EC250 Laboratory Project #2
PN Junction Diode Modeling

Team Members:________________ ___________________
Date Performed: ________________ Lab Station #: _______

Parts needed: 1N4148 small-signal (small glass package) diode, 1N4004 power diode, red LED, three 1 kΩ resistors, breadboard, wire strippers, hookup wire.
Prelab Work: Please complete the requested formula derivation and also the simulated test data analysis required on p. 3 *before* coming to the laboratory. (See Appendix A for a review of using Microsoft Excel to plot data and fit the plot to a straight line.)

1. **The pn junction diode as a "unidirectional flow valve"**

Connect a small-signal 1N4148 diode in series with a 1 kΩ resistor and a 5 V dc power supply, as shown in Fig. 1. Begin by connecting the "bar" end of the diode package to the (-) terminal of the 5 V supply. Measure the voltage across the diode (*Vd*) and the voltage across the resistor (*Vr*), the sum of these two readings better equal 5.0 V. Indicate whether the diode is "forward-biased" or "reverse-biased". Now reverse the power supply terminals and again measure *Vd* and Vr. Repeat for the 1N4004 power diode and a red LED:

1N4148 small signal diode with "bar" end connected to (-) terminal of 5 V supply:

Vd = _________ Vr = _________ Fwd or Reverse Bias_____

1N4148 small signal diode with bar end connected to (+) terminal of 5 V supply.

Vd = _________ Vr = _________ Fwd or Reverse Bias_____

1N4004 power diode with bar end connected to (-) terminal of 5 V supply:

Vd = _________ Vr = _________ Fwd or Reverse Bias_____

1N4004 power diode with bar end connected to (+) terminal of 5 V supply.

Vd = _________ Vr = _________ Fwd or Reverse Bias_____

Red LED with short lead connected to (-) terminal of 5 V supply.

Vd = _________ Vr = _________ Fwd or Reverse Bias_____

Red LED with short lead connected to (+) terminal of 5 V supply.

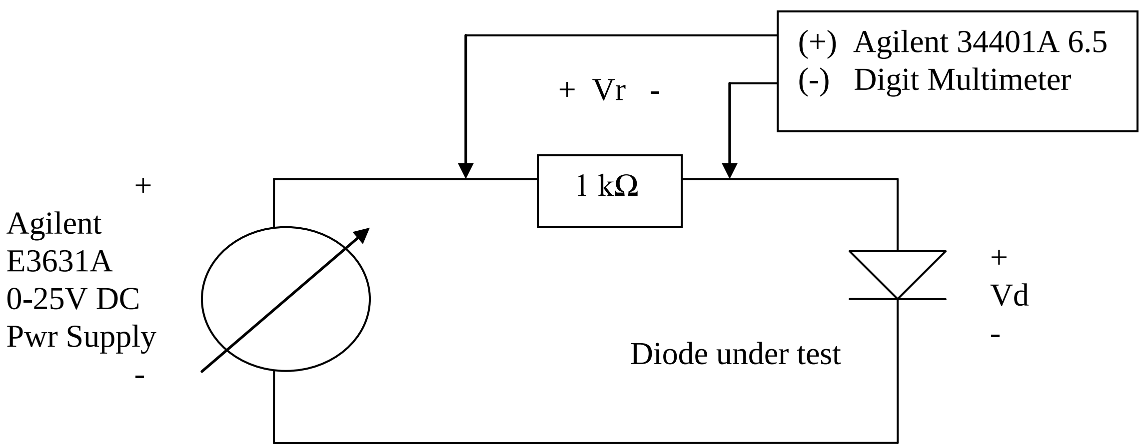
Vd = _________ Vr = _________ Fwd or Reverse Bias_____

In the space below, sketch each of these diodes, and below each sketch, draw the correct corresponding diode symbol. Does the "bar" on the diode package match with the bar (cathode terminal) in the diode symbol? Which lead of the LED, long lead or short lead (with the flattened rim), corresponds to the cathode terminal in the diode symbol?

2. Diode Model Parameter Determination (Finding n and Is)

We shall use a 1 kΩ resistor as a "current sensing" element, which is connected in series with a 1N4148 small-signal diode (connected so the diode will be forward-biased) and your variable dc bench power supply, as shown in Figure 1. Record the DVM voltage measurements across the diode, and also across the current sensing resistor (*Vd* and *Vr*). Use the Microsoft Excel spreadsheet program to make a table of your results. Start by entering side-by-side columns for *Vd* and *Vr*. Then, from the *Vr* column, calculate additional columns that display *Id* (in Amperes) and also the natural log of *Id*, ln(*Id*). Now vary your dc supply voltage so that you obtain data points corresponding to *Vr* = 20 V, 10 V, 5V, 2.5 V, 1.25 V, 0.625 V, 0.3125 V (or as close as you can come to these values.) Please remember that *Vr* is the voltage <u>across</u> the 1 kΩ resistor, ***not*** the dc power supply voltage, which must be set slightly higher than *Vr* to overcome the diode junction drop.

Figure 1. Diode I-V Curve Measurement Circuit



Repeat these measurements using a 1N4004 power diode and a Red LED. Attach this table (including you measurements for each of these three diodes) ***as "Exhibit A"***. From your recorded data, list the observed "diode forward voltage drop" at at a forward diode current of 10 mA for each of these three common types of diodes?

Small Signal Diode Forward Voltage Drop at 10 mA = ________ Volts
Power Diode Forward Voltage Drop at 10 mA = _____________ Volts
Red LED Forward Voltage Drop at 10 mA = _____________ Volts

For your small-signal diode data, use Microsoft Excel (see Appendix A) to plot Vd vs. Id and also plot *Vd* vs. ln(*Id*). Attach these two plots as "***Exhibit B***". Which of these two plots appears to be more "linear"? _______

In the space below, start with the ideal diode equation

$$Id = Is[\exp(Vd/(n*Vt)) - 1], \qquad \text{where } Vt = k*T / q$$

throw out the "-1" (go to the forward-bias approximation), and derive formulas for finding *n* and *Is* from the slope (*m*) and y intercept (*b*) of the linear least squares curve fit (linear regression) of the *Vd* vs. ln(*Id*) plot, which is of the form $Vd = m*\ln(Id) + b$. You may assume that the thermal energy per coulomb of charge is given by $Vt = kT / q = 0.026$ Volts, since our laboratory is at "room temperature". You should be able to show that

$$Is = \exp(-b / m) \quad \text{and} \quad n = m / Vt$$

Derivation of expressions for Is and n in terms of linear regression parameters m and b

First use the Microsoft Excel spreadsheet to perform a linear least squares regression analysis on the following PSPICE simulated data. Follow the instructions in Appendix A.

Vr	Vd(D1N4148)	Vd(D1N4002)
20 V	0.765 V	0.727 V
10 V	0.723 V	0.691 V
5 V	0.685 V	0.656 V
2.5 V	0.650 V	0.620 V
1.25 V	0.615 V	0.584 V
0.625 V	0.582 V	0.549 V
0.3125 V	0.549 V	0.513 V

Use the Microsoft Excel spreadsheet to perform a linear least squares regression analysis on this simulated *Vd* vs. ln(*Id*) data for the two diodes indicated, which were taken from the PSPICE "Eval" library. Attach your computer-generated EXCEL spreadsheet, as well as each of the two linear regression plots, as ***Exhibit C***. Fill in your regression results, and also calculate the corresponding *n* and *Is* values for each of the diodes right on the spreadsheet. You ***MUST SHOW*** that your answers come out to n = 1.981 and Is = 7.809×10^{-9} A, with $R^2 = 0.998$ for the

D1N4148 simulated diode, and n = 1.977 and Is = 1.439×10^{-8} A with R^2 = 1.00 for the D1N4002 simulated power diode. If you cannot get your spreadsheet to give the correct answers with these simulated data, please get help! ***No credit will be given for this entire laboratory if this check data cannot be properly analyzed in Exhibit C!***

Once you have gotten the correct answers for the simulated data, repeat your analysis with the live data that you have collected for the three "real" diodes you recorded in Part A, be sure to include your R^2 value, whose closeness to 1 indicates how reliably your measurements were. Include your spreadsheet as ***Exhibit D***.

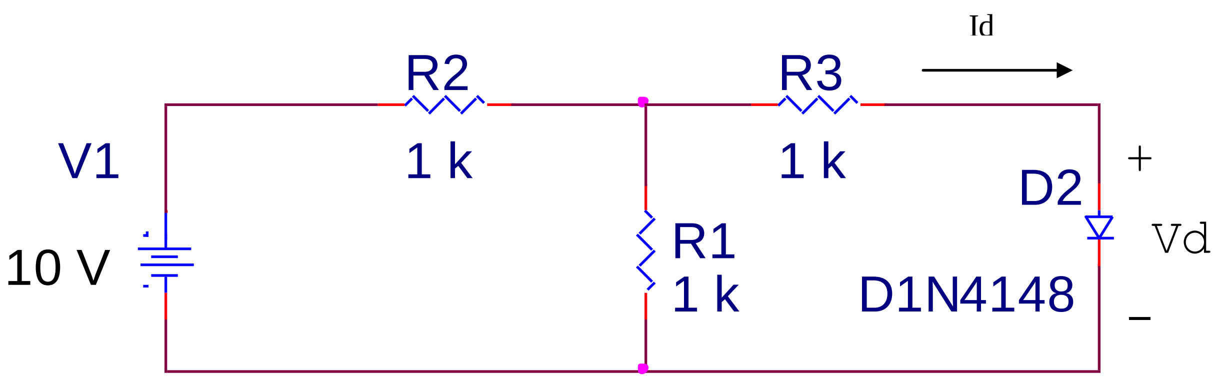
1N4148 m = ____________ b = ____________ n = ______ Is = _________A_ R^2 = ______

1N4004 m = ____________ b = ____________ n = ______ Is = _________A_ R^2 = ______

Red LED m = ____________ b = ____________ n = ______ Is = _________A_ R^2 = ______

3. Application of Diode Model to Solve for Vd and Id

Use the *n* and *Is* values obtained above for your 1N4148 diode to (numerically) solve (using MAPLE or MathCad) for the diode current *Id* and the diode voltage *Vd* when it is placed in the circuit drawn below. Start by finding the Thevenin Equivalent of what is seen looking out from the diode terminals. Include your MAPLE or MathCad work as "***Exhibit E***".



Finally, build this circuit and compare the measured *Id* and *Vd* values (*Id* can be found by measuring the voltage across resistor R3) with the predicted ones using the diode model. Fill in the summary table below:

Measured Values	Predicted Values	% Error (Pred – Meas) / Pred
Id =___________	____________	_______
Vd = _________	____________	_______

Now assume that the forward-biased diode has a constant 0.7 V forward voltage drop, and therefore it simply acts like a 0.7 V battery. Now re-calculate Id and compared with the predicted value for *Id* above. Calculate the % error incurred by adopting this MUCH SIMPLER diode model.

Method 1 Pred Id (from above) Using diode equation	Method 2 Pred Id using simplified Constant 0.7 V model	% Error (Meth2-Meth1)/Meth1
Id = ___________	Id = ____________	_____________

4. Using an LED as a "reciprocal" transducer

In Part 1 you should have already observed that the LED lights when it is forward biased. In this case, current (or voltage) is the stimulus or input variable, and light is the result, or output variable. Likewise, it turns out that, like most transducers, the LED can be used in the reciprocal sense; that is, light can be used as the stimulus (or input), and then voltage will be generated across the LED as the result, or output variable. Investigate this phenomenon using your bench dc voltmeter and fill in the blanks below:

NO light (LED well covered by fingers): Vd (anode w.r.t. cathode) = ________ V

Moderate light (LED aimed toward room lights): Vd (anode w.r.t. cathode) = ________ V

Bright light (overhead projector?): Vd (anode w.r.t. cathode) = _________V

Appendix A. Plotting Data and Least-Squares Curve Fitting with Excel 2007

1) *Bring up Microsoft Excel (**Start – All Programs – Microsoft Office - Microsoft Office Excel 2007**). Enter the Vr values (20 V, 10 V, 5 V, 2.5 V, 1.25 V, 0.625 V, 0.3125 V) in the first column of the spreadsheet. Label the top of each column, as shown in the example spreadsheet below. From the Vr values, calculate the diode current values in Amperes (Id) in the 2nd column. Do this by clicking on the first row of the Id column, and enter the equation*

   =A2/1000

   where A2 identifies the location of the top entry in the Vr column, and this value is divided by the value of the 1000 ohm resistor. You may then copy this entry into the remaining positions of the Id column. Next, calculate the corresponding ln(Id) values in the 3rd column. Do this by typing the following equation into the first row of the ln(Id) column:

   =ln(B2)

   where B2 is the location of the top entry in the Id column. You may then copy this entry into the remaining positions of the ln(Id) column. Finally, enter the diode voltage (Vd) data in the 4^{th} column.

2) *By holding down the left mouse button and dragging it downward, select the ln(Id) column. Next, hold down the Ctrl key and select the Vd column. **Note that the leftmost column selected will go onto the horizontal axis of the plot. Therefore, it is important to place the Vd column to the right of the ln(Id) column, so that the ln(Id) data goes on the horizontal axis and the Vd data goes on the vertical axis.***

3) *Now click on the **Insert** tab and select **Scatter.** Then select the scatter plot icon with the smooth lines drawn through the points. The desired plot should appear with ln(Id) on the horizontal axis and Vd on the vertical axis, as desired.*

4) *To add an appropriate plot title and both horizontal and vertical axis titles, click anywhere inside the chart (to select it), and then click on the **Layout** tab at the top of the screen. Select **Chart Title** and enter it (in this case "**Vd vs. ln(Id) Plot for 1N4148 Diode**". In similar fashion click on the **Layout** tab once again, but this time select **Axis Titles.** Label the vertical axis "**Vd in volts**" and label the horizontal axis "**ln(Id), where Id is in Amperes**". Note that we cannot ascribe any units to the natural log of Id, ln(Id). However we might as well point out that Id is in Amperes.*

5) *The resulting scatter plot can be sized in the usual way by applying the mouse to the chart borders. Likewise, the chart can be dragged out to any desired position on the spreadsheet. Likewise the axis labels and chart label can be dragged to any desired position within the chart area.*

6) *To add least-squares linear curve fit (regression) trend line, **LEFT CLICK** on the data line in the plot so that the points on the line are highlighted. Then left click on the **Layout** tab at the top of the page and select "**Trendline**". Click on the "More Trendline Options" at the bottom of the list. A "Trendline Options" box should appear. In the "**Trend/Regression Type**" box, click on "**Linear**". Now click the "**Options**" tab. Check the box labeled "**Display Equation on Chart**". This equation is of the* form ***y = mx + b**, where "y" is the dependent variable on the vertical (in this case Vd), and "x" is the independent variable on the*

horizontal axis (in this case ln(Id)). Likewise, m is the slope of the line and b is the y-intercept.

7) *Also check the box labeled "**Display R^2 value on chart**". R is called the "linear correlation coefficient", which varies between (0, 1). The closer to 1 it is, the better the linear curve fit is, and hence the more closely your data falls along a straight line. Thus the closer the R^2 value is to one, the "better" your data is! Hit the **close** button. The linear curve fit equation, as well as the linear correlation coefficient can now be "dragged and dropped" wherever you would like them to be placed on the chart.*

Your spreadsheet should now look like the one shown below:

Vr	Id(1N4148)	ln(Id)	Vd(1N4148)
20	0.02	-3.91202	0.765
10	0.01	-4.60517	0.723
5	0.005	-5.29832	0.685
2.5	0.0025	-5.99146	0.65
1.25	0.00125	-6.68461	0.615
0.625	0.000625	-7.37776	0.582
0.3125	0.0003125	-8.07091	0.549