Temperature and Resistance of Electrical Components

Introduction

Our history, which has been (and continues to be) shaped by the discovery and development of new materials, has shown that understanding the structure and properties of these materials is essential for fueling scientific innovation and technological progress. Advances in materials science and engineering influence almost every aspect of our lives (including its quality and longevity) and often have wide-ranging implications, some of global consequence. They affect how we communicate, travel, power our homes and devices, practice medicine, package and purchase food, play sports, gather and store information, build structures, fight wars, and entertain ourselves. The drive for “smaller, faster, better” has given us ultra-thin televisions, hand-held devices that allow “anyone, anytime, anywhere” wireless communication, and highly-accurate GPS-based navigation, positioning, and target-tracking. Developments in materials research and design continuously transform how we live and often tantalize us with how we could live. As our lives and needs change, we are challenged to think in new ways and explore new ideas and possibilities. This drives innovation and change.

Recognizing the potential applications or implications of any new material requires both creativity and knowledge. Understanding the properties (e.g., structural, electrical, thermal, optical, magnetic, chemical) and limitations of a given material and how it acts or functions under a given set of conditions is especially critical. The effect that temperature has on the properties of a material is particularly important in design and development. In 1986, the Space Shuttle Challenger disintegrated not long after liftoff, and seven lives were lost. Subsequent investigation revealed that this tragedy was due to the failure of the O-rings that were used to seal the joints of the solid rocket boosters. Low overnight and morning temperatures reduced the resiliency of these rubber O-rings, which led to their malfunction and inability to properly seal the joints during liftoff. This tragedy underscores the importance of knowing how temperature affects the performance and behavior of a material.

In this experiment, you will explore how temperature affects the conductivity of different types of materials. Specifically, you will investigate how the resistance of several electrical components (a metal conductor and select semiconductor devices) changes as a function of temperature. You will use these experimental measurements to determine the temperature coefficient of resistance ($\alpha$) for copper and the band gap energy ($E_{\text{gap}}$) of a semiconductor material.

Electrical conductivity is a measure of a material’s ability to conduct a current. Alternatively, it is a relative measure of the mobility of the electrons in a material. In some materials, electrical current flows easily (conductors); in others, it does not (insulators). The band theory of solids helps explain why materials vary in their ability to carry an electric current. Most metals are excellent conductors of electricity because the valence electrons are delocalized over the structure and highly mobile. In the case of metal conductors, the valence and conduction bands border one another or even overlap. Hence, the band gap (the energy difference between the top of the valence band and the bottom of the conduction band) is negligible to nonexistent. On the other
hand, *insulators* (e.g., glass, plastic, and wood) exhibit a high resistance to the flow of current. In insulating materials, the valence electrons are usually tightly bound and the energy gap ($E_{\text{gap}}$) between the valence and conduction bands is considerable (see Figure 1). At ordinary temperatures, this large energy gap effectively prohibits the promotion of electrons from the valence band to the conduction band. The lack of charge carriers in the conduction band explains why insulators are very poor conductors. Some materials, including silicon and germanium, are categorized as semiconductors. As the name implies, the conductivity of these materials is intermediate to that of a conductor and an insulator. This is because $E_{\text{gap}}$ is smaller for semiconductors than it is for insulators (as depicted in Figure 1). Refer to Chapter 8 of your text *(Chemistry for Engineering Students*, by Brown and Holme) for additional information about the band theory of solids.

Electrical conductivity is strongly dependent on temperature. The small band gap in semiconductor materials means that these solids can conduct electricity if sufficient energy (enough to bridge the gap) is supplied to the valence electrons. The number of electrons that are promoted (and hence the conductivity of the semiconductor material) is temperature dependent. In general, the conductivity of semiconductors increases with increasing temperature. At low temperatures, the conductivity of semiconductors is quite low. As temperature increases, more electrons can make the “jump” to the conduction band, resulting in increased conductivity. The density of charge carriers or the number of conduction electrons increases rapidly with temperature. According to the Boltzmann distribution, the relative number of electrons ($n$) that will become conduction electrons by receiving the amount of energy $E_{\text{gap}}$ at a given absolute temperature $T$ is given by:

$$n = n_0 e^{-E_{\text{gap}}/k_B T}$$  \hspace{1cm} (1)
where \( n_0 \) is the maximum number of electrons that could be promoted in this process at high temperatures, \( k_B \) is Boltzmann’s constant \((k_B = 1.38 \times 10^{-23} \text{ J} \cdot \text{K}^{-1} \text{ or } 8.62 \times 10^{-5} \text{ eV} \cdot \text{K}^{-1})\), and \( E_{\text{gap}} \) is the band gap energy (usually in eV) of the semiconductor. Metals also exhibit a temperature-dependent conductivity. In contrast to semiconductors, conductivity in metals decreases with increasing temperature. A dominating reason for this behavior is increased scattering of conduction electrons by lattice vibrations, which impedes directional electron drift, thereby reducing the current. Increased random motion of the free electrons also contributes. Mathematically, electrical resistivity is the reciprocal of conductivity. This inverse relationship means that the resistivity (and thus, the resistance) of a metal increases with increasing temperature. Conversely, the resistance of a semiconductor decreases with increasing temperature.

In this experiment, you will explore how temperature affects the conductivity of different materials by measuring the resistance of electrical components at various temperatures. In the first part of this experiment, the resistance values of a set of reference carbon film resistors will be measured at room temperature using a ranged digital multimeter (DMM). The objective of this exercise is to acquaint you with the basics of using a DMM to measure resistance. In the second part of this experiment, you will explore how resistance (and hence conductivity) changes with temperature for three different electrical components, namely a choke (a metal conductor), a silicon diode (a semiconductor), and a thermistor (a semiconductor). Pictures of these components are given in Figure 2. A choke or choke coil is an inductor that consists of a coil of conducting wire (usually solid copper) wound around a central core. In Figure 2a, the outer, black sleeve has been removed from an axial choke so that you can see the copper coil surrounding the ferrite core. The choke coil used in this study is an RF choke used to attenuate or “choke” radio frequency interference. Two electrical components constructed of semiconductor materials, namely a diode and a thermistor, will also be studied. The diode used in this investigation is made of silicon. This diode is a rectifier, which means that it allows current to flow in only a single direction (i.e., it provides reverse voltage protection) and converts alternating current to direct current. The final component that will be studied in this investigation is a thermistor. This special type of resistor, typically composed of a solid, metal oxide semiconductor material, has an electrical resistance that varies significantly and predictably with temperature.

The resistance measurements made with the choke coil will be used to determine the temperature coefficient of resistance (\( \alpha \)) for copper. The resistance of a conductor at a given temperature \( T \) can be determined from the following relationship:

![Figure 2. Pictures of the (a) choke (with and without the outer plastic sleeve), (b) silicon diode, and (c) thermistor used in this experiment.]
\[ R_T = R_{20} [1 + \alpha (T - 20^\circ C)] \]  \hspace{1cm} (2)

where \( R_T \) is the resistance of the conductor at temperature \( T \), \( R_{20} \) is the resistance of the conductor at 20 °C, \( \alpha \) is the temperature coefficient of resistance for the conductor, and \( T \) is the conductor temperature in °C. Rearranging this equation and solving for \( \alpha \) gives:

\[ \alpha = \frac{R_T - R_{20}}{R_{20} (T - 20^\circ C)} = \frac{1}{R_{20}} \times \frac{R_T - R_{20}}{T - 20^\circ C} = \frac{1}{R_{20}} \times \frac{\Delta R}{\Delta T} \] \hspace{1cm} (3)

In Part 2 of this experiment, you will measure the resistance of copper at several different temperatures and use the resulting data to construct a graph of resistance versus temperature, which should be fairly linear according to Eq. (2). A linear regression of these data will be performed to give the equation of the best-fit line. This equation will be of the form \( R_T = mT + b \), where \( m \) is the slope of the line, which corresponds to \( \Delta R/\Delta T \), and \( b \) is the y-intercept. Substituting \( T = 20 \) °C into this equation will allow calculation of \( R_{20} \). The temperature coefficient of resistance for copper will be calculated by dividing the slope of the best-fit line by the value of \( R_{20} \).

The temperature-dependent resistance measurements made with the thermistor will be used to estimate the band gap energy, \( E_{\text{gap}} \), of the semiconductor material used in this device. Using the relationship in Eq. (1), it can be shown that the resistance \( (R) \) of a semiconductor depends on temperature (in K) according to the following expression:

\[ \ln R = \left( \frac{E_{\text{gap}}}{2k_B} \right) \times \left( \frac{1}{T} \right) + \ln R_0 \] \hspace{1cm} (4)

where \( R \) is the resistance at temperature \( T \), \( R_0 \) is a resistance at some reference temperature (for example 20 °C or 293 K), \( k_B \) is Boltzmann’s constant \( (k_B = 8.62 \times 10^{-5} \text{ eV} \cdot \text{K}^{-1}) \), and \( E_{\text{gap}} \) is the band gap energy (in eV) of the semiconductor. \( E_{\text{gap}} \) for this material can be estimated by plotting \( \ln(R) \) versus \( 1/T \) and determining the slope of the best-fit line. As indicated in Eq. (4), the slope of the best-fit line should be equal to \( E_{\text{gap}}/(2k_B) \).

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**Pre-lab**

**Safety:** Goggles must be worn at all times. When taking the temperature-dependent resistance readings, make sure that you hold on to the test leads in such a way that you avoid burning your fingers and hands. Also, avoid touching the top or sides of the hot plates with your body or with the lead wires. Care should also be taken when transporting materials across the room.

**Pre-lab Assignment:** Please write out the following in your lab notebook. This assignment must be completed before the beginning of lab. You will not be allowed to start the experiment until this assignment has been completed and accepted by your TA.

1) Briefly describe the objectives of this experiment.
2) Write out the experimental procedure in your lab notebook according to the “Guidelines for Keeping a Laboratory Notebook” handout.

In addition to these pre-lab requirements, a short quiz will be given at the beginning of lab based on the material in this lab write-up.

Procedure

**Part 1 - Predict and Measure the Resistance of Several Carbon Film Resistors**

In the first part of this experiment, the resistance values of several reference carbon film resistors will be measured using a switched-range, digital multimeter (DMM). The colored bands printed along the body of each resistor specify the resistance and tolerance of these passive electrical components. The Resistor Color Code Table given in Figure 3 can be used as an aid in determining the resistance of a given carbon film resistor. The purpose of this preliminary exercise is to help you become familiar with using a ranged DMM to measure resistance. Step-by-step procedures are given below.

1. Each group will be assigned an electrical components box. Open your assigned box and remove the plastic bag labeled *Carbon Film Resistors*. There should be a blue number (1-5) written on the outside of the bag. Record this number in your lab notebook. Verify that there are 5 resistors in the bag, each labeled with a unique set of colored bands. These markings identify the component’s value and tolerance (see Figure 3). In this case, the tolerance indicates the potential range of variance from the specified resistance value. Construct a table in your lab notebook similar to the one shown in Table 1, and record the sequence of colored bands found on each resistor. You must record these colors in the same order that they appear on the resistor. In all cases, the 4th band (*i.e.*, the tolerance band) will be gold, indicating a ±5% tolerance. Use the Resistor Color Code Table in Figure 3 to predict the resistance rating of each resistor included in your bag. Record these predictions in your table using the appropriate units (*e.g.*, \(\Omega\), k\(\Omega\), or M\(\Omega\)). In the subsequent steps, you will use a digital multimeter (DMM) to measure the resistance values of these 5 resistors and compare your results with your predictions.

2. Obtain a digital multimeter and a pair of red and black mini-clip test leads. The multimeter that will be used in these studies is a MASTECH MS8230B. A picture of this device is shown in Figure 4. Insert the test leads into the proper jacks. Plug the black test lead into the COM jack and the red test lead into the jack labeled V\(\Omega\)mA.
### Table 1. Resistance Values of Carbon Film Resistors in Bag # ______

<table>
<thead>
<tr>
<th>Resistor #</th>
<th>Color of 1st Band</th>
<th>Color of 2nd Band</th>
<th>Color of 3rd Band</th>
<th>Color of 4th Band</th>
<th>Predicted Resistance</th>
<th>Measured Resistance</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td></td>
<td></td>
<td></td>
<td>GOLD</td>
<td></td>
<td></td>
</tr>
<tr>
<td>2</td>
<td></td>
<td></td>
<td></td>
<td>GOLD</td>
<td></td>
<td></td>
</tr>
<tr>
<td>3</td>
<td></td>
<td></td>
<td></td>
<td>GOLD</td>
<td></td>
<td></td>
</tr>
<tr>
<td>4</td>
<td></td>
<td></td>
<td></td>
<td>GOLD</td>
<td></td>
<td></td>
</tr>
<tr>
<td>5</td>
<td></td>
<td></td>
<td></td>
<td>GOLD</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

3. The center dial on the DMM should be in the OFF position. The DMMs used in this experiment are not auto-ranging. This means that you have to manually switch the center dial to the appropriate function and range to take measurements of a specific type, e.g., resistance (Ω), voltage (V), or current (A), and value. In this experiment, we will be using the DMM as an Ohmmeter as we are interested in taking resistance readings which are measured in Ohms (Ω). A multimeter measures resistance by setting a known voltage difference between two test probes and then monitoring the current that flows when an electrical component is placed between the probes. These data allow the instrument to compute the resistance of the component using Ohm’s Law (R = V/I). The DMMs in this experiment have 5 resistance ranges. These ranges determine the amount of current the multimeter uses during the resistance measurement. As indicated in Figures 4 and 5, these ranges are 200 Ω, 2 kΩ, 20 kΩ, 200 kΩ, and 2 MΩ. These labels represent an upper limit for each setting. The resolution of these ranges are 0.1 Ω, 0.001 kΩ, 0.01 kΩ, 0.1 kΩ, and 0.001 MΩ, respectively. When taking resistance measurements, you should turn the dial to the correct range in the Ω mode. The optimal range is the one that gives you the most precise measurement (and hence, the highest resolution). In general, setting the dial to the lowest possible range gives the measurement with the greatest resolution. Keep in mind, however, that the measured resistance must be less than the number associated with a given range to avoid an “over-range” or “out-of-range” situation. When the measured resistance is “out-of-range” for a particular DMM setting, a “1” will be displayed on the screen. A “1” will also be displayed if there is an open circuit (i.e., if an electrical component is not connected to the lead wires). Turn the dial on your DMM to one of the ranges/settings in the Ω mode. A “1” should be displayed on the LCD screen because of the open circuit.

4. Measure the resistance of one of your carbon film resistors by connecting the black and red mini-clip leads to the terminal wires on either side of the resistor (see Figure 6). Make sure that the multimeter is set in the appropriate range to ensure the most precise data as discussed in Step 3. As a general rule, the center switch should be turned to the lowest resistance range.
5. Repeat Step 4 for the other four carbon film resistors.
6. Return all five resistors to the Carbon Film Resistors bag. Place the bag back in your electrical components box.

**Part 2 - Examining the Temperature-Dependent Resistance of Different Components**

In this part of this experiment, you will explore how resistance (and hence conductivity) changes with temperature for three different electrical components, namely a choke (a metal conductor), a silicon diode (a semiconductor), and a thermistor (also a semiconductor). Pictures of these components are shown in Figure 2.

1. In this part of the experiment, you will be using a Vernier temperature probe to take temperature readings. Verify that the Vernier equipment is set up properly. The Vernier LabPro interface box should be connected to the computer via a USB cable. A power supply line should also run from the LabPro box to an electrical outlet. The stainless steel temperature probe should be connected to the CH1 port in the LabPro box.

2. Launch the Logger Pro software by clicking the Logger Pro desktop icon. If the Vernier equipment is set up properly, then real-time temperature readings should be displayed in the lower, left-hand corner of the screen. Notify your TA if these readings do not automatically show up on the Logger Pro screen.

3. Construct a table in your lab notebook similar to the one shown below in Table 2.
Table 2. Temperature and Resistance Readings for Different Electrical Components

<table>
<thead>
<tr>
<th>Component</th>
<th>Temp. (°C)</th>
<th>Resistance</th>
<th>Temp. (°C)</th>
<th>Resistance</th>
<th>Temp. (°C)</th>
<th>Resistance</th>
</tr>
</thead>
<tbody>
<tr>
<td>Choke Coil</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Silicon Diode</td>
<td></td>
<td></td>
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<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Thermistor</td>
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<td></td>
<td></td>
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<td></td>
<td></td>
</tr>
</tbody>
</table>

4. Remove the choke, silicon diode, and thermistor from the plastic bags in your electrical components box.

5. Fill a 250 mL beaker with ~200 mL of ice water. Immerse the temperature probe into the ice water. Connect the multimeter test leads to the choke and then immerse the choke in the ice water. Once the reading on the multimeter has stabilized (~ 1 min), record the resistance of the choke and the associated temperature. Make sure that the multimeter is set in the appropriate range to ensure the most precise data.

6. Repeat Step 5 for the thermistor.

7. Repeat Step 5 for the silicon diode. **IMPORTANT:** Care must be taken when measuring the “resistance” of a diode since they are non-Ohmic electronic devices that have polarity. When taking resistance measurements of the diode, **ALWAYS** use the 200 kΩ range setting on the DMM and **ALWAYS** connect the black test lead to the diode terminal marked with a white band. The red test lead should be connected to the opposite terminal. Additional information about diodes is given on the next page.

8. Repeat Steps 5-7 using room temperature water.

9. Several “water baths” should be set up around the laboratory; each is set to a different temperature. Go to each station and take resistance measurements of your choke, diode, and thermistor. (Note: Continue to use the 200 kΩ range setting on the DMM for all measurements involving the diode.) Be careful transporting materials across the lab. When taking resistance measurements, make sure that you hold on to the test leads in such a way that you avoid burning your fingers and hands. Also avoid touching the top or sides of the hot plates with your body or with the lead wires. Record the resistance and temperature data in your notebook.

10. Dry all of the electrical components with a paper towel before placing them in their respective bags. Put these bags in your electrical components box and seal the container with the locking lid. Turn off the DMM by turning the center dial to the OFF position. Place the test leads back in the original packaging (if applicable). Return all equipment (electrical components box, digital multimeter, test leads) to the proper storage location in the laboratory.
### Diodes: I-V Characteristics and Polarity

Diodes have nonlinear current versus voltage (I-V) curves, which means that the resistance of a diode is not constant and depends on the applied voltage. Silicon diodes also exhibit a forward-bias voltage drop of ~0.7 V. Recall that the range settings on the DMM determine the amount of current the multimeter uses during the resistance measurement. The nonlinear I-V characteristics of a diode combined with the DMM range-dependent test voltages means that when a diode is connected to a DMM the resistance readings on the meter may change value as the DMM dial is switched between different range settings. Therefore, when testing a diode with the DMM in Ohmmeter mode, the resulting readings will have only qualitative (not quantitative) meaning. It is for this reason that you are asked to use the same DMM range setting (200 kΩ) for ALL diode measurements.

The polarity of the applied voltage is important when measuring the “resistance” of a diode. Diodes are directional devices that conduct in only one direction. Because of this, you must attach the black test lead to the cathode terminal and the red test lead to the anode terminal. The cathode terminal of the 1N4001 diode used in this experiment, to which the black test lead should be attached, is indicated by a white stripe. Thus, the black test lead should be connected to the marked terminal. If the leads are reversed, your DMM will likely read “1” for all resistance ranges, as the resistance will exceed the upper limit of the DMM’s range.

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### Glossary

<table>
<thead>
<tr>
<th><strong>band gap, ( E_{\text{gap}} )</strong></th>
<th><strong>diode</strong></th>
</tr>
</thead>
<tbody>
<tr>
<td>energy difference between the conduction band and the valence band of a material; the energy that must be provided to an electron in a material for it to be free to conduct</td>
<td>a component that allows current to flow in only a single direction typically by using a junction between two materials with different valence band energies</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th><strong>Boltzmann’s constant, ( k_B )</strong></th>
<th><strong>insulator</strong></th>
</tr>
</thead>
<tbody>
<tr>
<td>a fundamental constant relating molecular energy to temperature; ( k_B = R/N_A ) where ( R ) is the gas constant and ( N_A ) is Avogadro’s number</td>
<td>a material with high resistance to the flow of electrons; a material with a large band gap</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th><strong>conductor</strong></th>
<th><strong>metal</strong></th>
</tr>
</thead>
<tbody>
<tr>
<td>a material with low resistance to the flow of electrons; a material with a zero or negligible band gap</td>
<td>a malleable and ductile material that typically exhibits a silvery sheen and high electrical and thermal conductivity</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th><strong>conductivity</strong></th>
<th><strong>resistance, ( R )</strong></th>
</tr>
</thead>
<tbody>
<tr>
<td>a measure of the ease with which electrical current flows through a material</td>
<td>a measure of the difficulty of conducting electrical current through a material; ( R = V/I ) where ( V ) is the applied voltage and ( I ) is the current, such that the larger the current for a given voltage the smaller the resistance; inversely related to the conductivity</td>
</tr>
</tbody>
</table>
**semiconductor**

a material through which current flows upon the application of sufficient energy; a material with a moderate band gap; also called a semimetal or metalloid

**thermistor**

a type of resistor, typically composed of a solid, metal oxide semiconductor material, that has an electrical resistance that varies significantly and predictably with temperature; a device used to measure temperature through electrical resistance