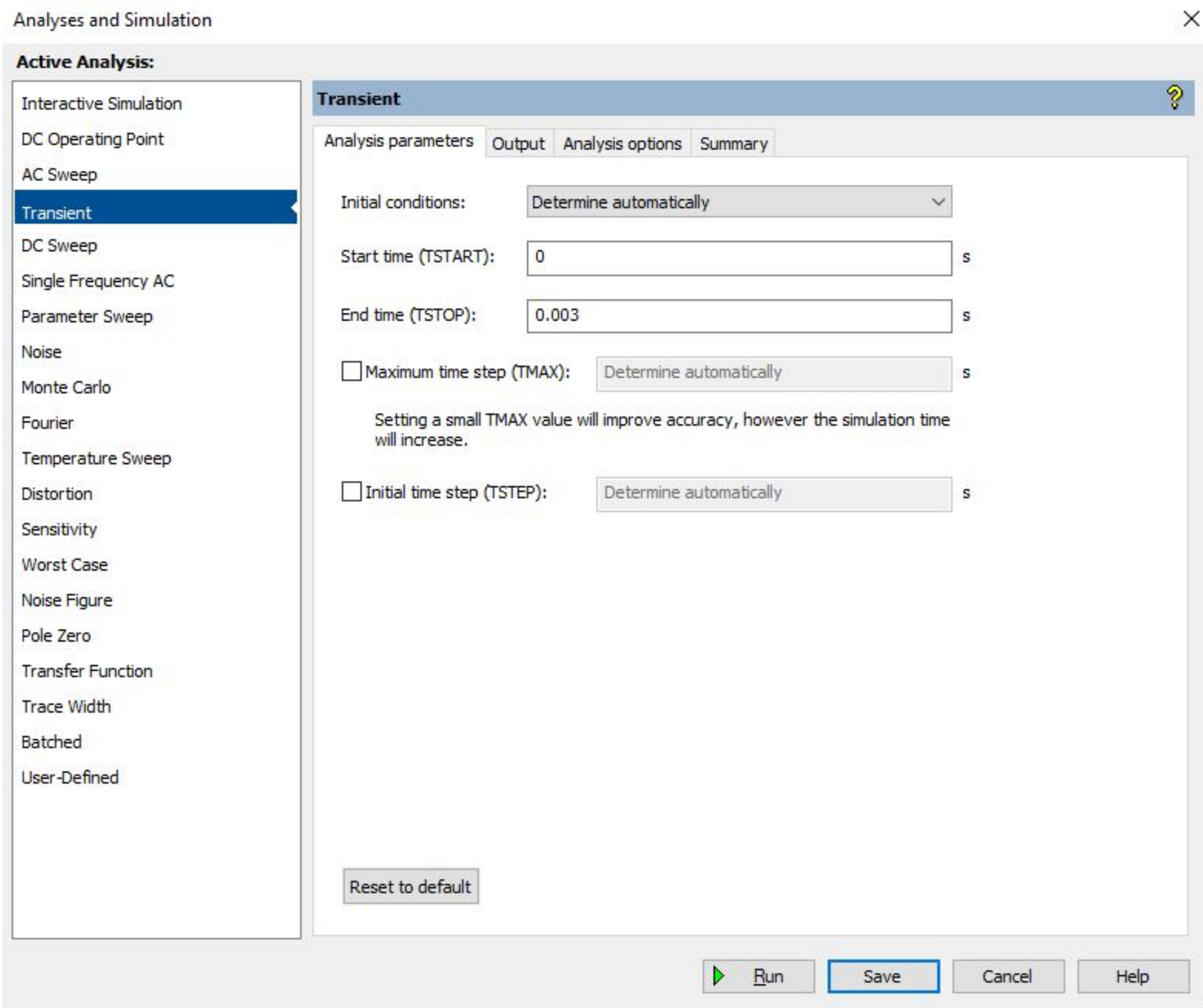
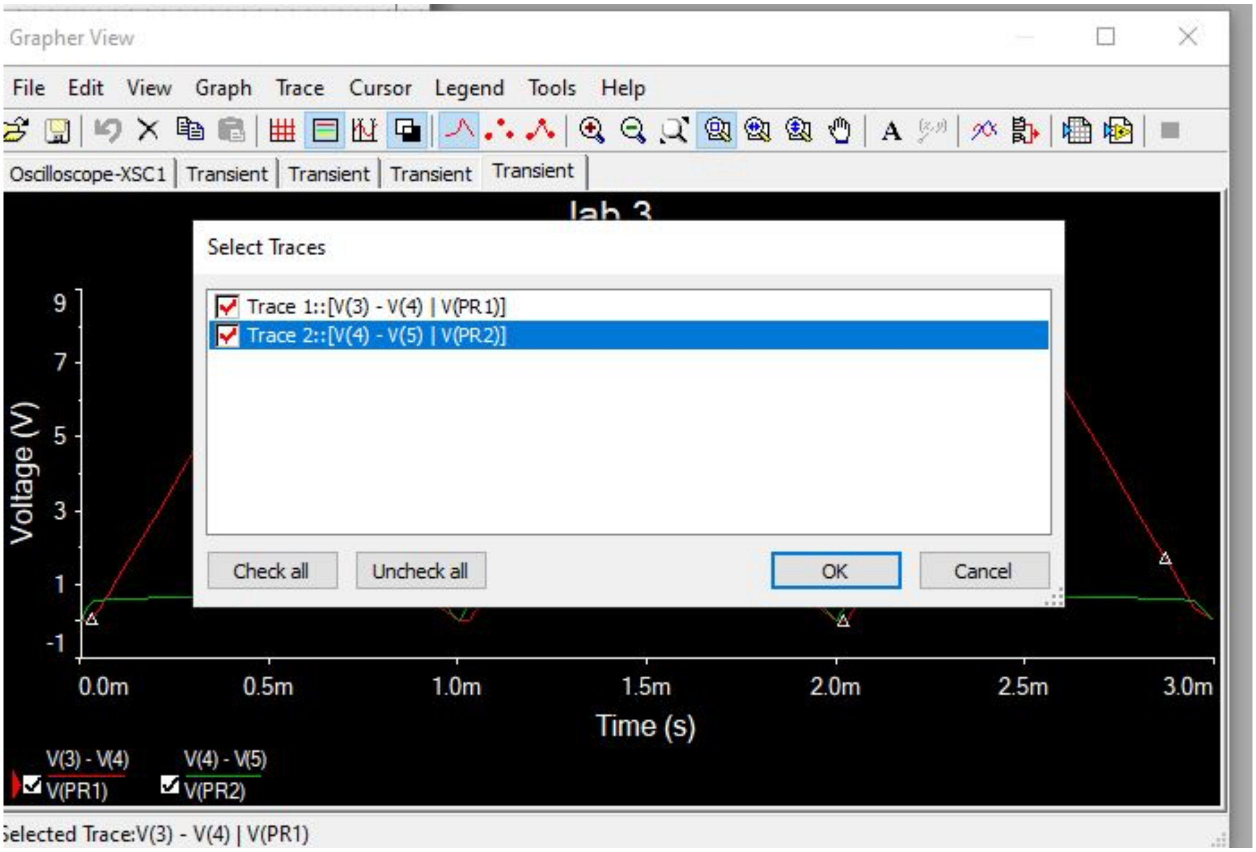


Figure 7. Expected result for the experiment

Step 1. Collect the voltages with respect to time using the transient plot with the settings given below.


Analyses and Simulation
Active Analysis:
Interactive Simulation
DC Operating Point
AC Sweep
Transient
DC Sweep
Single Frequency AC
Parameter Sweep
Noise
Monte Carlo
Fourier
Temperature Sweep
Distortion
Sensitivity
Worst Case
Noise Figure
Pole Zero
Transfer Function
Trace Width
Batched
User-Defined
Transient
Analysis parameters
Output
Analysis options
Summary
Initial conditions:
Determine automatically
Start time (TSTART):
0
s
End time (TSTOP):
0.003
s
Maximum time step (TMAX):
Determine automatically
s
Setting a small TMAX value will improve accuracy, however the simulation time will increase.
Initial time step (TSTEP):
Determine automatically
s
Reset to default
Run
Save
Cancel
Help

Step 2. Export the data to excel using under the Tools tab (highlighted) Once you click okay an excel file will pop up with the data saved
Note: Make sure that you selected both of the traces before continuing



Step 3: The resulting excel graph will have each selected trace, where the x is the time and the Y is the voltage. Use this to plot a scatter plot of the two-voltage data

4. Add one more 1N4148 diode in series (pointed the same direction)
5. Make another Excel graph

3. Analysis

These questions will help you review and interpret the concepts learned in this lab.

- Present your I-V curves for one and two diodes. The series combination should require about twice as much voltage to get the same forward current as the single diode. Why? Support your answer by drawing a line on the XY plot
- What would happen if an additional diode was placed in parallel? How much the current will be?

APPENDIX

The following is the template of the ECE 3313 report. Note that the report must be typed using Microsoft Words/Excel. Please download the template from the Canvas website.

ECE 3313 Lab X Report   Your Name

Title: Lab 1: Observation, Modeling, and Communication

NAME: **Partner:**

General Objective: One or two sentences that describe the objective of this specific lab.

1.0 Prelab Activities: If there is any

2.0 Background Activities: Read background information and summarize important theory, equation, etc.

3.0 Procedure: Describe step-by-step procedure, including circuit schematic, calculation, and etc.

4.0 Results: A lab often includes questions. Please include your answer under the result sections.

4.1 Simulation Results: Make sure to fully discuss about the results, figure, etc.

4.2 Experimental Results: Make sure to fully discuss about the results, figure, etc.

5.0 Conclusions

Remark: Your lab report should include ALL relevant calculations, pictures and work needed for completion of the experiment. Circuit output validation using Multisim is also required. Detailed explanations for decisions made throughout the lab need to be included in the Discussion section of your report as outlined in the Report Guidelines.

Disclaimer: Some of this lab contents includes portion of National Instruments' published resources in their website (NI.com). The permission is obtained from the National Instruments.