Resistivity
Four-Terminal Sensing

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Abstract
The purpose of our experiment was to determine the resistivity of copper, aluminum, and silicon using the four-terminal sensing technique. The resistivity of aluminum was obtained with only a 1% of error while silicon data gave us a 100% of error. The equipment did not measure any resistivity for the copper sample.

1 Introduction

Electrical resistance and resistivity are properties that describe how strongly a material resists the flow of current. A material with an undistorted crystalline structure will have the same *resistivity* regardless of its shape because this property is intrinsic to the material. However, the *resistance* of a material changes depending on the size and shape of the sample. These properties are often used to characterize and classify materials like metals, semiconductors, and insulators. Furthermore, they are used for device structures like diodes, transistors, and LEDs. In this experiment we determine the resistivity of the metals copper, aluminium, and silicon using the four-terminal sensing technique for different temperatures.

2 Experimental Theory

Ohm's law is usually referred to for predicting the behaviour of a material if the resistance remains constant over a considerable range of voltage.

$$R = V/I. \tag{1}$$

However, resistance can also be described in terms of the bulk resistivity of a material by Pouillet's law. We can define resistance by considering the dependence on the physical properties of a material as

$$R = \rho L/A, \tag{2}$$

where L corresponds to the length, A the cross sectional area, and ρ is the resistivity defined as the ratio of electric field and current density measured in Ohms centimetres. Resistance can be measured using the four-terminal sensing technique which determines the voltage drop between two electrodes that impinge a defined current into a material. The technique uses four sharp probes that are placed on the flat surface of a material. Current is passed through the two outer electrodes, and the floating potential is measured across the inner pair ***(fig. 1)***. If the flat surface on which the probes rest is adequately large, then it may be considered a semi-infinite volume. To prevent minority carrier injection and make good contact, the surface on which the probes rest may be mechanically lapped. The identification of the voltage drop value with the resistance of the sample usually has errors as it includes contact resistance at the positions of the probes, which are in series with the resistance of the sample.

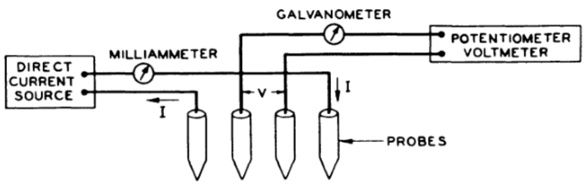

Figure 1. Four-Sensing technique circuit used for resistivity measurement [3].

This problem was first encountered and solved in 1915 by Frank Wenner, while he was trying to measure the resistivity of the Earth. He proposed an inline equidistant four-point (4P) geometry for minimizing contributions caused by the wiring and/or contacts. His technique is now referred in the geophysical community as the Wenner method. In 1954, Leopoldo Valdes used this idea of a 4P geometry to measure the resistivity ρ of a semiconductor wafer and from 1975 this method was established throughout the microelectronics industry as a reference procedure. The resistivity for the ideal case of a semi-infinite volume material with four electrodes equally spaced and aligned in a straight line is

$$\rho = \frac{V}{I}\, 2\pi s, \tag{3}$$

where V is the measured voltage drop between inner probes, I the current flowing through the outer probes, and s the probe spacing. A correction factor for this technique is needed due to the thickness of the samples being small compared to the probe distance of 2.0 millimetres. The correction factor for samples with thickness w less than 0.5mm is given by

$$G\left(\frac{w}{s}\right) = \frac{2s}{w}\, \ln(2). \tag{4}$$

3 Equipment & Procedure

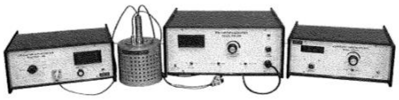

Figure 2. Four Probe research model setup. [1]

The equipment ***(fig. 2)*** consisted of a PID controller with oven unit used to control the temperature up to 200 Celsius, constant current generators to provide the outer probes specified currents up to 200mA, a D.C. Microvoltmeter for measuring low D.C. voltage ranging from 1mV to 10V, the four probe arrangement ***(fig. 3)***, and three test samples copper, aluminium, and silicon. The equipment was already mounted and calibrated. It was required to clean the samples, understand the equipment, and begin taking the data necessary to calculate resistance and resistivity following the formulas provided by the instruction manual.

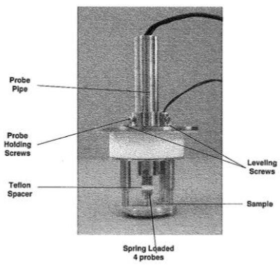

Figure 3. Four Probe arrangement. [1]

The procedure consisted of placing the samples in the four-probe arrangement ***(fig. 3)*** and writing down various voltage and current values for different temperatures. The current and the temperatures were manually selected while the voltage was read in the microvoltmeter display. The aluminum sample had a thickness of 0.16mm and silicon 0.50mm.

4 Data & Results

The equipment did not pickup any resistivity for the copper sample although being cleaned thoroughly. Therefore, we moved on to the other two samples. Firstly, we made an I-V graph and as expected we obtained a linear curve ***(fig. 4, 5)*** showing the relationship between the current and voltage for both samples. Some practical resistors may exhibit non-linear behaviour under certain conditions for example, when exposed to high temperatures. However, our temperatures did not exceed the 200 degrees Celsius and our samples were not resistors.

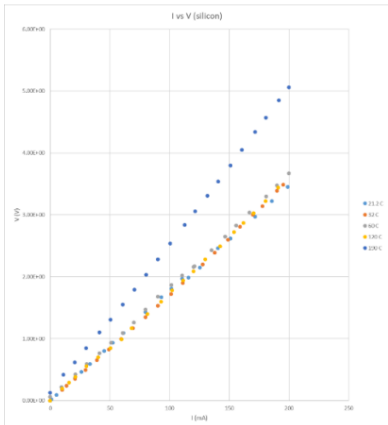

Figure 4. I-V graph for the silicon sample at different temperatures.

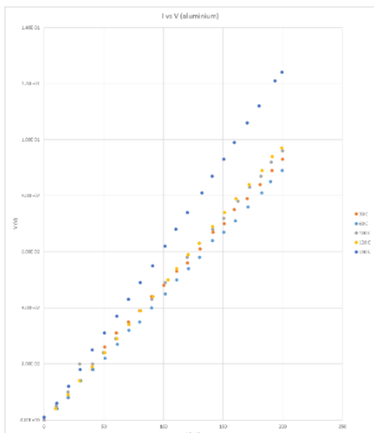

Figure 5. I-V graph for the aluminium sample at different temperatures.

To calculate the resistivity with formula ***(3)*** we first needed to determine the mean resistance of the samples at different temperatures using formula ***(1)***. The mean resistances for the silicon and the aluminium samples are displayed in ***(table 1)*** respectively. From these values we plotted a graph of temperature against resistance for both samples ***(fig. 6, 7).*** The mean resistance was used to calculate the resistivity of the samples ***(table 2, 3)*** where G is the correction factor using formula ***(4)***. A graph of temperature against the corrected resistivity is displayed in ***(fig. 8, 9)***.

Silicon		Aluminum	
Temperature (C)	Resistance	Temperature (C)	Resistance
21.1	1.77E-02	30	4.66E-04
32	1.72E-02	60	4.38E-04
60	1.86E-02	100	4.93E-04
120	1.77E-02	120	4.78E-04
190	2.63E-02	190	6.10E-04

Table 1. Values of the resistances at various temperatures for the silicon and aluminum samples.

Silicon			
Temperature (C)	Resistivity (Ω cm)	G	Corrected Resistivity (Ω cm)
21.1	2.22E-02	5.55E+00	4.00E-03
32	2.17E-02	5.55E+00	3.91E-03
60	2.34E-02	5.55E+00	4.22E-03
120	2.22E-02	5.55E+00	4.01E-03
190	3.30E-02	5.55E+00	5.95E-03

Table 2. Values of the resistivity at various temperatures for the silicon sample.

Aluminuim			
Temperature (C)	Resistivity (Ω cm)	G	Corrected Resistivity (Ω cm)
30	5.86E-04	2.77E+02	2.11E-06
60	5.51E-04	2.77E+02	1.99E-06
100	6.19E-04	2.77E+02	2.23E-06
120	6.00E-04	2.77E+02	2.17E-06
190	7.67E-04	2.77E+02	2.77E-06

Table 3. Values of the resistivity at various temperatures for the aluminum sample.

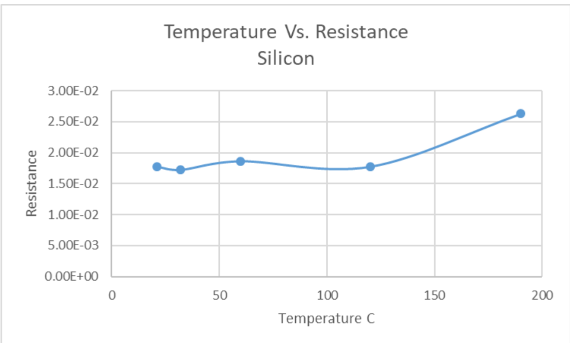

Figure 6. Graph of the T- R relationship for the silicon sample.

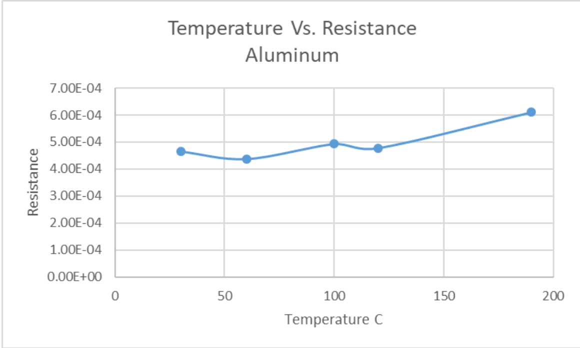

Figure 7. Graph of the T- R relationship for the aluminum sample.

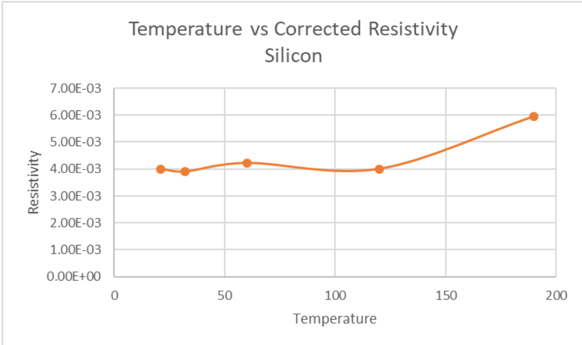

Figure 8. Graph of the T- ρ relationship for the silicon sample.

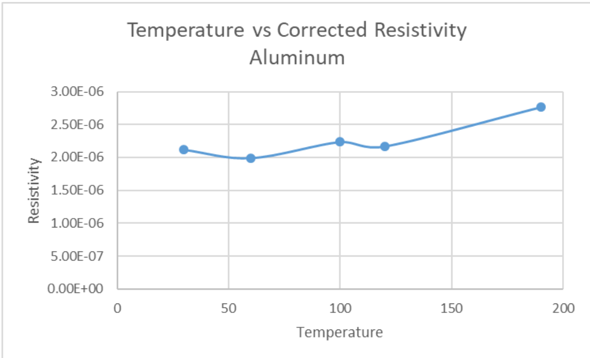

Figure 9. Graph of the T- ρ relationship for the aluminum sample.

The theoretical values for the resistivity of silicon and aluminium were provided by the instruction manual. These were 6 Ωcm for silicon and 2.80×10^{-6} Ωcm for the aluminium sample. Silicon data shows a 100% of error and this is expected given that the calculated resistivity is of order $\times 10^{-3}$ unlike the theoretical value with an order of $\times 10^{1}$. The graphs ***(fig. 6, 8)*** show that for the applied temperatures silicon's resistance and resistivity both remain mostly constant until reaching the 120 degrees Celsius where it begins to increase until 190 degrees. For the aluminium sample we obtained resistivity errors ranging from 20% to 30% except for the

190 degrees data point which gave a 1% of error with a resistivity of $2.77 x 10^{-6}$, the closest value to the theoretical. The graphs ***(fig. 7, 9)*** show the same behaviour that was observed for the silicon sample. The resistance and resistivity clearly begin to increase at 120 degrees Celsius and this is to be expected according to theory.

5 Conclusions

The samples in which we could measure resistance and resistivity using the four-terminal sensing technique were silicon and aluminium. The high silicon percentages of error are probably due to oxidation. However, they could also be due to errors in the calculations and equipment used to apply the constant current. Acceptable percentages of error were obtained for the aluminium sample. Therefore, we succeeded in calculating the resistivity for aluminium but not for the silicon sample.

6 References

[1] "Four Probe Set-up for Measuring the Resistivity of Very Low to Highly Resistive Samples at Different Temperature," SVSLabs Inc.

[2] "Resistivity by Four Probe Method (Theory)." [Online]. Available: https://vlab.amrita.edu/?sub=1&brch=282&sim=1512 cnt=1

[3] L. B. Valdes. *Resistivity Measurements on Germanium for Transistors*. Retrieved from http://lampx.tugraz.at/~hadley/sem/4pt/Resistivity.pdf

[4] I. Miccoli, F. Edler, H. Pfnur, C. Tegenkamp. (May 2015). *The 100th Anniversary of the Four-Point probe techinque*. Journal of Physics: Condensed Matter, Vol. 27, Number 22. Retrieved from https://iopscience.iop.org/article/10.1088/0953-8984/27/22/223201