

ELECTRICAL RESISTIVITY AS A FUNCTION OF TEMPERATURE

Introduction

The ability of materials to conduct electric charge gives us the means to invent an amazing array of electrical and electronic devices, especially considering the extraordinarily wide range of conductivity available, with insulators on one end and superconductors on the other. (Semiconductors, thermoelectric materials, opto-electronic materials and magneto-resistive materials are whole other matters) Between these extremes are materials which offer a small degree of resistance to flow of electrons, such as ordinary copper wire used in household wiring, nichrome heater wire used in toasters and ovens, and many other useful materials. This experiment focuses on the resistance of wires made of materials such as copper and nichrome, or more specifically, the resistivity of copper and nichrome as functions of temperature.

Conductivity – The electrical conductivity of materials is generally expressed by the equation

$$\sigma = nq\mu \quad (1)$$

where n is the number of charge carriers, q is the charge of the ion, electron or hole, and μ is the mobility of the charged species. The value of q is either the charge of an electron or a hole, but may be several times that if the charge is carried by multivalent ions.

Resistivity – The resistivity of materials is simply the inverse of the conductivity

$$\rho = \frac{1}{\sigma}. \quad (2)$$

and the temperature dependence of resistivity is often represented by the empirical relationship

$$\rho = \rho_0 + \alpha T \quad (3)$$

where ρ_0 is the resistivity at a reference temperature, usually room temperature, and α is the temperature coefficient. Typical values of ρ_0 and α are listed in table 1 along with the calculated resistivity at 100°C.

In metals, where the valence electrons easily move in and out of the conduction bands, the number of charge carriers n is large. Resistivity in metals is therefore more a function of the mobility of the electrons. In a perfect crystalline lattice the electrons are accelerated by an electric field and move with very little difficulty. Even in a pure material, thermal oscillations of the atoms will scatter these moving electrons., increasing the resistivity somewhat. Impurity atoms and defects such as vacancies, dislocations, twin and grain boundaries, will scatter these electrons even more. The combined effect of thermal, impurity, and defects on the resistivity is given by Mathesson's rule where

$$\rho_{total} = \rho_{thermal} + \rho_{impurity} + \rho_{defect} \quad (4)$$

For pure elements the contribution of defects is on the order of 0.1 percent of the total but for heavily cold worked metals it can be as high as 5 percent.

Table 1. Resistivity values of common metals [1]

Material	ρ_0 microohm·cm	α microohm·cm /K <small>Note 1</small>	Resistivity at 100°C microohm·cm
Aluminum	2.284	0.0039	3.064
Copper, Annealed	1.7241	0.00393	2.5101
Copper, Hard Drawn	1.771	0.00382	2.535
Brass	7	0.002	7.4
Gold	2.44	0.0034	3.12
Iron	9.71	0.00651	11.012
Lead	20.648	0.00336	21.32
Nickel	11	0.006	12.2
Silver	1.59	0.0038	2.35
Steel	10.4	0.005	11.4
Nichrome	100	0.0004	100.08
Platinum	10	0.003	10.6
Tungsten	5.6	0.0045	6.5

Note 1. Determined at 25°C

Resistance – Resistance is an extrinsic property of a device which is represented by the equation

$$R = \rho \frac{l}{A} \quad (5)$$

where A is the cross-sectional area and l its length. Practical devices are manufactured using a number of techniques and geometries, including:

- Winding a metal wire on a cylindrical ceramic core. These resistors generally have a high power ratings.
- Coating a cylindrical ceramic core with a material that has the desired resistivity. Controlling the film thickness and length (the film may be applied in a helical pattern) is critical.
- Applying a thin film of a material with the desired resistivity to a flat ceramic substrate. After firing or curing this film can be laser “trimmed” to obtain a more precise resistance.

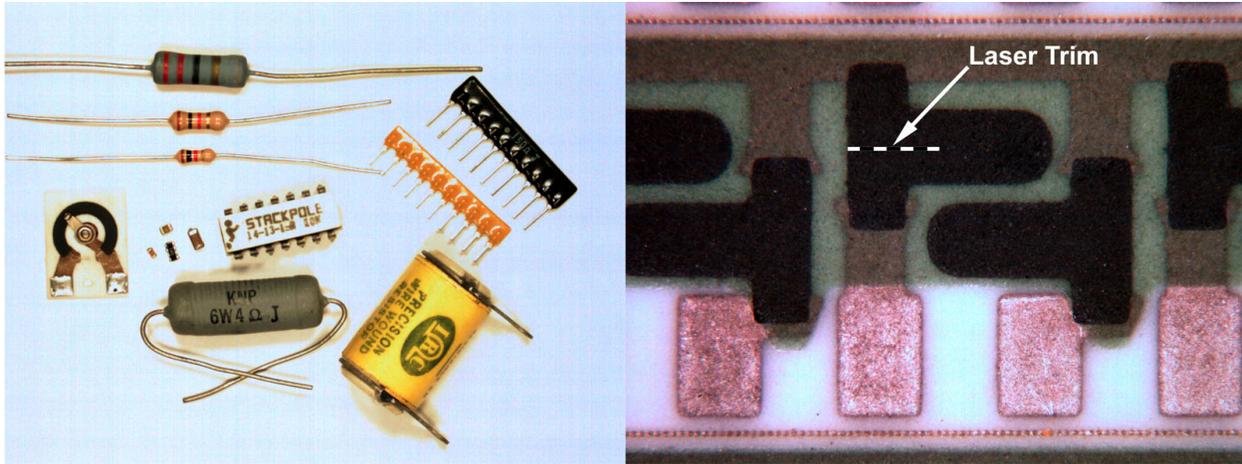


Figure 1 On the left are a number of different types of resistors, including $\frac{1}{8}$, $\frac{1}{4}$, and 1 watt axial resistors, single and dual in-line networks, precision wire wound resistors and four tiny surface mount resistors. On the right is a magnified image of a couple of the carbon film resistors in SIPs and DIPs like those shown on the left. The little “hats” are laser trimmed to obtain a resistance within 2% of the desired value.

This method is used to put many resistors on a single SIP or DIP resistor package.

In practical applications the temperature dependence of the resistance of a device may be an issue. When selecting a resistor for use in a circuit one can specify the thermal tolerances along with its resistance value and power rating.

Procedure

This experiment has two parts, performing preliminary calculations to , then the resistivity measurements made in the laboratory. Perform the following calculations using spreadsheets or similar software tools:

- Calculate the resistivity of all of the materials listed in table 1 from room temperature to 1000°C and examining the range of values and the trends.
- Calculate the resistance of these materials when they are in the form of 2 meter lengths of 24 gage wire.
- Calculate the output voltages from Wheatstone bridge where $R_1=R_2=1000$ ohms, $R_3=1$ ohm. Assume the lead resistance is zero.

The experiment involves the following steps:

- Preheat the tube furnace to a suitably high temperature, such as 800°C , but not high enough to melt the sample.
- Set up the data acquisition system (Figure 2 shows how the equipment is connected.)
- Short the leads to the Wheatstone bridge to find the lead resistance.
- Test the system using several low-resistance (0.5 to 2 ohms) resistors.

Prepare the sample by cutting a two meter length of wire, straightening it, measuring its length, then clean it using alcohol. Wrap the wire around a small diameter rod, then carefully slip it over a slightly larger diameter ceramic tube, making sure the coils do not touch each other. Insert the thermocouple in this tube and this assembly is placed inside another ceramic tube.

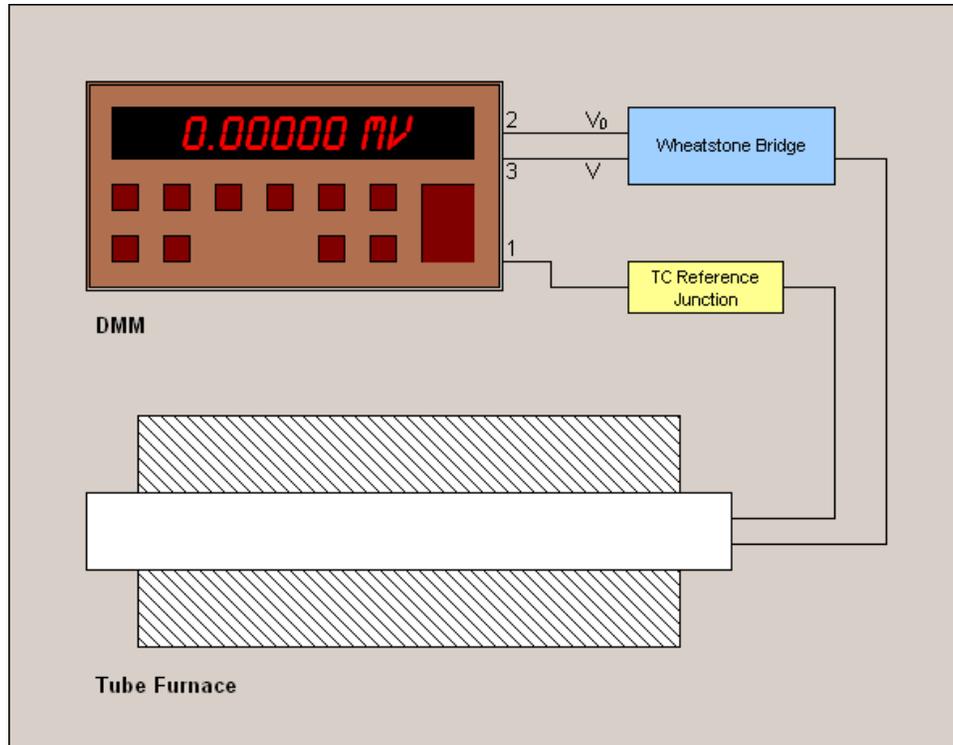


Figure 2 The basic equipment setup used in this experiment.

Connect the thermocouple and wire to the data logging system and then insert the assembly into the tube furnace. Once the sample assembly reaches the desired temperature remove it from the furnace, place it on a heat resistant surface, and the immediately start the data acquisition software. The data acquisition software will record and plot temperature versus resistance. Figure 3 shows a screen shot of the data acquisition software and the last page in this manuscript is a sample printout. Once the sample assembly has cooled it can be safely disassembled and the wire inspected for excessive oxidation, shorting, or other potential problems.

Results

Import the data into a spreadsheet to plot it and analyze the results. From the measured resistance and wire dimensions the values of ρ_0 and α can be determined.

Analysis

The results obtained in this experiment are fairly straightforward and it seems the only question would be do the results compare well with the values listed in table 1, and do the results agree with the calculations? Problems, if they are encountered, might be due to the experimental apparatus and procedure (lead resistance errors, temperature gradient along the wire, different temperature at the thermocouple and the wire) or due to overlooked materials issues, such as oxidation, recrystallization, phase changes. How would these factors affect the results? Do you see any of these problems in the data?

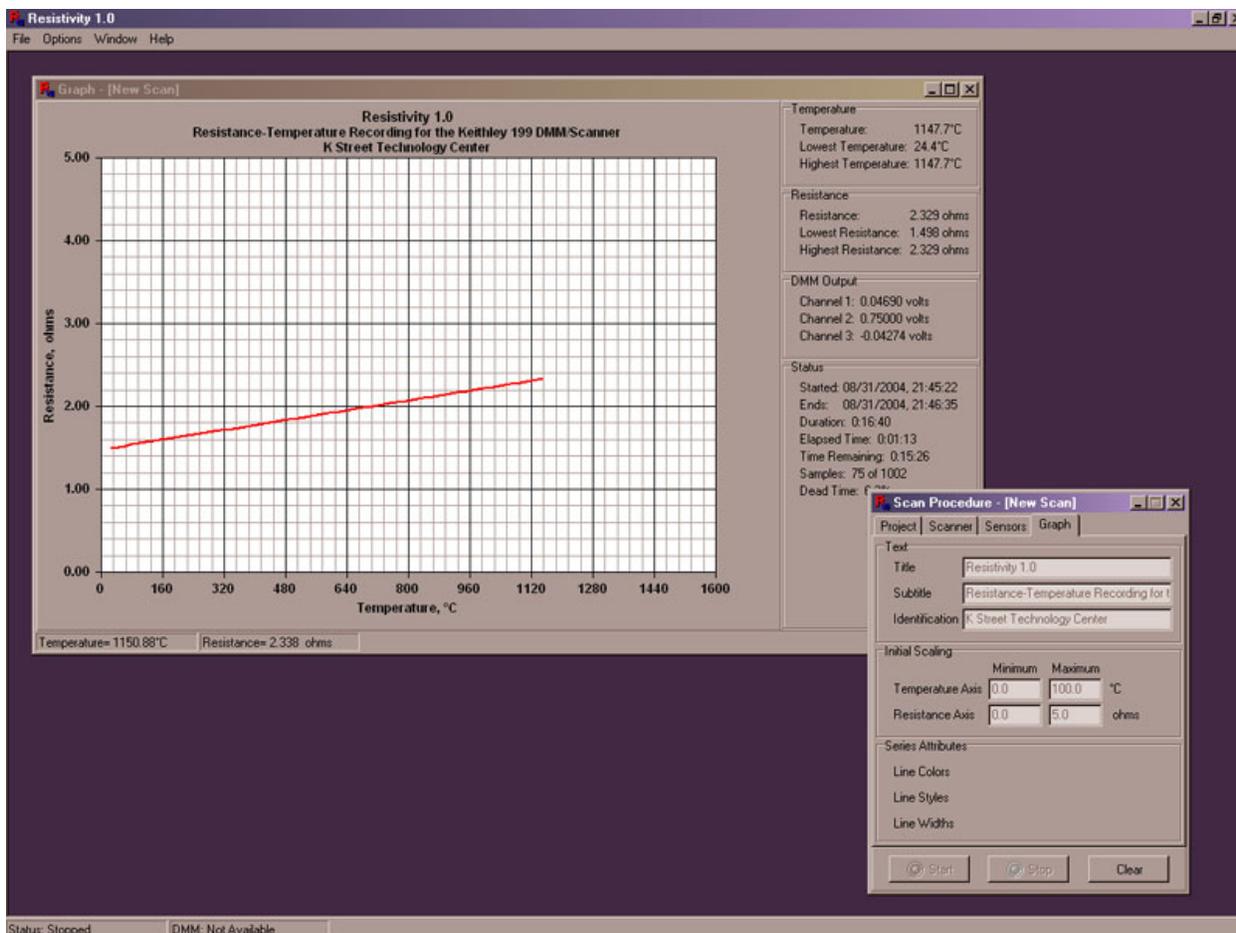


Figure 3 Screen shot of the data acquisition software.

References

1. CRC Handbook of Chemistry and Physics, 65th edition, CRC Press, Inc, Boca Raton, FL, pp. F-114 - F-120, (1984-85).

Appendix 1. AWG Wire Gages

Wire Gage	Diameter in mils at 20°C	Diameter in millimeters at 20°C
8	128.5	3.26
10	101.9	2.59
12	80.81	2.05
14	64.08	1.63
16	50.82	1.29
18	40.30	1.02
20	31.96	0.81
22	25.35	0.64
24	20.10	0.51
26	15.94	0.40
28	12.64	0.32
30	10.03	0.25
32	7.950	0.20
34	6.305	0.16

Appendix 2. Wheatstone Bridge

This experiment uses a standard wheatstone bridge. In the circuit used here R_A and R_B serve as current limiting resistors for cases where R and R_3 are low, such as during a short circuit when configured to measure low values of R . The circuit diagram is shown in figure 4.

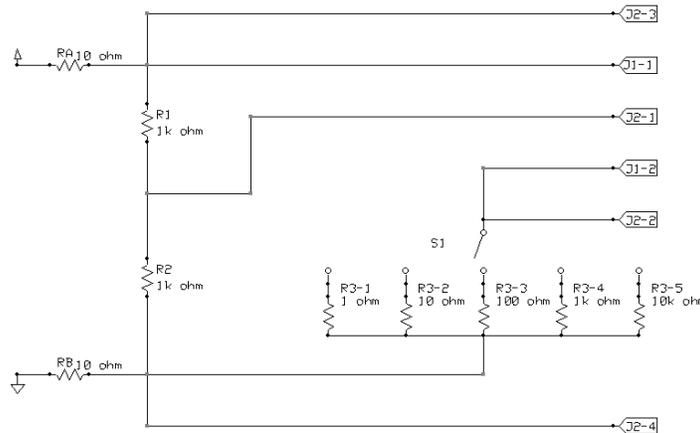


Figure 4 This circuit is a standard wheatstone bright that has two current limiting resistors (R_A and R_B) and a selection or resistors R_{3-1} - R_{3-5}) that allows one to select the best resistance range.

Circuit Equations

V_S is the voltage of the power source, such as a battery and is typically 1.5 volts. Higher voltages can lead to high current passing through the 1 - 2 ohm resistor being measured. All resistor values are in ohms.

$$V = V_1 - V_0$$

$$V_1 = V_S \left(\frac{R_3 + R_0}{R_A + R_L + R + R_3 + R_B} \right)$$

$$V_0 = V_S \left(\frac{R_2 + R_B}{R_A + R_1 + R_2 + R_B} \right)$$

$$R = V_S \frac{R_3 + R_B}{V + V_0} - R_A - R_L - R_3 - R_B$$

$$R_L = V_S \frac{R_3 + R_B}{V + V_0} - R_A - R_3 - R_B, \quad R=0$$

Appendix 3. Safety Considerations

Chemical Hazards	The methanol used to clean the wire poses fire and health hazards. Handle this solvent carefully. Use only small quantities, clean up any spills immediately, and keep it and its fumes away from the hot furnaces. An MSDS for methanol can be provided on request.
Physical Hazards	<p><i>Burns</i> – The temperatures used in this experiment can cause serious burns and even fires if flammable materials come in contact with the hot parts. Be extremely careful when working with the furnaces and the hot specimens, be careful and deliberate when removing and handling the hot specimens, and remember, parts do not have to be glowing to be very hot.</p> <p><i>Electrical</i> – There is a minor electrical hazard in this experiment, similar to that one ... with when dealing with any small electrical appliance.</p> <p><i>Fire</i> – The combination of high temperatures, electrical appliances, and flammable methanol presents a definite fire hazard. Keep the methanol away from the furnaces, clean up any spills immediately and work with on small quantities of this flammable solvent.</p>
Biohazards	None.
Radiation Hazards	None.
Protective Equipment	Recommended: safety glasses Required: heat-resistant gloves, as needed

Resistivity 1.0

Resistance-Temperature Recording for the Keithley 199 DMM/Scanner

Version: 1.0 alpha, October 24, 2002

Project

Name: Resistivity 1.0

Description: Resistance-Temperature Recording for the Keithley 199 DMM/Scanner

Owner: K Street Technology Center

Data File: Resistivity10.csv

Sensor Parameters

Thermocouple Type: K

Resistance RA: 10.00 ohms

Resistance R1: 1000.00 ohms

Resistance R3: 1.00 ohms

Resistance VS: 1.50 volts

Resistance RB: 10.00 ohms

Resistance R2: 1000.00 ohms

Resistance RL: 0.00 ohms

DMM/Scanner Parameters

DMM Status String: n/a

Function: DC Volts

Range: 300 mV

Resolution: 4½ digits

Channel 1: Temperature

Channel 2: V0

Channel 3: Resistance

Sampling Parameters

Period: 1 second

Channels Scanned: 1 through 3

Start Time: 09/02/04, 22:47:41

End Time: 09/02/04, 22:48:26

Duration: 0:00:45 (45.4 s)

Samples: 47

Comments

Sample Data
Resistance-Temperature Recording for the Keithley 199 DMM/Scanner
NEW Update 2004

