

# Ohm's Law and Resistive Circuits

**Objectives:** To study Ohm's law and its application in simple series circuits; to determine the relationships between voltage, current, and resistance in ohmic and non-ohmic devices; to examine data fitting methods.

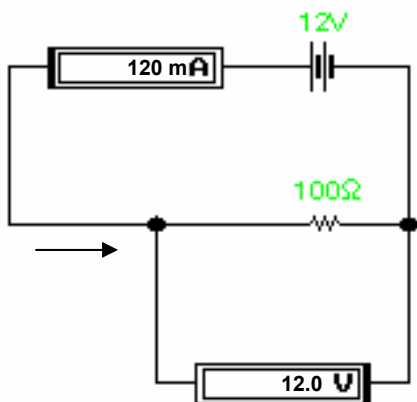
**Equipment:** 2 Multimeters (test instruments that read current, voltage and resistance), 100  $\Omega$  1% resistor, IN5400 diode, 25 watt light bulb, DC power source, Excel spreadsheet.

**Definitions:** *Ampere (A):* a unit of electrical current flow (coulomb/second).  
*Volt (V):* a unit of electrical potential (joule/coulomb).  
*Ohm ( $\Omega$ ):* a unit of resistance to the flow of electrical current (volt/amp).  
*Ohmic:* a device that obeys Ohm's law

*As you read this procedure be sure to keep track of all terms in italic (make a list) and be sure that you are familiar with their definitions. Each of these terms will be used frequently in the coming lab procedures.*

## Discussion

**Test Instruments and Simple Circuits** All circuits contain some resistance. Even if there are no resistors or other devices connected in a circuit the connecting wires and power supply will have a small amount of resistance to current flow. In general we assume that all of the resistance in most circuits resides in the resistors and that the connecting wires and power supply are free of significant resistance. In this procedure you will explore the relationship between voltage and current for three different types of resistive circuits: linear (ohmic), non-linear (non-ohmic), and a circuit containing a diode.



Consider a circuit containing a 12-volt power supply connected in series with a 100-ohm resistor as shown in Figure 1. An ammeter (a device that measures electrical current or *amperage*) is connected in *series* with the resistor and a voltmeter (a device that measures electrical potential or *voltage*) is connected in *parallel* with the resistor. In any electrical circuit correctly connected test instruments have a very small effect on the operation of the circuit while incorrectly connected test instruments have a large, generally undesirable, effect on the operation of a circuit.

**Figure 1.** A simple series resistive circuit with multimeters.

The circuit in Figure 1 has an *applied voltage* of 12 volts. This means that the electrical potential of the left terminal of the power supply is 12 *V higher* than the electrical potential of the right (generally this means that the high potential terminal is at 12 *V* and the low potential terminal is at 0 *V* but they may be at any respective values that are 12 *V* apart). As current flows around the circuit (counterclockwise in this case) the potential decreases as the current passes through the resistor. Ignoring the small amount of resistance in the connecting wires, the potential drop across the resistor in this (single resistor) circuit equals the applied voltage. This would be the case regardless of the value of the resistor, i.e., the drop would be 12 volts if the resistor were 1 ohm or 10000000 ohms. This electrical energy is converted to heat by the resistor.

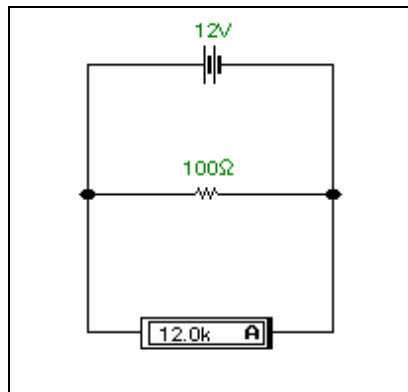
Unlike electrical potential, which decreases as resistance is encountered in a circuit, current is not "used up" as it flows through a resistor. The current in Figure 1 is the same whether it is measured before or after the resistor. The amount of current flow is determined for a circuit by the amount of voltage available to the circuit (applied voltage) and the amount of resistance in the circuit. This relationship is quantified in Ohm's Law:  $V = IR$ . In this example the current is:

$$\frac{12V}{100\Omega} = 0.12A$$

Note that this is the same as  $120 \times 10^{-3}$  amperes or 120 mA. This is the amount of current that *any* 12 *V* circuit will draw with a *load* of 100-ohms.

An ideal ammeter or voltmeter would measure current or voltage without otherwise affecting the circuit. Unfortunately real test instruments do affect circuits in a small way. Usually this effect is negligible but sometimes it is not. Well-designed instruments, correctly connected, minimize the interruption to normal circuit operation.

Ammeters have extremely small internal resistances (about  $1 \times 10^{-3} \Omega$ ) and must be connected

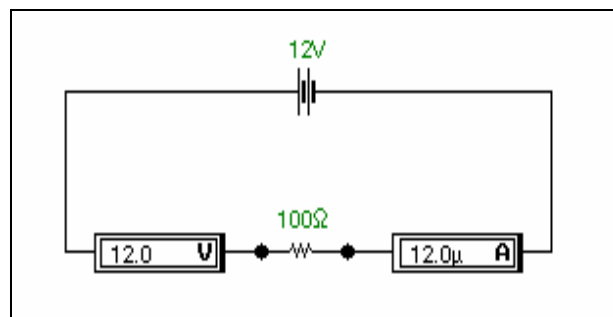


**Figure 2. An incorrectly connected ammeter changes the flow of current in a circuit.**

in *series* with the resistor or other circuit component through which one wishes to measure current. Resistors in series are added by summing their values. In this case the value of the resistor in the circuit being examined and the value of the internal resistance of the ammeter are simply added together:  $R_{\text{circuit}} + R_{\text{ammeter}} = R_{\text{total}}$ . The low value of the internal resistance of an ammeter does not appreciably contribute to  $R_{\text{total}}$  and may be ignored. If the ammeter in Figure 1 were to be connected in *parallel* with the resistor (as in Figure 2) the current would have a choice of paths to take and the majority of it would follow the path of lowest resistance through the ammeter rather than the resistor. Resistors in parallel are added by summing their inverses, e.g.,  $1/R_c + 1/R_a = 1/R_t$ . A small value of  $R_a$  results in a large increase in the value of  $1/R_a$ . This results in a significant decrease in the overall

resistance of the circuit, which results in an increase in the current flowing through the circuit. An ammeter, when connected in parallel, significantly alters the operation of the circuit. Therefore, *ammeters are always connected in series in a circuit.*

Voltmeters have extremely high internal resistances (about  $1 \times 10^6 \Omega$  - much greater than most resistors) and are connected in parallel with the component across which one wishes to measure a potential drop. A voltmeter, with its extremely high internal resistance, connected in parallel with a resistor has little effect on the operation of a circuit because most of the current follows the path of least resistance through the resistor. Since resistors in parallel are added by summing their inverses (e.g.,  $1/R_c + 1/R_v = 1/R_t$ ) a large value of  $R_v$  decreases the value of  $1/R_v$  so that the value of  $R_c$  approaches that of  $R_t$ . The result is a very small change in the overall resistance of the circuit. On the other hand, when a voltmeter is connected in series with a resistor the result is a significant rise in the overall resistance of the circuit (recall that  $R_c + R_v = R_t$  for resistors in series). This increased resistance lowers the flow of current through the circuit. A voltmeter, when connected in series, significantly alters the operation of the circuit. Therefore, *voltmeters are always connected in parallel in a circuit.*



**Figure 3. An incorrectly connected voltmeter alters the flow of current in a circuit.**

**Ohmic and Non-Ohmic Resistors** An *ohmic* resistor is one in which the value of the resistor does not change over a fairly wide range of applied voltages and currents. A graph of voltage vs. current for an ohmic circuit is shown in Figure 4. Since the ratio of voltage to current is fixed, the resulting plot is *linear*, i.e., it is a straight line that follows the relationship  $y = mx + b$  (the point, slope, intercept formula for a straight line).

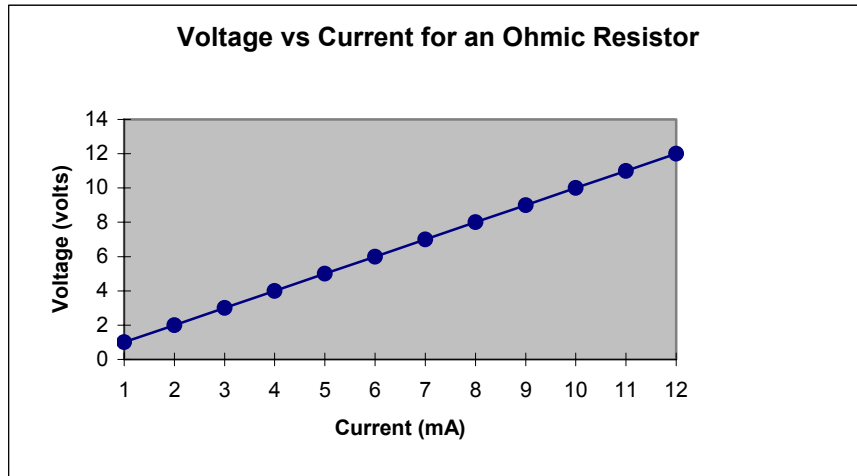


Figure 4.

Non-ohmic resistors are also referred to as non-linear because a plot of voltage vs. current for such a resistor will not be a straight line (Figure 5.). In this case a linear fit of the data points obtained while measuring voltage and current won't work and a curved *exponential fit* of the data will be necessary. Such resistors have a non-constant resistance to current flow.

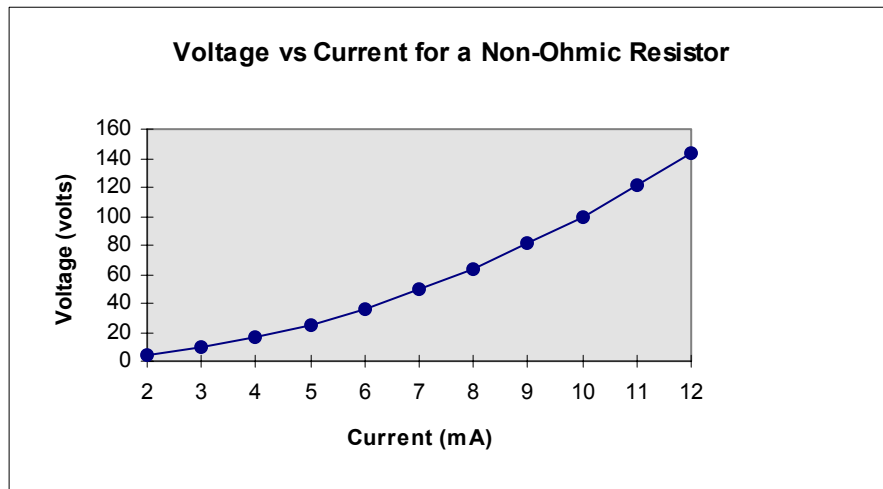
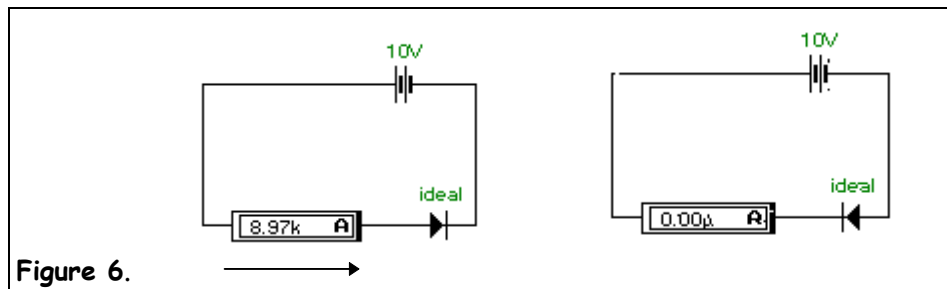


Figure 5.

Notice that the value of the ohmic resistor may be obtained from Figure 4 simply by determining the *slope* ( $m$ ) of the plot. This is clearly not the case in Figure 5 where the plot is a curved line. The best we can do in this case is to obtain the resistance at a specific voltage and current and to look at the resistance or slope point by point.

It is of interest to note that most ohmic resistors will behave non-ohmically outside of a given range of temperature, pressure, etc.

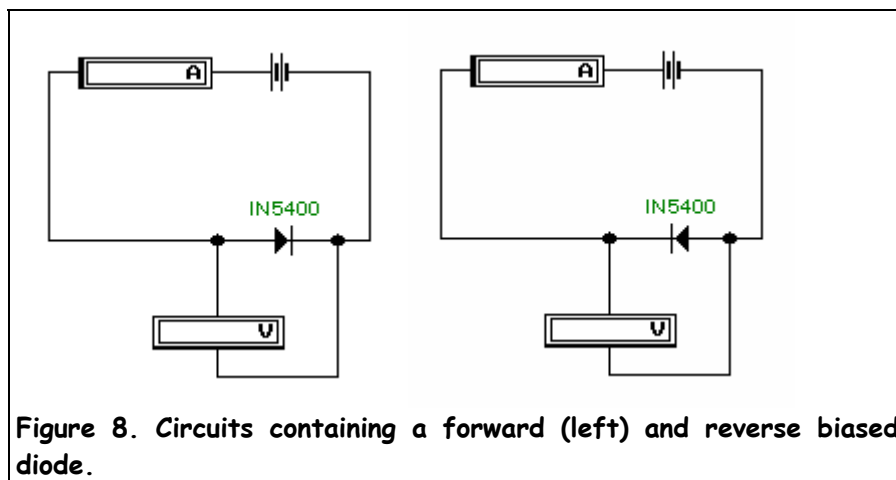
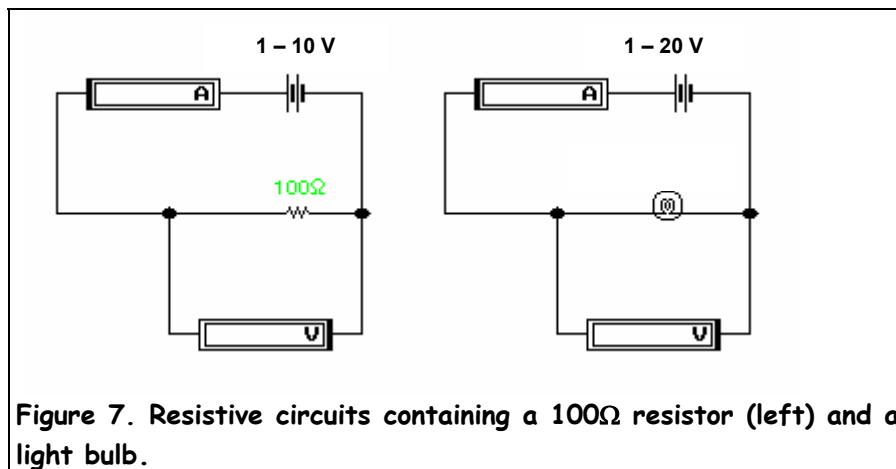
**AC/DC, Current Direction, Diodes** Most resistors are oblivious to which direction the current is flowing or even whether the current is *direct* or *alternating*. A diode is a circuit element that allows current to flow freely only in one direction. Figure 6 shows a diode in its two possible configurations: forward and reverse bias. The circuit on the left contains a forward biased diode, which acts like an extremely small resistor that does nothing to impede the flow of current. The circuit on the right contains a diode that has been inserted in the direction of reverse bias. In this direction the diode acts essentially as a resistor of infinite value. It is important to note that all reverse biased diodes will allow current to flow if the applied voltage is large enough.



In the following procedure you will construct four simple circuits containing a variety resistors and diodes and study the operation of these circuits with ammeters and voltmeters. The multimeters you are using in this procedure function as ammeters and voltmeters by changing the front panel settings. It is important that you review the information covered up to this point in these instructions before proceeding. You and your lab partner should inspect each circuit carefully to make sure that it has been assembled correctly. Do not energize any of the circuits until your lab instructor has checked your work.

## Experimental

Four circuits are to be examined. These are shown below. *Be sure to have your lab instructor inspect each circuit before you turn on the power.*



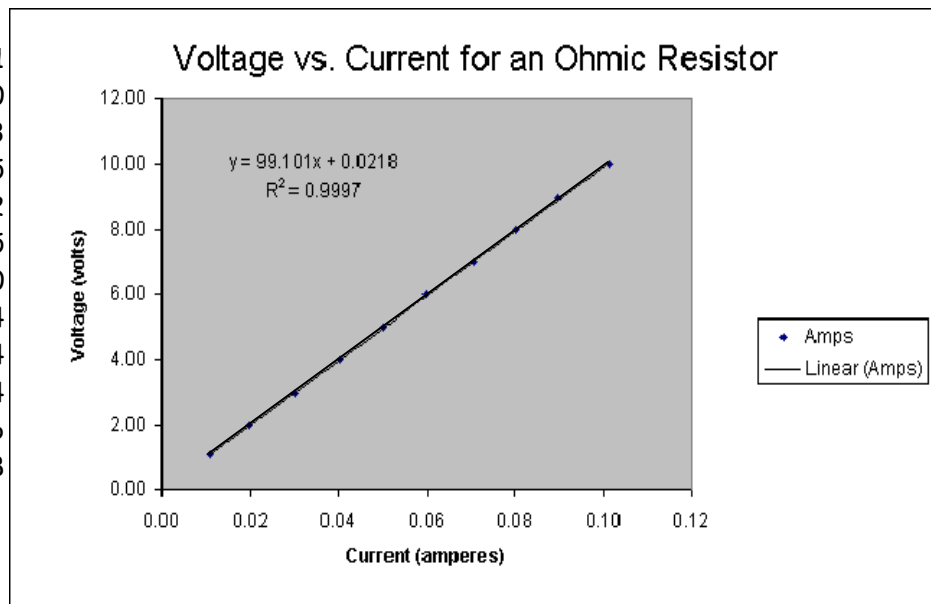
**Resistors** Begin by assembling the circuit on the left in Figure 7. Your lab instructor will help you identify the circuit symbols and what they represent. Be sure that the voltmeter is set to the 200-volt DCV range and the ammeter is set to the 200 DCMA range. Turn up the power supply until the potential across the resistor is one volt as indicated by the voltmeter. Record the current from the ammeter in your notebook. Increase the potential in one-volt increments and record the current for each increment. Continue until you have acquired ten data points.

From this data make a plot similar to Figure 4 in your lab notebook. Be sure to plot the voltage values, in volts, on the vertical axis and the current values, in amperes, on the horizontal axis (since your ammeter is in the mA scale remember that 1 mA is  $10^{-3}$  amperes). This plot should occupy most of a page and should be rotated  $90^{\circ}$  to make it as big as possible. Use the grid in your lab notebook for a scale and be as neat and accurate as possible.

Once you have plotted your data points (make them small), draw the best (narrow) straight line that you can that best fits the data points. Use a straightedge. Do not "connect the dots" this line must be straight! Compute the slope of this plot. Recall that this is accomplished by dividing the "rise over the run" between two points on the straight line. In general you should not use data points for this calculation but rather points exactly along the straight line that are easily read. The value you obtain from this calculation should be very near the value of the resistor. Compute the percent variation between this value and the value of the resistor and examine your data fit. Is this resistor ohmic or non-ohmic?

Your lab instructor will show you how to open an Excel spreadsheet, **114-214ohm1.xls** on your computer. Enter the data from your lab notebook into the appropriate columns of the spreadsheet and Excel will create a plot similar (hopefully) to what you created manually in your lab notebook. The Excel chart contains some very useful additional information.

Volts	Amps	Slope
1.07	0.0108	99.1
2.00	0.0198	101.0
3.00	0.0302	99.3
4.00	0.0402	99.5
5.00	0.0504	99.2
6.00	0.0597	100.5
7.00	0.0707	99.0
8.00	0.0805	99.4
9.00	0.0896	100.4
10.00	0.1016	98.4
	<b>ave</b>	99.6
	<b>std</b>	0.8

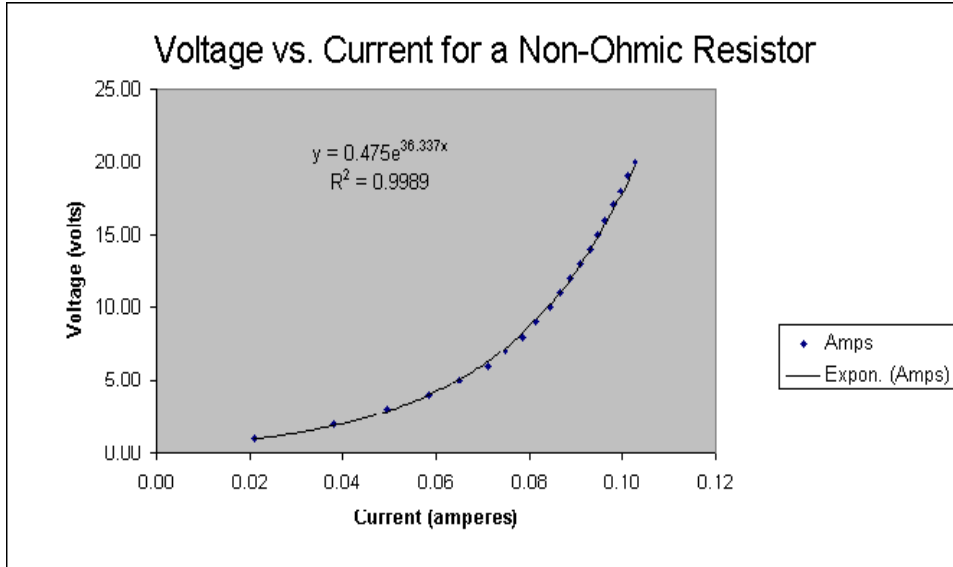


Notice that the Excel chart has fit the best straight line it can through the data points using a least squares regression algorithm. Notice also that it has given you the equation that describes this *linear* fit ( $y = mx + b$ ) with  $m$  being the slope of the data fit (the value of the resistor in this case),  $b$  being the  $y$ -axis intercept (very close to zero as we would expect). Another parameter  $R^2$ , also known as *coefficient of determination* or the *correlation coefficient*, is listed just below this equation. This last value is of particular interest to us because it is a measure of how good the straight line fits the data. In this case the value is well over 99%, which is excellent (in general any value over 96% is really good). Formally this means that over 99% of the variation in the data in this particular example is explained by the linear relationship  $y = 99.101x + 0.0218$ . We have, therefore, a high degree of confidence that this straight line does represent the slope of the data and is therefore an accurate indicator of the value for the resistor.

Repeat the procedure outlined above for the circuit on the right in Figure 7, but this time start with a potential of one volt and increase it in one volt increments until you have acquired 20 data points. Compute the resistance of the light bulb for each data point. From this data make a plot similar to Figure 4 in your lab notebook. Again be sure to plot the voltage values, in volts, on the vertical axis and the current values, in amperes, on the horizontal axis. Once you have plotted your data points (make them small), draw the best (narrow) curved line that you can that best fits the data points. This line should be a smooth curve (do not "connect the dots"). Is the light bulb ohmic or non-ohmic? Compute the slope of your plot at each data point.

Open the Excel spreadsheet, **114-214ohm2.xls** on your computer. Enter the data from your lab notebook into the appropriate columns of the spreadsheet and Excel will create a plot like that below. Again, this plot contains some useful additional information.

Volts	Amps
1.00	0.0211
2.00	0.0380
3.00	0.0495
4.00	0.0586
5.00	0.0651
6.00	0.0712
7.00	0.0750
8.00	0.0787
9.00	0.0814
10.00	0.0845
11.00	0.0866
12.00	0.0889
13.00	0.0910
14.00	0.0930
15.00	0.0946
16.00	0.0963
17.00	0.0979
18.00	0.0996
19.00	0.1012
20.00	0.1026



Notice that the Excel chart has fit the best curve that it can through the data points using an exponential function. This time the relationship between the dependent and independent variables is more complex. The correlation coefficient,  $R^2$ , has the same meaning but is computed differently for this fit. Since the slope of the data fit changes the resistance varies with current and voltage. With a value of over 99% we have a high degree of confidence that this exponential fit does represent the slope of the data.

**Diodes** Repeat the procedure again for the circuit on the left in Figure 8. Start with a potential of 0.1 volts and increase the potential in 0.1-volt increments as far as you can go. There is no need to use Excel for this or the following step so you only have to create a graph in your lab notebook.

Finally, repeat the procedure for the circuit on the right in Figure 8. Start with a potential of 1 volt and increase in 2-volt increments to until you have acquired 10 data points.

**Data Analysis** Describe the behavior of the ratio of voltage to current for each resistor. Which is ohmic and which is non-ohmic? Describe the behavior of the non-ohmic resistor.

There are many types of data fitting methods besides the linear and exponential fits we used in this procedure. Polynomial, logarithmic and other fits are commonly used. Why do you think that we used the two types of fits that we did? Is there a method by which one may anticipate what type of fit may work the best for a given type of data?

Describe the behavior of the diode in the circuit with both forward and reverse bias based on your data. Examine your voltage vs. current curve for each. Does your data confirm the theoretical behavior of a diode?

**Light Bulb Filaments** Examine the light bulb data again. We employed an exponential fit to compute the resistance of this circuit. Physically this is because the resistance of most materials increases with the temperature of the material. Let's see how much the temperature of the filament increases from 20 volts (where we stopped taking data) up to 120 volts. Examine your data and use the value of the resistance for the tungsten filament at 20 volts,  $R$ , to compute the temperature of the light bulb:

$$R = R_{20} \left[ 1 + \alpha (T - 20^\circ \text{C}) \right]$$

where  $R_{20}$  is the resistance of the tungsten element at  $20^\circ\text{C}$  (use  $50 \Omega$ )  $\alpha$  is the temperature coefficient of resistance for tungsten ( $4.5 \times 10^{-3} \text{ }^\circ\text{C}^{-1}$ ), and  $T$  is the temperature in degrees centigrade. You should obtain a value of somewhere between  $500^\circ$  and  $1000^\circ \text{C}$ .

The power consumption of this particular light bulb is 25 watts under normal conditions (120 VAC). Use  $P = IV$  to compute the current consumption of the light bulb at 120 volts. Once you have determined the current flow through the bulb you can calculate the resistance of the filament under normal operating conditions using Ohm's Law. Calculate  $\Delta T$  for the filament from 20 volts to 120 volts (expect about an order of magnitude difference).

## Exercises

Resistors in parallel:  $\frac{1}{R_1} + \frac{1}{R_2} = \frac{1}{R_{eq}}$

Resistors in series:  $R_1 + R_2 = R_{eq}$

1. Assume that the ammeter in Figure 2 has an internal resistance of  $1 \times 10^{-3} \Omega$ . Compute an equivalent resistance for this circuit and verify that the current flowing through the circuit is about 12,000 amps. Now make a diagram of the circuit with the ammeter connected correctly. Compute an equivalent resistance for this circuit and verify that the current flowing through the resistor is about 120 mA. What is responsible for the difference?
2. Assume that the voltmeter in Figure 3 has an internal resistance of  $1 \times 10^6 \Omega$ . Compute an equivalent resistance for this circuit and verify that the current in the circuit is about  $12 \mu\text{A}$ . Now make a diagram of the circuit with the voltmeter connected correctly. Compute an equivalent resistance for this circuit and verify that the current flowing through the resistor is about 120 mA. What is responsible for the difference?
3. Is the behavior of the filament in the light bulb ohmic or non-ohmic? What relationship can you derive between the temperature of the filament and its resistance? What would explain this behavior?
4. Would your plot of V vs. I for the  $100\Omega$  resistor be different if the current in the circuit were reversed? What conclusion can you draw about the polarity of resistors?
5. Using your graphs, explain the bias characteristics of the IN5400 diode.
6. **(214 only)** Ohm's law is sometimes written:  $\vec{J} = \sigma\vec{E}$  where  $J$  is current density (I/A) and  $\sigma$  is a constant of proportionality known as *conductivity*. Show that for a conductor of length  $\ell$  and area  $A$ , this is equivalent to the more familiar  $V = IR$ .
7. What is the physical relationship between the dependent and independent variables for data that conform to a linear fit? Consider the behavior of the equation  $y = x$ . Is this equation linear? If so what are the values of  $m$  and  $b$ ?
8. In this procedure you plotted the voltage on the  $y$ -axis and the current on the  $x$ -axis. Normally we'd think of the  $y$ -axis variable as being the *dependant* variable and the  $x$ -axis variable as being *independent*. Why did we switch this convention here?