SECOND YEAR LABORATORY

LOW TEMPERATURE RESISTANCE

1 Aims

To understand the difference between linear (i.e. ohmic) and non-linear (e.g. diode) current-voltage relationships and how the resistance of different materials varies with temperature. To gain familiarity with equipment that cools samples to low temperatures.

2 Objectives

1. To measure I-V curves for copper, constantan, germanium and a silicon diode at room temperature.
2. To measure the resistance (or *I-V* curve) of these samples over a range of temperature.
3. To explain the observed behaviours qualitatively and to estimate the energy gap in a silicon diode.

3 Apparatus

The specimens are mounted on a copper block as illustrated in Fig. 1. The specimen holder is placed in cylinder that is located in a double-walled flask (dewar) as shown in Fig. 2. Liquid nitrogen can be added to the flask to cool the specimens to low temperature. Helium gas can be introduced into the sample space to act as a thermal link between the specimen holder and the liquid nitrogen bath. A heater (of resistance 25 Ω) is also mounted on the specimen holder. Further diagrams and instructions on using the vacuum system are provided in the supplementary materials available on Blackboard. If you have any doubts, consult a demonstrator or technician.

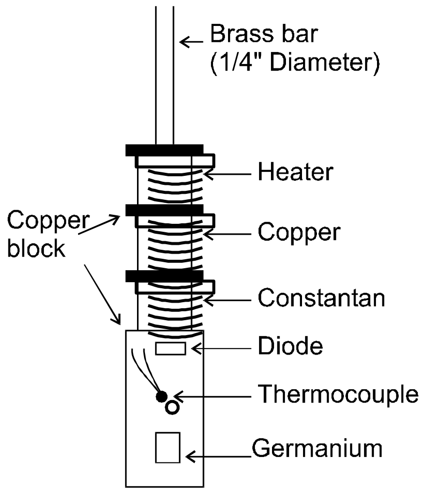

Fig. 1. Specimen holder.

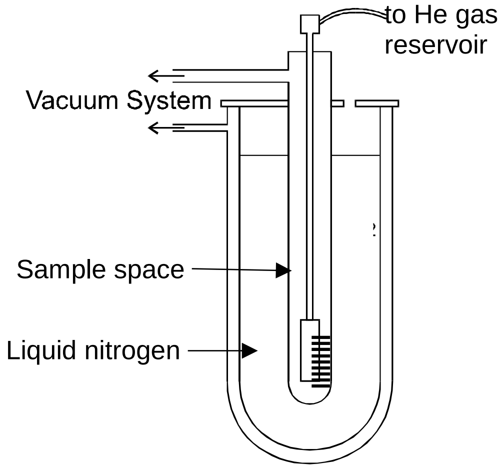

Fig. 2. Cylinder for specimen holder.

The temperature may be controlled by varying the helium pressure and the heater current and is monitored using a thermocouple.

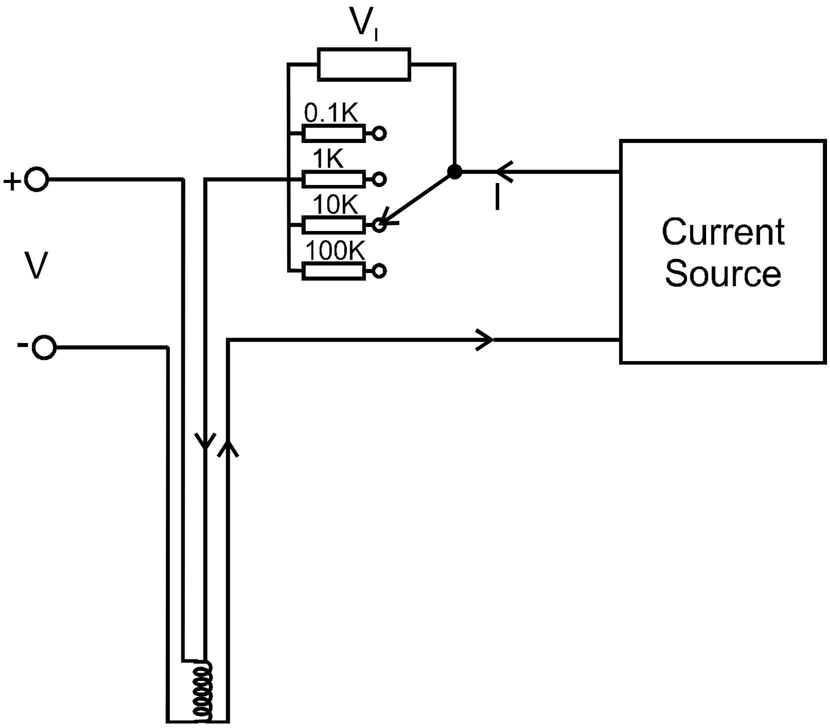

Fig. 3. Circuit diagram.

The voltage V across the specimen is measured by an accurate DVM as a known current is passed through it. The current in turn is determined by measuring the voltage drop V_I across one of four precision resistors (0.1 k, 1 k, 10 k, 100 k). Currents from 1 μA to 10 mA can thus be measured. The four specimens can be selected in turn by a switch. The same switch can select the Type T (copper/constantan) thermocouple whose voltage (again measured by the DVM) monitors the temperature of the copper block. Table 1 (taken from [1]) shows how the voltage of the thermocouple varies with temperature. Note that a second thermocouple, placed in melting ice (ice-water mixture) provides a fixed reference temperature.

Temp (°C)	**0**	**10**	**20**	**30**	**40**	**50**	**60**	**70**	**80**	**90**
-300				-6.258	-6.232	-6.181	-6.105	-6.007	-5.889	-5.753
-200	-5.603	-5.439	-5.261	-5.069	-4.865	-4.648	-4.419	-4.177	-3.923	-3.656
-100	-3.378	-3.089	-2.788	-2.475	-2.152	-1.819	-1.475	-1.121	-0.757	-0.383
0	0	0.391	0.789	1.196	1.611	2.035	2.467	2.908	3.357	3.813
100	4.277	4.749	5.227	5.712	6.204	6.702	7.207	7.718	8.235	8.757
200	9.286	9.820	10.360	10.905	11.456	12.011	12.572	13.137	13.707	14.281
300	14.860	15.443	16.030	16.621	17.217	17.816	18.420	19.027	19.638	20.252
400	20.869									

Table 1. Output (in mV) of a Type T (copper/constantan) thermocouple. These data are also available in an Excel file on Blackboard.

4 Experimental Procedure

a) An example specimen holder is displayed with the equipment to demonstrate the way it is arranged. You should not attempt to remove the specimen holder from your apparatus. Evacuate the cylinder containing the specimen holder. Do not fill the liquid nitrogen cylinder yet.

b) Measure the resistance of the copper, constantan and germanium specimens at room temperature by plotting *V* against *I* over an appropriate range of *I*. For the diode, measure the current-voltage characteristics for a range of currents. (Large steps in the current range can be made, e.g. 0.1 μA, 0.3 μA, 1 μA, 3 μA, … 1 mA.)

c) Repeat the above measurements for a number of temperatures between room temperature and 80 °C. By this time the vacuum should be established (i.e. the pressure should be low) and there should be little difficulty in maintaining the specimen at constant temperature. The germanium resistance varies considerably between ± 50 °C and additional measurements in this range are needed for this material. You should consider whether you need to obtain full *I*-*V* curves at each temperature. Discuss this with your demonstrator.

d) Pour liquid nitrogen into the dewar. Do not allow air at atmospheric pressure into the specimen space after this, or oxygen will begin to condense around the specimen. The temperature of a specimen will be affected by the pressure of the helium gas surrounding it. At pressures below about 0.01 mbar, little conduction takes place. At pressures above this, conduction takes place and the specimen cools. The temperature may be controlled and stabilized by adjusting the pressure. The pressure may be increased by carefully introducing some helium from the gas reservoir. Measure the resistance and current-voltage characteristics at about 50 °C intervals down to the lowest temperature possible.

e) Plot graphs to show the variation in resistance of copper, constantan and germanium with temperature. For germanium it is also interesting to plot the variation in conductivity versus 1/*T*. Explain the form of this graph.

f) The temperature of the specimen is affected by:

   (i) conduction (and convection) through the pressure of helium gas in the sample space.

   (ii) radiation from and to the specimen holder;

   (iii)conduction along the brass bar;

   (iv)the heater (resistance 25 Ω, max current 0.5 A).

   Estimate the rate of heat change due to each of these mechanisms.

The expected diode characteristics are given by

$$I = I_o \mathrm{e}^{\frac{-E_g}{kT}} \left(\mathrm{e}^{\frac{eV}{kT}} - 1 \right) \qquad (1)$$

where E_g is the energy gap in the material and I_0 is constant.

What is the approximate size of $\frac{eV}{kT}$ in the experiment? In practice an extra factor *n* may multiply the Boltzmann energy *kT* in this equation. Plot graphs of *V* against ln(*I*) for various fixed temperatures. Also plot graphs of *V* against *T* for some fixed currents and estimate the energy gap E_g.

Questions: Can you explain the physical processes responsible for the resistance of each material and any associated temperature dependence? What might happen in each case if the temperature could be reduced even further? What could a sharp change in resistance at a particular temperature indicate? Which material would work best as a thermometer over the temperature range spanned in this experiment? A qualitative understanding of the results may be found in the references.

5 Essential Precautions

5.1 Liquid Nitrogen

You must wear the personal protective equipment (PPE) provided when handling liquid nitrogen. Use the step and funnel provided when transferring liquid nitrogen into the apparatus. Avoid overfilling the apparatus or spilling liquid nitrogen on your clothes or shoes. Liquid nitrogen can cause very painful burns if it comes into prolonged contact with your skin. There is a metal dipstick provided to measure the level of liquid nitrogen in the apparatus. **Never** touch any metal object (such as the dipstick) that has recently been immersed in liquid nitrogen. A good rule: it isn't safe to touch until the ice has melted. If you have any doubts or queries about handling liquid nitrogen or the apparatus then please consult a demonstrator or technician.

5.2 The Vacuum System

Once a vacuum valve has been closed there is nothing to be gained, and much to be lost, by further tightening. Don't exert too much force. Valves can be closed by turning in a clockwise direction (and anticlockwise to open). Make sure that you close the valve to the helium gas reservoir is always closed before opening the valve to the vacuum pump.

The lab technician is responsible for switching the outer cylinder’s vacuum system on and off. Experimental work should finish each day by **16:45**, to allow time for the diffusion pump of the outer cylinder’s vacuum system to cool during the shut-down procedure.

6 References

[1] G. W. C. Kaye and T. H. Laby, *Tables of Physical and Chemical Constants* (Longman, 1986).

7 Bibliography

J. R. Hook and H. E. Hall, *Solid State Physics* (2nd edition) (John Wiley & Sons, 1991) (Pages 86-96, 149-152).

B. I. Bleaney and B. Bleaney, *Electricity and Magnetism* (3rd edition) (Oxford University Press, 1976) (Pages 353, 528, 567).

Last revised by Dr. Paul Walmsley and Prof. George King, October 2018.

Original version by Dr. Andrew Tyler, revisions by Dr. Ian Duerdoth.