The Effect of Temperature on Resistivity of Conductors

Introduction

When an electronic device heats up, two things happen. As current flows through a conductor, electrons collide with atoms, transferring some kinetic energy to them. Thus, the conductor’s temperature, the measure of the average kinetic energy of atoms, increases. This is known as “Joule heating”.

The current heats the wire because of friction from resistance. Increasing the thermal energy of the atoms in a conductor causes resistivity to increase; when atoms vibrate more vigorously, electrons are more likely to collide with them.The purpose of resistivity is to quantify the opposition to the flow of electrical current without regard to length or cross-sectional area of conductors. It is an intrinsic property. Thus, resistivity is only affected by physical properties such as temperature.

Research Question

How does the temperature of a conductor affect its resistivity?

Hypothesis

As temperature of a conductor increases, so will its resistivity.

Variables

Independent	1. Temperature of Conductor	- The deionized water induces heat in the conductor
Dependent	1. Resistivity	- Measure resistance using a digital ammeter - Calculate resistivity from resistance, cross-sectional area, current, and potential difference across the conductor
Controlled	1. Solution 2. Conductor 3. Total Voltage	- 500 mL H_2O - 91.4 meters of 28 AWG shielded cadmium copper alloy wire coil - 0.6 V

The independent variable, the temperature of the conductor, is controlled by changing the temperature of the deionized water that conductor is submerged in; the heat energy is transferred to the conductor through inductive heating.

Because resistivity is an intrinsic property, it cannot be measured. Instead, it must be calculated using resistance, length, and cross-sectional area, all of which are measurable extrinsic properties.

The resistance of the conductor used in this investigation, cadmium copper, is incredibly low. Thus, a wire of a substantial length must be used, such that its resistance is measurable (hence the 91.4 meter cadmium copper coil).

Cadmium copper is an excellent conductor of heat energy, but it is difficult to measure its temperature directly. Thus, the cadmium copper coil is submerged in water, because the temperature of water is much more easy to measure using a Vernier digital temperature probe. Although the wiring on the coil is shielded as a precaution to ensure that the circuit does not short past the coil, deionized water is used.

Materials

To reproduce this experiment, the following materials are required:

- 91.4 m of coiled, 28 AWG shielded cadmium copper wire with both electrodes stripped
- 500 mL glass beaker
- 500 mL of deionized water
- Adjustable heat pad
- Vernier digital temperature probe
- Vernier power amplifier function generator with built-in ammeter
- Vernier instrumentation amplifier voltmeter

Safety

- Assume all wires are hot, both thermally and electrically. Do not touch the conductive end of any wire.
- Shoes must be worn at all times so that, in the case of an accident, electricity does not short through your body to ground.
- Ensure that nothing is at risk of melting or burning on the adjustable heating pad.
- Be careful around potentially hot surfaces and objects, such as the heating pad, beaker, water in the beaker, and the coil.
- <u>In case of an electrical fire:</u>
    - Disconnect the power supply immediately.
    - Do not use liquids to extinguish the fire.
    - Use either baking soda or a class C or ABC fire extinguisher to extinguish the fire.

Method

A. <u>Preparation:</u>
    1. Connect the two electrodes of the Vernier power amplifier function generator to the two stripped electrodes of the coil.
    2. Connect the Vernier instrumentation amplifier voltmeter in parallel with the coil in a way such that the voltmeter’s positive and negative electrodes are also connected to the function generator’s positive and negative electrodes, respectively.
    3. Turn the function generator on.

4. From the software tool, starting from 0 volts, repeatedly increment the function generator’s direct current output by 0.1 volts until the current being drawn is approximately 0.5 A.
5. Turn the heating pad on.

Figure 1: Electrical Diagram

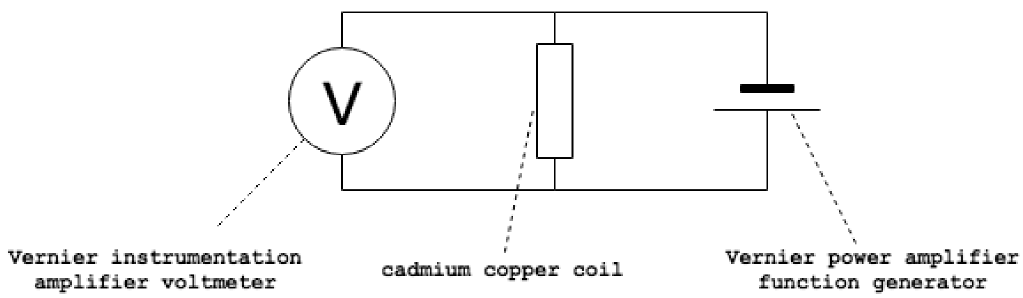
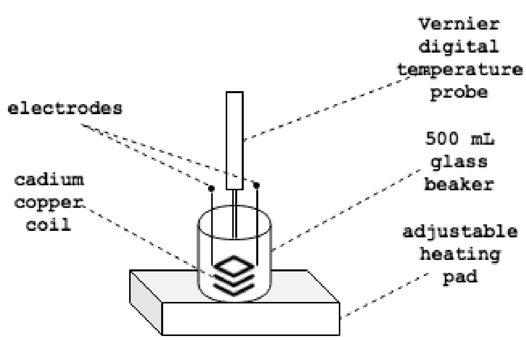


Figure 2: Setup



B. <u>Repeat the following process three times:</u>
   1. Turn the function generator on if it is not already on.
   2. Fill the 500 mL glass beaker with 500 mL of 20 °C of deionized water.
   3. Place the coiled cadmium copper wire in the beaker such that it is completely submerged in the water, other than the two exposed electrodes.
   4. Submerge the Vernier digital temperature probe in the water as much as possible, but ensure that it does not touch the bottom of the beaker.
   5. Place the beaker on the adjustable heating pad,
   6. Begin recording data with three columns: temperature, current, and potential difference.

7. Wait until the temperature reaches 90 °C, then stop recording data.
8. Turn the function generator off.
9. Carefully remove the coil from the beaker, dump out the water in the beaker, and allow the coil to cool down back to room temperature.

Results

Figure 3: Calculating Resistivity

$$\rho = \frac{\pi r^2 V}{IL}$$

Resistivity is an intrinsic property and therefore must be calculated. The resistivity of the coiled wire is related to resistance by its cross-sectional area divided by its length. And, using Ohm's law along with the current and voltage measurements from the experiment, resistance can be calculated.

In order to calculate the resistivity of the conductor using the equation $\rho = R\frac{A}{L}$ derived from Pouillet's law, the resistance (R) is needed. The data from the experiment includes current (I) and potential difference (V). Therefore, Ohm's law ($R = \frac{V}{I}$) can be used to solve for resistance which can then be substituted into the Pouillet's law derivation. Finally, because the cross-sectional area (A) of a wire is circular, πr^2 can be substituted for A. These substitutions result in the equation in *Figure 3*.

The wire used in this experiment is assumed to have an exact radius (r) of 1.6×10^{-4} m (28 AWG) and a length (L) of 91.4 m.

Figure 4: Average Resistivity of Cadmium Copper

Temperature (±0.1 °C)	Cadmium Copper Resistivity (10^{-8} $\pm 2\times10^{-10}$ Ωm)			
	Trial 1	Trial 2	Trial 3	Average
20	1.68	1.69	1.69	1.68
30	1.70	1.74	1.73	1.72
40	1.78	1.80	1.80	1.79
50	1.84	1.86	1.86	1.85
60	1.90	1.92	1.92	1.92
70	1.97	1.98	1.98	1.98
80	2.01	2.04	2.03	2.03
90	2.09	2.09	2.09	2.09

Qualitative Observations:

- The function generator warmed up only slightly after each trial. Because it was essentially a short circuit, one would expect it to warm up much more.

Data Analysis

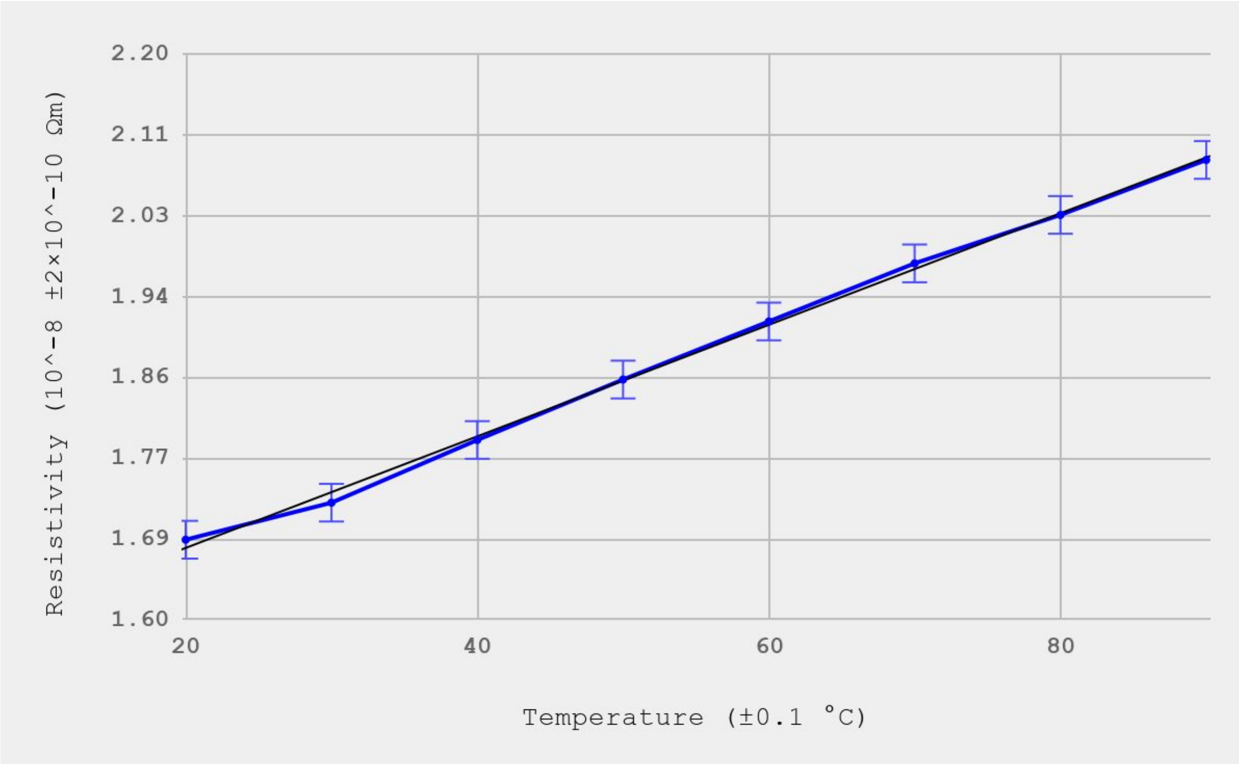
Figure 5: Uncertainty of Resistivity Averages

$$U_a = \frac{\Delta\rho}{2} = \frac{max - min}{2} = \frac{1.74\times10^{-8}\ \Omega m - 1.70\times10^{-8}\ \Omega m}{2} = \frac{0.04\times10^{-8}\ \Omega m}{2} = 2\times10^{-10}\ \Omega m$$

Calculation of Uncertainty of Averages:

The equation in *Figure 5* was used to calculate the uncertainty of the averages for each trial. The numbers that replace *min-max* are the minimum and maximum resistivities from the trials in *Figure 4* with the greatest difference for a given temperature (in this case, 30 °C).

Figure 6: Temperature v.s. Average Resistivity



Conclusion

Based on the data, I can conclude that the higher the temperature, the higher the resistivity of a conductor. In fact, as shown in *Figure 6*, there is a linear relationship between temperature and resistivity. The value relating temperature and resistivity is known as the coefficient of resistivity and is unique to the conductive substance.

Error Analysis:

The purpose of the following equations is to compare the well-known value for the coefficient of resistivity of cadmium copper to that of the experimental value.

1. Calculating experimental temperature coefficient of resistivity of cadmium copper:

$$\Delta\rho = \alpha \Delta T \rho_0$$

$$\alpha = \frac{\Delta\rho}{\Delta T \rho_0} = \frac{\rho_1 - \rho_0}{(T_1 - T_0)\rho_0}$$

$$\alpha = \frac{(2.09\times10^{-8}\ \Omega m) - (1.68\times10^{-8}\ \Omega m)}{(90\ °C - 20\ °C) \times (1.68\times10^{-8}\ \Omega m)} = 0.00349\ \frac{\Omega m}{°C}$$

2. Calculating coefficient's percent error using the experimental temperature coefficient of resistivity of cadmium copper, $0.00349\ \frac{\Omega m}{°C}$:

$$\%_{error} = \left| \frac{\#_{experimental} - \#_{theoretical}}{\#_{theoretical}} \right| \times 100$$

$$\%_{error} = \left| \frac{(0.00349\ \frac{\Omega m}{°C}) - (0.00349\ \frac{\Omega m}{°C})}{(0.00349\ \frac{\Omega m}{°C})} \right| \times 100 = 0\%$$

Admittedly, I am surprised that the percent error for the coefficient of resistivity of cadmium copper is 0%. There are multiple factors, both systematic and random, that contributed to inaccuracies that I expected to be more significant.

Error	Type	Effect	Solution
As the current increases, the temperature also increases. Thus, the temperature of the conductor is never the same as that of the water.	Random	Inaccurate data	No solution
By coiling the cadmium copper wire, an inductor is created. Inductors pick up current from the air.	Systematic	Current slightly offset	Avoid coiling wires; perform the experiment in a faraday cage
Heat is not evenly distributed throughout the beaker; convection currents take time. Thus, the temperature that the temperature probe reads is not the same as that of the conductor.	Systematic	Temperature slightly offset	Use a magnetic stirring plate
The current going through the heat pad is generating an electromagnetic field that induces a current in the wire.	Systematic	Resistivity values slightly offset	Use a bunsen burner instead of an electric heating pad
An arbitrary amount of temperature probe is exposed to air.	Systematic	Variation in temperature	Make probe be in a fixed position

Further Investigations:

Given the opportunity to continue investigating resistivity, I would test multiple different conductors and look for a trend in the gradient of the temperature vs. resistivity graph. I would look for a pattern in the gradient with some other intrinsic property of conductors to find where the gradient number comes from.

Because the relationship between temperature and resistivity of a conductor is linear, I would also investigate its bounds; as the temperature approaches absolute zero, the mechanism that causes electrical resistance ceases to be significant. However, as resistance approaches zero, assuming the voltage potential is constant, current approaches infinity.

When I first did the lab work, I did not know that the coil I was using was cadmium copper instead of pure copper. Given the opportunity to continue investigating, I would also find the relationship between composition of alloys and resistivity.

Bibliography

1. https://www.electronics-tutorials.ws/resistor/resistivity.html
2. http://www.endmemo.com/physics/resistt.php