Low temperature resistance

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This experiment was performed in collaboration with *John Cobbledick*.

Abstract

Through measurements with a Digital Multi Meter, the voltage-current characteristics at different temperatures for copper, constantan, germanium and a diode were compared. The measured resistance of copper increased with temperature, constantan was nearly uniform but increased slightly whereas germanium decreased. The diode was found to have exponential voltage-current characteristics. These measurements led to a diode energy gap of 1334 ± 2 meV. The accuracy of the result was limited by not being able to keep the temperature exactly constant during measurements.

1. Introduction

Materials such as copper (Cu), constantan (Const) and germanium (Ge) have different voltage-current characteristics to diodes. The former materials follow Ohm's law (a linear law), usually written as

$$V = IR\,, \tag{1}$$

where V is voltage, I is current and R is resistance. Semiconductors, however, follow exponential voltage-current relationships such as

$$I = I_0 e^{\frac{-eE_g}{kT}} (e^{\frac{eV}{kT}} - 1)\,, \tag{2}$$

where e is the charge of an electron ($1.602\text{x}10^{-19}$C), E_g is the energy gap, k is Boltzmann's constant ($1.381\text{x}10^{-23}\text{JK}^{-1}$), T is temperature and I_0 is a constant current.

It is useful to observe any change in these relationships as a function of temperature. Cooling samples to low temperatures may lead to superconductivity, which has implications for a number of areas, such as transport [1]. Research into higher temperatures superconductors is ongoing [2].

2. Theory

From Equation 1, linear materials have constant resistance for constant temperature. Resistance can be found by taking the gradient of a voltage-current graph. Resistance increases with temperature due to the charge carriers' extra energy causing more collisions, as illustrated in Figure 1. More collisions mean charge carriers do not move along the material as fast, meaning less current and therefore higher resistance for the same voltage. The opposite holds for decreasing temperature. Resistance against temperature is plotted to verify this.

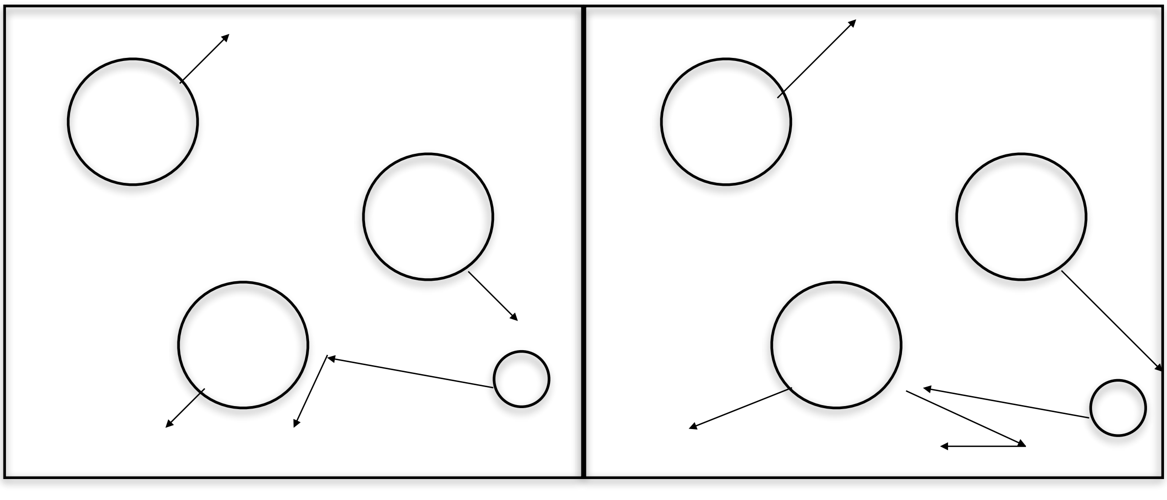

Fig 1. A simple diagram contrasting electrical resistance at lower temperature (left) with higher temperature (right). The smaller circles are charge carriers and are moving left. The larger circles are usually metal ions. The diagram shows the ions vibrating more at higher temperature, therefore causing more collisions with the charge carriers which leads to higher resistance.

For semiconductors to conduct, a charge carrier has to be excited from the valence band to the conductance band, separated by an energy gap. If voltage is insufficient to excite many charge carriers, current is low. However, since the charge carriers' energies follow Maxwell-Boltzmann distributions, some will be able to move along the material [3]. With higher voltage, more charge carriers will be excited into the conductance band, leading to the material conducting more, as shown in Figure 2.

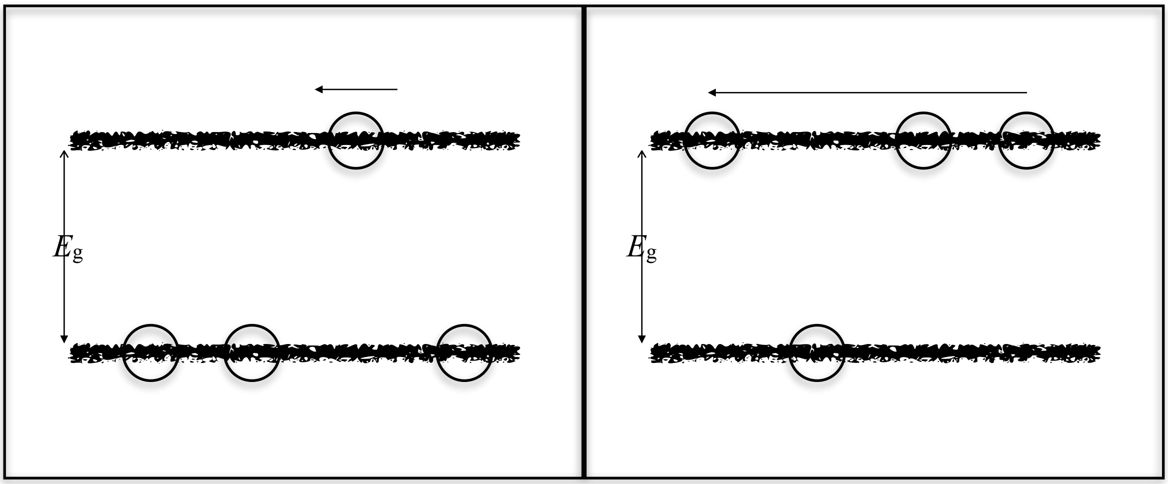

Fig 2. A diagram contrasting electrical conduction in semiconductors at low temperature (left) with high temperature (right). The circles are charge carriers and move left when in the higher energy level (conductance band), but do not conduct when in the lower level (valence band). The higher the temperature the more charge carriers will be in the conductance band. The energy difference between levels is E_g. The arrows show the relative size of currents in both situations.

With the values of voltage and temperature in this experiment, *eV/kT* was about 20, allowing *eV/kT* - 1 to be approximated as *eV/kT*. Equation 2 thus linearises to give

$$V = \frac{k}{e}\ln\left(\frac{I}{I_0}\right)T + E_g \quad (3)$$

Plotting T on the x-axis and V on the y-axis for constant I gives E_g as the intercept.

3. Experimental method

The apparatus used was a vacuum system with a number of valves, as shown in Figure 3. A rotary pump was maintained to evacuate the outer skin of a specimen chamber, where the samples were held. Separately, a vacuum pump was turned on to evacuate the space between the samples and liquid nitrogen which was used to cool the samples; or helium, used to conduct heat to or from the samples. A thermocouple was used to measure the samples' temperature, which in turn was connected to a digital multi meter (DMM) to display temperature. The DMM also displayed the samples' voltage when using the appropriate setting, and was accurate to 0.016%, as indicated on the DMM. The thermocouple was connected to ice for calibration. Pressure gauges measured pressure at different points. Inside the specimen chamber there was a heater whose current was adjustable and resistors of 0.1, 1, 10 and 100 kΩ in a circuit.

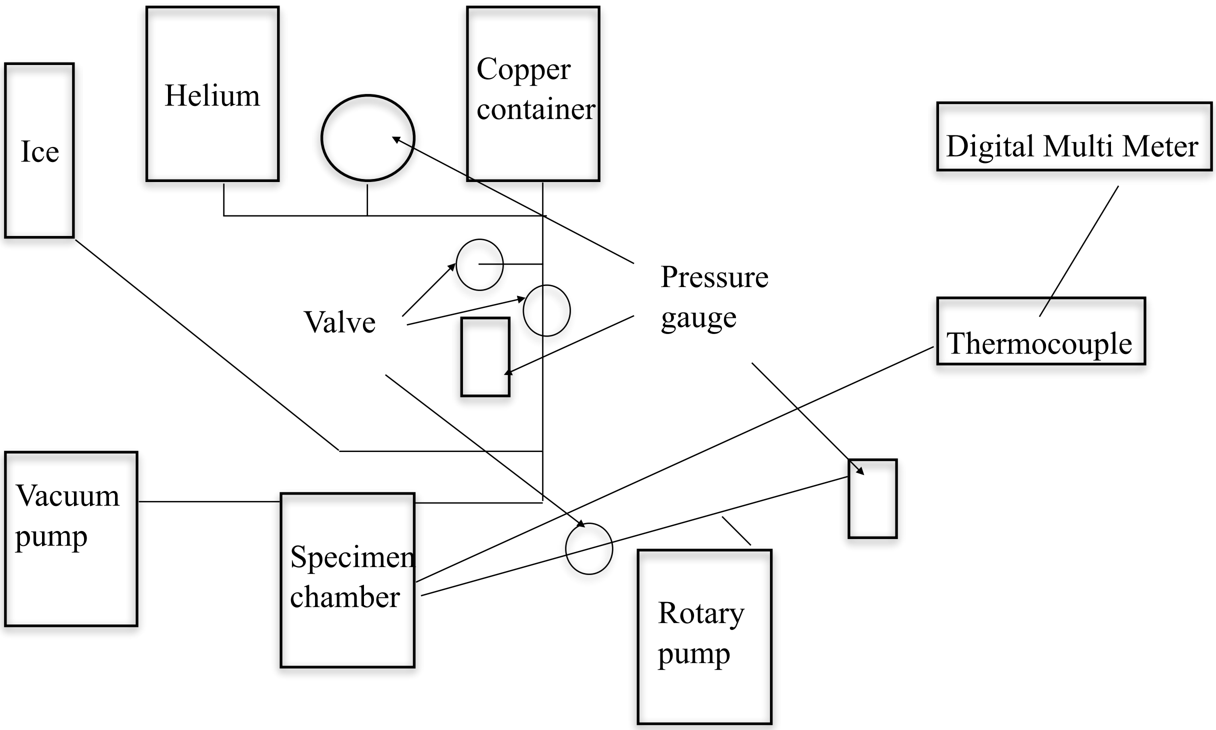

Fig 3. A simple schematic diagram of the vacuum system used.

The voltage-current characteristics of each sample were first measured at room temperature. In doing so, each resistor was used and the input voltage to the circuit varied. For the diode, a range of input currents were used to determine E_g by plotting the data and using Equation 3.

These measurements were repeated for temperature ~ 30 to 80^{0}C, in 10^{0}C intervals. To raise temperature the heater current was increased and helium was allowed into the specimen chamber to conduct heat to the samples. To stabilise temperature the pressure was adjusted by allowing for more or less helium.

The same measurements were repeated for -120, -70 and -20^{0}C. Liquid nitrogen was poured into the specimen chamber for the samples to reach the lowest temperature possible. Raising temperature depended on heater use, as any helium would conduct heat from the samples. Temperature stabilisation was performed as before. For Ge, measurements were repeated at finer 10^{0}C intervals from -50^{0}C to 20^{0}C as resistance varied considerably in this range.

4. Results

The lowest temperature achieved was -120.27 ± 0.03 ^{0}C, as recorded on the thermocouple.

Figure 4 from MATLAB's [4] lsfr fit shows the measured resistance for Cu. Resistance is seen to increase with temperature, as expected.

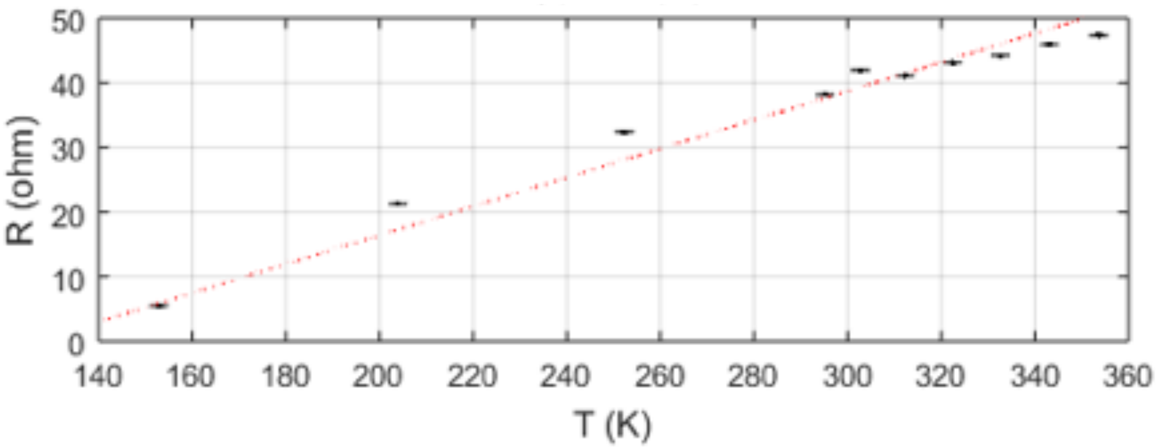

Fig 4. A plot of T in K against R in Ω for Cu. The gradient of the plot is 223.25 ± 0.01 mΩK^{-1}. The temperature is measured using the thermocouple.

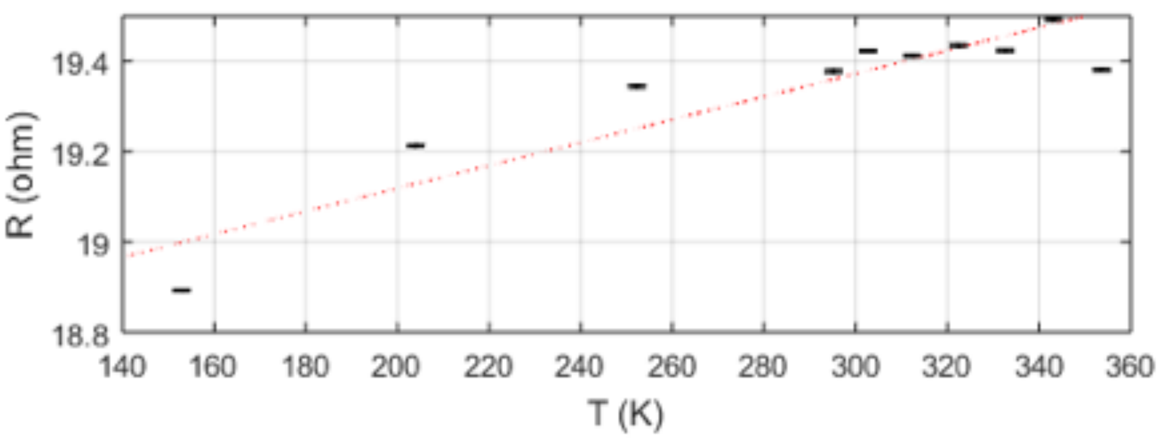

Fig 5. As Figure 4 but for Const. The gradient of the plot is 2.54 ± 0.01 mΩK^{-1}.

From Figure 5, the measured resistance for Const is more uniform compared to Cu, with gradients of 2.54 ± 0.01 and 223.25 ± 0.01 mΩK^{-1} respectively, hence the name constantan.

The measured resistance for Ge decreases with temperature, as seen in Figure 6. A large variation in resistance is evident between 200 and 300K, which is why extra measurements for this range were made.

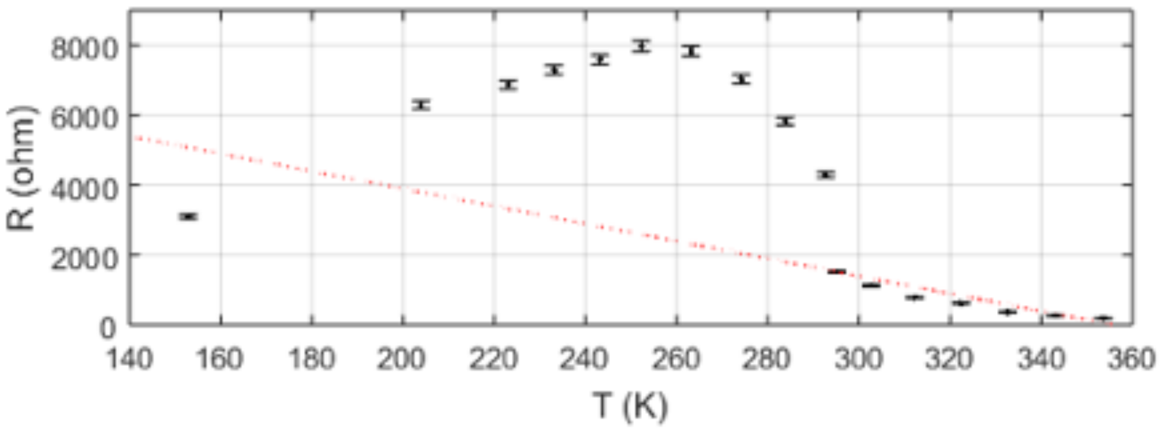

Fig 6. As Figures 4 and 5 but for Ge.

Plotting ln$I$ against V in Figure 7 shows exponential voltage-current characteristics for the diode, as expected from Equation 2. A weighted average on the intercepts from constant current plots, as illustrated in Figure 8, led to an eE_g of 1334 ± 2 meV through Equation 3.

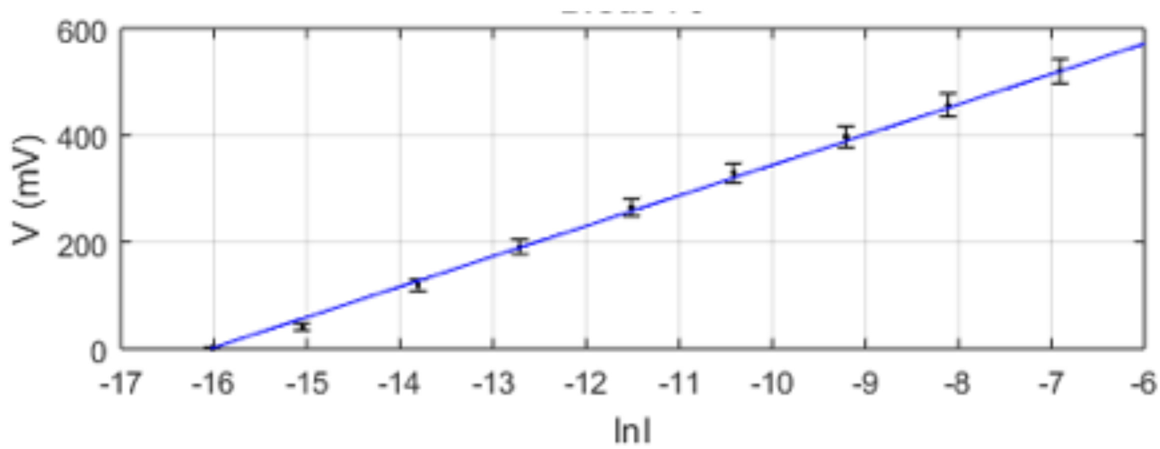

Fig 7. An example of a plot of ln$I$ against V in mV for constant T for the diode. This particular plot is from measurements at 70^0C.

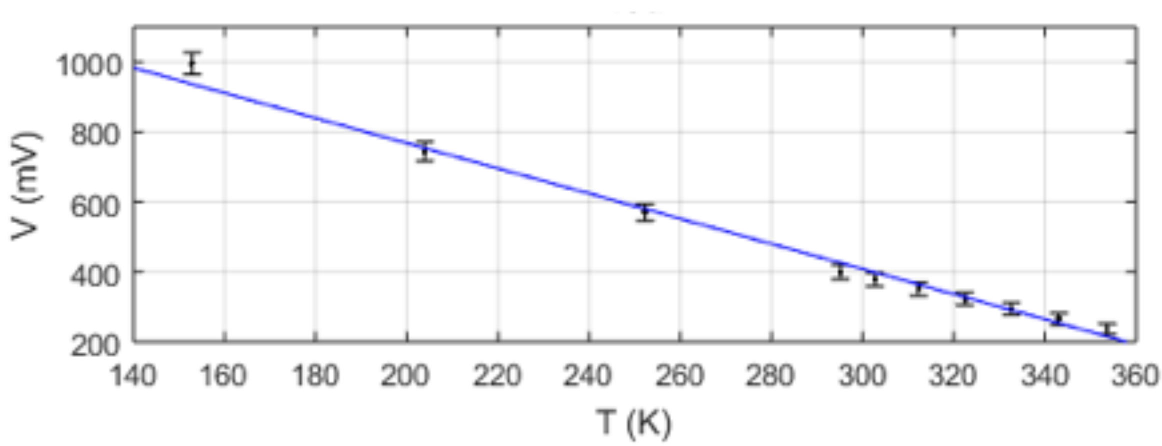

Fig 8. An example of a plot of T in K against V in mV for constant I for the diode. This particular plot is from measurements at 10μA. This plot has an intercept of 1487 ± 7 mV.

5. Discussion

The resistances used in the resistance-temperature plots for Cu, Const and Ge were obtained by plotting voltage-current graphs for constant temperature then taking the gradient. Linearity was verified before plotting temperature against resistance. For this, uncertainties in voltage were estimated as the quadrature sum of the amount by which the reading fluctuated, the DMM accuracy and the smallest reading possible.

Since the resistance of Cu spanned a larger range than that of Const, Cu had a lower resistance than Const at lower temperatures, but the opposite was true for higher temperatures. For all temperature the resistance of Ge was higher than both Cu and Const. It seems that Ge is ohmic until a threshold temperature (peak of Figure 6), then it shows semiconductor behaviour. This might be explained by the valence & conductance bands overlapping at lower temperatures, then a band gap is present at higher temperatures. The diode was found to obey exponential voltage-current characteristics well.

6. Summary

The voltage-current characteristics of different materials can differ from each other, some are linear and others exponential. Additionally, the behaviour of resistance with increasing temperature varies between materials, some increase, some decrease whilst others stay nearly constant.

References

[1] Cooper, E., “Maglev: The Newest Cog in the Nation’s Transportation Infrastructure”, *Quest,* Volume 6, Issue 1, 2013.

[2] Cartlidge, E., “Superconductivity record sparks wave of follow up physics”, *Nature*, Volume 524, Issue 277, 2015.

[3] Eisberg, R. & Resnick, R., *Quantum Physics of Atoms, Molecules, Solids, Nuclei and Particles*, Wiley, Second Edition, 1985, page 467.

[4] MATLAB, Version 5, The Math Works Inc, Natick, Mass 01760.

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