Experiment #2: Electrical Measurements

Overview. In this experiment you will measure electrical resistance in three different contexts:

- Thin wires → resistance *vs.* length → determine resistivity
- Thin conductive coating (ITO on glass) → measure sheet resistance
- Temperature dependent electrical properties of metals and silicon

You will also get some practice with linear regression, making publication-quality figures, and reporting measurement results with uncertainty/error estimates (*e.g.*, using R^2).

Procedure 1: Determining the resistivity of thin wires from R versus L

This procedure is designed to verify that resistance increases linearly with wire length, and by performing a linear fit on this data, we can extract the resistivity (ρ).

What you will measure:

- Length (L) of the distance between sense leads
- Resistance (R) of each wire over length L
- Diameter (d) of each wire

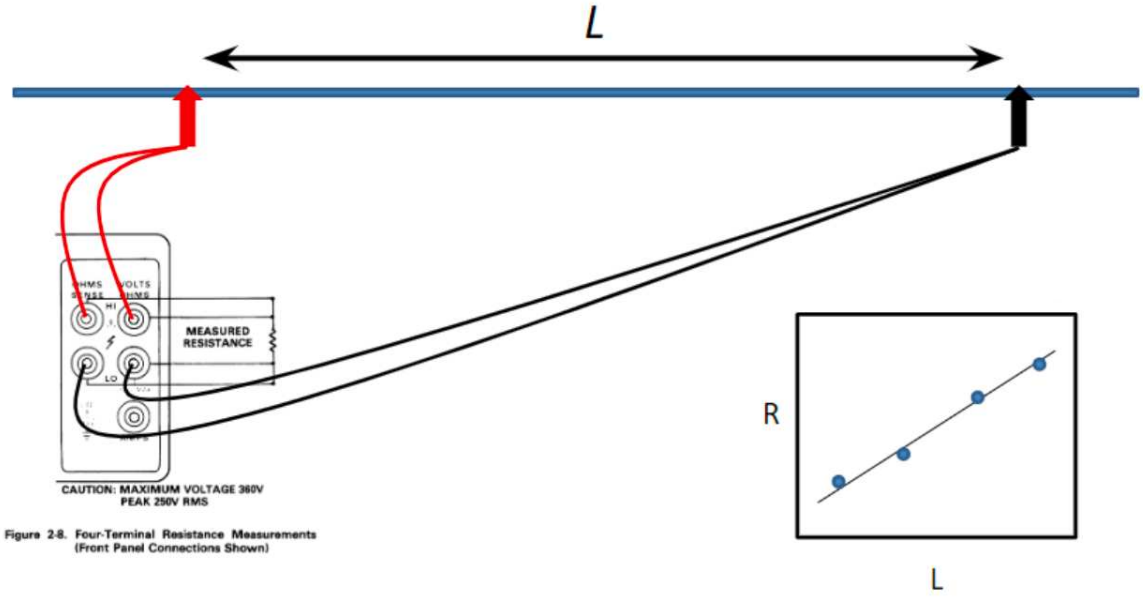

Figure 1 | Thin Wire Schematic. Illustration of Procedure 1, showing use of 4-point probe to acquire various resistance measures at various lengths of a given wire to produce a linear regression plot. Repeat for each wire.

Step-by-step walkthrough:



Wire set

1. Measure each wire diameter
   - Use the micrometer to measure the diameter of each wire.
   - Measure and record the diameter five times at different points along each wire.
   - Compute the average diameter of each wire: d_{avg}
2. Measure the resistance (R) at different lengths (L)
   - Choose at least five different lengths along each wire.
   - For each length:
     - Measure the lead spacing L using a ruler or calipers.
     - Measure the resistance R (in ohms) using the multimeter.
   - Record your data in a table.
3. Plot R versus L using Excel
   - This should be a scatter plot where R is the y-axis and L is the x-axis
   - Fit the data using least-squared linear regression
   - Report three values: the slope (m), y-intercept (b), and quality of fit (R^2)
4. Calculate the resistivity (ρ)
   - Use $R = \rho L/A$ and the linear fit to determine the resistivity. Notice the similarity between this equation and $y = mx + b$.
   - Be sure to report the number of measurements that were used to derive the resistivity in each case, as well as the R^2 values. Beyond that, don't worry about reporting standard deviation values.
5. Identify each wire material
   - Use online reference values of resistivity (at room temperature).
   - Compare your measured ρ to common metals/alloys (search online).
   - Report your best guess for each wire material and briefly justify it.

Procedure 2: Measuring sheet resistance of a thin conductive coating (ITO on glass)

ITO (Indium Tin Oxide) is a transparent, electrically conductive oxide coating that is commonly deposited as a very thin film on glass or plastic. It's widely used in technologies like touchscreens, displays, solar cells, and transparent electrodes because it can conduct electricity while still letting visible light pass through.

Sheet resistance is a convenient way to describe the resistance of a thin film without needing to know the film thickness. Instead of reporting resistance in ohms between two specific points (which depends on the size and geometry), sheet resistance characterizes how resistive the film is "per square" of material (**Ω/sq**). For a film of length L, width W, and thickness t, the sheet resistance (R_s) is related to the usual resistance through:

$$R = \frac{\rho}{t}\frac{L}{W} = R_{\mathrm{s}}\frac{L}{W}$$

What you will measure:

- The sheet resistance (R_s)
- The sample dimensions

Four-point probe



Step-by-step walkthrough:

1. Place the sample on the probe station
    - Place the ITO-coated glass sample on the stage.
    - Center it under the probe head.
    - If the sample is rectangular: align the long edge parallel to the row of probes.
2. Set film thickness to 0.000 (instrument input)
    - If the instrument asks for thickness, set it to 0.000 – This tells the instrument to report sheet resistance rather than bulk resistivity.
3. Bring the probes into contact
    - Lower the probe head until the probes just touch the sample surface.
4. Apply consistent contact force
    - After initial contact, turn the micrometer one full rotation. The goal is for the probes to retract about halfway into their housings. This ensures stable electrical contact with minimal risk of damaging the glass.

5. Measure sheet resistance
    - Click the "Measure" button in the program to start.
    - Record the sheet resistance value displayed by the instrument.
    - Repeat at 3 different locations on the sample: center left side right side.
    - Record all values and compute an average.
6. Estimate bulk resistance across the sample
    - For very thin samples (thickness $t \ll$ pin gaps), we can use the below equation:

$$R = \frac{\rho}{2\pi t} \ln 2 \text{ where } \rho = R_s t$$

    - From this, compute the bulk resistance (R) and report it.

Procedure 3: Temperature dependence of resistance

These measurements will demonstrate how resistance changes with temperature for:

- Metals: resistance should *increase* with temperature
- Semiconductors: resistance should *decrease* with temperature

We'll confirm these expected trends on three materials:

Copper (metal), Constantan (copper-nickel alloy, metal), and Silicon (semiconductor).

What you will measure:

- Temperature (T)
- Resistance (R)

Step-by-step walkthrough: (the TA will help with this)

1. Connect the measurement setup
    - Connect the heater to the power supply.
    - Connect each sample to a Digital Multimeter (DMM) to measure resistance.
    - Connect the thermocouple to the temperature-reading DMM.
2. Begin heating the oil bath gradually
    - Do *not* heat too quickly. You want stable measurements.

3. Record resistance and temperature
    - Record data at every 3° increase.
    - At each temperature step, record T and R.
    - Start at room temperature (~21 °C) and continue to 72 °C.
4. Data analysis for metals
    - Plot R versus T for each metal using Excel and perform a linear fitting.
    - Determine the temperature coefficient of resistance (α): $\Delta R/R_0 = \alpha \Delta T$
    - Be sure to report R^2 for each metal and linear fit.
5. Data analysis for silicon
    - Plot ln R versus $1/T$, ensuring the temperature is in Kelvin (not °C).
    - Make a linear fit and record the slope, y-intercept, and R^2.
    - Determine the activation energy from your data using the below equation:

$$\frac{1}{\rho} = \frac{1}{\rho_0} \exp(-\Delta E/2k_B T)$$

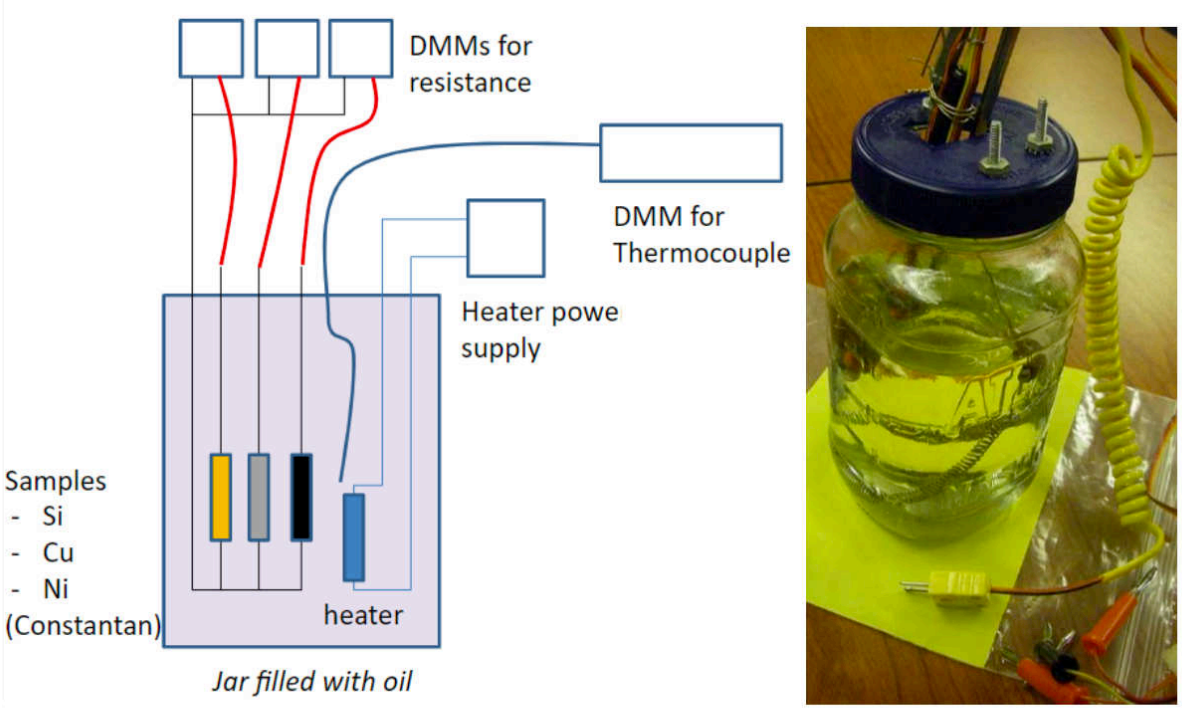

Figure 2 | Thermal Resistance Vessel. Schematic and picture of the experimental set up used in measuring the resistance with increasing temperature with various metal and semiconductor components.