

Ohm's Law and Resistive Circuits

Objectives: To study Ohm's law. To determine the relationships that exist between voltage, current, and resistance in ohmic and non-ohmic devices. To learn about ammeters and voltmeters.

Equipment: 2 Multimeters, 100 Ω 1% resistor, IN5400 diode, 25 watt light bulb, DC power source, Excel spreadsheet.

Definitions:

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

Discussion

Test Instruments and Simple Circuits All circuits (except superconducting 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 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.

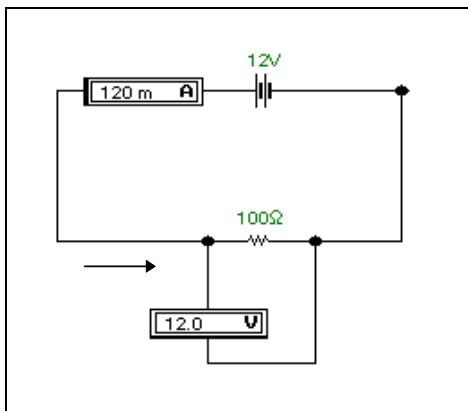


Figure 1. A simple resistive circuit.

Consider a circuit containing a 12 volt power supply connected in series with a 100 ohm resistor such as that 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 of voltage) is connected in *parallel* with the resistor. In any electrical circuit, correctly connected test instruments have a 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.

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 12V higher than the electrical potential of the right (generally this means that the high potential terminal is at 12V and the low potential terminal is at 0V). As current flows around the circuit (counterclockwise in this case) the potential decreases each time the current passes through a resistor. Ignoring the small amount of resistance in the connecting wires, the potential drop across the resistor in this 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:

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

which is the same as 120×10^{-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.

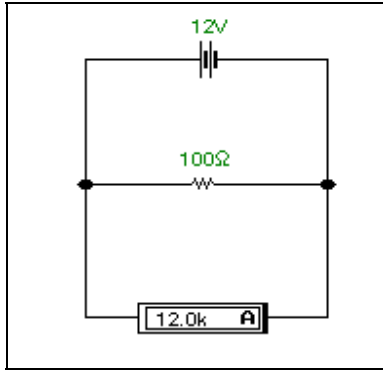


Figure 2. An *incorrectly* connected ammeter changes the flow of current in a circuit.

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.*

Ammeters have extremely small internal resistances (about $1 \times 10^{-3} \Omega$) and are connected in *series* with the 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 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_{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

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

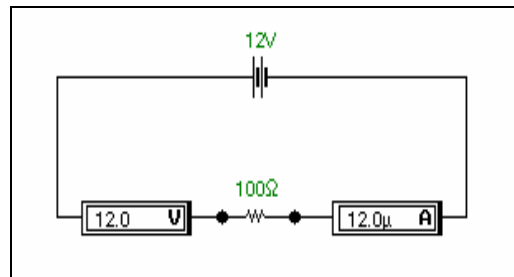


Figure 3. An *incorrectly* connected voltmeter alters the flow of current in a circuit.

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.*

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).

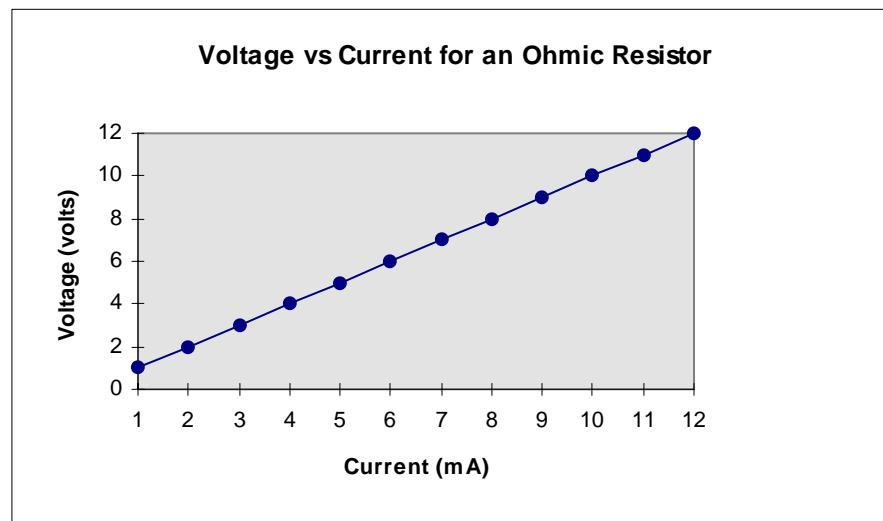
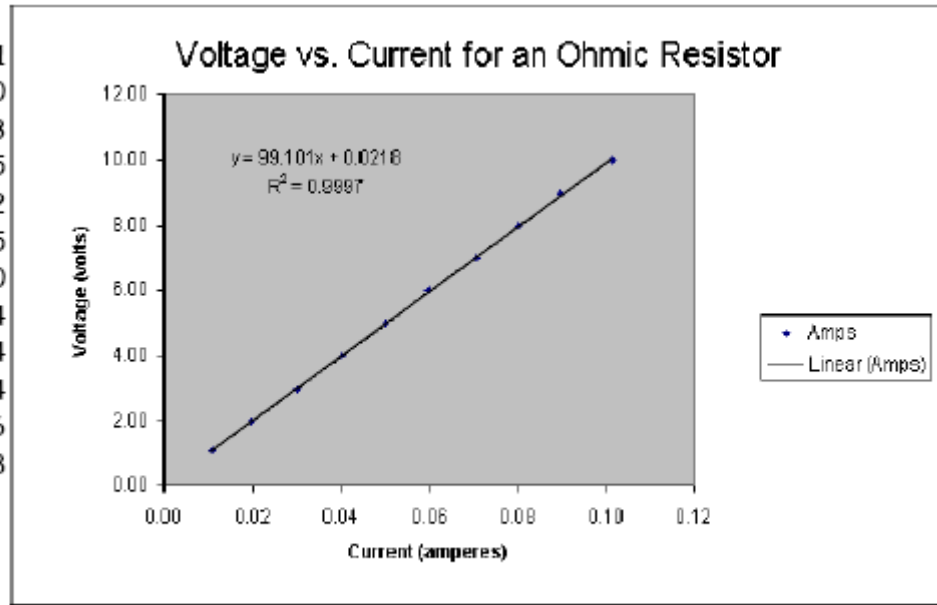


Figure 4.

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

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
	ave	99.6
	std	0.8



Notice that the Excel chart above 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.

A non-ohmic resistor has a value that depends upon the applied voltage and current. 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.

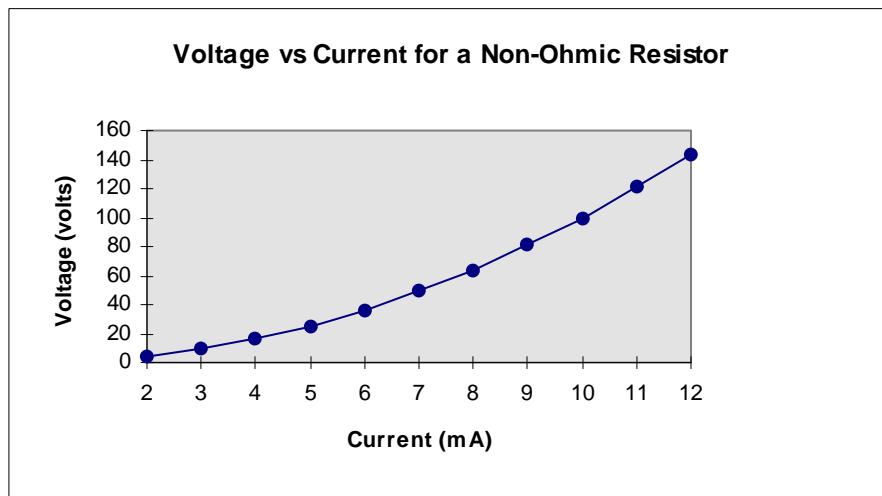


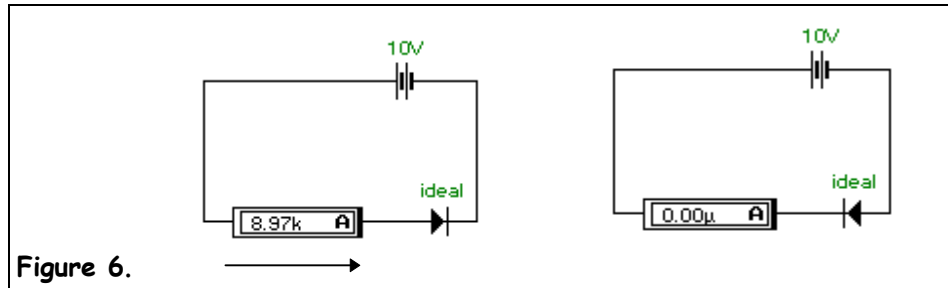
Figure 5.

Notice that the value of the ohmic resistor may be obtained from Figure 4 simply by determining the slope (rise/run) 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.

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 resistor of infinite value. It is

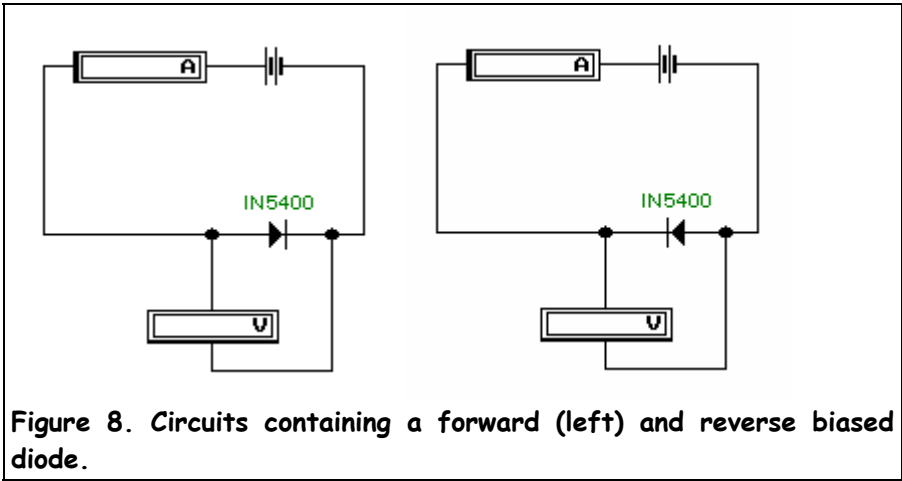
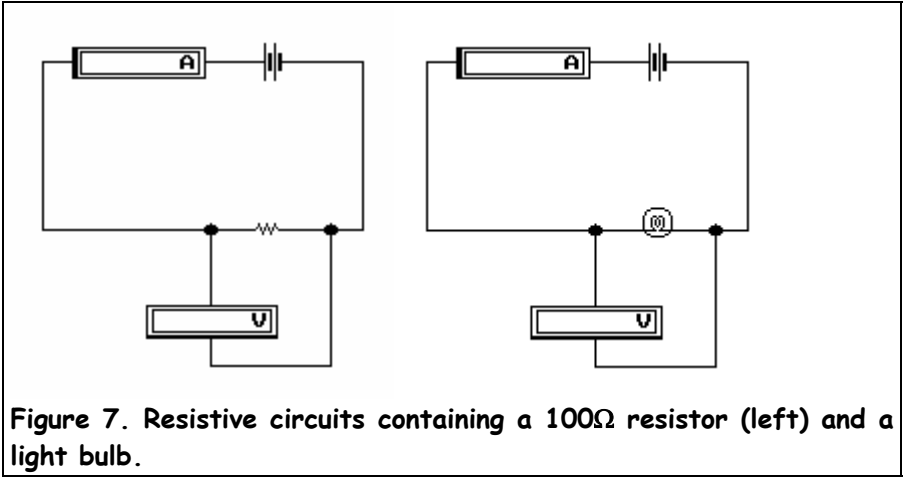
important to note that all reverse biased diodes will allow current to flow if the applied voltage is large enough.



In the following experiment you will construct four simple circuits containing a variety of test instruments, resistors and diodes and study the operation of these circuits. It is important that you review the information covered up to this point 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.*



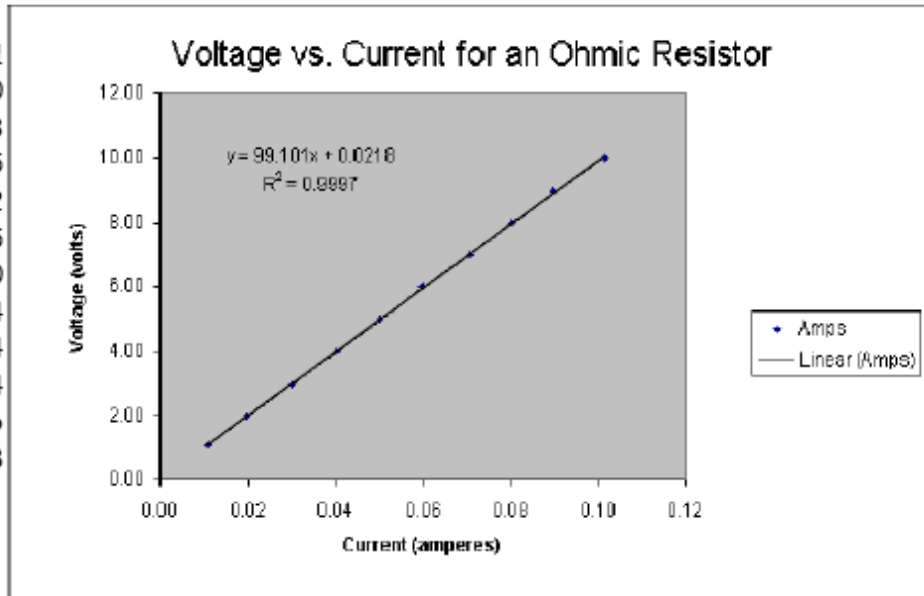
Resistors Begin by assembling the circuit on the left in Figure 7. Be sure that the voltmeter is set to the 200 volt DCV range and the ammeter is set to the 200 DCMA range. Turn up the power supply until the potential across the resistor is 1 volt. Record the current below. Increase the potential in 1 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 of your data. 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) 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. 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 your data into the appropriate columns of the spreadsheet and Excel will create a plot similar (hopefully) to what you created manually. The Excel chart contains form 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
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10.00	0.1016	98.4
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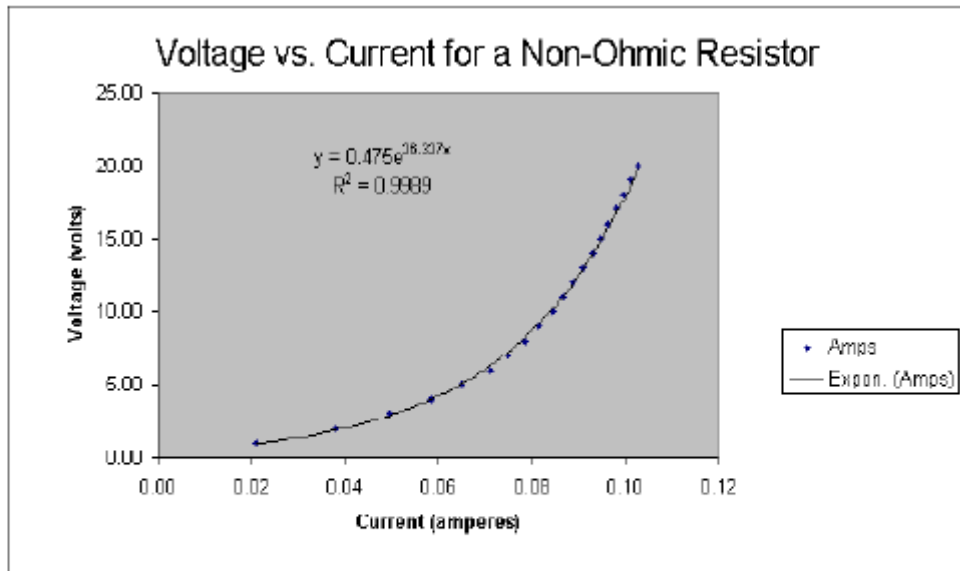
Notice that the Excel chart has fit the best straight line it can through the data points using a least squares regression algorithm. Notice also that it has given you the equation that describes this linear fit ($y = mx + b$) with m being the slope of the data fit (the value of the resistor in this 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. 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 your data 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 above 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.

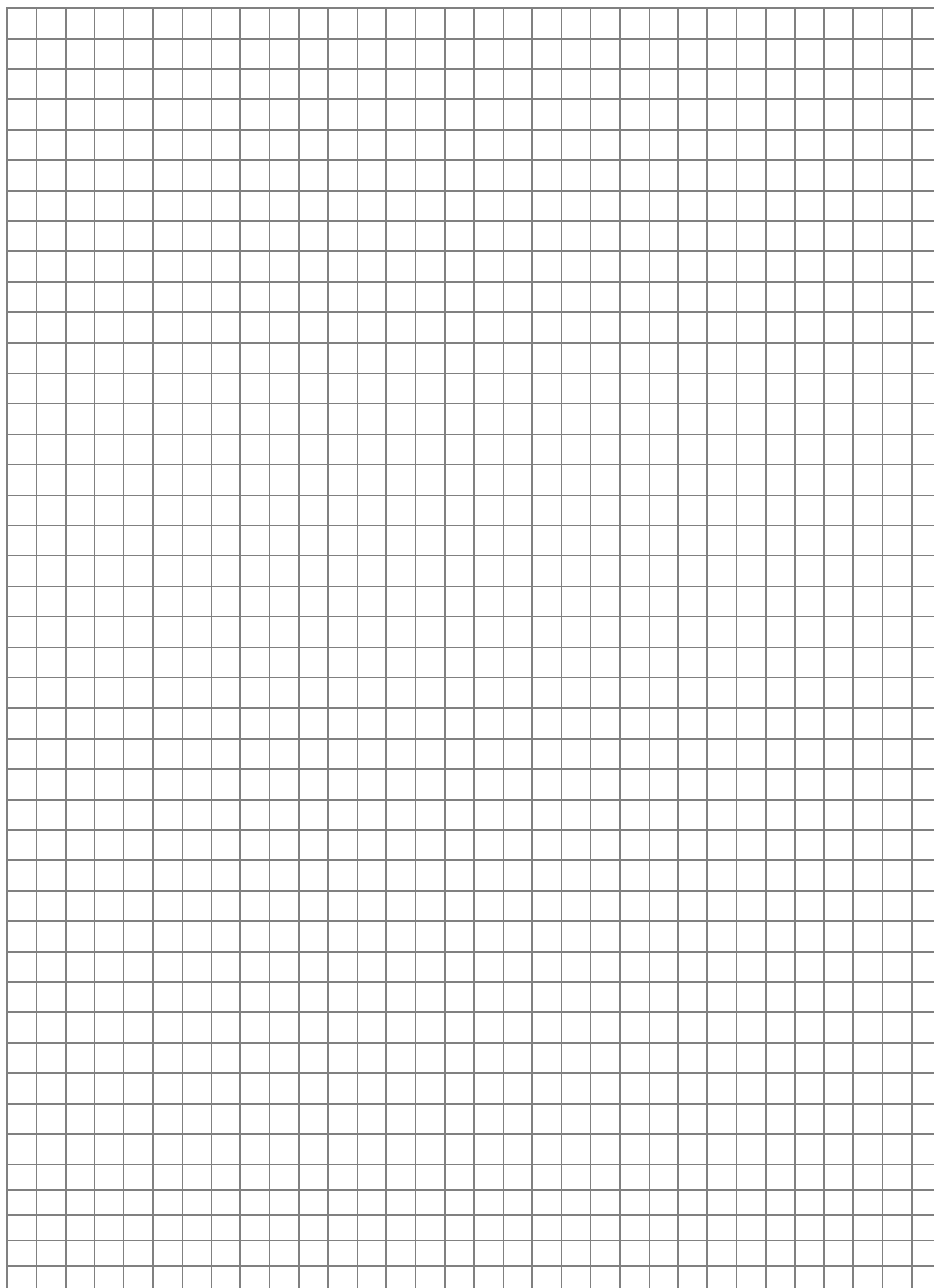
Diodes Repeat the procedure again for the circuit on the left in Figure 8. Start with a potential of 0.1 volts and increase the potential in 0.1 volt increments as far

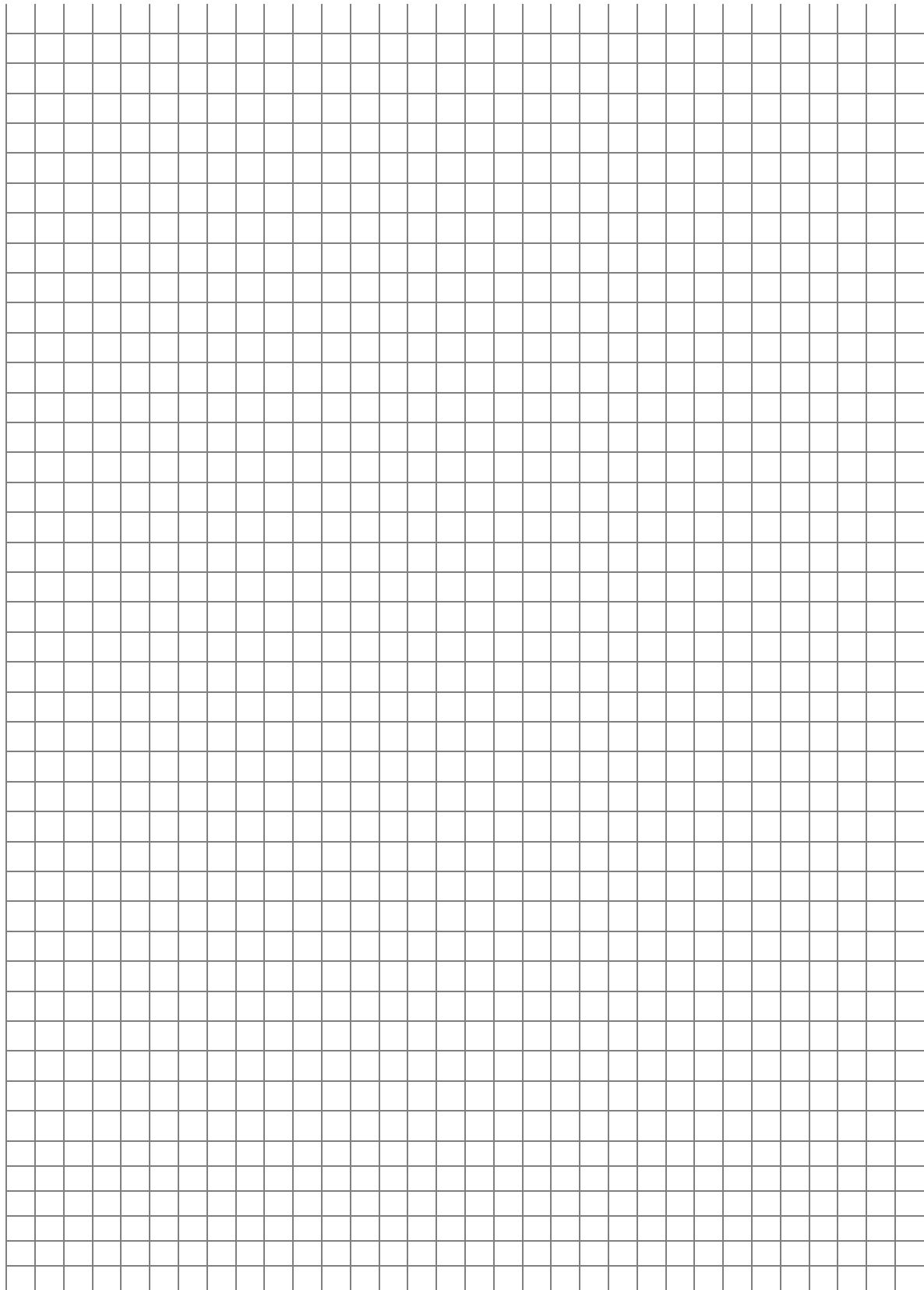
as you can go. There is no need to use Excel for this or the following step as you only have to create a graph below.

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.

Resistor

<u>Volts (V)</u>	<u>Current (mA)</u>
1	_____
2	_____
3	_____
4	_____
5	_____
6	_____
7	_____
8	_____
9	_____
10	_____



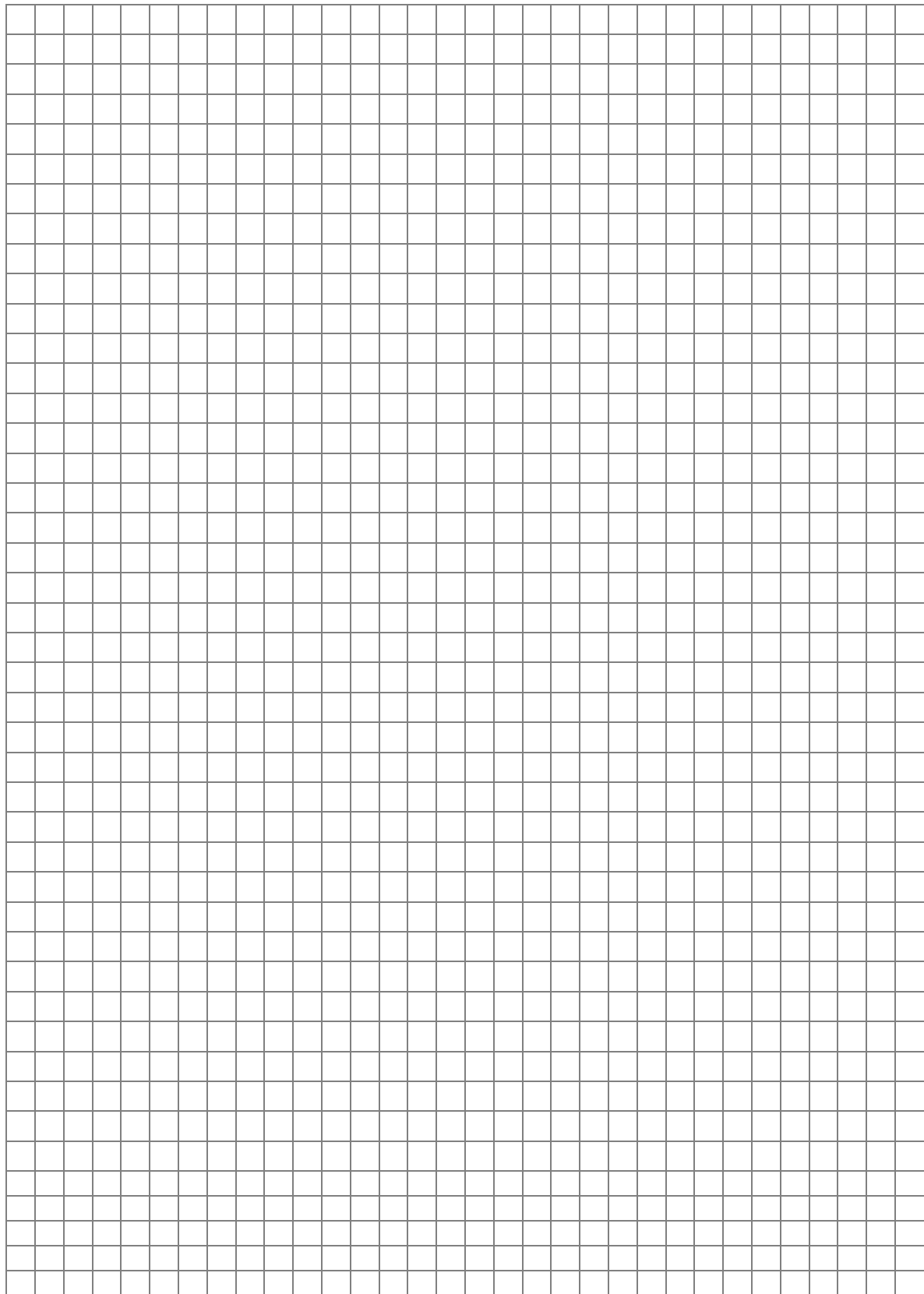


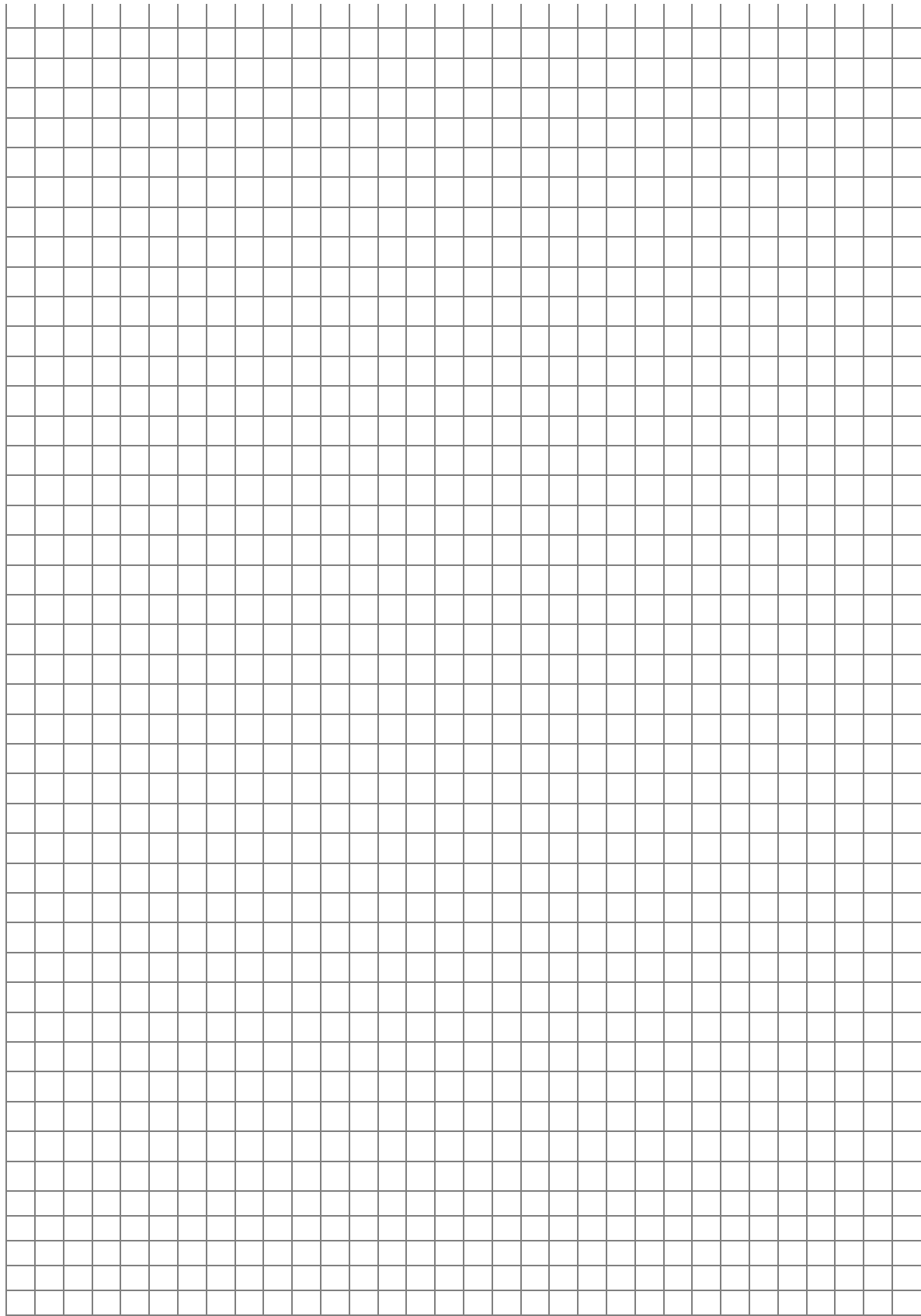
Diode Forward Bias

Volts (V)	Current (mA)
0.1	_____
0.2	_____
0.3	_____
0.4	_____
0.5	_____
0.6	_____
0.7	_____
0.8	_____
0.9	_____
1	_____

Diode Reverse Bias

Volts (V)	Current (mA)
1	_____
3	_____
5	_____
7	_____
9	_____
11	_____
13	_____
15	_____
17	_____
19	_____





(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:

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

where R_{20} is the resistance of the tungsten element at $20^\circ C$ (use 50Ω) α is the temperature coefficient of resistance for tungsten ($4.5 \times 10^{-3} \text{ }^\circ C^{-1}$), and T is the temperature in degrees centigrade. You should obtain a value of somewhere between 5000 and 10000 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 ΔT for the filament from 20 volts to 120 volts (expect about an order of magnitude difference).

Exercises

1. 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?
2. Would your plot of V vs. I for the 100Ω resistor be different if the current in the circuit were reversed? What conclusion can you draw about the polarity of resistors?
3. Using your data, explain the bias characteristics of the IN5400 diode.
4. 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 $y = mx + b$. Is this equation linear? If so what are the values of m and b ?
5. 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?