Hall effect in germanium

Principle

The resistance and Hall voltage are measured on rectangular pieces of germanium as a function of the doping of the crystal, temperature and of magnetic field. From the results obtained the energy gap, conductivity, type of charge carrier, carrier concentration and carrier mobility are determined.

There are two parts to this experiment:

1. The band-gap of an undoped sample of germanium will be determined from the conductivity of the sample as a function of temperature.
2. The Hall voltage of both p-type and n-type germanium samples are measured as a function of the current through the sample, magnetic field and temperature.

Theory

The conductivity, σ, of a material is defined as,

$$\sigma = \frac{1}{\rho} = \frac{l}{A}\frac{I}{V} \qquad (1)$$

where ρ = resistivity, l = length of the sample, A = cross sectional area of the sample, I = current and V = voltage. The dimensions of the germanium samples you will be using are 20 mm long by 10mm high by 1mm deep.

The conductivity of a semiconductor is a function of temperature. In an ideal sample three ranges can be distinguished and these are highlighted in figure 1. At low temperatures there is **extrinsic conduction** (range I), i.e. as the temperature rises charge carriers are activated from the impurities, this occurs until all the impurities are activated. At moderate temperatures (range II) there is **impurity depletion,** since all the impurities are activated a further temperature rise no longer produces more impurity generated carriers so the conductivity does not change. At high temperatures (range III) it is **intrinsic conduction** which predominates (see Fig. 3). In this region charge carriers are created by thermal excitation from the valence band to the conduction band. The temperature dependence is in this case described by an exponential function,.

$$\sigma = \sigma_0 \exp\left(-\frac{E_g}{2kT}\right) \qquad (2)$$

Where E_g = energy gap, k = Boltzmann's constant and T = absolute temperature.
Therefore by plotting *ln(σ)* against *1/T* (with T in Kelvin) you should obtain a straight line with a slope, b. Where,

$$b = -\frac{E_g}{2k} \qquad (3)$$

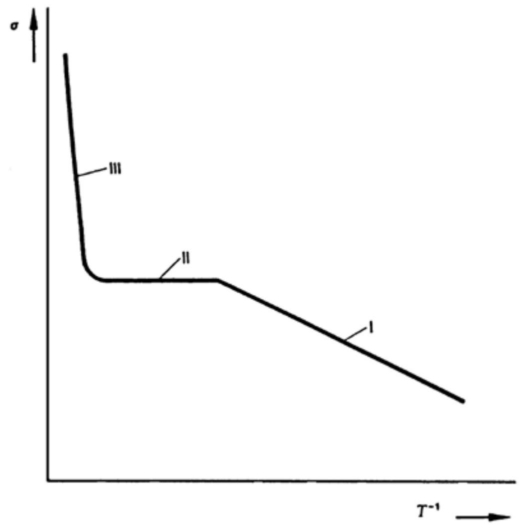

Figure 1. Conductivity of an ideal semi-conductor as a function of the reciprocal of the temperature

If a current *I* flows through a conducting strip of rectangular section and if the strip is traversed by a magnetic field at right angles to the direction of the current, a voltage is produced between the two opposite sides of the strip. This voltage is known as the Hall voltage. See figure 2.

This phenomenon is due to the Lorentz force acting on the charge carriers which are responsible for the current flow through the sample. This Lorentz force deflects the carriers in a direction that is normal to both the direction of the current and the magnetic field, *B*. The force acting on the carriers can be simply determined from the following equation,

$$\vec{F} = e\left(\vec{v} \times \vec{B}\right) \qquad (4)$$

where *F* is the force acting on the charge carriers, *v* is their velocity and *e* is the elementary charge.

Since negative and positive charge carriers (electrons and holes) in a semiconductor move in opposite directions, they are deflected in the same direction. Therefore if one knows the direction of the current and the magnetic field the type of charge carrier (electrons or holes) causing the flow of current can therefore be determined from the polarity of the Hall voltage.

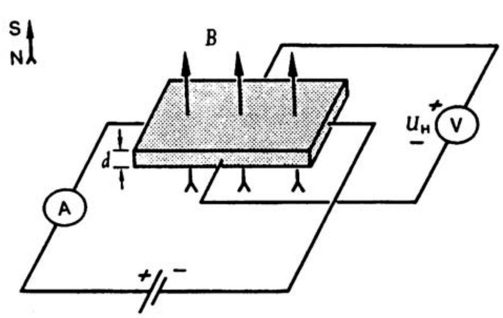

Figure 2. Schematic of the Hall effect.

Part 1: The band gap of undoped (intrinsic) germanium
Tasks

1. The current and voltage are to be measured across a germanium sample as a function of temperature.
2. From the measurements, the conductivity, σ, is calculated and plotted against the reciprocal of the temperature, T. From this graph the energy gap of germanium can be determined.

Set-up and procedure

The undoped Ge sample is put into the hall-effect-module via the guide-groove. The module is directly connected with the 12 VAC output of the power unit through the AC-input on the backside of the module. The voltage across the sample is measured with a voltmeter using the two lower sockets on the front-side of the module. The current and temperature can be easily read on the integrated display of the module. Be sure, that the display is in the temperature mode during the measurement. You can change the mode with the ”Display” knob. At the beginning, set the current to a value of ~5 mA. The current remains constant during the measurement, but the voltage changes with the temperature of the sample. Set the display to the temperature mode. Start the measurement by activating the heating coil with the ”on/off” knob on the backside of the module. Determine the change in voltage with temperature for a temperature range of room temperature to a maximum of 170°C or 140°C, depending on the apparatus you have been given. It is best to let the sample heat up to the maximum temperature first and record data as it cools down.
Determine the band gap, E_g for germanium from your data. The literature value is 0.67 eV. Consider the sources of error in this experiment and record them in you log book.

Part 2: Hall measurements of n-type and p-type germanium
Tasks

1. At room temperature and with a uniform magnetic field measure the Hall voltage as a function of the current through the samples and plot the values on a graph.
2. At room temperature and with a constant current through the sample, measure the voltage across the sample (Sample voltage) as a function of the magnetic flux density, B, and plot the results on a graph.
3. At room temperature, measure the Hall Voltage, V_H, as a function of the magnetic flux density, B. From the readings taken, determine the Hall coefficient, R_H, and the sign of the charge carriers. Also calculate the Hall mobility, μ_H, and the carrier density, n.
4. Measure the Hall voltage, V_H, as a function of temperature at uniform magnetic flux density, B, and plot the readings on a graph.

Set-up and Procedure

Perform all of these measurements with both the n-type and p-type samples.

Place one of the doped germanium samples into the hall-effect-module via the guide-groove. The module is directly connected with the 12 VAC output of the power unit through the ac-input on the backside of the module. The sample has to be placed inside the magnet. Do this very carefully so as not to damage the crystal, in particular avoid bending the board holding the sample or scratching the sample on the magnet. The Hall voltage and the sample voltage (voltage across the sample) are measured with a multimeter. The upper set of sockets are to measure the Hall voltage (marked U_H) and the lower set are to measure the sample voltage. The magnetic flux density has to be measured with the teslameter via a Hall probe, which can be directly put into the hole in the top of the module. To ensure that your measurement of the magnetic flux is measured directly on the germanium sample. Make sure that the teslameter is reading zero when the Hall probe is removed from the magnet.

1. Set the magnetic field to a value of 250 mT by changing the voltage and current on the power supply. Connect the multimeter to the sockets of the hall voltage (V_H) on the front-side of the module. Set the display on the module into the ”current-mode”. Determine the Hall voltage as a function of the current from -60 mA up to 60 mA in steps of ~5 mA. Plot the Hall voltage as a function of the current through the sample.
2. Set the control current to 25mA. Connect the multimeter to the sockets of the sample voltage. Determine the sample voltage as a function of the positive magnetic flux density from 0 to 300mT. Note that the change in sample voltage with magnetic field is very small and hence you will need a lot of precision in the voltage measured. If the sample voltage is greater than 2V lower the current as the 20V range on the meter will not give you sufficient precision to see the effect.
3. Set the current to a value of 30 mA. Connect the multimeter to the sockets of the Hall voltage (V_H) on the front-side of the module. Determine the Hall voltage as a function of the magnetic flux density over the range –300mT to 300mT. Start with -300 mT by changing the polarity of the coil-current and increase the magnetic flux density in steps of ~20 mT. At zero point, you have to change the polarity.
4. Set the current to 30 mA and the magnetic flux density to 300 mT. Determine the Hall voltage as a function of the temperature. Set the display in the temperature mode. Start the measurement by activating the heating coil with the ”on/off” knob on the backside of the module. Make sure you remove the Hall probe before you heat up the sample or else you can damage it.

1. From the results obtained you should be able to see that there is a linear relationship between the current I and the Hall voltage V_B

$$V_H = \alpha I \qquad (5)$$

where α = constant of proportionality.

2. The change in the resistance of the specimen in a magnetic field is related to a decrease in the mean free path of the carriers. Your data should show a non-linear (quadratic) change in resistance with increasing field strength.

3. With the direction of sample current and magnetic field illustrated in figure 5, the charge carriers which produce the current are deflected towards the front edge of the sample. If, therefore, the current is due mainly to electrons the front edge becomes negatively charged whereas if the current is due to holes it becomes positively charged.

The conductivity, σ_0, carrier mobility, μ_H, and the carrier concentration, n are all connected by a factor called the Hall coefficient, R_H.

$$R_H = \frac{V_H}{B}\frac{d}{I} \qquad (6)$$

$$\mu_H = R_H \sigma_0 \qquad (7)$$

$$n = \frac{1}{eR_H} \qquad (8)$$

Plotting the Hall voltage as a function of magnetic flux density, B you should therefore obtain a straight line the gradient of which should give you the Hall coefficient, R_H.

The conductivity of the sample at room temperature calculated from the length, l, of the sample, its cross-sectional area and its resistance, R_0,

$$\sigma_0 = \frac{l}{R_0 A} \qquad (11)$$

Measure the conductivity of the two doped samples (c.f. part 1) and thus calculate the mobilities of the charge carriers and their concentrations in the two samples. Present these values in units of cm^2/Vs for mobility and cm^{-3} for the concentration.

4. From your data on the hall voltage as a function of temperature you should see the Hall voltage decreases with increasing temperature. Since the measurements were taken with a constant current, it can be seen that the increase in the number of charge carriers (transition from extrinsic to intrinsic conduction) causes an associated reduction in the drift velocity. (Equal currents with increased numbers of charge carriers imply reduced drift velocity). The drift velocity is related to the Hall voltage through the Lorentz force.

The current in the crystal is made up of both electrons and holes, moving in opposite directions,

$$I = Ae(v_n n + v_p p) \qquad (10)$$

Since in the intrinsic conduction region the concentrations of electrons, n, and holes, p, are approximately equal, those charge carriers which have the greatest velocity, and hence mobility ($v=\mu E$) will make a greater contribution to the Hall voltage. You might therefore see a reversal of sign for the Hall voltage for the p-type sample as the temperature is increased and the contribution from the intrinsic hole concentration becomes insignificant.